Ceramic Matrix Composites for High Performance Friction Applications

Walter Krenkel and Nico Langhof

Abstract Ceramic Matrix Composites (CMC) show due to their fiber reinforcement high strength, thermal shock resistance and damage tolerance, a low coefficient of thermal expansion (CTE) and a partially porous and micro-cracks containing matrix. Hence, C-fiber reinforced silicon carbide materials (C/SiC resp. C/C-SiC), manufactured by the LSI (Liquid Silicon Infiltration) process, are very suitable for friction applications, e.g. for brake discs and pads, because of their low wear rates and high coefficients of friction (COF). Fundamental studies and ongoing investigations are the basis for the introduction of fiber reinforced ceramic brake discs for passenger cars since more than 10 years. Today, C/SiC friction materials can be found in emergency brakes for elevators, conveying systems and passenger cars. With respect to the selected friction couple, the tribological performance remains on a high level over a large range of sliding speed and braking pressure. In order to develop C/SiC lifetime brakes for passenger cars, the corresponding brake pads have to be modified appropriately as well. Within a certain friction system, the C/SiC ceramic brake discs withstand a mileage up to 300,000 km, compared with about 70,000 km of grey cast iron rotors. The economic success of these innovative, damage tolerant ceramics depends on the further reduction of the fabrication costs, which are considerable higher, compared to the competing metallic materials. This article describes the technological steps in the development of ceramic friction materials and the current status. It gives an overview about the most important, forthcoming challenges in terms of the material's development and processing.

Keywords Friction · Ceramic brakes · C/SiC · Ceramic matrix composites · Tribology

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1 Introduction

Carbon fiber reinforced ceramic friction materials are promising for several engineering applications, especially if lightweight, high power densities and high temperature stability are required. Therefore, these materials are suitable candidates for e.g. transportations systems in the aerospace sector, for railways and automotive applications. In general, all engineering components that contain translational or rotational inertia masses and other devices that have to be decelerated by an incorporated brake system are interesting applications of ceramic matrix composites. Nowadays, braking of huge amounts of kinetic energies can be realized by the application of regenerative brakes. Nevertheless, a secondary emergency brake, which is based on friction, is still required for the case that the primary brake system fails.

In the field of Ceramic Matrix Composites, Carbon/Carbon materials (C/C) are already in use for friction applications in airplanes and Formula One race cars, since several decades [1–4]. However, C/C shows some drawbacks, in terms of their low COF at low temperatures and high humidity resp. under "cold" and "wet" conditions. Therefore, this material is not suitable for lifetime brakes in passenger cars or further engineering applications. Only at temperatures above 400 °C carbon/carbon brakes are favorable and show very promising performances. However, such temperatures are accompanied with high wear rates due to the oxidation of carbon. Based on these drawbacks and the time and cost consuming fabrication process, C/C brakes are not suitable for service brake applications.

Due to the replacing of the carbon matrix by SiC in C/SiC composites, a material is obtained, which shows a significantly enhanced wear and oxidation resistance compared to C/C. Furthermore, the tribological performance of the material is improved as well. C/SiC is a material with open porosities $< 3\ \%$. The infiltration of liquid silicon occurs under vacuum conditions into a porous carbon/carbon preform without the requirement of any external pressure, only by capillary forces and the good wetting behavior of silicon on carbon. The excess of the supplied silicon, which means, more than the required stoichiometric amount to form SiC, causes the formation of an almost dense material including some residual free silicon. Originally, the Liquid Silicon Infiltration process was developed to produce C/SiC for thermal protection systems in space shuttles and similar reentry vehicles in the aerospace sector [5].

Figure 1 shows the flowchart of the LSI-process, which consists of three main steps. Within the first step C-short fiber bundles are mixed resp. C-fiber fabrics are laminated with a phenolic resin, e.g. Novolac. The addition of fillers, e.g. graphite powder enables the modification of the desired frictional properties. This compound is warm pressed and the CFRP evolved at temperatures up to 300 °C and pressures up to 5 MPa. During the second step, the CFRP is carbonized under inert conditions at temperatures beyond 900 °C. Due to the pyrolysis and partial degradation of the phenolic resin, the matrix shrinks and loses about 50 % of its mass. The shrinkage and the fiber matrix bonding must be tailored, in order to prevent a debonding of the matrix from the C-fibers. The resulting C/C body contains between 20 and 30 % of open porosity. The cracks form an interconnecting network of narrow channels between distinct C/C-segments in the microstructure. Within the third step, the porous C/C preform is infiltrated with liquid silicon under vacuum and temperatures above 1420 °C. Finally, the liquid Si reacts with the solid amorphous carbon matrix to form SiC in a diffusion controlled process.

