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Review paper

Preparation, performances and application of carbon-ceramic brake discs

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Abstract

Carbon-ceramic brake discs, known for their superior mechanical properties and thermal stability, are pivotal in high-performance braking systems. This paper reviews their development, focusing on preparation methods, performance features and applications in aviation, automotive and rail sectors. Made from carbon fibres and silicon carbide, these discs undergo complex manufacturing processes like carbonization and silicification, leading to excellent friction performance, wear resistance and thermal shock resilience. As manufacturing technology progresses and costs decrease, their use is expected to expand significantly. The paper also explores potential optimizations and future roles of carbon-ceramic discs in improving transportation safety and environmental sustainability.

Keywords: *carbon-ceramic brake discs, fabrication, performance, thermal stability, applications*

Contents

I. Introduction

The braking system is a crucial safety component in modern transportation tools. Since the late 20th century, with the rapid development of high-performance sports cars, aircraft and high-speed trains, traditional brake discs made of cast iron or steel have gradually failed to meet the extreme requirements for braking performance of these high-end transportation means. This is mainly due to the performance degradation of traditional brake discs under high-speed operation or extreme conditions, such as thermal fade, strength reduction at high temperatures and unstable friction performance [1]. The emergence of carbon-ceramic brake disc technology, especially the development of carbon fibre reinforced carbon-silicon carbide (C/C-SiC) composite materials, provided a new solution for high-performance braking systems. This draws on earlier foundational work which explored the wear behaviour of similar high-entropy alloy coatings [2]. These materials, with their excellent high-temperature friction properties, superior thermal stability and lightweight characteristics, have be-

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gun to be widely used in fields requiring extremely high-performance braking systems [3]. Carbon-ceramic (C/C) brake discs are not only lightweight and wear-resistant but also maintain good performance in high-temperature environments, showing great potential in aviation and high-performance racing fields. Figure 1 shows the surface structure of the new C/C-SiC ceramic composite material. The difference between composites shown in Figs. 1a and 1b lies in the choice of fabric. The first one uses ordinary carbon fabric, while the second composite uses "short fibre" carbon fabric, with different fibre types and weaving methods [1].

In recent years, with the advancement of manufacturing technology, especially the application of liquid silicon infiltration (LSI) technology, the production cost of carbon-ceramic brake discs has decreased, expanding their application from aviation and racing to commercial vehicles and motorcycles. This technology allows for the manufacture of stable-performance carbon-ceramic brake discs at a lower cost, providing possibilities for a broader market [4].

Furthermore, with the increasing awareness of environmental protection and the demand for lightweight design, carbon-ceramic brake discs are attracting attention for their potential contribution to improving fuel economy and reducing vehicle exhaust emissions. The use of C/C brake discs can significantly reduce the unsprung weight of vehicles, thereby improving the overall dynamic performance and operational responsiveness of the vehicle [1]. The research and application of carbon-ceramic brake discs have also driven technological advancements in related fields, including the development of high-performance composite materials, the exploration of advanced manufacturing technologies, and the design of new efficient braking systems. These technological developments not only enhance the performance of brake discs but also provide valuable experience and data for material research in other high-temperature and high-load applications [5].

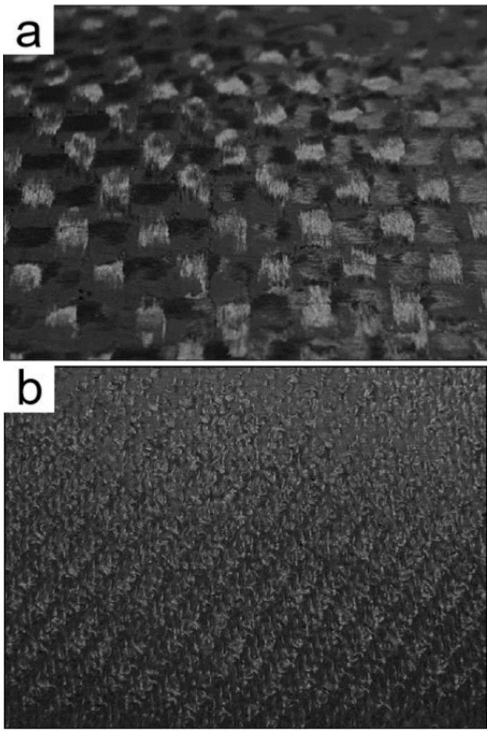


Figure 1. Surface structure of new ceramic composite materials: a) ordinary carbon fabric composite material and b) "short fibre" carbon fabric composite material [1]

This paper aims to comprehensively review and summarize the research and application progress of carbon-ceramic brake discs, emphasizing their important position in modern high-performance braking systems. Through an in-depth analysis of the preparation methods, performance characteristics, performance optimization technologies and practical application cases of carbon-ceramic brake discs, this paper hopes to provide a theoretical basis and technical guidance for future research and development of carbon-ceramic brake technology. Additionally, this paper will discuss and predict future development trends of carbon-ceramic brake disc technology, including potential market applications and technical challenges.

II. Preparation methods of C/C brake discs

The preparation methods of carbon-ceramic brake discs mainly include chemical vapour infiltration (CVI), liquid silicon infiltration (LSI), and reactive melt infiltration (RMI) technologies. These methods each focus on improving the microstructure and overall performance of carbon-ceramic brake discs in different ways [6]. The key steps in preparing carbon-ceramic brake discs include material selection, fabric preparation, preform preparation, carbonization, silicification and subsequent treatments [1]. Figure 2 shows the conventional preparation process of carbon-ceramic discs. In the first step, carbon fibres are woven and needled to form a three-dimensional needled carbon fibre preform. The preform is then processed through chemical vapour infiltration to deposit pyrolytic carbon, creating a porous C/C blank. After high-temperature treatment and rough machining, the C/C blank undergoes reactive melt infiltration where silicon is infiltrated into the blank to form ceramic carbon-ceramic composite material. The final carbon-ceramic brake disc product is obtained through fine machining, non-destructive testing and performance testing.

Fabric processing plays an integral role in forming the structural foundation of these brake discs. SiC/SiC woven fabrics are often used due to their high thermal stability and mechanical properties. Techniques such as chemical vapour infiltration (CVI) and electrophoretic deposition (EPD) help ensure uniform matrix infiltration into these fibre preforms, enhancing the overall density and toughness of the composite. The precise stabilization of the fibre preform before infiltration, which helps prevent shrinkage and improves carbon yield, is also a critical step in ensuring high-quality brake disc production [7–10].

