

PROGRESS OF CERAMIC MATRIX COMPOSITES BRAKE MATERIALS FOR AIRCRAFT APPLICATION

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Abstract. Carbon fiber reinforced silicon carbide (C/SiC) brake materials are new highly competitive brake materials. They possess a series of outstanding advantages such as high strength, low density, good high temperature resistance, excellent friction properties, low wear rate and long life. Up to now, it has been equipped in some type of aircraft, and high end cars. The paper presents a brief state of the art of C/SiC brake materials. The attention is focused on manufacturing process, properties and wear mechanisms of C/SiC aircraft brake materials, as well as progress and future of the aircraft brake materials.

1. INTRODUCTION

Aircraft brakes are a key component for aircraft landing and take off safely, which must perform as friction parts to generate required stopping torque under various service environmental conditions, as heat sinks to absorb the kinetic energy of the aircraft and keep lower temperature, and as structural elements to transfer torque to the tyres. The aircraft brakes have experienced the development from organic materials (such as: asbestos fiber reinforced resin matrix composites, non-asbestos organic brake materials), to powder metallurgy materials (such as: copper and iron based metallics) and Carbon/Carbon composites brakes (carbon brakes).

With the rapid development of aviation science and technology, aircraft with a considerable increase in size and weight are observed, for instance A380 and B747-8, while some special types of aircraft demand shorter and shorter landing/take off distance, which result in significantly increased landing and

take off energy. Therefore, the trend in the development focused on brake materials always desire for higher energy adsorptions, and the brake temperatures may be higher than that could be burdened by traditional brake materials (organic and steel brake materials). For the traditional brakes, to bear the high brake energy, the weight of brakes was increased to improve the thermal capacity of the brakes and reduce the brake temperature, which resulted in more fuel consumption and engine emissions.

Till mid-1970s, Dunlop first successfully introduced Carbon/Carbon composites brakes (carbon brakes) on the Concorde [1,2]. Owing to their outstanding mechanical and thermal properties at elevated temperatures, the carbon brakes can deal with the low temperature resistant of the traditional brakes. Moreover, carbon brakes offer significant weight savings compared to steel brakes, which directly contributes to less fuel consumption and

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associated reductions in engine emissions. For example, the carbon brake system on the Boeing 737 NG is 300 kg lighter than the steel design. In addition the carbon brakes have longer lifetime than the traditional brakes. Till now, the carbon brakes became the mainstay of the aircraft brake industry.

However, the carbon brakes suffer from unstable and low friction coefficient under wet condition besides the low average friction coefficient in static or low-speed sliding configuration [3-6]. These disadvantages have been overcome by C/SiC composites brakes, which have also retained the advantages of carbon brakes. With excellent properties such as high and stable friction coefficient, long life, and lower sensibility to surroundings and oxidation [7-11], C/SiC brake materials have been coming into focus as the fourth generation aircraft brake materials.

The aim of this paper is to give an overview of the state of the art in the material processing and properties control of C/SiC brake materials and require a significant effort of research.

2. PROGRESS OF C/SiC BRAKES

A great deal of research interests have been focused on C/SiC brake materials [8,12-17]. In the early 1990s, Krenkel et al. from German Aerospace Center in Stuttgart initiated investigations on C/SiC composites for high performance automobile applications [17]. First prototypes of full-sized brake disks for high speed trains and passenger cars were developed between 1994 and 1997 from the German Aerospace Center in Stuttgart [18]. The C/SiC brake disk was first introduced into the Porsche 911 GT2 in 2001 [19]. The abrasion resistance of the C/SiC disks guarantees a service life of up to 300,000 km for automobiles, which is 4 times greater than that of steel disks [11,12]. And 50% in unsprung weight reduction compared to the steel brakes, which benefit the driving performance, agility, handling, for quicker turns and gas mileage. Currently, more than 100,000 C/SiC brake disks are produced commercially per year by different manufacturers and to be applied in high-end cars [18]. Brembo SGL Carbon Ceramic Brakes is currently the leading producer of C/SiC brake discs, and supplies their products for the most exclusive models.

For high-performance elevators, the temperatures of brake pads under emergency brake condition could be up to 1200 °C, which is far beyond thermal stability and wear resistance limitation of conventional braking materials (organic or powder metallurgy materials). The C/SiC brake materials offer

potential for emergency brakes for elevators and cranes, as shown by Krenkel et al's recent report [20].

The investigation of C/SiC brake materials has been initiated in China since 2001, with the first prototype of full-sized aircraft C/SiC brake disks prepared in early 2005, by Northwestern Polytechnical University and Xi'an Aviation Braking Science and Technology Co., Ltd. in China. In 2008, the C/SiC aircraft brakes were successfully trialled on a certain airplane [21,22]. At present, C/SiC aircraft brakes have been applied in several military airplane types in small batch.

3. MANUFACTURING PROCESS OF C/SiC BRAKES

The typical processes of C/SiC brakes are polymer infiltration and pyrolysis technology (PIP) and liquid silicon infiltration technology (LSI). Each of these processes has advantages and drawbacks that will be briefly discussed as follow.

3.1. PIP process

In the PIP-process, a fiber preform is impregnated with a Si-C precursor, such as polycarbosilanes (PCS) or poly (vinylsilanes) in the molten state or in an organic solution under vacuum by resin transfer moulding (RTM) [23-26]. The pre-impregnated material is cured and pyrolyzed to get the C/SiC composites. The yield of SiC of the precursors is about 65%, therefore, there is a significant shrinkage and residual porosity during pyrolysis. In order to diminish the residual porosity of the ceramic matrix, the infiltration-pyrolysis cycle must be repeated 4-10 times. One way to reduce the number of PIP cycles is to load the liquid polymer precursor with a filler, that can be pure silicon carbide or a mixture of SiC with additives [27-32]. For different shapes, the process could be varied (as shown in Fig. 1).

Currently, the C/SiC brake disks are produced with the PIP process by Starfire Systems in USA. The disks with outstanding frictional properties have been only offered for high end performance cars, like Porsche and Ferrari. Starfire participated in the Ceramic Composite Aircraft Brake (CCAB) program which was funded by the Air Force Research Lab (AFRL) and the Ohio Aerospace Institute (OAI) to develop a ceramic braking system for commercial aircraft. Starfire Systems and finished the preparation and test of sub-scale aircraft brake materials. The full sized testing and optimization design are in progress.

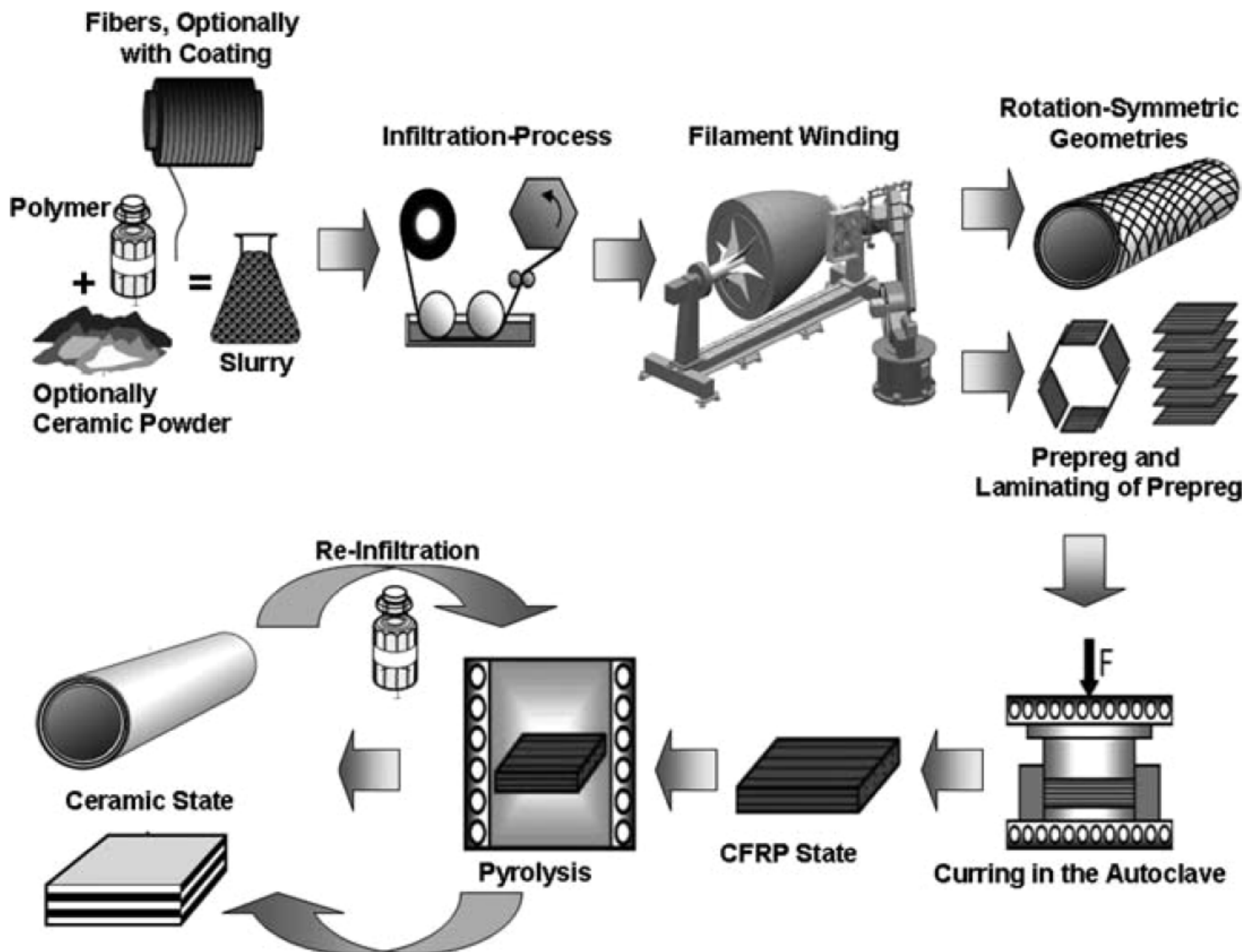


Fig. 1. Schematic flowchart of the PIP process. Reprinted with permission from G. Motz, S. Schmidt, S. Beyer, in *Ceramic Matrix Composites: Fiber Reinforced Ceramics and their Applications* (Eds: W. Krenkel), WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2008, p. 165. © 2008 Wiley-VCH Verlag GmbH & Co. KgaA.