C/SiC consists of three phases, carbon (fibers and matrix), SiC (matrix) and residual silicon (matrix). Typical microstructures of different C/SiC composites are shown in Fig. 2. If a dense friction material is desired, like for the most applications, C/SiC composites contain about 5 vol. % free silicon. This amount is required to compensate the 30 % lower molar volume of SiC compared to the sum of the molar volumes of Si and carbon. However, free silicon can be prevented, due to the addition of the stoichiometric amount of silicon, regarding to the existing amount of carbon, which should be converted into SiC. The final material is porous and show about 5 % open porosity and no residual silicon. Absolutely dense C/SiC materials without any free silicon can't be obtained by the LSI-process. Knowing these specific relations, C/SiC friction materials can be tailored to a certain degree towards the requirements of the application.

The braking energy which have to be absorbed by a brake disc and/or pad are exemplarily summarized in Table 1 for different transportation systems, where

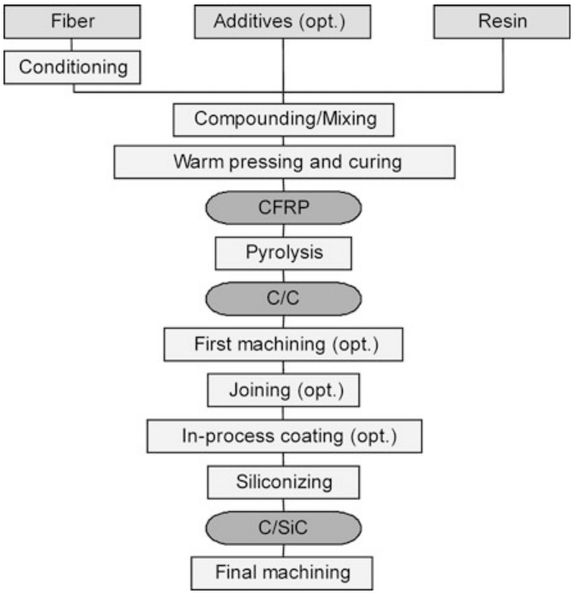


Fig. 1 Flowchart of the Liquid Silicon Infiltration process (LSI) for the manufacturing of C/SiC friction materials

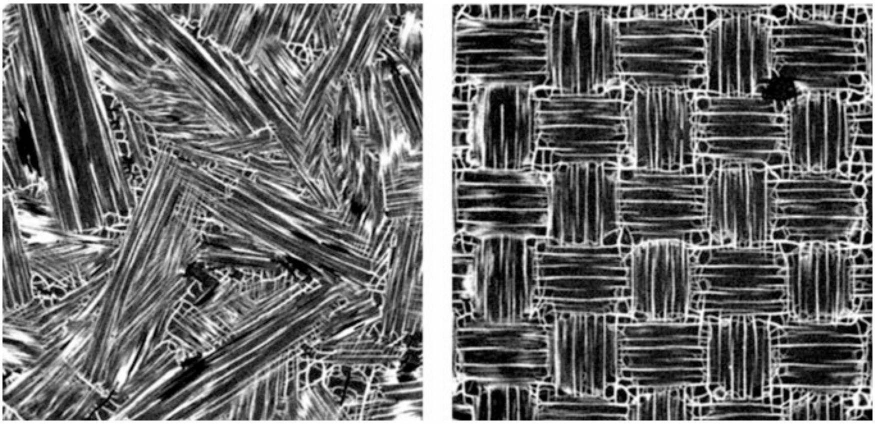


Fig. 2 C/SiC microstructures with C-short fibers (*left*) and C-fabric reinforcement (*right*) perpendicular to the press direction, i.e. the frictional surfaces are shown; carbon fibers (*black*); SiC and Si (*white*) [Fraunhofer-HTL]

ceramics are already in use or under investigation. Despite of the large numbers of brake discs in trains and airplanes, the energies per disc in these systems are remarkably higher compared to other service brakes in passenger cars or in emergency brakes for elevators or conveying systems. Therefore, each application requires a different, specific modified C/SiC friction material.

Some fundamental aspects of these material modifications will be discussed in the forthcoming chapter.

Table 1 Braking energies of different high performance friction applications (service and emergency brakes) [24]

	Train ICE1	Aircraft Boeing 777	Automative Porsche GT2	Elevator (emergency) Schindler 700	Crane (emergency) Mayr roba-stop
Max. speed (m/s)	91.7	72.2	88.9	13.8	30
Mass (10^3 kg)	440	208	1.7	18	3.1
Deceleration (m/s^2)	1.3	2.4	14.5		
Brake energy (MJ)	1850	542	6.7	1.7	1.4
No. of brake disks	192	48	4	8	1
Energy per brake disk (MJ)	7.2[1]	4.5[2]/20[3]	1.7	0.21	1.4

[1]75 % of brake energy
[2]40 % of brake energy
[3]Emergency (RTO = Rejected Take-Off)

2 Development of C/SiC Materials for High Performance Friction Applications

The development of C/SiC composites for braking systems has started in the early 90s of the former century and shows a successful spin off from space to terrestrial applications. In the beginning, the feasibility and manufacturing of prototypes for railway brake discs were in the focus of the research activities [6]. One big challenge was the transfer of the existing technology from thin-walled aerospace structures (thickness 3–6 mm) to large scaled (diameter up to 640 mm) and thick-walled components (up to 60 mm thickness) for brake rotors. Thereby, it is required to remain the mechanical properties and the quality of the materials.