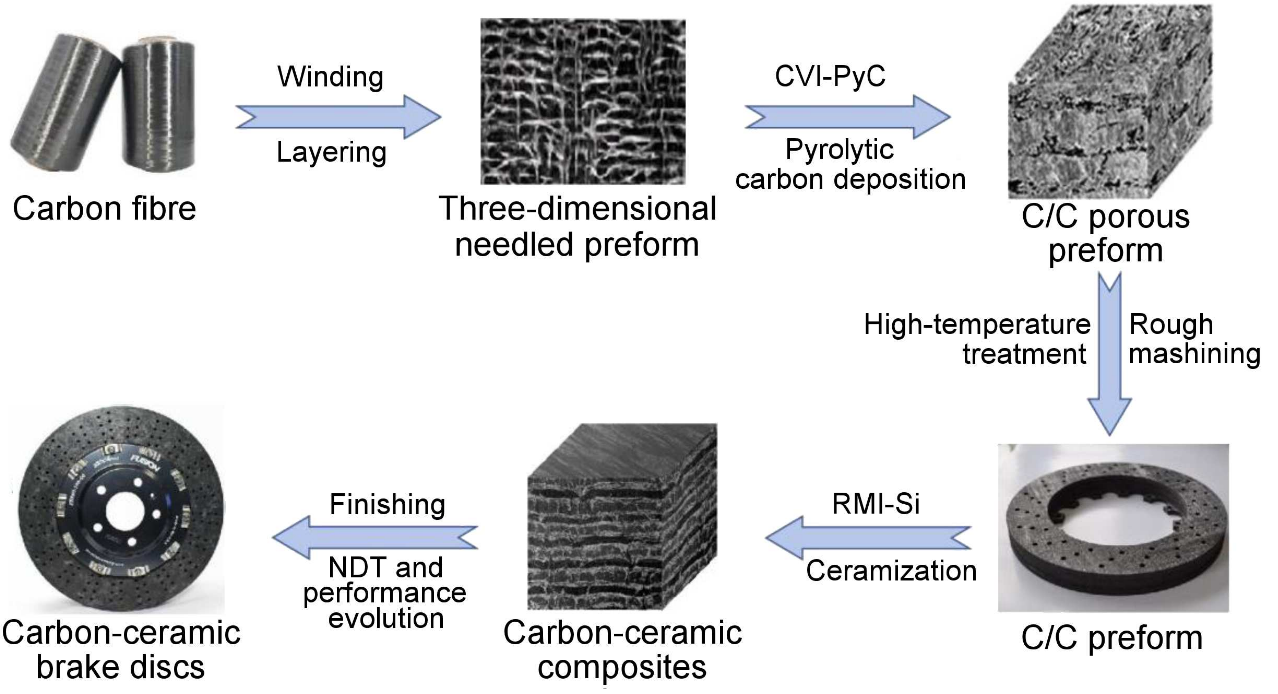


Figure 2. Preparation process of carbon-ceramic brake discs

The first step in preparing carbon-ceramic brake discs is selecting suitable raw materials, which typically include high-performance carbon fibres and silicon sources. Carbon fibres are preferred for reinforcement due to their high strength and low density [5]. The silicon source reacts with carbon in the subsequent silicification process to form silicon carbide (SiC), enhancing the wear resistance and thermal stability of the brake disc [11]. After mixing carbon fibres and the silicon source, a preform needs to be prepared, utilizing insights from previous studies on the microstructure and wear behaviour of high entropy alloys, which highlighted the impact of alloy composition on mechanical properties [12], usually through the resin transfer moulding (RTM) process or manual lay-up methods. At this stage, precise fibre layout and uniform resin distribution are crucial factors directly affecting the final performance of the composite material [13]. Once the preform is prepared, the next step is carbonization, where the resin matrix is converted into carbon. This process involves slowly heating the material in a controlled atmosphere to over 1000 °C to promote the pyrolysis and carbonization of the resin [14]. Carbonization not only improves the thermal stability of the material but also provides the necessary carbon matrix for the subsequent silicification process. The carbonized C/C composite material needs to undergo silicification treatment, typically using liquid silicon infiltration (LSI) technology. During this process, liquid silicon infiltrates the carbon matrix at high temperatures and reacts with carbon to form silicon carbide (SiC). The formation of this new phase significantly enhances the mechanical strength and wear resistance of the material [4]. Additionally, the silicification process improves the oxidation resistance of the material, which is crucial for enhancing the stability of the brake disc under high-temperature conditions. Finally, the siliconized carbon-ceramic brake disc may require mechanical processing, grinding, and other surface treatment techniques to optimize its dimensions and surface quality. Furthermore, quality control throughout the preparation process, including microstructure analysis and performance testing of the material, is essential to ensure the brake disc meets high-performance standards [15].

Through the detailed preparation process described above, carbon-ceramic brake discs not only exhibit excellent mechanical properties and thermal stability but their low weight and high wear resistance make them increasingly popular in high-performance braking systems. Future research will further explore new material systems and preparation technologies to achieve more efficient and cost-effective production processes.

III. Performance analysis of C/C brake discs

Carbon ceramic brake discs are increasingly used in high-performance braking systems due to their superior performance characteristics. These characteristics include excellent friction performance, thermal stability, wear resistance, and outstanding thermal shock resistance.

3.1. Fabric characterization

Fabric characterization plays a crucial role in understanding the mechanical performance of carbon-ceramic composites. SiC/SiC woven fabric laminates are often used due to their ability to withstand high mechanical loads while maintaining flexibility. Studies on the

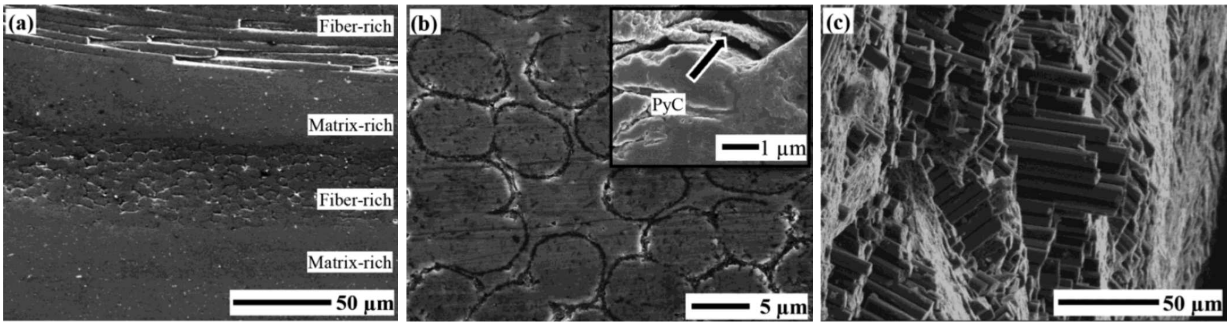


Figure 3. SEM images show: a) a polished SiC_f/SiC composite, featuring alternating layers rich in matrix and fibres, b) the existence of a PyC coating and c) the fractured surface with minimal fibre pull-out observed after a 3-point bending test [8]

folding endurance of SiC fibres indicate that fabrics with larger braiding angles demonstrate higher resistance to mechanical fatigue, making them more suitable for repeated use under stress conditions [16]. Studies on SiC_f/SiC composites fabricated through advanced methods like alternating current electrophoretic deposition (AC-EPD) combined with hot pressing, have significantly contributed to improving the density, mechanical strength and microstructural characteristics of these composites. In particular, the work by Raju *et al.* [8] demonstrates the effectiveness of AC-EPD in achieving a dense SiC_f/SiC composite with a high density of 96.5 %TD and a flexural strength of 413.9 MPa, obtained after hot pressing at 1750 °C for 1 h. Surface morphologies and fracture characteristics of the fabricated SiC_f/SiC composite by post hot-pressing are illustrated in Fig. 3. The alternating layers of fibre-rich and matrix-rich regions, visible in Fig. 3a, reveal efficient infiltration of the SiC and Al_2O_3-$Sc_2Si_2O_7$ particles into the composite's fine voids. The small intra-bundle pores observed in Fig. 3b are indicative of shrinkage in the matrix phase upon hot pressing, while Fig. 3c shows a fractured surface with minimal fibre pull-out, a result of a relatively strong matrix-fibre interface. This phenomenon enhances the material's fracture toughness by deflecting cracks at the PyC interface layer, as evidenced by the 400 nm-thick PyC coating observed in Fig. 3b.

3.2. Friction performance

The friction performance of carbon ceramic brake discs is one of their key characteristics, which builds on our prior research on the tribological performance in various ionic liquids and water environments, significantly impacting the frictional characteristics of different metallic alloys [17,18]. Bian *et al.* [11] chose two commercial C/C-SiC composite brake discs based on different SiC/Si and C/C content levels. The disc with a higher SiC/Si mass fraction was referred to as Brake-H, while the one with a lower fraction was referred to as Brake-L. A grey cast iron brake disc of BS EN 1561 grade was also tested under the same conditions. The results showed that the C/C-SiC composite exhibited a stable friction coefficient in various environments, such as dry friction and water-lubricated conditions. This stability ensures the reliability of the braking system under variable driving conditions. Under dry friction conditions, the average friction coefficient was 0.52, indicating effective performance in standard braking scenarios. The introduction of water significantly reduced the friction coefficient to below 0.1, demonstrating a sharp decline in performance under wet conditions due

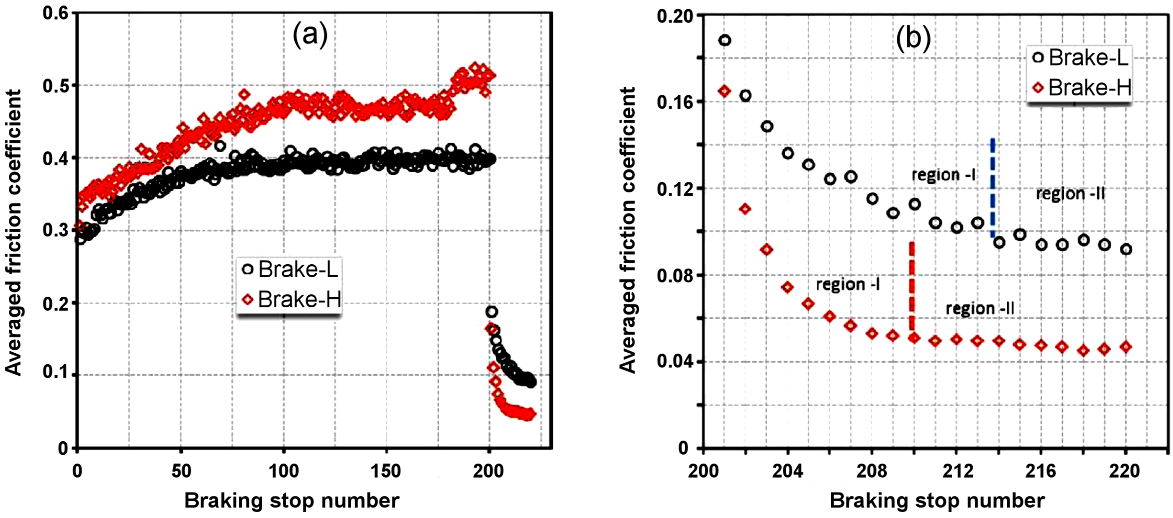


Figure 4. Friction coefficient vs. braking stops curve: a) dry friction conditions and b) water-lubricated conditions [11]