3.2. LSI process

The LSI process (Reactive Melt Infiltration), includes two steps. First step, porous C/C composites were fabricated by chemical vapor infiltration (CVI) or by liquid carbon precursor impregnation/pyrolysis. Second step, under vacuum condition, at above 1420 °C, molten silicon was infiltrated into porous C/C by capillary forces, and reacted with carbon to form SiC. The LSI process is a fast densification technique with low cost, and it yields composites with almost no residual open porosity as well as high thermal conductivity. With so many advantages, LSI process is a competitive process to produce the bulk C/SiC component, and predominant technique for commercial manufacture of C/SiC brakes, including products like short fiber reinforced SiC brake materials and 3D needle-punched C/SiC brake materials [7,9-14,34-49].

3.2.1. Short fiber reinforced SiC brake materials

Fig. 2 shows the LSI process of short fiber reinforced C/SiC composites. The C/SiC composites were prepared by five steps. Firstly the fibers were dipped with resin solution. The second step was chopping process to prepare the infiltrated short fibers. In the third warm pressing process the carbon fiber reinforced polymer (CFRP) green bodies were manufactured, followed by pyrolyzing process to manufacture porous C/C performs at 900 °C under argon atmosphere. And the final step was the LSI process (the molten silicon was infiltrated into porous carbon/carbon and reacted with the carbon matrix.). A photo of the C/SiC brakes for Porsche 911 GT2 is shown in Fig. 3, which is typical short fiber reinforced C/SiC brakes produced by a LSI process, which differs in some steps from the discribed process.

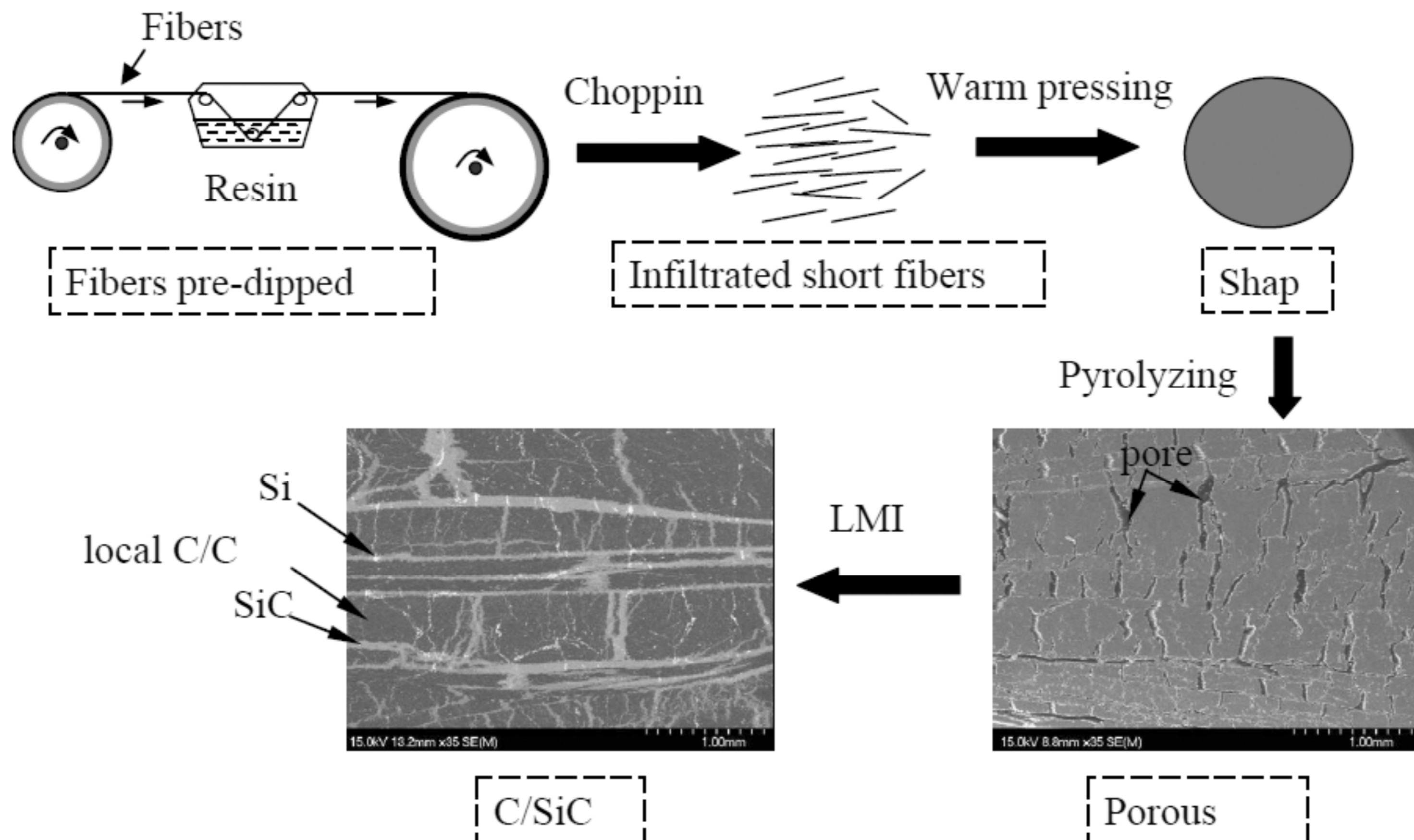


Fig. 2. LSI-process of short fiber reinforced C/SiC composites, see our work [39].



Fig. 3. C/SiC brakes for Porsche 911 GT2 (PCCB, Porsche Ceramic Composite Brake introduced in 2001). Reprinted with permission from W. Krenkel, F. Berndt//Materials Science and Engineering: A, Volume 412, Issues 1–2, (2005)177-181. © 2005 Elsevier B.V.

A number of institutions and companies, such as Stuttgart University, German Aerospace Center, University of Bayreuth and SGL Carbon company in Germany, Brembo Group in Italy, Central South University and Northwestern Polytechnical University (NPU) in China, have been continuously developing short fiber reinforced SiC brake materials, regarding scale-up and cost reduction [7,9,10,13,17,18,34-37,49]. Though Brembo SGL Carbon Ceramic Brakes company (SGL Carbon combined with Brembo Group) is now capable of production for more than 100,000 discs per year,

the costs of the carbon ceramic brakes are still too high and limit their application only to the luxury car. Challenges still lie in further cost reduction to widen the application.

3.2.2. 3D needle-punched C/SiC brake materials

The schematic diagram of preparation process is shown in Fig. 4. Firstly, the carbon fiber preform were prepared by the three-dimensional needling technique. Then, the porous C/C composites were prepared by CVI process. At last, C/SiC composites were prepared by LSI process.

This process was used by Surface Transforms Public Limited Company in United Kingdom, and NPU in China to produce the C/SiC brake materials. Surface Transforms' products are mainly applied to the luxury car, and they declared that it's next-generation carbon-ceramic materials are ideally suited for aircraft brake applications. NPU's brakes have been applied to several type aircraft. Fig. 5 is a type of C/SiC aircraft brakes made by NPU.

4. PROPERTIES AND WEAR MECHANISMS OF C/SiC AIRCRAFT BRAKES

4.1. Properties of C/SiC aircraft brakes

As structural and frictional elements, as well as heat sinks, aircraft brake materials should possess good frictional properties, mechanical properties, and ther-

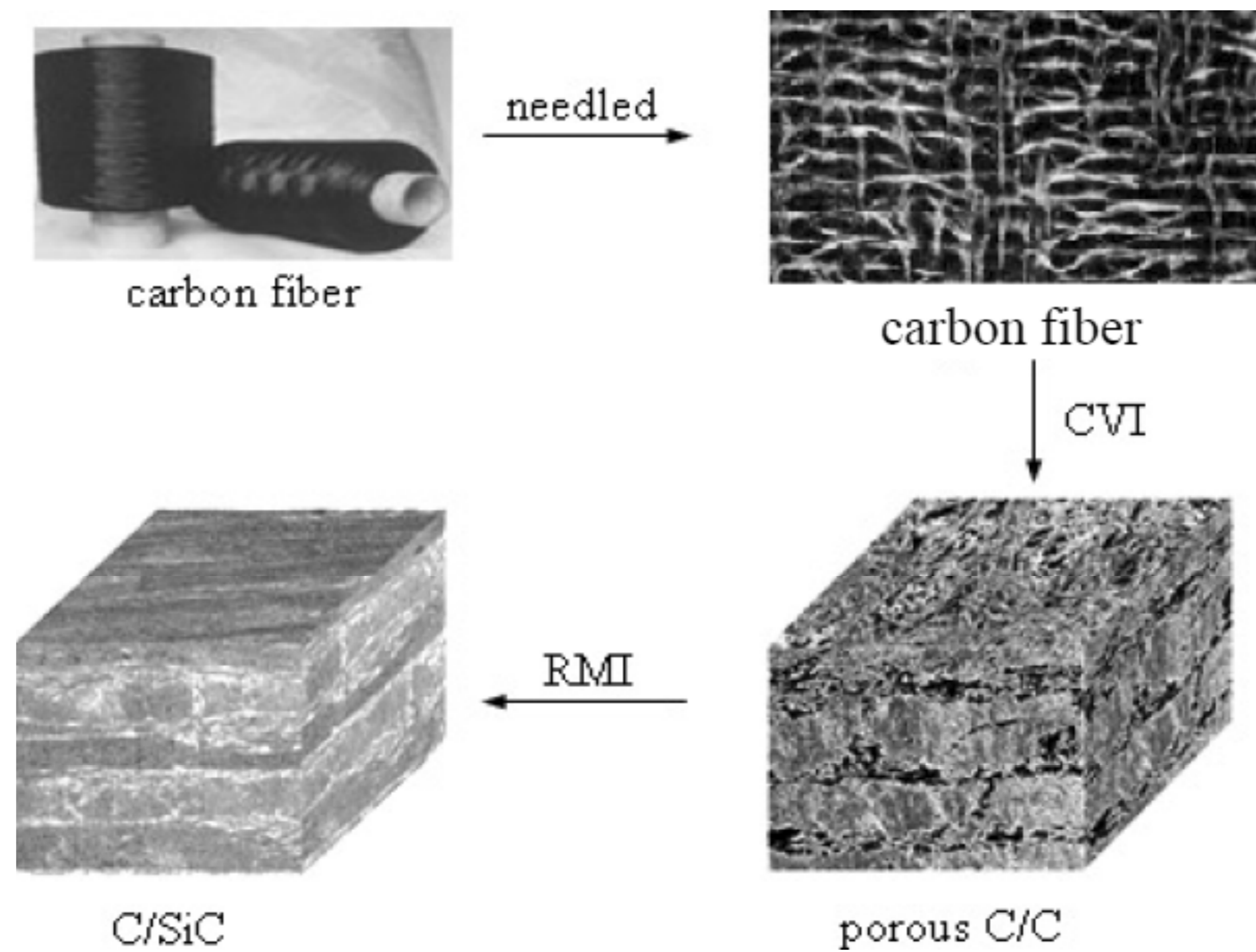


Fig. 4. Preparation process of 3D needed C/SiC composites, see our work [57].