In 1994 the German Aerospace Center in Stuttgart (DLR) started to collaborate with Porsche, in order to develop C/SiC brake pads and discs for passenger cars [7]. First tests showed the superior tribological and thermomechanical properties compared to grey cast iron and C/C. Nevertheless, the design and manufacturing have to be developed and some milestones in the material's improvements are described in the following.

2.1 Improvement of the Transversal Thermal Conductivity ($\lambda\perp$) to Stabilize the Coefficient of Friction (COF) of the C/SiC Materials

In principle, monolithic SiC is very suitable for friction applications, due to its high wear resistance and very high COF. However, the very brittle failure behavior prevents the application of monolithic SiC in brakes. In particular, thermal shocks are very critical and make SiC unfavorable for these safety components. Nevertheless, SiC within the matrix of damage tolerant C/SiC is very important, in order to enhance the COF and to increase the wear resistance, compared to the C/C material.

During tribological studies at moderate conditions and low braking energies on a disc-on-disc tribometer, it was found, that the COF of C/SiC is a superposition of the COFs of pure C/C and monolithic SiC (Fig. 3). At higher friction energies, this relation is less obvious and the COFs for all three materials are similar [8, 9].

First tests show an overheating of the frictional surfaces and the heat transfer into the volume of the rotor was not sufficient (Fig. 4). The main reason for this behavior was the low thermal conductivity, perpendicular to the fiber axis ($\sim$ 9 W/mK), of the 2D-reinforced C/SiC material. Due to some modifications of the microstructure and the phase composition, the thermal conductivity was increased significantly. One approach was the increase of the amount of SiC in the matrix by decreasing the content of the fibers, which increases the Si-uptake and enhance the SiC content and the density of the C/SiC materials (Figs. 5 and 6).

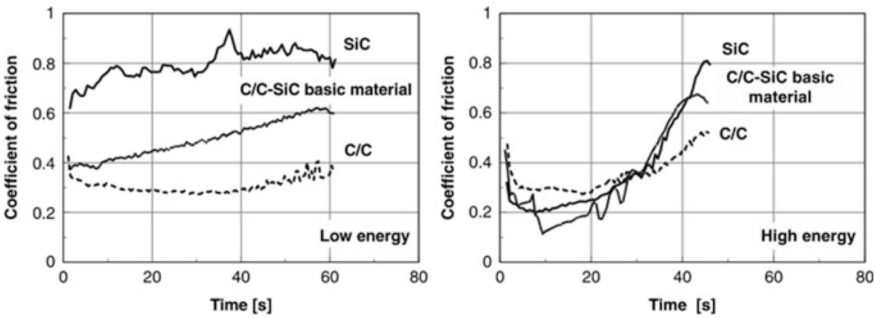


Fig. 3 Coefficient of friction (COF) of 2D-fabric reinforced C/SiC, monolithic SiC and C/C at low braking energies, resp. power intensities (v = 16 m/s, p = 0.1 MPa, *left*) and at higher braking energies (v = 16 m/s, p = 0.35 MPa, *right*)

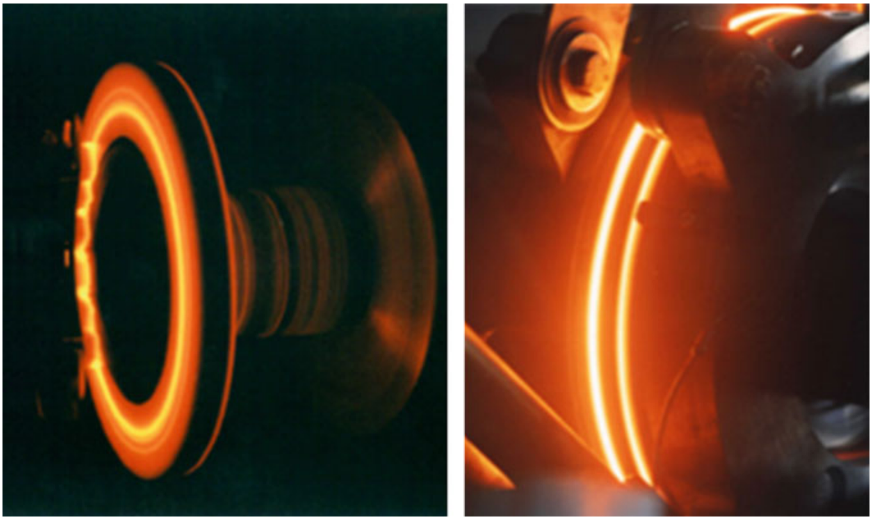


Fig. 4 High temperatures on the frictional surfaces due to low transversal thermal conductivity of fabric reinforced C/SiC [Knorr-Bremse, DLR]

Another way was to apply carbon fibers with a higher thermal conductivity, e.g. graphite-based fibers [10].