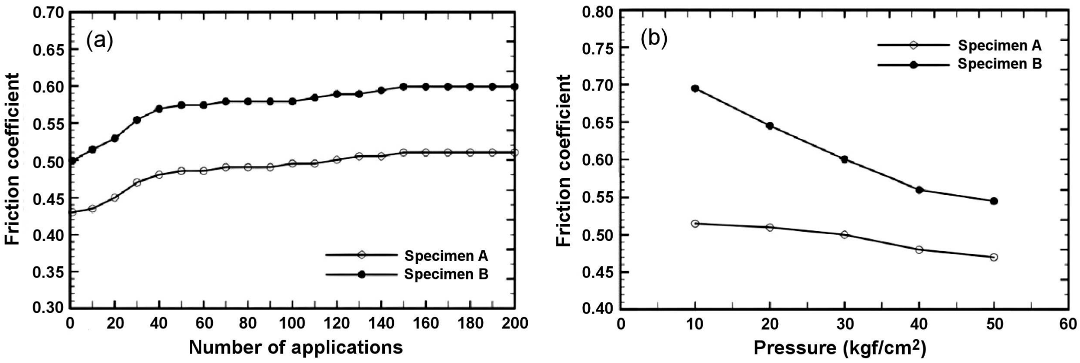
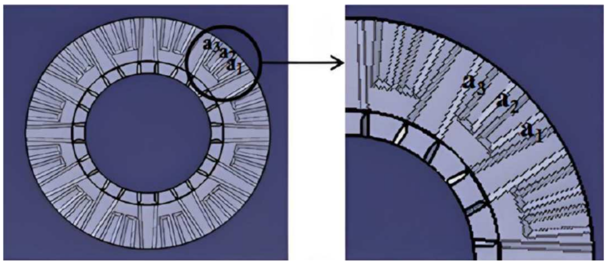
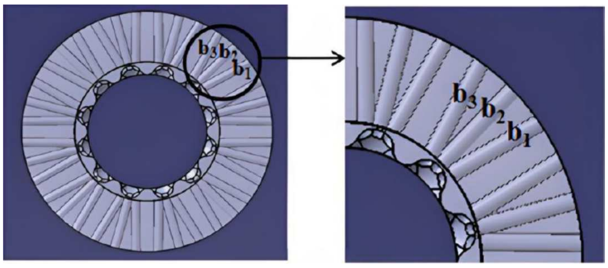


Figure 5. Friction coefficient vs. braking stops (a) and braking pressure curve (b) [13]



Model A disc



Model B disc

Figure 6. Two different ventilation hole shapes of carbon ceramic brake disc models [19]

to the hydrodynamic friction process, where water interfered with the contact and effective friction between the brake disc and the brake pad. Figure 4 shows the average friction coefficient measurements for each braking stop, including tests under dry friction and water-lubricated conditions. As shown in Fig. 4a, the friction coefficient increases in a roughly parabolic pattern as the number of braking stops increases [11]. For the Brake-H, the friction coefficient started at 0.3 and steadily increased to about 0.47 after approximately 100 braking stops.

Further braking saw little change in the friction coefficient until about 180 braking stops, where it remained at 0.47. From the 181st to the 200th braking stop, the friction coefficient slightly increased to another relatively stable level of 0.51. For the Brake-L, a similar upward trend was observed from the beginning to the 85th braking stop, maintaining a stable friction coefficient of 0.4 until the end of the test under dry friction conditions. Figure 4b shows the average friction coefficient for partial braking under water-lubricated conditions. When water was introduced, the friction coefficient immediately dropped to below 0.2, continuing to decrease as the test progressed with more braking stops, although the rate of decrease gradually slowed.

Furthermore, Jang *et al.* [14] confirmed the high friction performance of C/C-SiC composites, emphasizing their ability to maintain a stable friction coefficient under high load conditions. They prepared two different compositions of C/C-SiC composites and examined the effect of composition on their tribological properties. Using low-metal friction pads as the counterpart material, small sample friction tests were conducted on a dynamometer. The results showed that after continuous braking for 150 times, the friction coefficient of the B disc tended towards a stable value of 0.589, while that of the A disc stabilized at 0.512 (Fig. 5a). By changing the braking pressure, the relationship between friction coefficient and pressure was studied. The higher the braking pressure, the lower the coefficient, as it is shown in Fig. 5b.

3.3. Thermal stability

Another significant performance aspect of carbon ceramic brake discs is their excellent thermal stability. Mohanty [3] studied carbon-carbon brake discs for high-speed aircraft, showing that this material can maintain structural and performance stability even under extreme high-temperature conditions, which is crucial for ensuring safe aircraft landings. Ko *et al.* [19] investigated the effect of changes in straight-through ventilation hole shapes on the cooling efficiency of carbon ceramic brake discs. Using numerical methods, they analysed the temperature distribution of brake discs under AMS (Auto Motor Sport) decay mode, considering brake discs with two different straight-through ventilation hole shapes. The results showed that changing the shape and size of ventilation holes could significantly improve the cooling efficiency of brake discs. For example, in the model A, shortening the length of hole a_2 (Fig. 6a) from 94 to 59 mm reduced the average temperature of the middle plane and the entire disc by 1.9 and 3 °C, respectively. In the model B, removing the stagnant area of hole b_2 (Fig. 6b) and increasing the hole diameter from 13 to 17.6 mm reduced the average temperature of the entire disc and the middle plane by 2.8 and 18.7 °C, respectively. These changes increased the surface area of ventilation holes, improving cooling efficiency, further confirming its excellent thermal man-

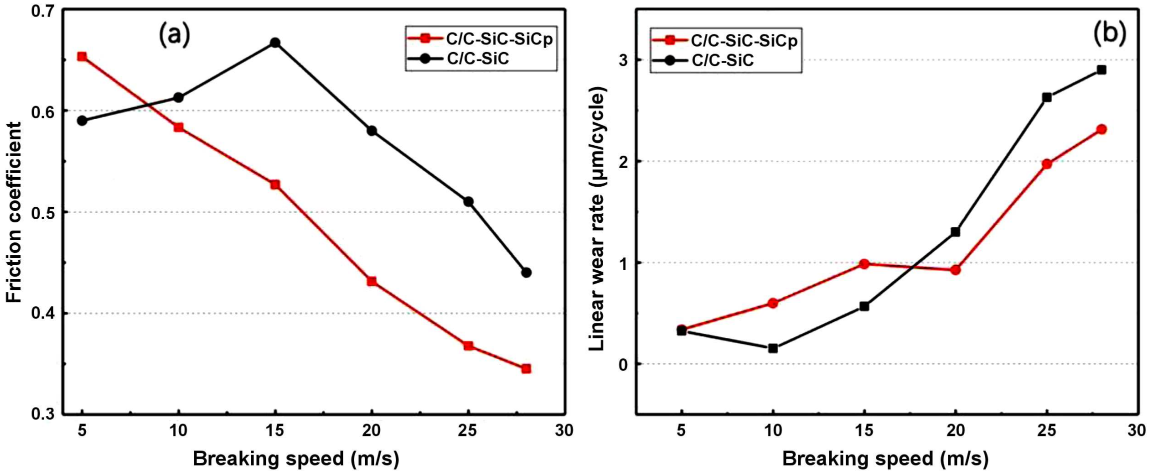


Figure 7. Average friction coefficient (a) and linear wear rate (b) under different conditions [21]

agement capabilities, which are crucial for maintaining braking performance and extending service life. Sivaiah and Lakshmaiah [20] designed three different models of brake discs made of carbon ceramic composites and Al_2O_3 materials, comparing the brake disc models using Catia V5 R20 for design and Ansys 15.0 for thermal analysis. The results showed that carbon ceramic composites exhibited the best performance in terms of heat flux, thermal error, temperature, and thermal stress.

3.4. *Wear resistance*

Wear resistance is another notable feature of carbon ceramic brake discs. Luan *et al.* [21] prepared C/C-SiC brake discs using chemical vapour infiltration and reactive melt infiltration (RMI), and introduced silicon carbide (SiC) via polymer impregnation pyrolysis (PIP) to obtain amorphous SiC ceramic C/C-SiC-SiC^p in the brake disc. As shown in Fig. 7a, compared to pre-PIP, the average friction coefficient of C/C-SiC was higher than that of C/C-SiC-SiC^p, except at 5 m/s. This is due to the formation of amorphous SiC after PMS cracking, which has lower hardness and easily forms a friction film during the friction process, reducing the friction coefficient. Figure 7b shows the linear wear rate, where C/C-SiC-SiC^p has lower linear wear at medium to high speeds than C/C-SiC, due to the amorphous SiC forming a friction film more quickly, which replaces the disc body in participating in friction on the disc surface, reducing linear wear.