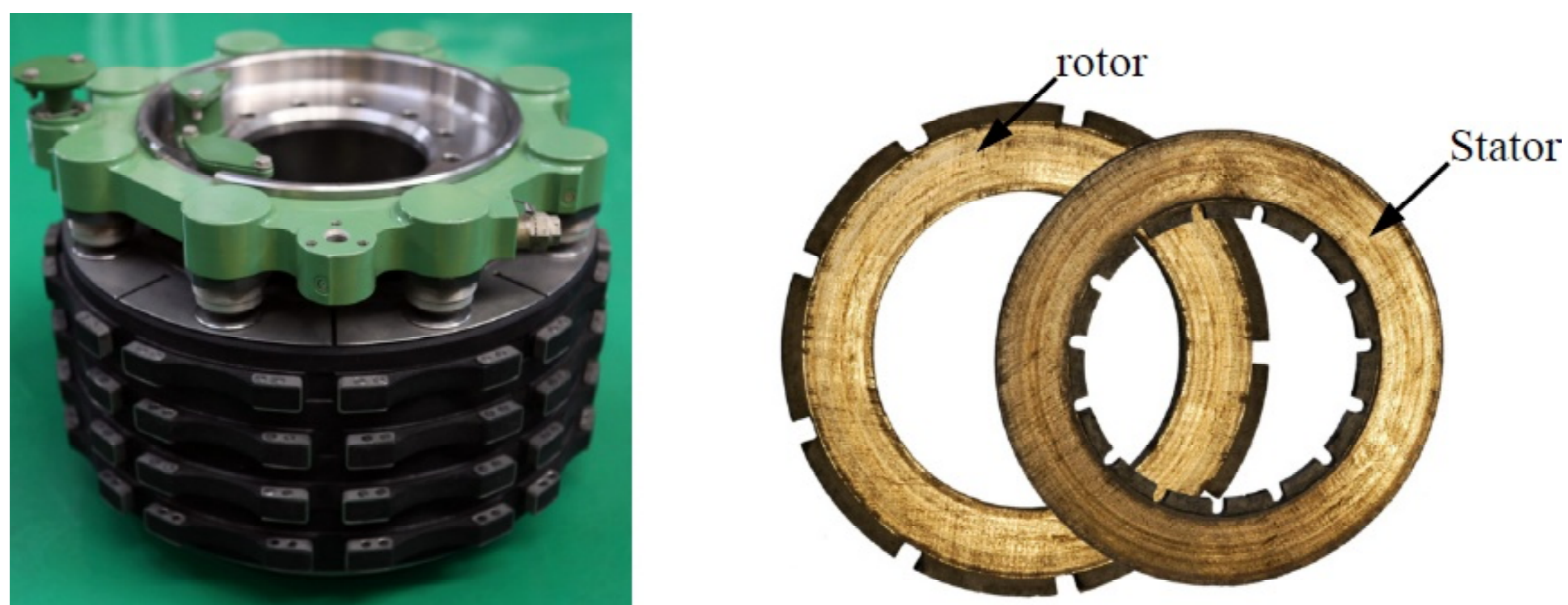


Fig. 5. A type of C/SiC aircraft brakes.

mal properties. The mechanical and thermal properties of the C/SiC brake materials are listed in Table 1. From Table 1, it indicated that 3D needle-punched C/SiC brake materials were more reliable than short fiber C/SiC for aircraft application.

The frictional properties of the 3D needed brake materials are listed in Table 2. Compared with 3D needed C/C aircraft brake materials, the C/SiC brakes exhibit high static friction coefficient, low wear rate, and lower sensibility to wet conditions.

Table 1. Mechanical and thermal properties of the C/SiC and C/C brake materials [12,14,22].

	3D needle-punched C/SiC(NPU)	short firber C/SiC(SGL)	C/C aircraft brake materials
Density(g/cm ³)	2.1±0.1	2.3-2.4	1.72-1.78
Tensile Strength (MPa)	145±35	20-40	—
Compressive Strength (MPa)	260±41	—	120-140
Flexural Strength (MPa)	165±30	80	60-90
Inter-laminar Shear Strength (MPa)	22±5	—	7.5-11.5
Thermal conductivity W/(mK)	40~80	40	45-110
Specific heat capacity J/(kgK)	1085-1685	800-1200	1200-1500
	(at 100-900 °C)	(at RT-1200 °C)	
Coefficient of Thermal Expansion (10 ⁻⁶ /K)	1.75- 4.41	1.8-3.0	—
	(at RT-1300 °C)	(at RT-1200 °C)	

Table 2. Friction and wear properties of 3D Needled C/C and C/SiC aircraft brakes, data from [51].

	dynamic friction coefficient			static friction coefficient	linear wear rate / (mm·side ⁻¹ ·cycle ⁻¹)
	dry	fresh water	sea water		
C/C	0.26~0.45	0.13~0.16	0.10~0.16	0.16~0.21	0.8~1.0
C/SiC	0.27~0.35	0.29~0.35	0.24~0.29	0.46~0.58	0.6~1.4

The typical braking curve of the 3D needled C/SiC materials under normal landing condition (NL) showed an upended trapezium shape (as shown in Fig. 6). The relation between brake moment and brake speed of the braking under NL condition matched the landing response of aircraft with anti-skid braking system, which would bring a higher brake efficiency[13].

4.2. Wear mechanisms of the C/SiC aircraft brakes

The main wear mechanisms of the 3D needled C/SiC brake materials prepared by CVI combined with LSI included grain-abrasion, oxidation-abrasion, fatigue wear, and adhesive wear. These wear mechanisms always simultaneously occurred and interacted between them [22]. The grain-abrasion, oxidation-abrasion and fatigue wear, were not inevitable. The grain-abrasion is beneficial to improve the frictional properties but would increase the wear in the meanwhile. Therefore, the SiC content and grain size of the C/SiC should be controlled.

The adhesive wear was uncontrolled wear style and very harmful to the tribological properties. The temperature of the friction surface was very high and sometimes exceeded the melting temperature of Si (1420 °C) during braking, so that the Si phase of the friction surface may be softened when braking, which could generate adhesion and lead to material trans-

fer (Fig. 7a). The adhesive wear could result in severe wear and grooves on the surface (Fig. 7b). Under the adhesive wear condition, the brake moment was abruptly enhanced at the end of the braking (as shown in Fig. 8), which led to unstable frictional properties.

When the Si in the C/SiC brake materials was removed, the adhesive wear didn't happen again, the friction surface was smooth, and the braking moment was not enhanced severely at the end of the braking (Fig. 9). It is indicated that the Si in the C/SiC brake materials is a significant factor in the adhesive wear.

When the Si content reached some point, the rotor and stator could stick together after braking, which lead to the wheel of the aircraft could not run. If the brake disks stick together after the aircraft taxi braking and land off, the disaster would happen during landing. Adhesive wear could cause a serious wear rate, a huge unstable friction coefficient,

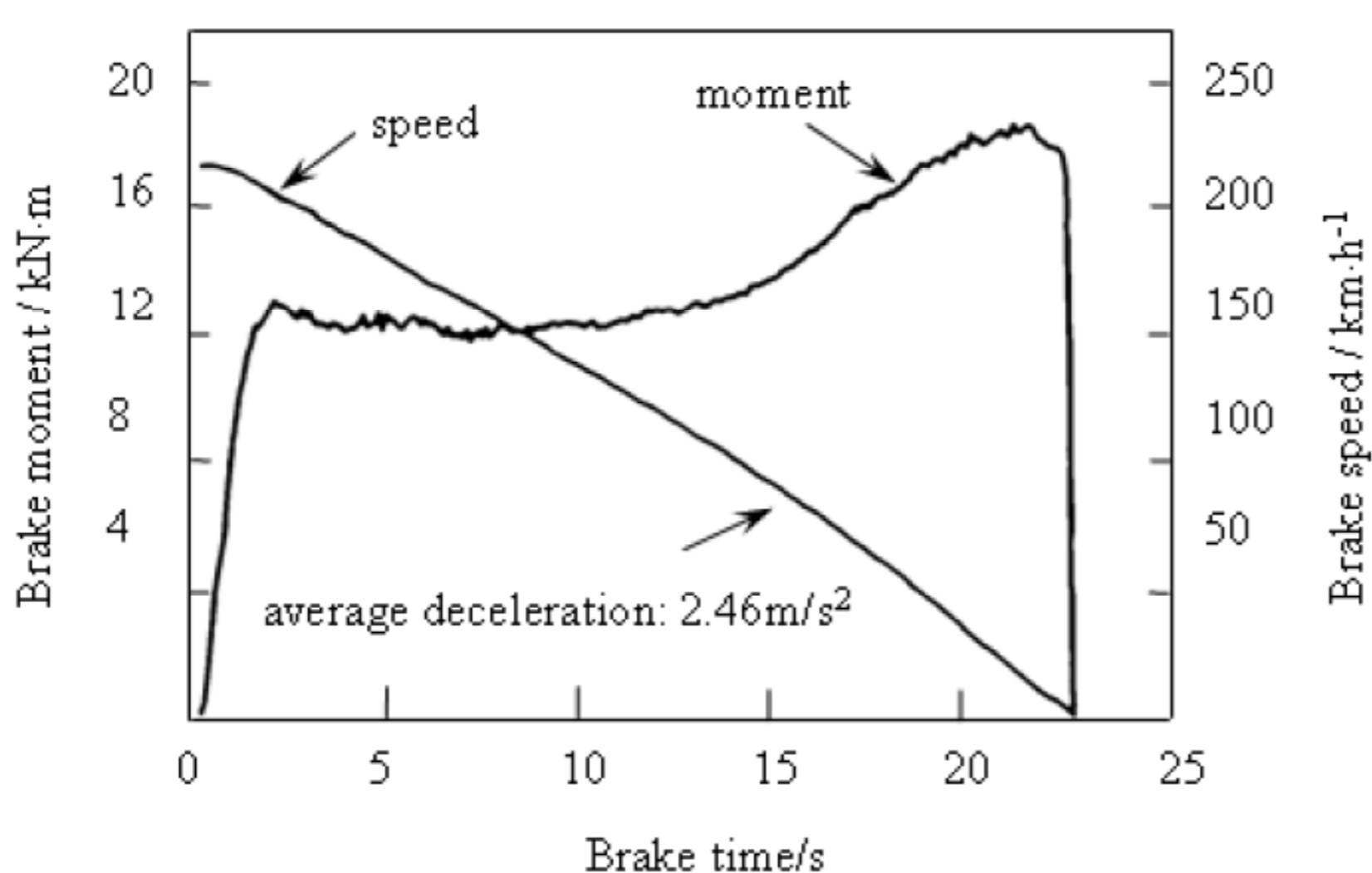


Fig. 6. Typical braking curve of C/SiC brake materials under dry normal landing condition, see our work [13].