On the one hand, the thermal conductivity increases with the decrease of the fiber volume content and the increase of the density. On the other hand, the mechanical strength and the fracture toughness decrease. Therefore, the microstructure and the composition of C/SiC have to be balanced between mechanical and thermal requirements of the desired application.

In order to reach high thermal conductivities of about 40 W/mK, the fiber volume content is between 30 and 50 % and the open porosity below 5 %. Due to the

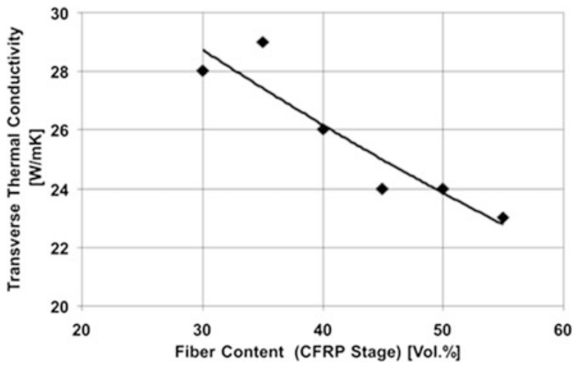


Fig. 5 Transversal thermal conductivities of C/SiC versus fiber volume content (carbon short fiber reinforcement; measured at 50 °C)

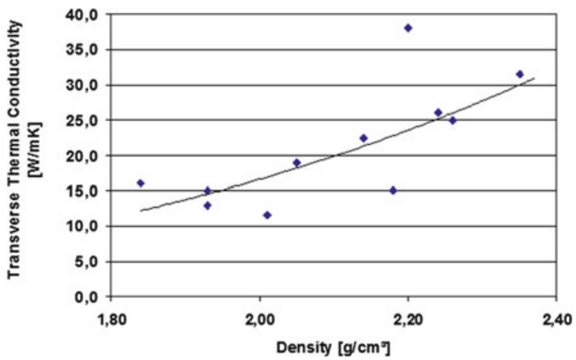


Fig. 6 Transverse thermal conductivity of C/SiC versus density (carbon short fiber reinforcement; measured at 50 °C)

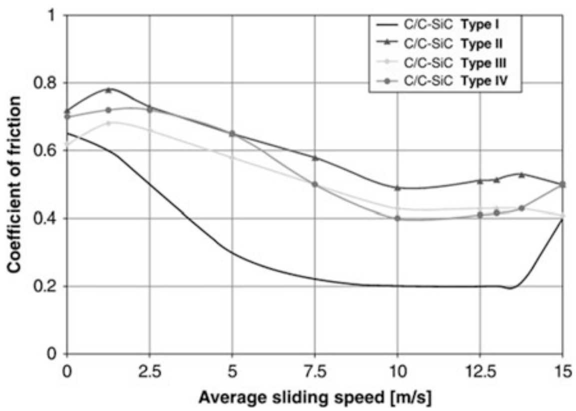


Fig. 7 COF in dependence on the average sliding speeds of several C/SiC materials, with different thermal conductivities (*Type I* low thermal conductivity with 2D-fabric reinforcement; *Type II–IV* high thermal conductivity with graphite-fibers, high SiC contents resp. some additional fibers in transversal direction) [10]

favorable thermal conductivity, the friction-induced heat is transferred easily from the surface into the main body of the ceramic C/SiC friction material. Hence, overheating of the surface does not occur and the COF is now much more stable (Fig. 7). The wear rate remains constant, unless the higher thermal conductivity [11].

2.2 *Lower Wear Rates by Modifying the C/SiC Friction Materials*

C/SiC materials show a significantly higher wear resistance, compared to C/C. Nevertheless, for the application in lifetime service brakes, the wear rates were still too high. The most promising approach to improve the wear stability is to increase the SiC content on the frictional surfaces of C/SiC brake disks or pads.

Two different strategies were developed successfully. By one approach, the gradation of C/SiC laminates with a steadily increasing SiC-content from the center towards the friction surface is suitable for short-term applications, like emergency brakes for elevators or conveying systems. The CFRP-laminate comprises for example different thermal pretreated C-fiber fabrics. With an increasing of the pretreatment temperature, the carbon fibers convert more and more to SiC during the siliconizing step. In order to avoid deformations due to the mismatches of the coefficients of thermal expansion, a symmetric lay-up of the fabrics is required (Fig. 8).