To further improve wear resistance, researchers have attempted to optimize the performance of carbon ceramic brake discs through material modification, friction surface morphology and manufacturing processes. For example, Ma *et al.* [22] pointed out that introducing $FeSi_2$ and other ductile phases into brake pads can effectively reduce the friction coefficient and significantly improve wear resistance. The friction surface can maintain integrity under high pressure and wear resistance is an order of magnitude higher than untreated carbon ceramic materials. As shown in Figs. 8a and 8b, the wear rate of SD-SP (SD: C/C-SiC brake disc; SP: C/C-SiC brake pad) is higher overall than that of SD-FP (FP: $FeSi_2$ modified C/C-SiC brake pad) at 3.0 MPa, and the wear rate decreases significantly with increasing speed, especially under high-speed braking. Under all braking pressure ranges, the wear rate of SD-FP is consistently lower than that of SD-SP, indicating better wear resistance of SD-FP. With increasing braking pressure, the wear rates of both friction materials show an upward trend, but the increase in SD-FP is smaller, further indicating its superior performance. The average friction coefficient (COF) of the two friction pairs under SAE-J2522 test conditions is shown in Fig. 8e. The COF of the two friction pairs is generally greater than 0.5, with a maximum value of up to 0.8, which is too high for automotive or train applications. Comparatively, the COF of SD-SP is more stable but higher than that of SD-FP, which achieves relatively lower COF (<0.5) that is more valuable for applications. In addition, the COF shows significant fluctuations in tests such as speed-pressure sensitivity, thermal decay 1, pressure-temperature sensitivity, and thermal decay 2. This means that when braking speed, pressure, or temperature changes, the COF easily changes. Therefore, clarifying the changes in friction performance under different braking conditions helps understand the braking performance of full carbon/ceramics pairs.

After studying the impact of introducing $FeSi_2$ on the braking performance of full carbon/ceramics pairs, Ma *et al.* [22] further investigated the effect of adding copper (Cu) to FeSi75 alloy modified C/C-SiC composites. They mixed FeSi75 alloy and Cu powder, impregnated these mixed powders into porous C/C preforms, and finally obtained Fe-Si-Cu modified C/C-SiC brake pads (CP). Adding Cu significantly improved the wear resistance and friction coefficient stability of the braking material. Figure 9 shows the wear comparison of different braking pairs after a series of braking tests. After 255 repetitive braking tests, the brake disc wear of SD-CP was reduced to half the value of SD-FP (FP: FeSi75 modified C/C-SiC brake pad), while the brake pad wear of the disc SD-CP was reduced to one-third

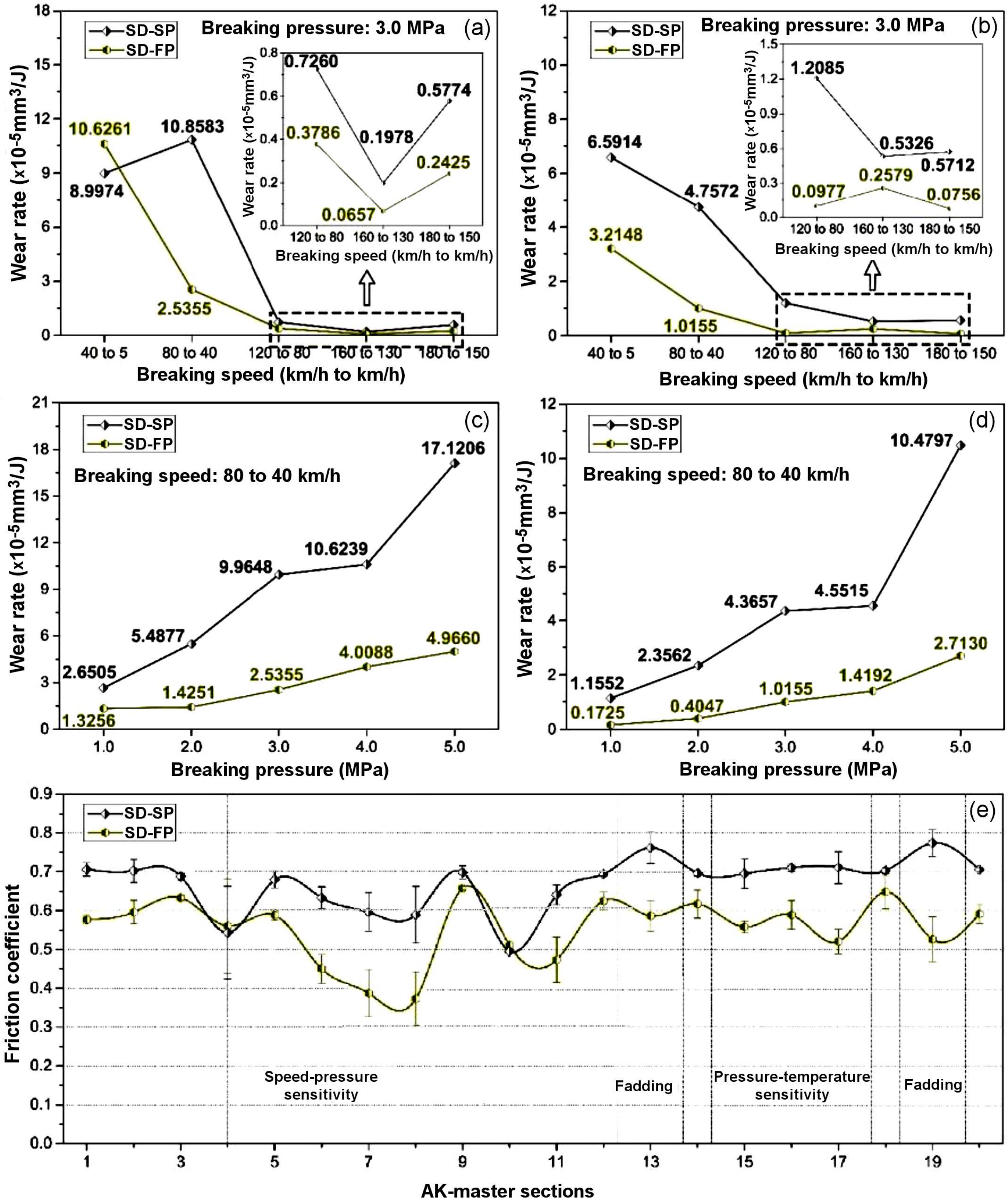


Figure 8. Brake disc wear (a) and brake pad wear (b) at different braking speeds; disc wear (c) and pad wear (d) at different braking pressures; average COF (e) of two friction pairs under SAE-J2522 conditions [22]

of SD-FP. Compared to the unmodified C/C-SiC brake pads, Fe-Si-Cu modification reduced the wear of the disc by about 90% and the pad by about 85%. Comparing the wear performance of the prepared Fe-Si-Cu modified brake pads and powder metallurgy (PM) brake pads shows that the wear loss of the former is 60% lower than that of the latter, indicating the great potential of Fe-Si-Cu mixed modification in improving the wear resistance of full carbon/ceramic brake pads [23,24,25].

3.5. *Thermal shock resistance*

Additionally, the thermal shock resistance of carbon ceramic brake discs is also crucial to their performance and lifespan. Studies show that carbon fibre reinforced silicon carbide-based composites have excellent thermal shock resistance, maintaining structural integrity at high temperatures [27]. For example, C/C-SiC composites prepared by liquid phase silicon infiltration exhibited excellent thermal stability and thermal shock resis-

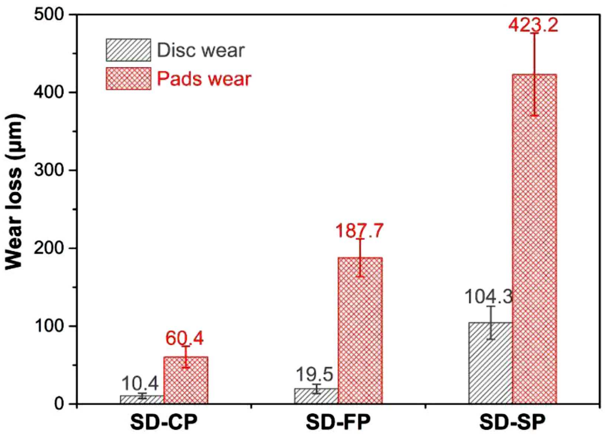


Figure 9. Wear of different braking pairs under SAE-J2522 conditions [26]

tance under high-temperature conditions [1]. Furthermore, Harada *et al.* [28] found that adding vanadium to brake disc materials can significantly improve their thermal shock resistance and wear resistance. Mohanty *et al.* [3] prepared 2D reinforced carbon composite laminates through a pitch impregnation process, using multilayer ceramic coatings to enhance the thermal shock resistance of carbon-carbon composites.