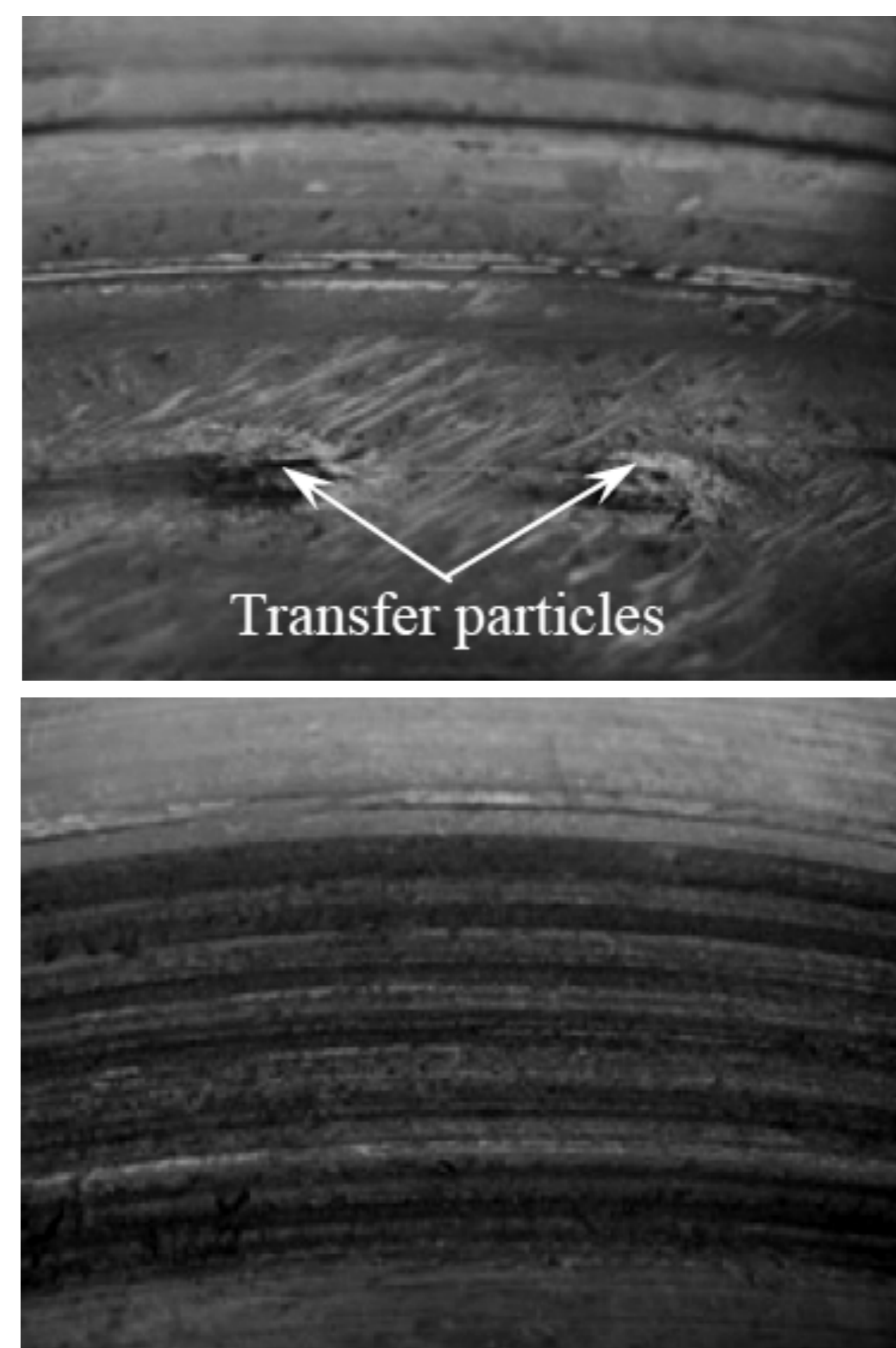


Fig. 7. The typical macrostructures of the friction surface formed by adhesive wear of the C/SiC brake materials: (a) transfer particles in friction surface, (b) grooves of the friction surface, see our work [22].

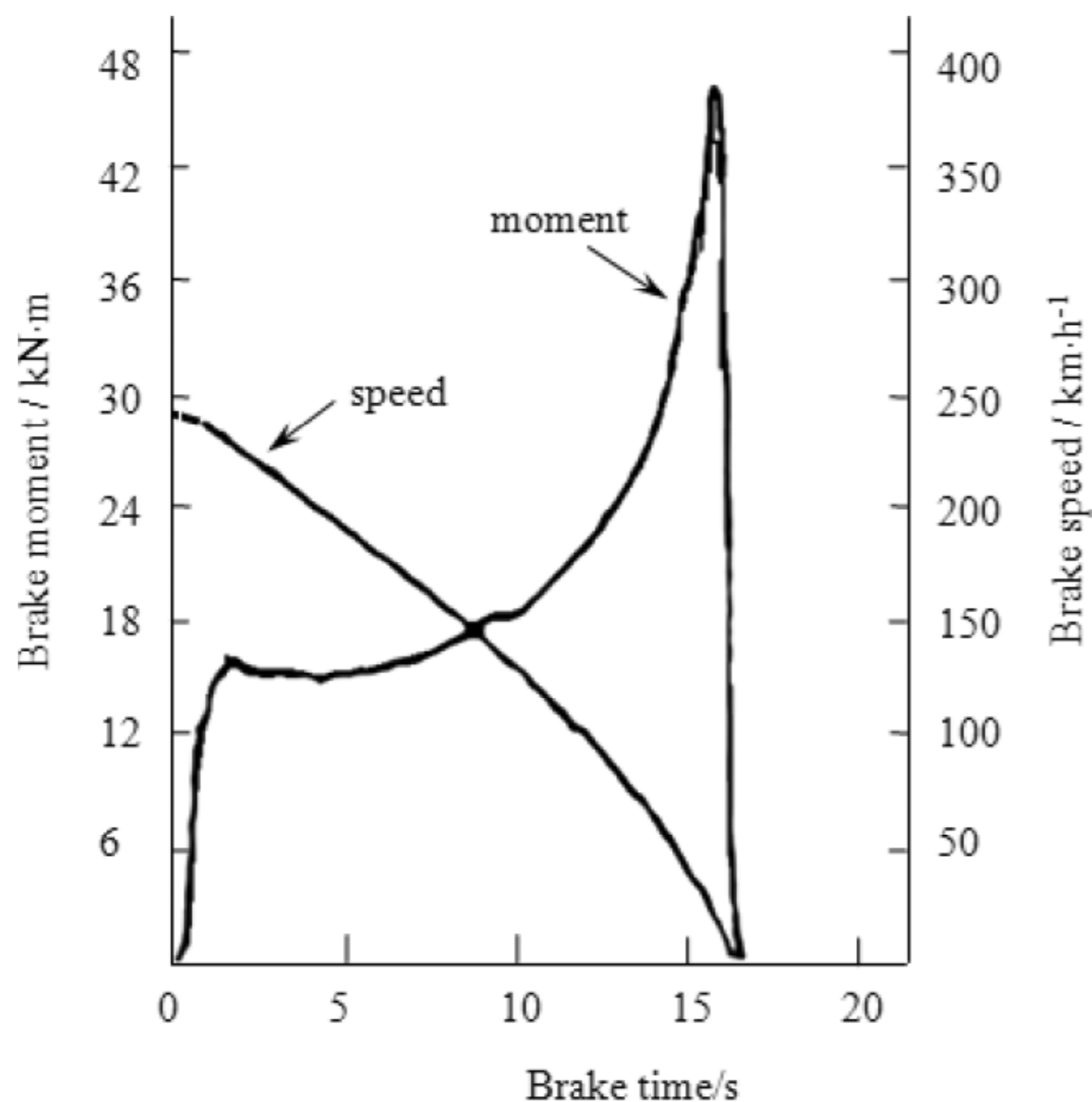


Fig. 8. The typical braking curve under the adhesive wear condition, see our work [22].