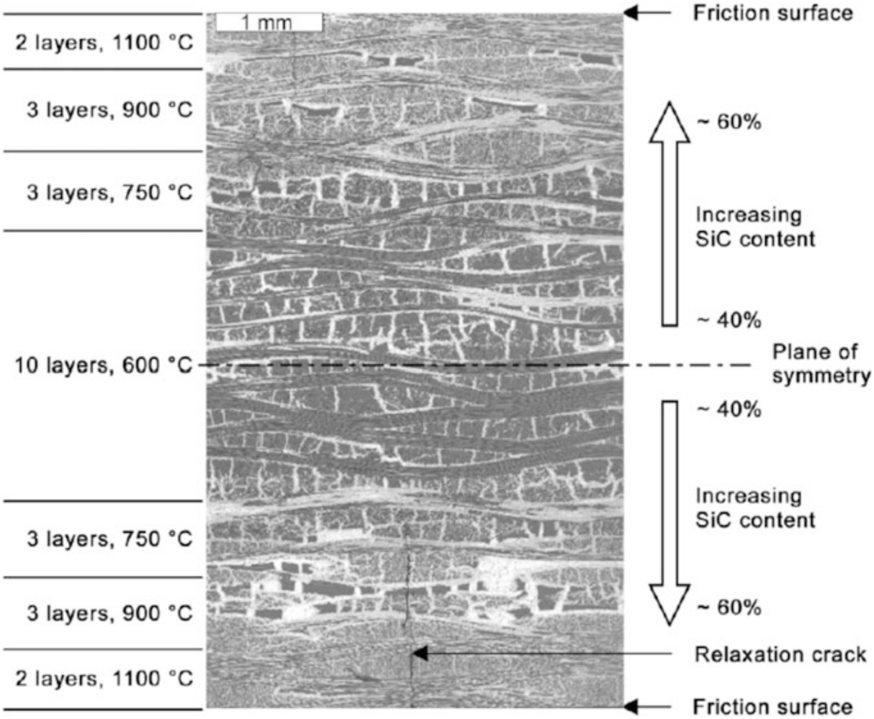


Fig. 8 Cross section (thickness ~ 6 mm) of a graded C/SiC friction pad, developed for emergency brakes in high-rise elevators [16]

For long-term applications, e.g. service brakes for passenger cars, another approach was developed. On the friction surfaces of a carbon fiber-rich C/SiC core material, a reaction-bonded SiSiC layer was added (Fig. 9). The SiSiC formation is realized during the siliconization step, without the requirement of an additional high temperature treatment step. Therefore, a porous, highly carbon containing layer is applied on the surface of the carbon/carbon material after the pyrolysis. During the subsequent siliconization, this porous carbonaceous layer is converted into SiC and the remaining pores are filled with silicon. Due to the residual silicon, the application temperature is limited to about 1300 °C [11, 12].

The development of this monolithic SiSiC friction layer on C/SiC substrates enables a novel friction system, which results in lifetime brake discs with low wear rates ($< 1 \times 10^{-5}$ mm^3/J). Furthermore, the oxidation resistance and the thermal conductivity of these coated C/SiC discs increase considerably.

On the frictional surfaces of such C/SiC brake discs, a characteristic crack pattern occurs during the manufacturing, due to the CTE-mismatch between the substrate and the SiSiC coating. In dependence of the extent of this CTE-mismatch, the crack pattern is more or less pronounced. Furthermore, the crack orientation and distribution depend on the fiber orientation below the SiSiC friction layer (Fig. 9).

If the core material contains 2D-carbon fiber fabrics, the number of cracks in the SiSiC friction layer is higher compared to a short fiber reinforced substrate. Brake discs for passenger cars are mainly reinforced with short fibers, because of fewer cracks in the friction layer, lower manufacturing costs and the feasibility of a near-net shape fabrication.

Both approaches, the gradation and the reaction-bonded coating, are successfully used in current C/SiC friction materials for emergency and services brake applications.

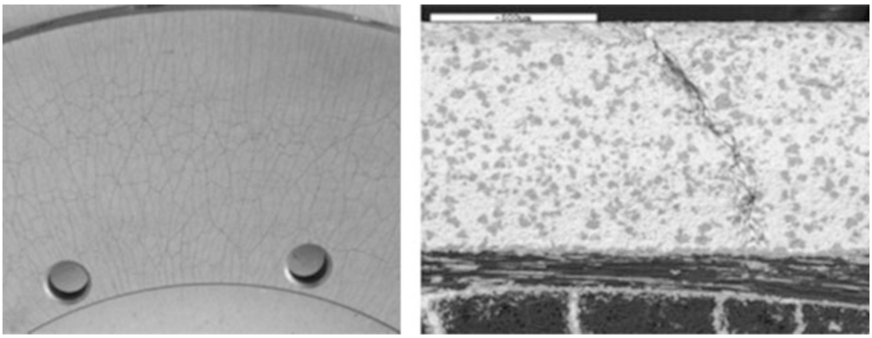


Fig. 9 SiSiC friction layer and the regarding crack pattern on the surface of a C/SiC brake disc for passenger cars, that causes considerably higher wear resistance and the invention of lifetime brakes. *left*: Top view on the crack containing friction layer (width about 60 mm); *right*: cross section through the SiSiC friction layer, accompanied with a relaxation crack [11]

In the case of a misuse with resulting thermal overloads, oxidative sensitive inserts acting as wear indicators, that show, when the amount of wear gets critical for the brake discs in automotive applications (Fig. 10).