Dynamic and static oxidation tests up to 1200 °C showed that specific coatings significantly improved the oxidation resistance of carbon-carbon composites, particularly in dynamic and static oxidation tests. The results indicated that specific multilayer coatings (especially C-SiC-BC) effectively improved the performance of materials in high-temperature oxidation environments, significantly enhancing the thermal shock resistance of carbon-carbon composites. As shown in Figs. 10a and 10b, uncoated materials performed the worst under high-temperature conditions, rapidly degrading and losing weight during continuous isothermal tests. In contrast, SiC coatings significantly improved the thermal stability of the materials, especially in dynamic oxidation tests (Fig. 10c). Although SiC-MoS_2-Al_2O_3 coatings also performed well in dynamic tests (Fig. 10e), they still showed rapid mass loss during prolonged isothermal tests (Fig. 10f). Meanwhile, SiC-B_4C coatings displayed excellent protective performance un-

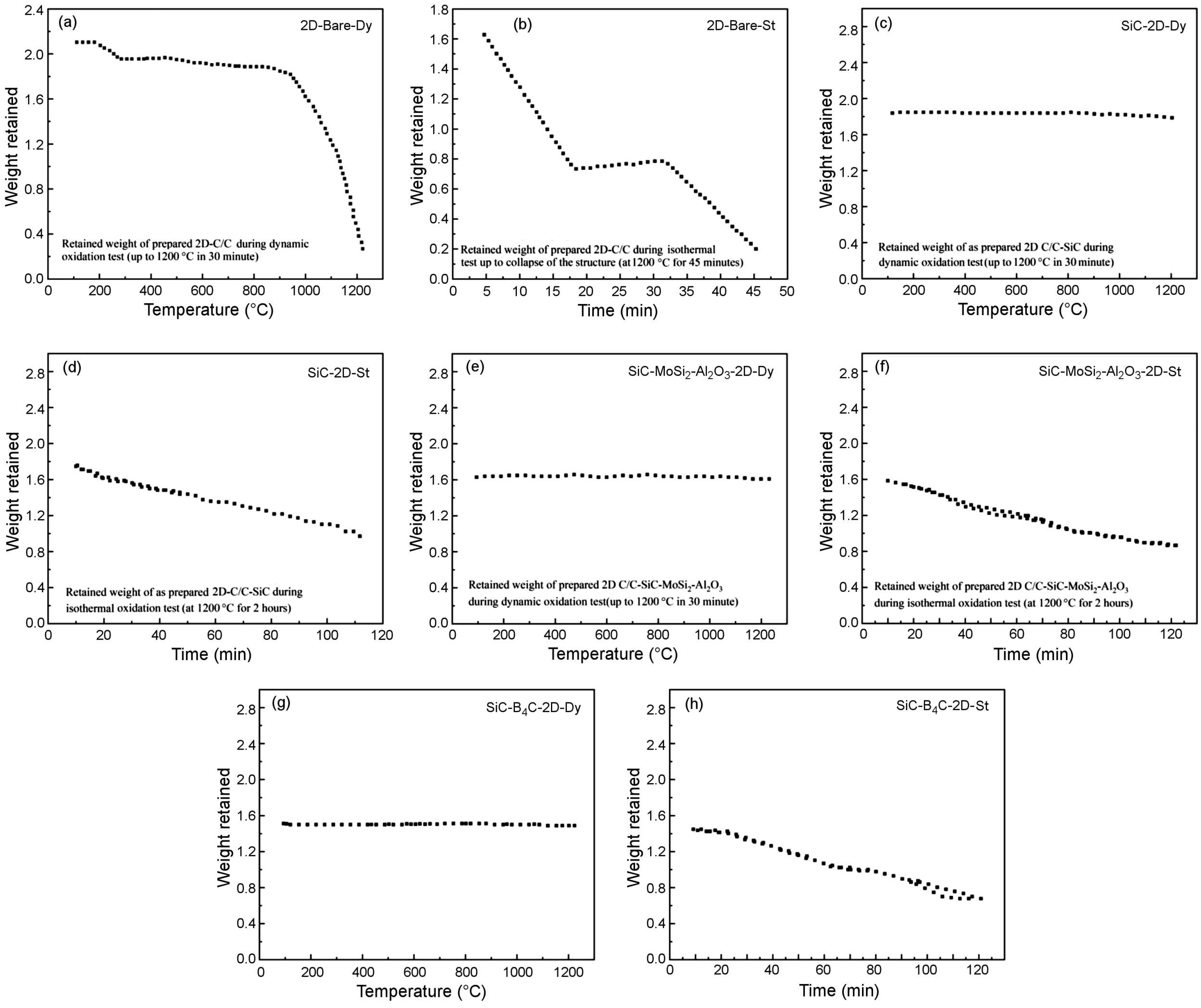


Figure 10. Performance comparison of different coatings on 2D C/C composites in high-temperature oxidation tests: (a, b) No coating; (c, d) SiC coating; (e, f) SiC-MoS_2-Al_2O_3 coating; (g, h) SiC-B_4C coating [3]

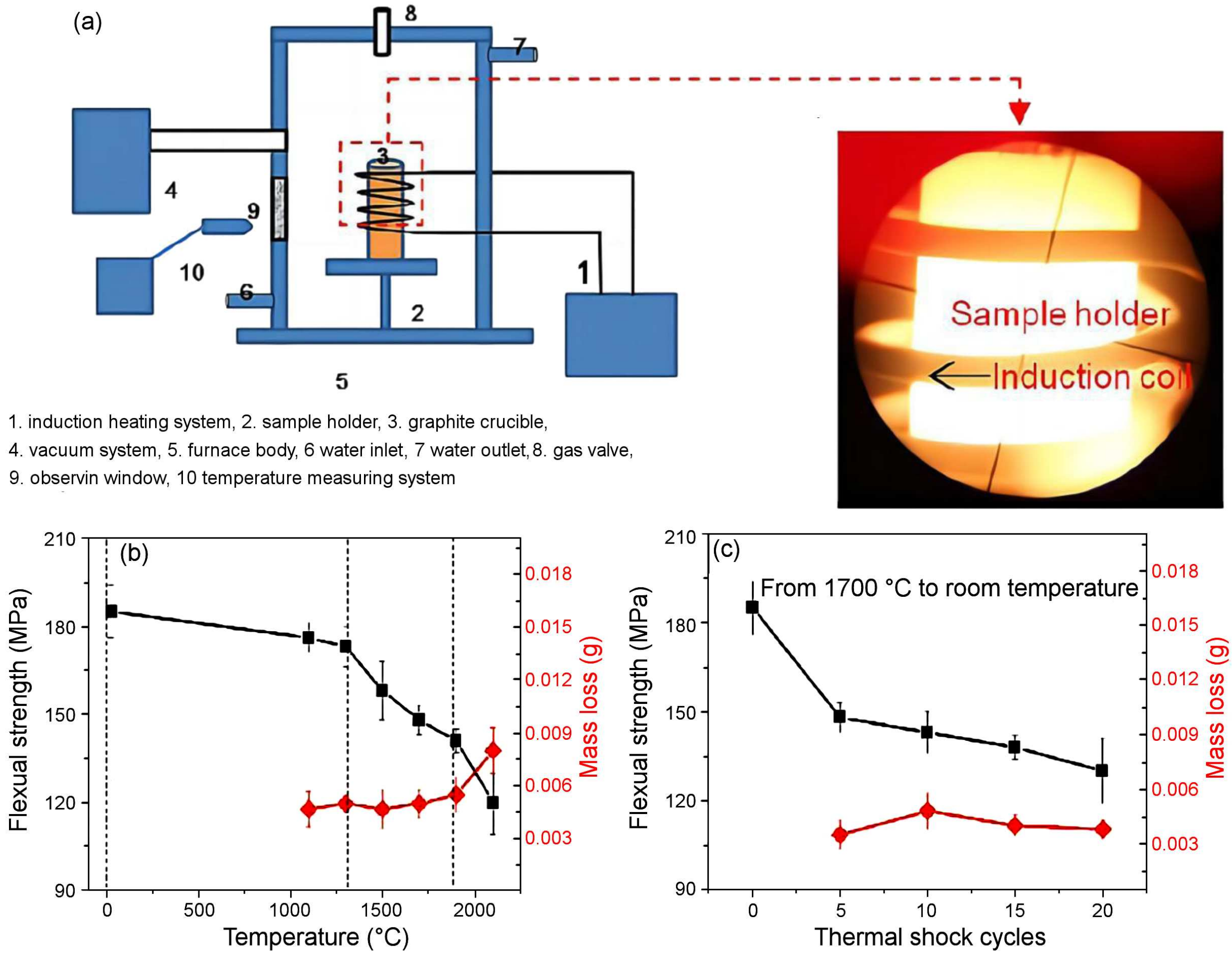


Figure 11. Thermal shock testing equipment (a) for C/C-ZrC composites and bending strength and mass loss after 5 thermal cycles at different temperatures (b), and after different number of thermal shock cycles (c) [30]

der all test conditions, maintaining low mass loss rates during isothermal conditions (Figs. 10g and 10h). These results highlight the importance of optimizing coating configurations for carbon-carbon composite brake discs in extreme high-temperature applications, pointing to effective ways to improve their performance and stability.