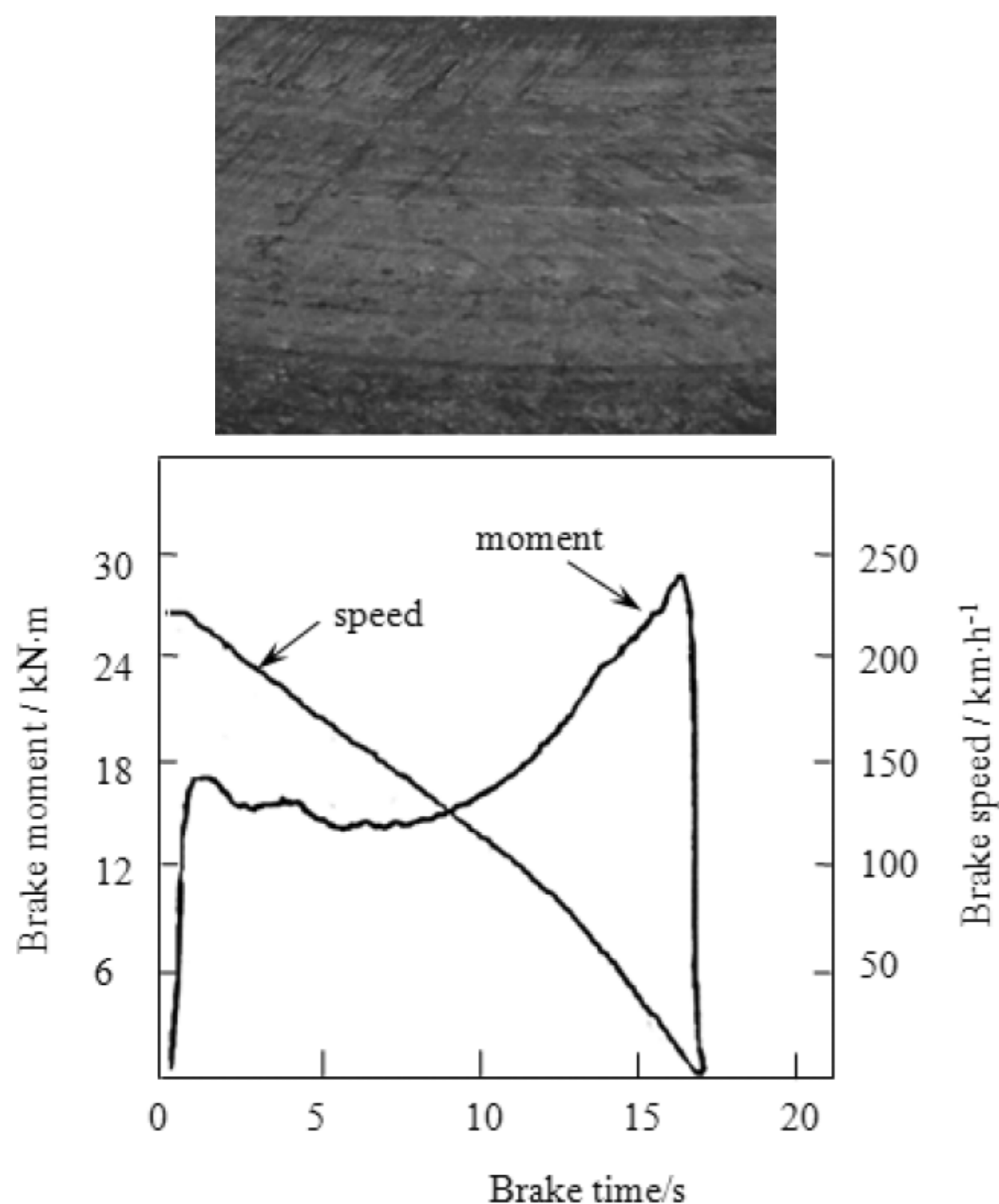


Fig. 9. The macrostructure of friction surface and braking curve for C/SiC brake materials (Si was removed): (a) macrostructure of friction surface, (b) braking curve, see our work [22].

and even disaster, so that the Si content in the C/SiC brake materials must be controlled.

5. PROGRESS OF C/SiC AIRCRAFT BRAKES

At present, the structure of the C/SiC aircraft brakes was 3D needed structure. The 3D needed C/SiC

brake materials prepared by CVI combined with LSI containing about 8 wt% Si, and the silicon showed clumped distribution (as shown in Fig. 10). When the braking energy was high enough, adhesive wear would happen and result in unstable frictional properties. In theory, lower content and well dispersed Si could improve the friction properties. The methods to decrease and disperse the Si would be presented as following.

5.1. C/SiC brake materials with sandwich structure

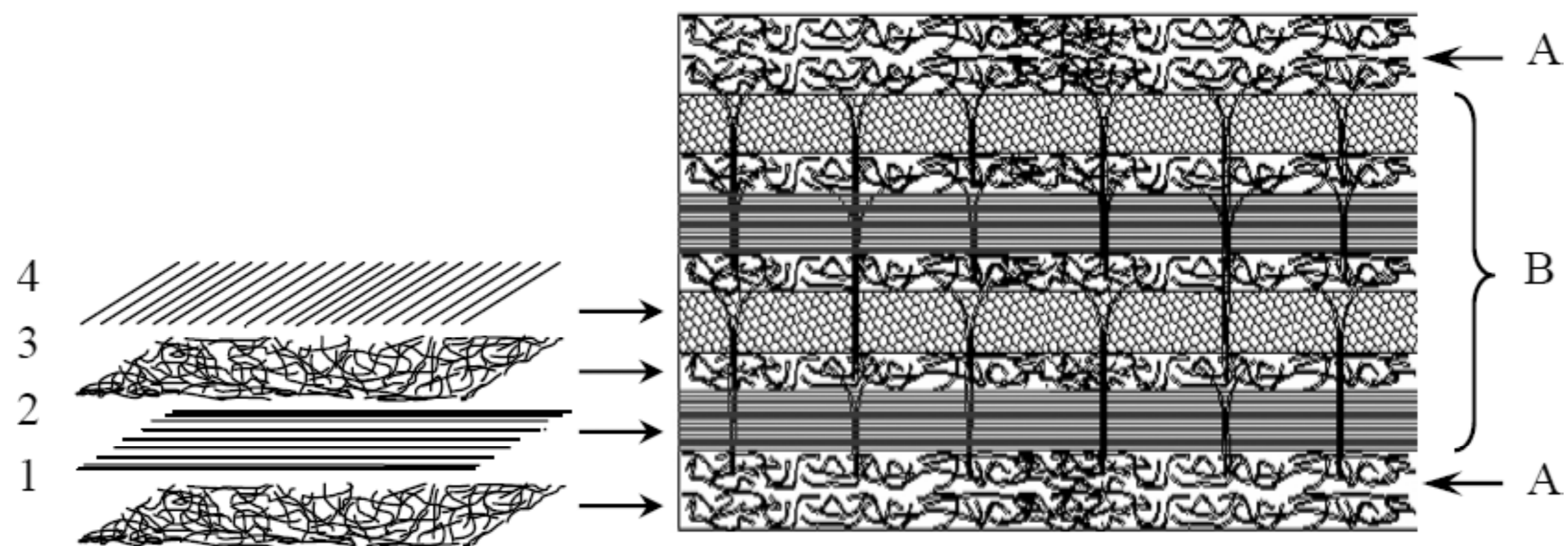
For improving the phases distributed well in the materials, the C/SiC brake materials with a sandwich structure were developed. The sandwich structure material was composed of two outer functional layers for friction, and a inner mechanical functional layer.

The C/SiC brake materials with a sandwich structure have been prepared by a combined process of the chemical vapor infiltration, graphite slurry infiltration and the liquid silicon infiltration process with 3D needed carbon fiber preform with sandwich structure (as shown in Fig.11). The phase distribution in the functional layers for friction is homogeneous, with fewer Si in the friction functional layers (as shown in Figs. 12 and 13), which is 2 wt.% compared to 4 wt.% in the mechanical layer, both well dispersed. The mechanical layer was dense to supply enough mechanical properties.

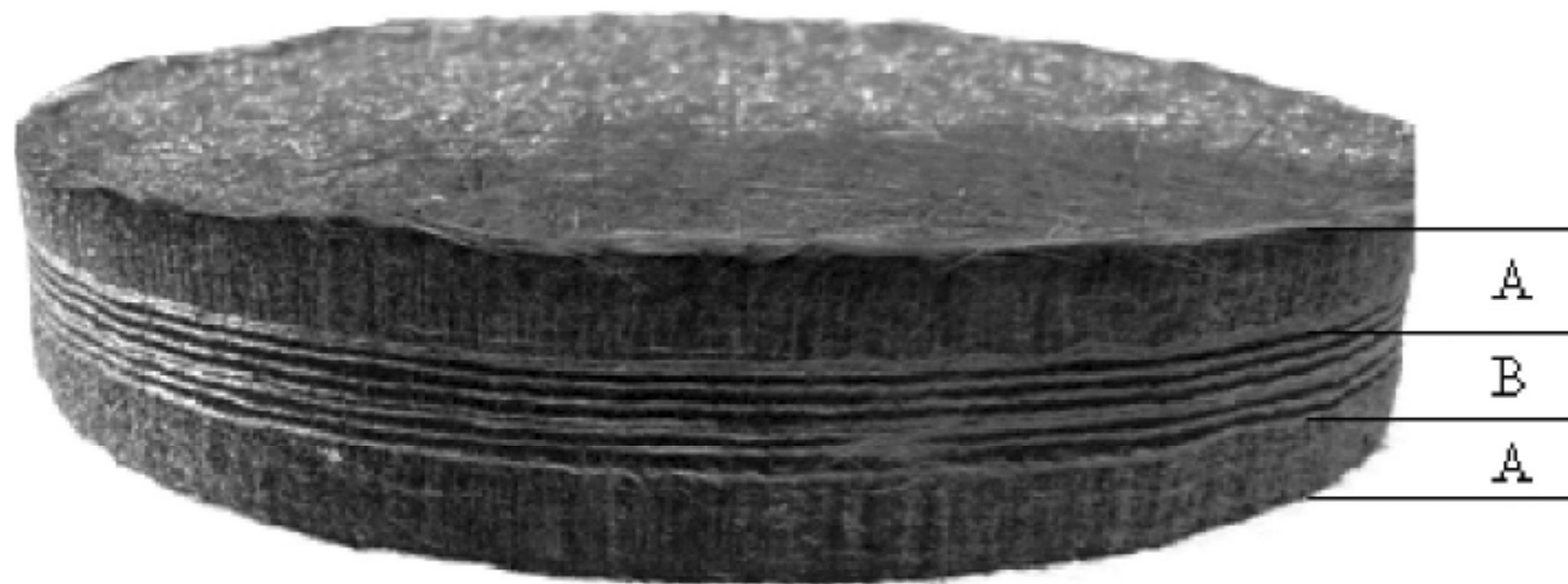
Fig. 14 is the typical braking curves of 3D needed C/SiC and C/SiC with sandwich structure brake materials. It showed that the braking was smoother for C/SiC with sandwich structure than that for the 3D needed C/SiC. The frictional properties of the 3D needed C/SiC and C/SiC with sandwich structure are listed in Table 3. It indicated that



Fig. 10. The BSE micrographs of the 3D needed C/SiC unmodified with graphite. SiC: in grey regions, Si: in white regions, and pyrolytic carbon and carbon fibers: in black regions, see our work [43].



(a) Schematic diagram



(b) Macro photograph

Fig. 11. 3D needed carbon fiber preform with sandwich structure. 1 and 3 were short-cut fiber web, 2 was 0° non-woven fiber cloth, and 4 was 90° non-woven fiber cloth. A was functional layer for friction, and B was mechanical functional layer for load-carrying, see our work [44].