2.3 Near Net Shape Fabrication by Applying Short Fiber Reinforcement

At the beginning of the development, first C/SiC brake disc prototypes were cut-out of 2D-fabric reinforced composite plates (Fig. 11). However, the demand for a more cost-effective fabrication requires a technology, which enables a near net shape production of brake discs and brake pads. Instead of the expensive autoclave method used conventionally in aerospace engineering for the manufacture of the CFRP green bodies, a particular method of manufacturing via warm pressing of compounds including short fiber C-bundles and phenolic resin powders was developed. Subsequently to the warm pressing, the green body is subjected to a thermal treatment including pyrolysis and liquid silicon infiltration. During the heat treatment only a small shrinkage of approximately 5 % in thickness and 1 % in diameter is observed. In contrast to the fabric reinforced C/SiC discs, the short fiber C/SiC discs exhibit a more planar isotropic fiber orientation and a higher ceramic content in the final product. Hence, the transversal heat conductivity of short fiber discs is higher and their strength is lower compared to 2D-fabric reinforced discs.

2.4 Joining of C/SiC Parts for the Fabrication of Ventilated Brake Discs

Conventional grey cast iron brake discs are quite often fabricated as ventilated discs with inner cooling channels. For metallic materials this complex disc geometry can

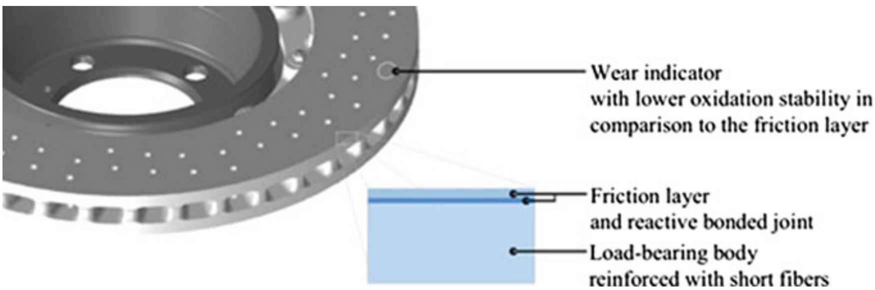


Fig. 10 Separation of functions between the load bearing, carbon fiber rich core and the tribological optimized SiSiC-friction layer, which includes some wear indicators [14]

Fig. 11 First generation of 2D-fabric reinforced C/SiC brake discs (*left*: DLR) and one current design of ventilated C/SiC brake discs with short fiber reinforcement (*right*: Audi AG)

be easily achieved during the casting process. As ceramic brake discs cannot be casted, a joining method of semi-finished parts was developed. Two friction rings are joined with the load-bearing body acting as cooling ribs (Fig. 12). A carbon containing paste is used for the joining of the single parts. This paste was developed to achieve a stoichiometric and similar materials composition in the joining gap [13]. The joining relies on the reaction bonding process of silicon and carbon during the siliconization step. Due to the fixation of the C/C parts during siliconizing, the joining of different parts is permanently and heat resistant. This method allows a modular design of complex shaped products. Thus, the friction rings can be significantly improved in terms of improved tribological properties (high thermal conductivity, high coefficient of friction and high wear resistance) whereas the core material can be optimized versus thermo-mechanical properties (high strength, stiffness and high heat capacity) (Fig. 13).

2.5 *Mechanical and Tribological Properties of C/SiC Composites*

The strength and damage behavior of C/SiC materials is highly determined by the fiber length and the fiber orientation. Current C/SiC brake discs are fabricated with carbon fibers of 5–15 mm length. The PAN-based C-fibers are used as fiber bundles (rovings) with up to 400,000 filaments per bundle. C/SiC composites exhibit a strong anisotropic behavior regarding their mechanical and thermal properties. Figure 14 shows an example of load-deflection curves in the tangential and radial direction of a short fiber reinforced C/SiC brake disc with quasi-isotropic and anisotropic fiber orientations [14].

As C/SiC composites exhibit a fiber-dominant behavior, the strength in radial and tangential direction differs significantly compared to a randomly oriented fiber distribution. Isotropic reinforcement shows similar strength in both directions, but

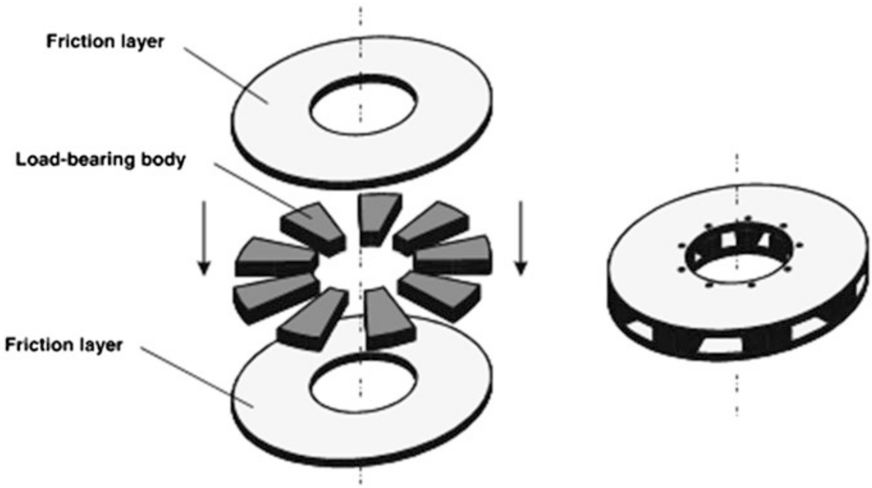


Fig. 12 Manufacture of a ventilated C/SiC brake disc with a modular design [13]