Thermomechanical analysis showed that functionally graded materials (FGM) exhibited higher safety factors under high-temperature conditions, with better thermal shock resistance [29]. Additionally, Tong *et al.* [30] prepared and evaluated the thermal shock resistance of continuous carbon fibre-reinforced ZrC-based ultra-high temperature ceramic composites (C/C-ZrC). Using a self-developed high heating-cooling rate device (Fig. 11a), thermal shock tests were conducted in a pure Ar atmosphere, testing samples from ultra-high temperatures (>1500 °C) to room temperature. Results showed that at temperatures below 1300 °C, the bending strength of the composites slightly decreased with no significant weight loss; between 1300 °C and 1900 °C, the bending strength significantly decreased, and above 1900 °C, it dropped sharply with noticeable weight loss (Fig. 11b). Figure 11c shows the bending strength and mass loss of the composites after different numbers of thermal shock cycles at 1700 °C to room temperature. The bending strength gradually decreased with increasing thermal shock cycles, with residual strength at about 130 MPa after 20 thermal shock cycles being 70.3% of the original strength. Below 1700 °C, there was no significant change in mass with increasing thermal shock cycles, indicating stable chemical composition and structure at this temperature.

Scanning electron microscopy analyses (Figs. 12 and 13) of the microstructure after thermal shock revealed that matrix cracking, interface debonding and matrix porosity were the main causes of strength reduction. These phenomena worsened with increasing thermal shock temperature, indicating more significant damage at higher temperatures. Additionally, the bending strength of the composites gradually decreased with increasing the number of thermal shock cycles, showing the significant impact of cumulative thermal stress on material performance. Numerical analysis indicated that computational fluid dynamics (CFD) methods could effectively predict the thermal behaviour of different materials under high temperatures, demonstrating that carbon ceramic materials exhibit higher thermal shock re-

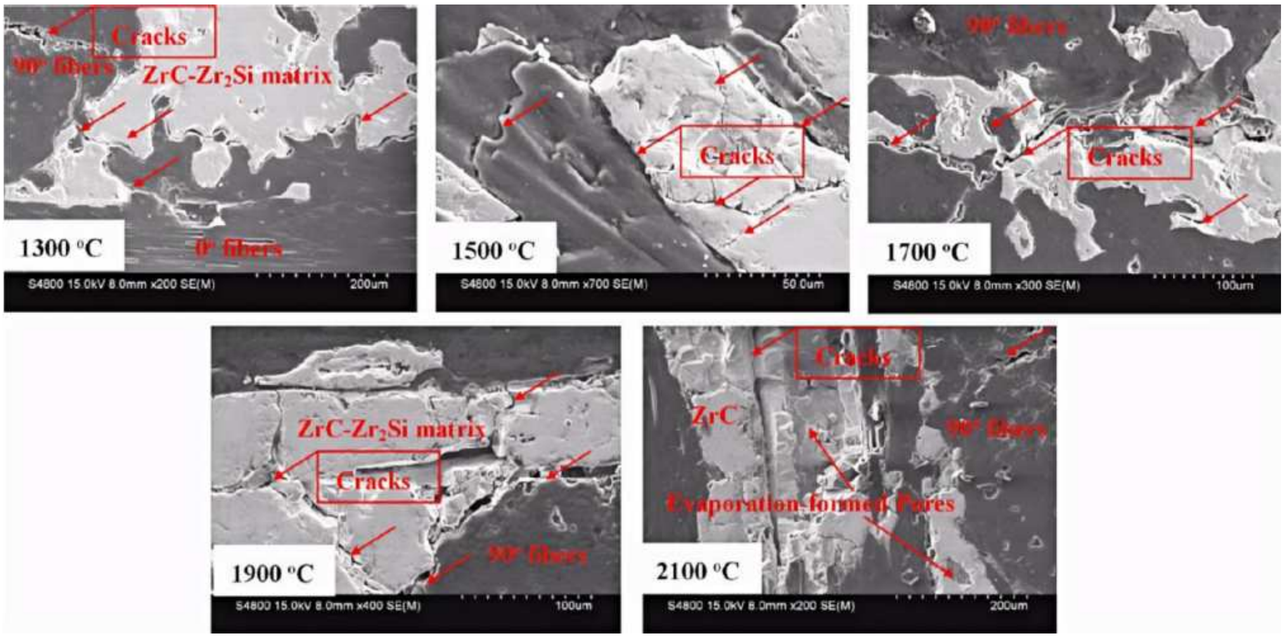


Figure 12. Microstructure of C/C-ZrC composites after 5 thermal shocks at different temperatures [30]

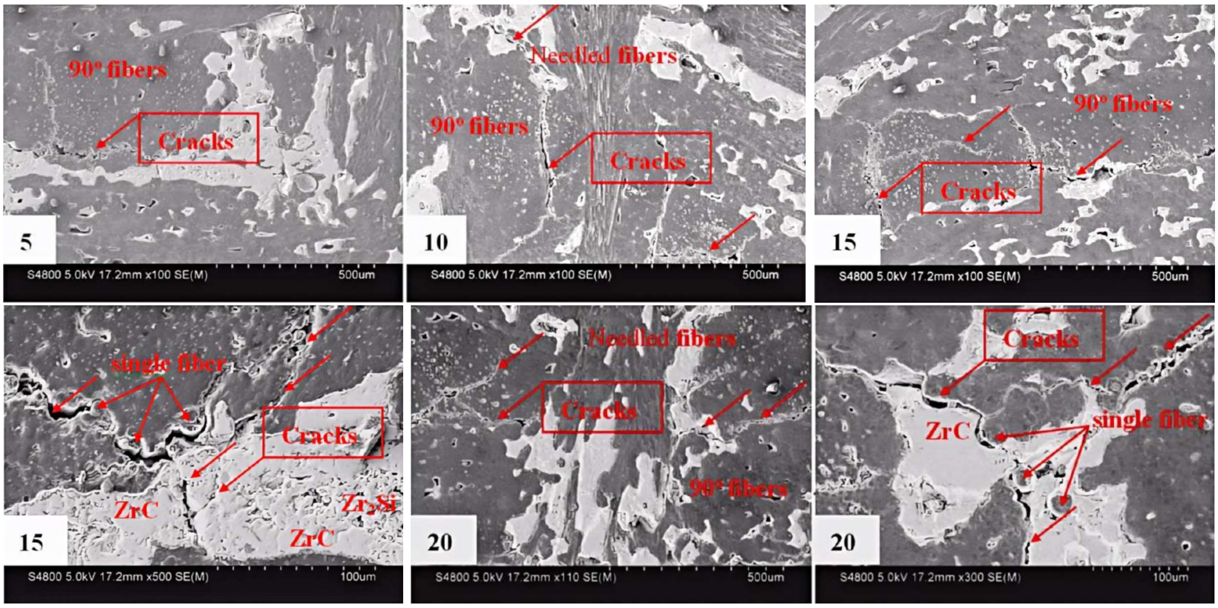


Figure 13. Microstructure of C/C-ZrC composites after different number of thermal shock cycles [30]

sistance at high temperatures [31]. Furthermore, finite element analysis (FEM) studies found that uneven temperature distribution in the brake disc could negatively impact friction performance, with mixed braking modes potentially leading to transient thermal shock [32]. To improve the thermal shock resistance of brake discs, researchers also developed ceramic matrix composites reinforced with carbon fibres, which exhibited excellent thermal shock resistance during rapid heating and cooling processes [33]. Overall, through material modification and advanced manufacturing techniques, carbon ceramic brake discs demonstrate excellent thermal shock resistance under high-temperature and high-load conditions, helping extend their lifespan and enhance safety performance. Future research should continue exploring new materials and processes to further enhance the comprehensive performance of carbon ceramic brake discs.

IV. Optimization approaches to C/C brake discs

Carbon-ceramic brake discs are widely used in high-performance vehicles due to their excellent properties. However, with advancements in technology and increased application demands, there is a higher requirement for optimizing the performance of carbon-ceramic brake discs. This section explores the main approaches to the performance optimization of carbon-ceramic brake discs, including material modification, structural design optimization, cooling efficiency enhancement, and multi-objective optimization strategies, along with a detailed analysis based on relevant literature.