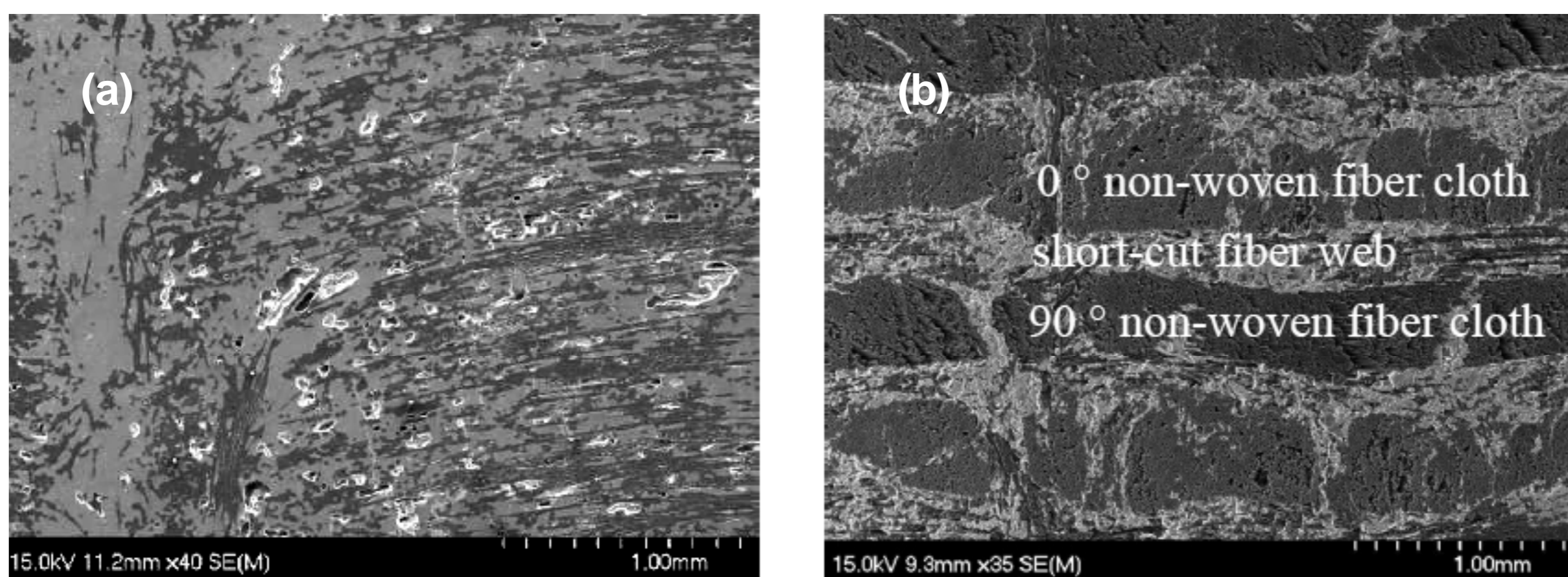


Fig. 12. The SEM micrographs of the 3D needed C/SiC with sandwich structure: (a) functional layer for friction, (b) mechanical functional layer, see our work [44].

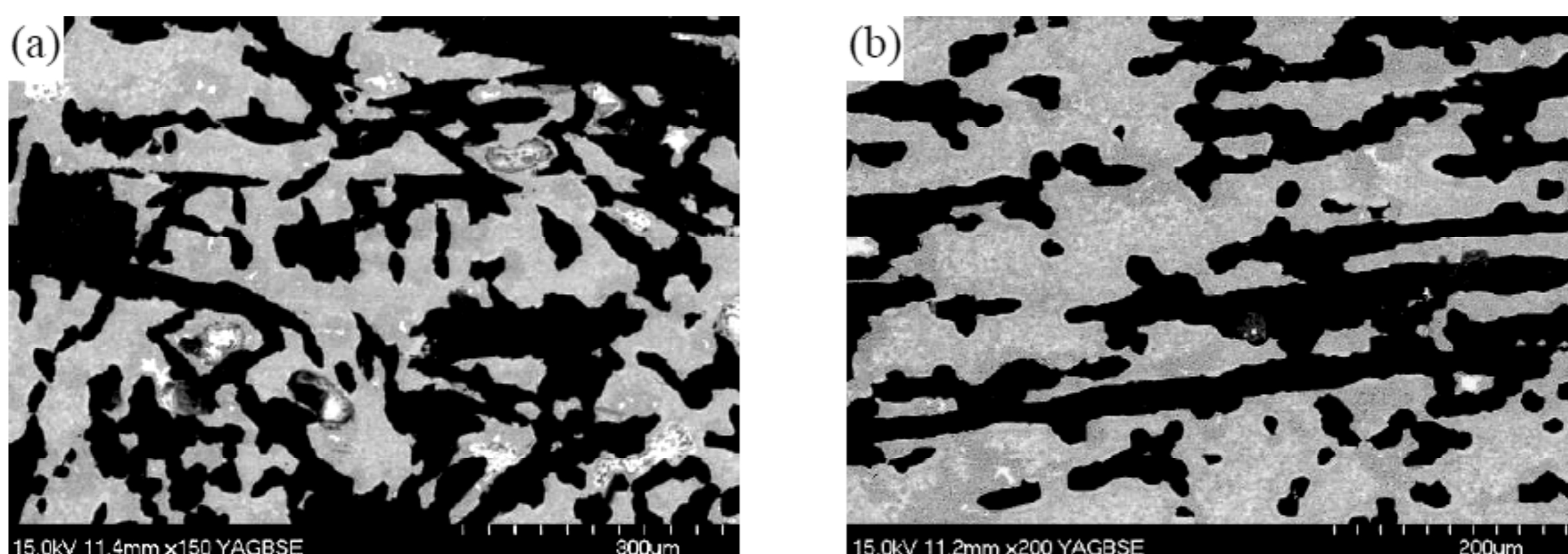


Fig. 13. The BSE micrographs of the functional layer for friction. (a) parallel to the non-woven fiber cloth layers, (b) perpendicular to the non-woven fiber cloth layers. SiC: in grey regions, Si: in white regions, and pyrolytic carbon and carbon fibers: in black regions, see our work [44].

frictional properties under wet condition of the C/SiC with sandwich structure was better than that of the 3D needled C/SiC. And the static friction coefficient of the C/SiC with sandwich structure was higher than that of the 3D needled C/SiC.

5.2. C/SiC brake materials modified with graphite

The 3D needled C/SiC brake materials modified with graphite was a good method to lower the Si content and improve the Si distribution in the materials prepared with LSI process [43]. The materials modified with graphite were composed of ~59 wt.% C, ~39 wt.% SiC, and ~2 wt.% Si. The content of the Si in the materials modified with graphite was far less than that (about 8 wt.%) in the unmodified C/SiC brake materials, and the Si was well dispersed (as shown in Fig. 15). The braking of the C/SiC modified with graphite was smooth (as shown in Fig. 16), which can decrease the impact force to the landing gear. The frictional properties under wet condition of the 3D needled C/SiC modified with graphite showed no fading. And the linear wear rate of the C/SiC modified with graphite was lower than that of the unmodified C/SiC (as shown in Table 4).

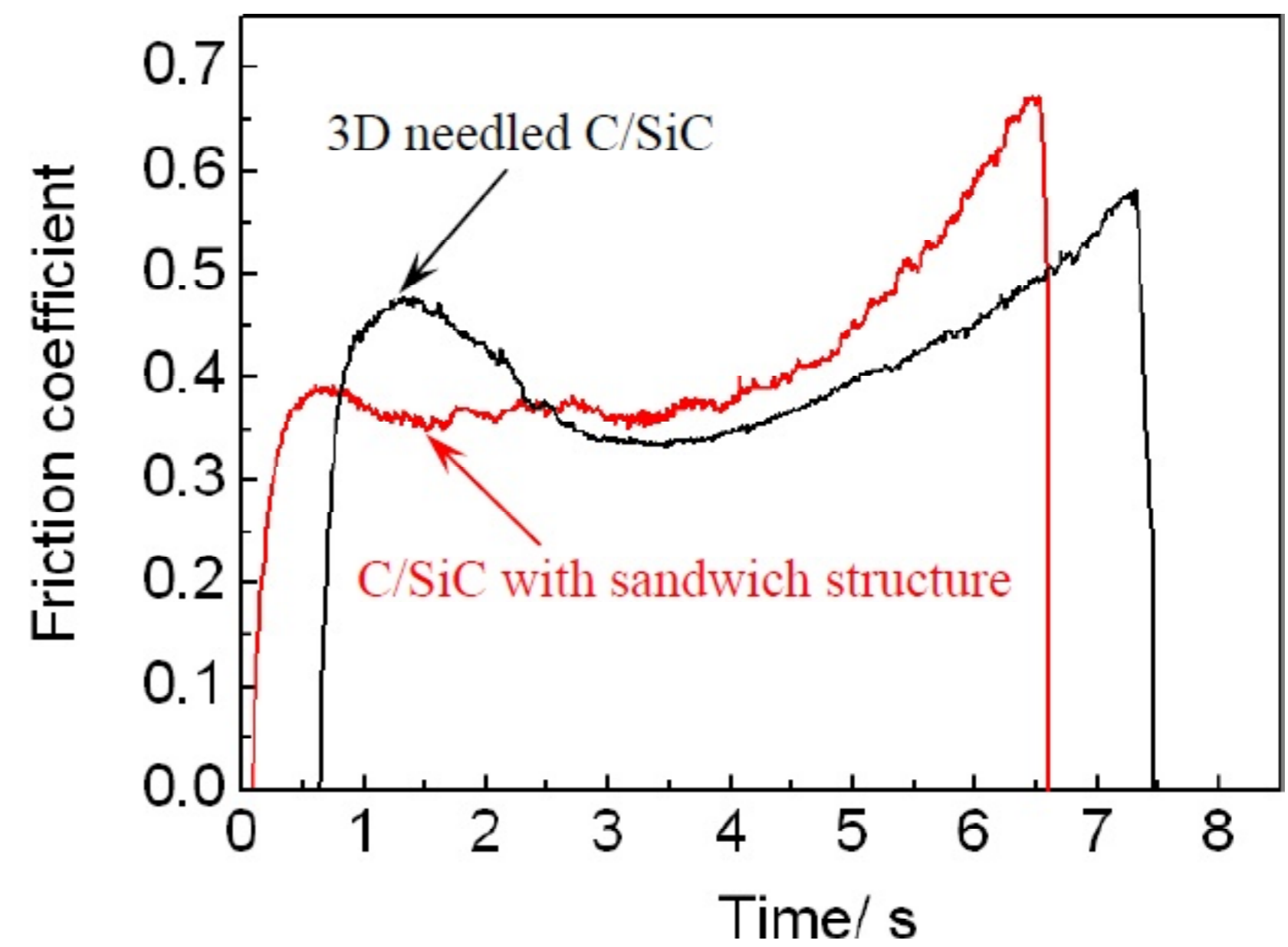


Fig. 14. Typical braking curves of 3D needled C/SiC and C/SiC with sandwich structure brake materials, see our work [44].