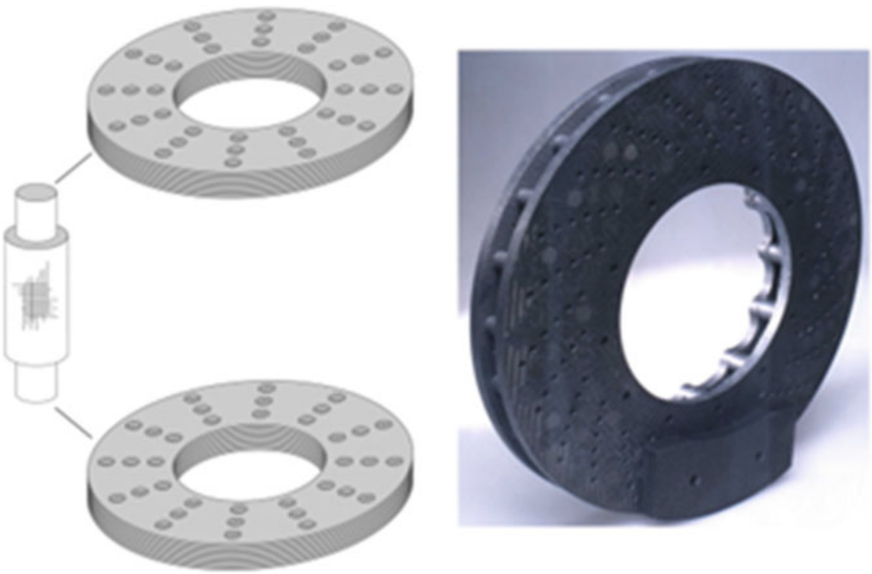


Fig. 13 C/SiC brake disc prototype as an assembly of the single components. The pins connect the frictional surfaces and transfer the heat to the ventilated core of the brake disc [17]

on a lower strength level. Figure 15 shows the dependency of the flexural strength at room temperature from the orientation of short fiber bundles with a fiber length of 6 mm. It is obvious, that the mean value of strength of the unidirectional reinforced short fiber composites, for all directions, is similar to the strength measured for

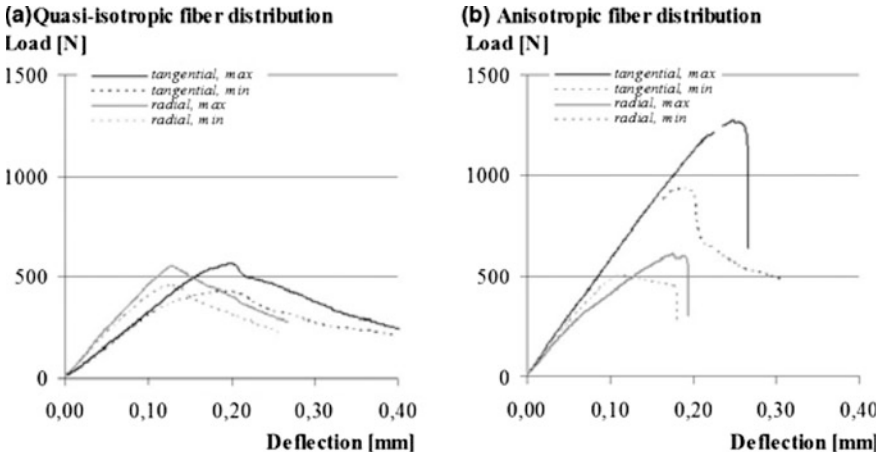
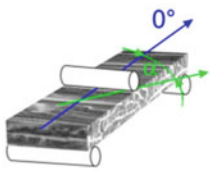


Fig. 14 Load-deflection curves of 3-point bending tests (DIN EN 658-3) for C/SiC composites with quasi-isotropic (*left*) and anisotropic (*right*) fiber reinforcement

Short Fibers (6mm)	Fiber Orientation								
	0°	15°	30°	45°	60°	75°	90°	Mean Value	Isotropic
Flexural Strength [MPa]	67	62	48	43	30	28	25	**44**	**45,6**
Young's Modulus [GPa]	45	40	30	25	22	19	16	**28**	**25**
Strain [%]	0,17	0,16	0,17	n.a.	0,17	0,16	0,16	**0,16**	**0,17**



Fiber Length	Flexural Strength [MPa]			
	MV	Max Min	SD	Var
3 mm ISO	43	57 30	6	30
6 mm ISO	44	57 26	8	80
9 mm ISO	88	115 63	12	197

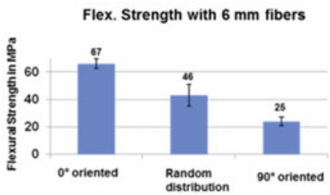


Fig. 15 Dependency of the fiber orientation and fiber length on the 3-point flexural strength of C/SiC composites

quasi-isotropic composites. In addition, the increase of fiber length to 9 mm doubles the strength, whereas the decrease to 3 mm fiber length seems to have only little influence.