4.1. Material modification

Material modification is the primary approach in order to improve the performance of carbon-ceramic brake discs. By adding new materials or altering the chemical composition of composite materials, the wear resistance and thermal stability of the brake discs can be significantly enhanced. For instance, Bian *et al.* [11] demonstrated that introducing new nano-fillers into carbon/silicon carbide composites can effectively improve their friction performance under various environmental conditions. Krenkel *et al.* [27] employed the liquid silicon infiltration (LSI) method to infiltrate silicon into carbon/carbon matrices, producing C/C-SiC composites with excellent tribological properties, low density, and high thermal shock resistance. The use of dual matrix technology (C/C-SiC) can improve the fracture toughness and wear resistance of brake discs. Krnel *et al.* [1] showed that these composites exhibit superior mechanical and thermo-physical properties, performing well under high temperatures and loads. Modifying the composition and structure of the matrix materials can further optimize their performance; for example, addition of copper (Cu) can significantly reduce the wear rate and improve the stability of the friction coefficient of traditional C/C-SiC brake discs [26]. In addition to modifying the matrix materials, surface coating material modification is another important approach for performance optimization. Mohanty [3] studied the oxidation behaviour of multi-layer ceramic coatings under high-temperature conditions and found that C-SiC-B_4C coatings performed excellently in an oxidation environment at 1200 °C.

4.2. Structural design optimization

Optimizing the structural design of brake discs is another key approach to enhance their performance. By optimizing the microstructure of materials, such as introducing carbon fibre-reinforced Si-SiC matrices, wear resistance and thermal stability can be improved. Casalegno *et al.* [34] studied the structural design optimization of the connection between carbon-ceramic brake discs and aluminium alloys, finding that using Supreme 42HT-2 epoxy adhesive and an optimized curing process can significantly improve bonding strength and thermal stability. The experimental results indicated that heat-treated curing can significantly increase bonding strength, with the adhesive showing excellent durability under multiple thermal cycles and salt spray environments. SEM analysis revealed a good mechanical interlocking structure between the adhesive and carbon-ceramic materials and aluminium alloy, maintaining good bonding strength under high temperature and high salt environments. This structural design can maintain the stability and durability of materials at high temperatures. Functionally graded materials (FGM) exhibit better thermal shock resistance at high temperatures, and their structural design can further enhance the comprehensive performance of brake discs [29]. Zhang *et al.* [35] showed that optimization of the internal and surface structures of brake discs can effectively improve their heat dissipation performance and structural stability. Additionally, Ko *et al.* [19] used two different shapes of carbon-ceramic brake discs (Fig. 6), where the model A had rectangular ventilation holes and the model B had cylindrical ventilation holes. By changing the diameter of the middle ventilation hole (b_2) to 17.6 mm, the cooling effect was studied. The results indicated that by appropriately shortening the length of the ventilation holes and increasing their diameter one can significantly enhance the cooling efficiency of carbon-ceramic brake discs. This optimized design cannot only effectively reduce the temperature of the brake discs but also improve the overall performance and reliability of the braking system. Furthermore, Li *et al.* [6] confirmed that improvement of the microstructure of materials can enhance the thermal conductivity and mechanical strength of brake discs.

4.3. Cooling efficiency enhancement

In high-performance applications, the cooling efficiency of brake discs is crucial for ensuring their stability and extending their service life. By improving the design of cooling channels and using more efficient heat dissipation materials, the temperature rise during braking can be significantly reduced. Missori *et al.* [36] proposed a method to optimize the proportion of railway brake discs by evaluating temperature transients, effectively enhancing the thermal efficiency of the braking system. Usage of X-shaped grating core ventilated brake discs can achieve a higher total Nusselt number at the same rotational speed, significantly improving cooling performance [37]. Using multi-row pin ventilated brake discs is also an effective cooling improvement method, where the multi-row configuration of pins can significantly increase the heat dissipation coefficient and reduce thermal stress accumulation [38]. Studies also show that installing axial ventilators on the rims can greatly enhance the cooling efficiency of brake discs, with temperature reductions of up to 54% [39]. Transverse drilled ventilated brake discs also exhibit significant heat dissipation advantages, with these holes accelerating boundary layer flow and enhancing local heat exchange [37]. Further research indicates that improved X-shaped grating core ventilated brake discs have an 18–21% higher steady-state overall cooling capacity within the typical operating range compared to traditional radial blade brake discs [40]. For railway systems, using newly designed brake discs with radial blades and annular columns can significantly reduce aerodynamic losses and improve cooling efficiency [41]. Designing and validating a specialized aerodynamic bench for wheel corner flow investigation also helps optimize the cooling performance of brake discs, with this bench setup simulating the cooling distribution of vehicle wheel corners [42]. The convective area and air velocity of brake discs significantly affect cooling efficiency, and optimizing the convective area of brake discs is key to improving cooling efficiency [43]. Improving the design of brake discs mounted on wheels can increase convective heat dissipation, enhancing overall cooling efficiency [44]. To enhance the cooling performance of brake discs, newly developed stir-cast main alloy brake discs can be used. This design has a higher heat conduction area, significantly reducing the temperature of the brake discs [45]. By improving air flow and heat dissipation design, the temperature and stress of brake discs in emergency braking conditions can be significantly decreased, reducing the risk of hot spot formation [46].

4.4. *Multi-objective optimization*

During the development of carbon-ceramic brake discs, it is often necessary to find the optimal balance among multiple performance indicators. Yin *et al.* [47] presented a multi-objective optimization method that successfully developed a brake disc design with better performance by simultaneously considering the weight, wear rate and heat dissipation performance of the brake discs. This method helps control manufacturing costs and complexity while ensuring performance. Other studies have also demonstrated similar multi-objective optimization methods. For example, Zhang *et al.* [35] proposed a multi-objective optimization design method based on thermal conductivity performance. Through finite element analysis and a central composite design (CCD) sampling scheme, the total thickness, ventilation slot height and rib angle of the brake discs were optimized, ultimately reducing the mass and peak temperature of the brake discs by 7.8% and 54%, respectively. Yan *et al.* [37] used the response surface method for multi-objective optimization design. Through second-order regression models and variance analysis, the geometric parameters of ventilated brake discs were optimized, reducing total deformation and equivalent stress by 10.28% and 9.12%, respectively. Additionally, Lin-Chao *et al.* [48] used genetic algorithms to optimize the design objectives of caliper disc brakes, achieving the lowest braking temperature and maximum braking torque. Yang *et al.* [49] conducted multi-objective optimization design for automotive drum brakes using penalty functions and the MATLAB optimization toolbox, effectively improving the efficiency factor of the brakes and reducing the heat on the friction surface. Sabarinath *et al.* [50] used the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to optimize the design of disc brakes, with the main goals of reducing the mass of the brakes and the stopping time. They improved the performance of the NSGA-II algorithm through virtual mapping procedures and control elite strategies, making the optimization results more reliable. Kursa *et al.* [51] studied the application of metal-ceramics composites in brake discs using multi-objective optimization methods, optimizing the thermomechanical properties of the composites to achieve the best performance in different application scenarios. Zhou *et al.* [52] proposed an optimization method combining the Analytical Hierarchy Process (AHP) and NSGA-II. By selecting non-dominated solution sets for analysis, multi-objective optimization of brake discs was achieved. Liang *et al.* [53] conducted matching analysis of carbon-ceramic brake discs for high-speed trains using a data-driven parametric approach, optimizing the assembly interface, physical properties, and braking performance of the brake discs, resulting in better matching performance under emergency braking conditions. Sheng *et al.* [54] proposed a multi-objective optimization model based on Radial Basis Function Neural Networks and improved Genetic Particle Swarm Optimization algorithms, optimizing the mass and natural frequency of EMU brake modules, significantly improving optimization efficiency and result accuracy. Thang *et al.* [55] used the NSGA-II algorithm to perform multi-objective optimization on magneto-rheological brakes, with the objectives of maximizing braking torque and minimizing brake mass, constrained by a thermal analysis model of the MRF temperature. Ultimately, through the aforementioned research and optimization measures, the comprehensive performance of carbon-ceramic brake discs can be significantly enhanced to meet the demands of high-performance applications.

V. Current status of C/C brake discs

Due to their superior mechanical properties and high-temperature resistance, carbon-ceramic brake discs have been applied in various high-performance fields. This article, based on multiple studies, analyses the current status of carbon-ceramic brake discs in aviation, automotive, high-speed rail and motorcycle applications, and explores future development directions for carbon-ceramic brake discs.

5.1. *Applications in the aviation field*

Research on the application of carbon-ceramic brake discs in the aviation field showed that they have excellent mechanical and thermal properties, making them widely used in high-performance aircraft braking systems. Krnel *et al.* [1] developed a carbon/carbon-silicon carbide (C/C-SiC) dual matrix composite material manufactured by liquid silicon infiltration, exhibiting high fracture toughness, good oxidation resistance and wear performance, making it an ideal material for aircraft brake discs. Mohanty [3] studied the performance of carbon-carbon composite brake discs in high humidity and high-temperature environments and found that the C-SiC-B_4C system has excellent oxidation resistance at 1200 °C, suitable for high-energy braking in aircraft. Kumar and Srivastava [56] reviewed the tribological properties of C/C-SiC composites, pointing out that this material, prepared by chemical vapour infiltration, polymer infiltration and pyrolysis and liquid silicon infiltration, has high hardness, thermal stability and low chemical reactivity, making it very suitable for aircraft brake discs. Zuber and Heidenreich [4] studied the net shape manufacturing method of monolithic ventilated C/C-SiC brake discs, demonstrating the potential of this technology in high-performance brake disc manufacturing. Krenkel [27] proposed the design of ceramic composite brake discs manufactured by molten silicon infiltration into carbon/carbon matrices, showing superior thermal shock stability and wear resistance in aviation braking systems. Li *et al.* [57] analysed the research status and development trends of ceramic brake discs, pointing out that research on high-temperature performance, biological structures, layered structures, porous structures and superhard structures helps improve the overall performance of brake discs. Su *et al.* [58] studied the application of nine different carbon/carbon composites in aircraft brake discs, analysing their mechanical, physical, thermal, friction and wear properties, concluding that high-quality home-made carbon brake discs can be used in large civil aircraft such as the Boeing 757-200. Zhao *et al.* [59] developed an efficient manufacturing method for aviation carbon brake discs, showing that the brake discs produced by this new method have better friction coefficient stability and microstructure than commercial brake discs.