5.3. C/SiC brake materials modified with Ti₃SiC₂

In order to decrease the Si content in the LSI C/C-SiC composites, a porous C/C was infiltrated with TiC slurry, then was infiltrated with liquid silicon, resulting in the formation of C/SiC-Ti₃SiC₂ composites. The C/SiC-Ti₃SiC₂ was composed of 73 vol.%

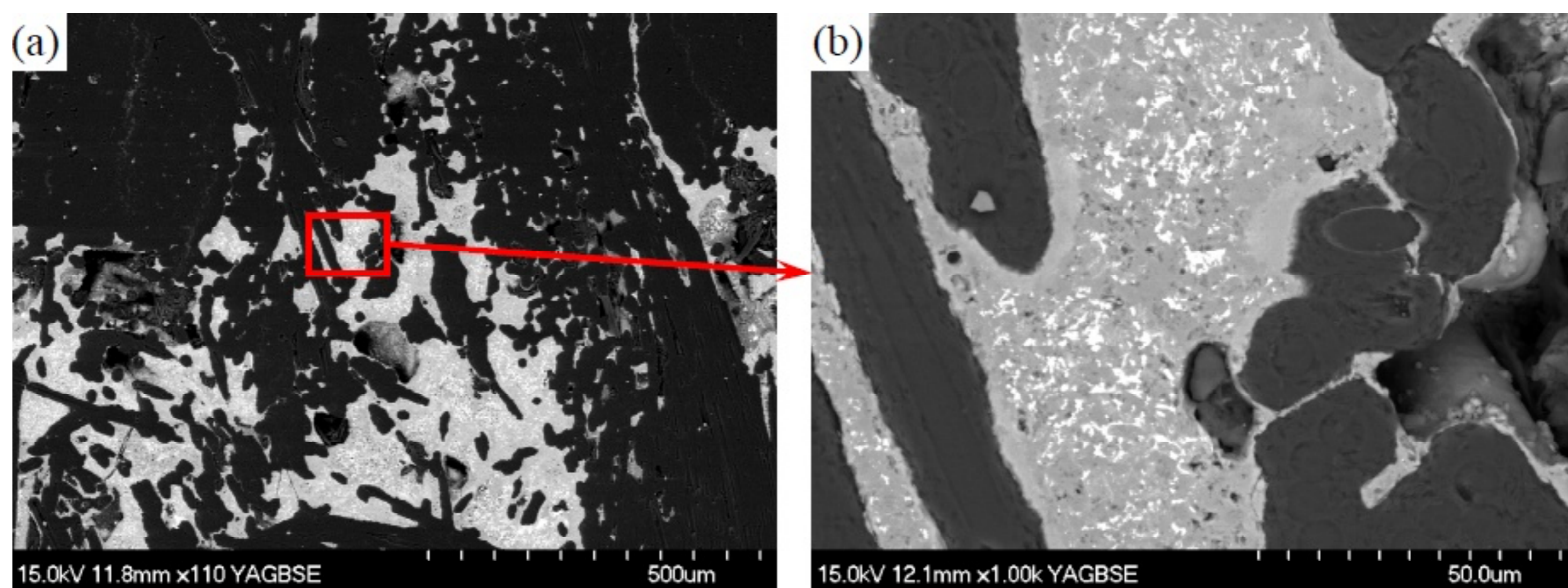


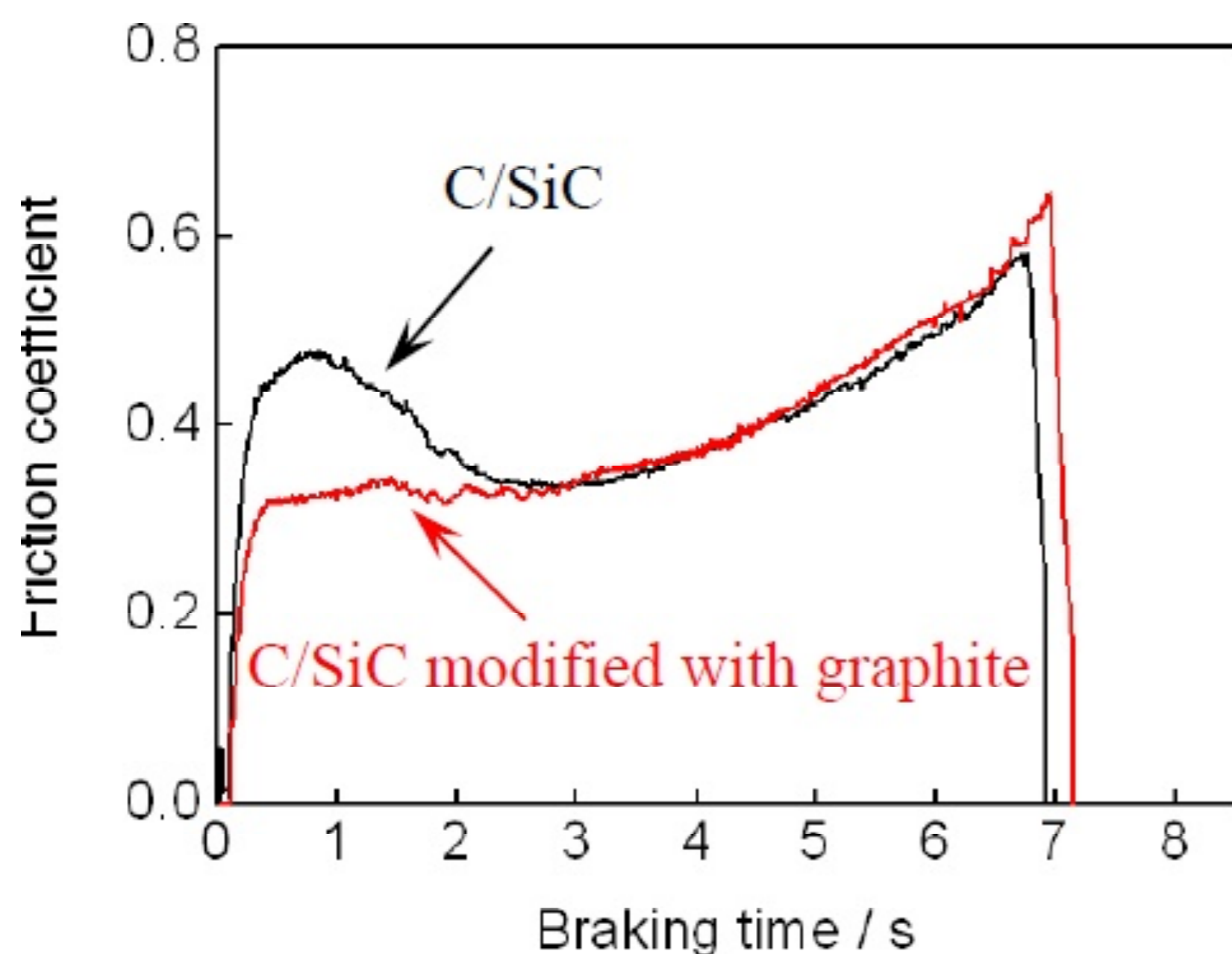
Fig. 15. The BSE micrographs of the 3D needled C/SiC brake materials modified with graphite. (a) the typical BSE micrographs, (b) amplification of local region in (a). SiC: in grey regions, Si: in white regions, and pyrolytic carbon and carbon fibers: in black regions, see our work [43].

Table 3. The frictional properties of the 3D needled C/SiC and C/SiC with sandwich structure, data from [40].

	Friction coefficient		Wet fading ratio D/%	Static friction coefficient	Linear wear rate / ($\mu\text{m}/\text{side}\cdot\text{cycle}$)
	dry	wet			
C/SiC with sandwich structure	0.36	0.36	0	0.79~0.87	2.48
3D needled C/SiC	0.38	0.34	10	0.45~0.68	2.16

Table 4. The frictional properties of the 3D needed C/SiC brake materials, data from [43].

3D needed C/SiC brake materials	Average friction coefficient		Wet fading ratio D/%	Static friction coefficient	Linear wear rate /($\mu\text{m}/\text{side}\cdot\text{cycle}$)
	dry	wet			
Modified with graphite	0.34	0.34	0	0.45 ~0.51	1.40
No modified	0.38	0.34	10	0.45~0.68	2.16