The friction and wear behavior of C/SiC materials is shown exemplarily in Fig. 16 (left) and (right). Disc-on-disc tests with a pair of similar ceramic materials show, that C/SiC materials have a significant lower wear rate than C/C [9, 15]. The high fading resistance of C/SiC composites is depicted in Fig. 16 (right). During repeated test runs (fading tests) the brake disc temperature rises up to more than

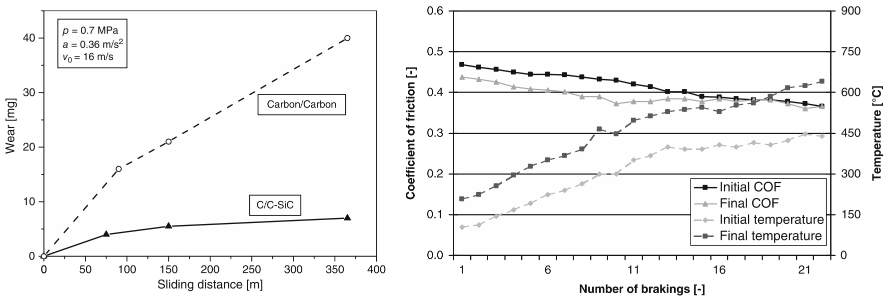


Fig. 16 Wear rate of C/C and C/SiC frictional couples tested in disc-on-disc configuration (*left*). Fading tests of C/SiC discs and phenolic resin-bonded LowMet pads (each braking represents a deceleration of a vehicle from 134 to 44 km/h) (*right*)

		Short-fiber C/SiC (Sigrasic SGL)	GG-20	Al-MMC (SiC-Particles)	C/C
Density	kg/dm³	2.3–2.45	7.25	2.7	1.7–1.8
Mass-specific heat capacity	J/kg K	800	500	820–886	700
Volume-specific heat capacity	J/dm³ K	1800	3600	2350	1200
CTE (in-plane)	10^{-6} 1/K	1 (RT) 2 (300°C)	9 (RT) 12 (300°C)	14–21	0.3
Thermal conductivity (transverse)	W/m K	40	54	160–185	13
Tensile strength (in-plane)	MPa	20–40	150–250	310–370	70–100
Young's modulus (in-plane)	GPa	30	90–110	86–125	40
Bending strength	MPa	50–80	150–250		
Strain (in-plane)	%	0.3	0.3–0.8	0.4–1.2	
Thermal shock resistance	W/m	>27 000	<14 000		
Maximum temperature	°C	1350	700	400	>1350

Fig. 17 Room temperature properties of different brake disc materials compared with C/SiC composites [18–23]

600 °C. However, the coefficient of friction remains considerably stable in the range of 0.35 to 0.45 [16]. The brake pads for these fading tests are phenolic resin bonded LowMet materials which limits the maximum temperature in this brake system.

3 Summary

In summary, the C/SiC composites are able to combine the outstanding thermo-mechanical properties of C/C with the high wear resistance and the high and stable coefficient of friction of silicon carbide. The damage tolerance of C/SiC is in the range of grey cast iron. Figure 17 shows a comparison of thermomechanical as well as thermophysical properties of C/SiC, C/C, grey cast iron, and SiC-particle reinforced aluminum (Al-MMC). The low density of C/SiC materials (2.0 to 2.5 g/cm^3) makes them to a first choice material for lightweight brake systems. Furthermore, it reduces considerably the unsprung mass in a vehicles chassis. The volume-specific heat capacity of C/SiC is lower than the corresponding value for grey cast iron. Hence, the replacement of a grey cast iron disc by a C/SiC disc is accompanied by a higher diameter and larger thickness of the ceramic disc. Nevertheless, the overall weight saving of the total braking system in a modern car is up to 50 % with the use of C/SiC compared to a grey cast iron disc.

The current annual production of C/SiC brake discs for automotive applications is in the range of more than 200,000 parts. The main challenge to achieve lower manufacture costs is the current high diversity of brake disc geometries and the demand for individual adjustments for the different cars with different applications (e.g. SUV, sedan, sports car, off-road vehicle) and performances. From the point of view of process technology, there is still a great potential for fabrication optimization and therefore cost reduction. For example the introduction of fully automated CFRP green body fabrication, continuously driven processes for pyrolysis and siliconizing, or faster micro-wave assisted heat-treatments are promising approaches. Further research and development is required to achieve a new class of ceramic-bonded brake pads with improved NVH-behavior (noise, vibration, harshness) for a full-ceramic brake system.

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