5.2. Applications in the automotive industry

In the automotive industry, carbon-ceramic brake discs have become an important component of high-performance and luxury vehicles braking systems. Li *et al.* [5] conducted a comprehensive analysis of the performance of automotive carbon-ceramic brake discs, highlighting their significant advantages in improving braking efficiency and reducing weight. Additionally, Renz *et al.* [60] explored the integration of composite material brake discs (CMC) in automotive braking systems, emphasizing their potential in enhancing overall vehicle performance and safety. Lim *et al.* [61] tested and evaluated the strength of carbon/carbon brake discs in automotive applications, finding that their high specific modulus, high specific strength and excellent thermal stability make them perform excellently under high-temperature conditions. Gadow and Speicher [62] studied the application of carbon fibre reinforced silicon carbide composites under high-temperature conditions, finding that this material has high potential for mass production of passenger car brake discs. Nilov *et al.* [63] conducted a detailed analysis of the production and application of ceramic matrix composite brake discs in heavy-duty braking systems, noting their excellent performance in improving braking performance and reducing wear. Casalegno *et al.* [34] studied the connection between ceramic matrix composites and aluminium alloys to achieve mechanical reliability and durability of high-performance road brake discs. Jang *et al.* [14] investigated the friction and wear properties of C/C-SiC composites prepared by liquid silicon infiltration, finding that high-silicon content discs can form a stable friction film under high pressure, significantly improving wear resistance.

5.3. Applications in the high-speed rail field

Research on the application of carbon-ceramic brake discs in the high-speed rail field shows significant advantages of their high strength and high thermal stability. Studies have shown that carbon-ceramic brake discs are more suitable and perform better in high-speed rail braking systems compared to traditional steel brake discs. Song *et al.* [64] reviewed the development of high-speed rail brake disc materials, including carbon-carbon composites, ceramic materials, and aluminium-based ceramic reinforced composites, emphasizing their potential in reducing weight and improving thermal performance. Yu *et al.* [65] studied the thermal behaviour of SiC/Al composite brake discs in emergency braking of CRH3 high-speed trains through finite element analysis and experimental simulation, finding that this composite material has excellent thermal stability and heat dissipation performance at high temperatures. Zhao *et al.* [66] studied the friction behaviour of Cu-based powder metallurgy brake pads and C/C-SiC brake discs in high-speed rail braking, showing that this combination has a high friction coefficient and stability at high speeds. Ma *et al.* [25] compared the friction behaviour of iron-based and copper-based powder metallurgy brake pads on C/C-SiC brake discs, finding that the C/C-SiC brake discs had almost no wear loss, while the wear mechanism of the powder metallurgy brake pads was mainly dominated by abrasion and fatigue spalling. Zhao *et al.* [67] studied the friction behaviour of C/C-SiC brake discs under wet braking conditions, finding that the lubrication effect of the water film significantly reduced the friction coefficient, but the recovery speed of the friction coefficient increased with the initial braking speed. Wang *et al.* [68] studied the friction behaviour and wear mechanism of all-carbon/ceramics brake pairs, finding that the introduction of $FeSi_2$ soft phase significantly improved the wear resistance and friction performance of the brake pads. Yu and Wang [69] improved the heat dissipation performance of high-speed rail brake discs by designing airways on the friction surface of the brake discs, significantly reducing thermal load. Luo *et al.* [70] studied the fatigue life of high-speed rail brake discs through thermal stress analysis and life prediction, establishing a reliability life analysis method based on load spectrum.

5.4. Applications in the motorcycle field

Motorcycle braking systems have also begun to adopt carbon-ceramic brake discs to meet the extreme braking demands at high speeds. Stadler *et al.* [71] developed a carbon/carbon-silicon carbide (C/C-SiC) composite brake disc manufactured by liquid silicon infiltration, featuring low density, extremely low wear rate and high thermal shock resistance, widely used in motorcycle braking systems. This new braking system adopts a "floating" fixation method and is equipped with zirconia toughened mullite pistons with low thermal conductivity and sintered metal brake pads, showing excellent safety and braking performance. Sivaiah and Lakshmaiah [21] designed and thermally analysed carbon-ceramic brake discs for high-performance motorcycles, finding that this material has low production costs and long service life. They determined the optimal brake disc design through comparisons of different materials and structural models, significantly improving thermal behaviour and stress distribution. Pillala *et al.* [72] studied the thermal stress analysis and modelling of carbon-ceramic brake discs for motorcycles, showing that this material has excellent thermal stability and wear performance under high-temperature conditions. It also exhibits excellent braking response and low wear characteristics, making it an ideal choice for high-performance motorcycle braking systems. Casalegno *et al.* [34] studied the connection between ceramic matrix composites and aluminium alloys to improve the mechanical reliability and durability of motorcycle brake discs. This combination method enhances the performance of brake discs under high temperature and high stress conditions, making them more suitable for high-performance motorcycles. Additionally, Langhof *et al.* [73] studied the application of all-ceramic braking systems in high-performance motorcycles, finding that the introduction of coke fillers significantly improved the wear resistance and friction performance of the brake pads.

5.5. Future development directions

The future development of carbon-ceramic brake discs will depend on continuous advancements in material science and manufacturing processes, driven by market demand and changes in application fields. With the continuous innovation of technology and the gradual maturation of the market, the application prospects of carbon-ceramic brake discs in high-performance braking systems will be broader, becoming an important force in promoting industrial technological progress in aviation, high-speed rail, automotive and other industries. The future development of carbon-ceramic brake discs will focus on the following aspects:

First, material innovation will be key to the development of carbon-ceramic brake discs. Research shows that by optimizing the ratio and structure of carbon fibres and ceramic matrices, the wear resistance and thermal crack resistance of brake discs can be further improved. Additionally, the introduction of new composite materials, such as doping nanoparticles and using high-performance resin matrices, is expected to significantly improve the overall performance of carbon-ceramic brake discs.

Second, advancements in manufacturing processes will also drive the application of carbon-ceramic brake discs. Additive manufacturing (3D printing) technology in the field of carbon-ceramic materials can achieve rapid forming of complex structures, reduce production costs and improve production efficiency. Meanwhile, advanced heat treatment and surface modification technologies help further enhance the mechanical properties and service life of carbon-ceramic brake discs.

In terms of application fields, with the popularity of electric and hybrid vehicles, the application of carbon-ceramic brake discs in these high-performance and energy-efficient vehicles will gradually increase. Due to the higher requirements of electric vehicles for braking systems, carbon-ceramic brake discs, with their excellent performance, have become the ideal choice. Additionally, the demand for high-performance and luxury vehicles braking systems will continue to drive the carbon-ceramic brake discs market growth.

Meanwhile, market demand is also driving the development of carbon-ceramic brake disc technology. The increasing demand for high-performance, long-life and low-maintenance braking systems from consumers is prompting manufacturers to increase research and development investment to develop more competitive products. Furthermore, with the global tightening of vehicle safety and environmental protection requirements, carbon-ceramic brake discs, as an environmentally friendly and efficient braking solution, have a broader market prospect.

VI. Summary

Carbon-ceramic brake discs have established themselves as critical for high-performance braking systems across various sectors, including high-performance vehicles, aviation and high-speed trains. These discs excel due to their superior friction performance, thermal stability, wear and thermal shock resistance, and lightweight properties. The transition from experimental to industrial production has been driven by advances in material science, composite technology, and precision manufacturing, resulting in broader applications due to cost reductions and improved production efficiency.

Future developments will focus on material and process innovations to enhance properties like thermal resistance and wear resistance. Nanotechnology and surface engineering will likely produce composites with improved functionality. As environmental concerns grow, the energy-saving potential of these lightweight discs will be increasingly leveraged, especially in electric and hybrid vehicles. Additionally, cost reductions and efficiency gains are anticipated to enable expansion into mid-range automotive and industrial markets. Research will also aim at integrating these discs with intelligent systems for real-time performance monitoring, thereby enhancing safety and reliability in braking systems.

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