**Fig. 16.** Typical braking curves of 3D needed C/SiC brake materials, see our work [44].

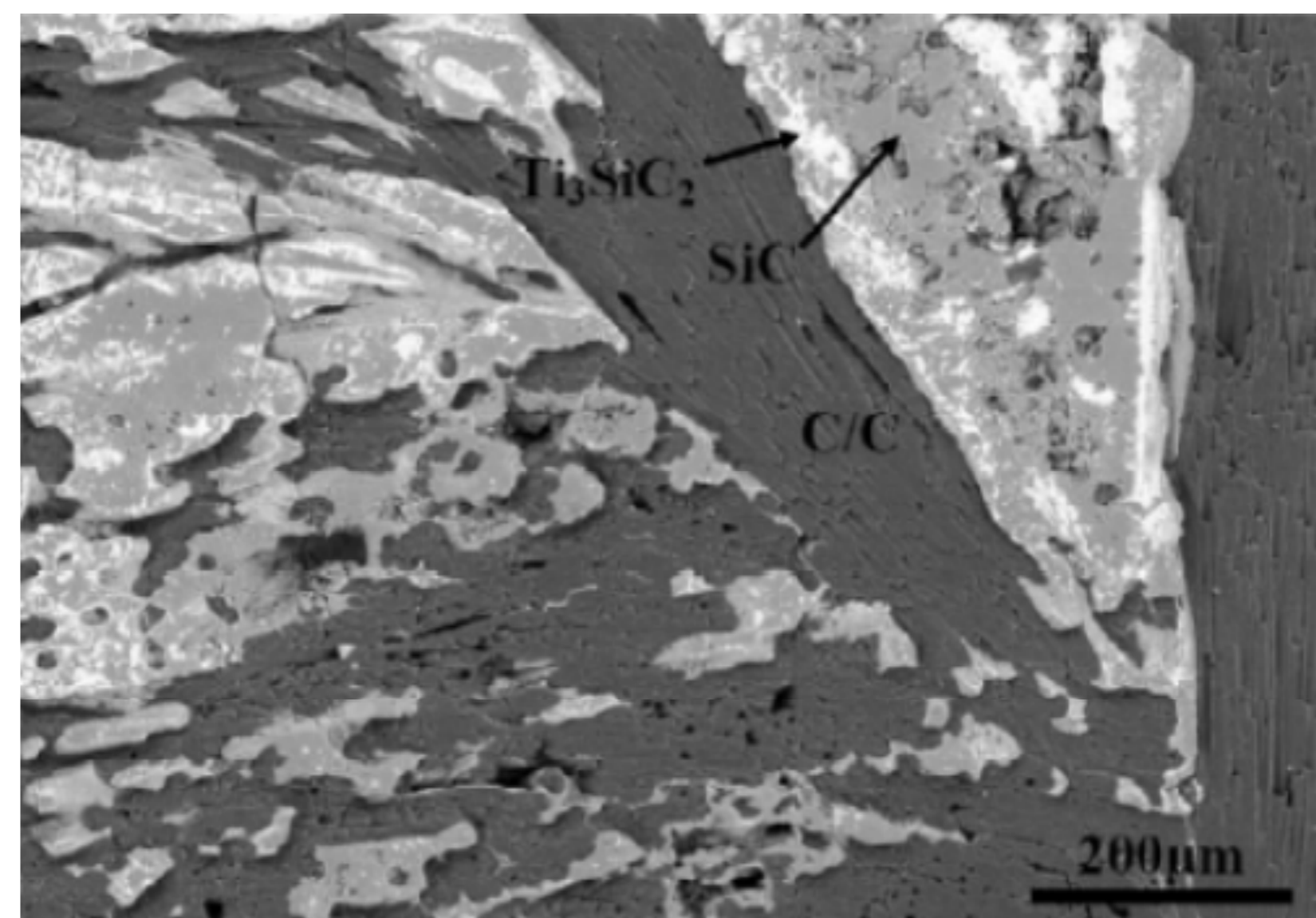
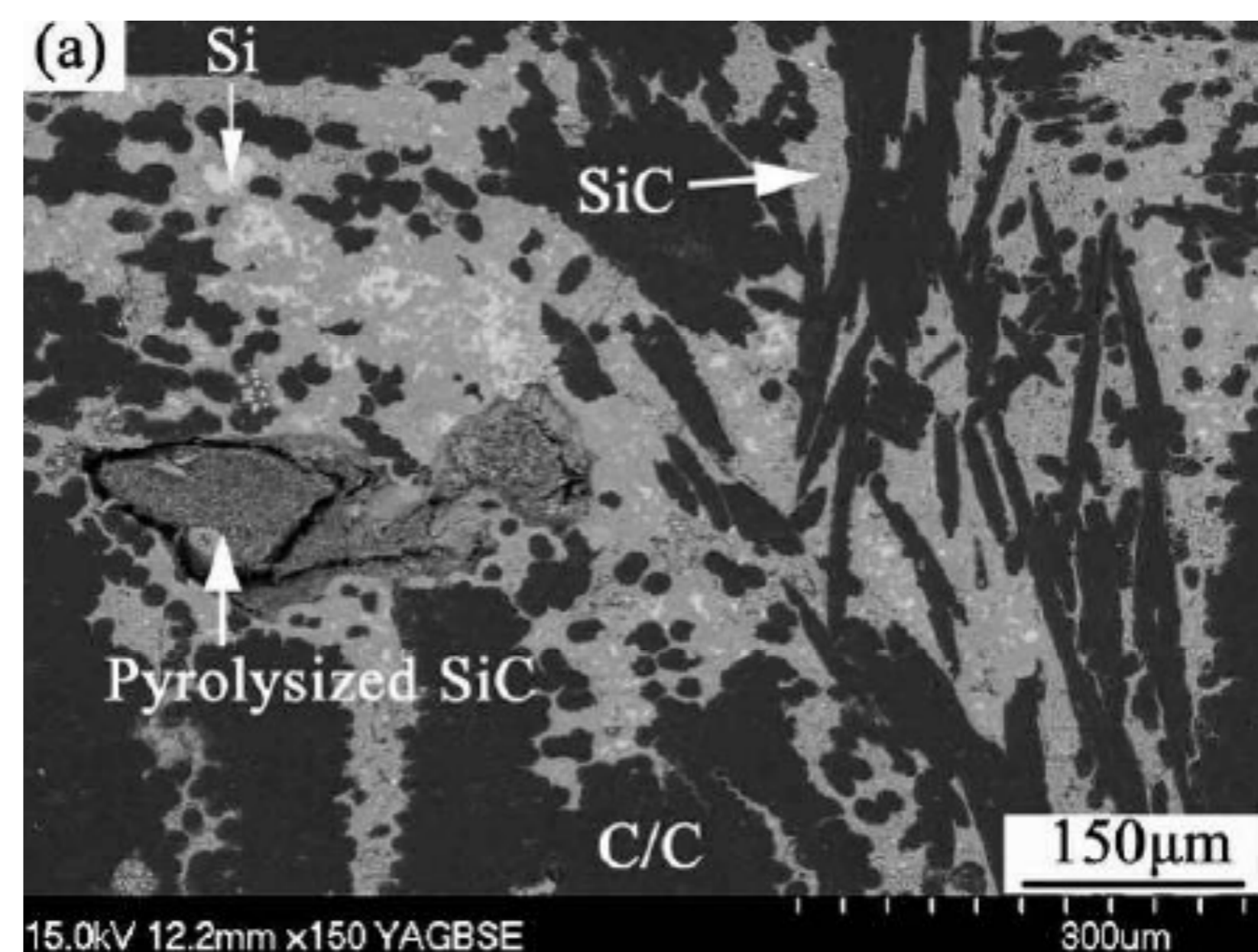
carbon, 22 vol.% SiC, 5 vol.% Ti_3SiC_2 , and 0 vol.% Si. The backscattered electron image of C/SiC- Ti_3SiC_2 was shown in Fig. 17. The C/SiC- Ti_3SiC_2 had not only higher friction stability coefficient but also much higher wear resistance than C/C-SiC fabricated by CVI combined with LSI. Meanwhile, it eliminated the adhesive wear [52].

5.4. C/SiC brake materials modified with PIP-SiC

In order to reduce and disperse residual free Si in the LSI C/C-SiC composites, a porous C/C was infiltrated with liquid polycarbosilanes (PCS), pyrolysed and derived SiC (PIP-SiC), then was infiltrated with liquid silicon, and formed C/SiC composites. PIP-SiC can effectively disperse the residual Si introduced by LSI. Moreover, the residual Si can react with free carbon existed in PIP-SiC, which help to reduce the silicon content. The residual Si content was about 6.6 wt.%. The backscattered electron image of the C/SiC modified with PIP-SiC was shown in Fig. 18. It was found that the content of Si in the C/SiC modified with PIP-SiC was low and well dispersed. The C/SiC modified with PIP-SiC exhibited not only improved the friction stability but also eliminated adhesive wear [53].

6. FUTURE OF THE C/SiC BRAKE MATERIALS

Though the C/SiC brake materials have been applied in several aircraft and some high end cars, the relationship between structure and properties of C/SiC brakes remains unknown. More efforts need to be invested to understand the effects of composition/structure of the C/SiC brake materials on the mechanical properties, thermal physical properties, tribological properties (under all possible service

**Fig. 17.** Backscattered electron (BSE) image of C/SiC- Ti_3SiC_2 . Reprinted with permission from X. Fan, X. Yin, S. He, L. Zhang, L. Cheng // Wear.274-275(2012)188. © 2011 Elsevier B.V.**Fig. 18.** Backscattered electron (BSE) image of C/SiC modified with PIP-SiC.

condition), develop database on the composition/structure and performance of C/SiC brake materials, and realize the designability of the properties. Since the performance requirement differs for different type of aircraft, with the database, the C/SiC brake materials could be tailored to suit the application. And the C/SiC brakes also show high potential to be applied to high speed train, heavy vehicles, emergency brakes for elevators and cranes, and so on.

Many creative idea should be produced to improve the properties, lower the cost of the C/SiC brakes. For example, C/SiC modified by FeSi75 [54], Ti₃SiC₂ [52], and graphite [43] could improve the frictional properties; the sandwich structure [40,55,56] is an excellent idea to realize the mechanical structure and frictional function integration design.

7. SUMMARY

This paper presents a brief review on the state of the art of advanced ceramic matrix composites aircraft brake materials. The progress and the typical processes of C/SiC brakes are introduced first, followed by focus on manufacturing process, properties and wear mechanisms of C/SiC aircraft brake materials, as well as progress and future of the aircraft brake materials. From the above review, some conclusions are drawn as following:

(1) The mechanical and thermal properties of the 3D needle-punched C/SiC brake materials were better than that of the short fiber C/SiC, which indicated the 3D needle-punched C/SiC brake materials were more reliable than short fiber C/SiC for aircraft application.

(2) The C/SiC brakes exhibited some superior frictional properties such as high static friction coefficient, low wear rate, less sensibility to wet conditions and a higher brake efficiency.

(3) The main wear mechanisms of the C/SiC brake materials were grain-abrasion, oxidation-abrasion, fatigue wear, and adhesive wear. The Si was a significant factor in the adhesive wear. Adhesive wear could cause a serious wear rates, a huge unstable friction coefficient, and even disaster, so that the Si content in the C/SiC brake materials must be controlled.

(4) The C/SiC brake materials modified by graphite, Ti₃SiC₂, or PIP-SiC could decrease and disperse the Si in the C/SiC, which not only improved the friction stability but also eliminated adhesive wear.

(5) The sandwich structure is a good designing idea to realize the mechanical structure and frictional function integration design.

The C/SiC brake materials are new highly competitive brake materials for aircraft, high speed train, heavy vehicles, emergency brakes for elevators and cranes, and so on. For widespread application of the C/SiC brake materials, more efforts should be paid to realize the designability of the properties and lower the costs.

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