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RECENT ADVANCES AND ENVIRONMENTAL CONSIDERATIONS IN BRAKE DISC MATERIAL DEVELOPMENT

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ABSTRACT

Brake discs operate under extreme thermal, mechanical, and chemical stresses, requiring materials that balance durability, braking efficiency, cost, and environmental impact. This paper reviews recent developments in grey cast iron, titanium alloys, and ceramic–matrix composites, along with surface coatings, cryogenic treatments, and design-based thermal management. Improvements in material microstructure, surface engineering, and rotor geometry have improved wear resistance, heat dissipation, and overall braking stability. Growing environmental concerns are encouraging the adoption of cleaner, more sustainable materials and designs that reduce particulate emissions and prolong component lifespan.

KEYWORDS: brake disc materials; tribology; thermal management; environmental impact.

1. INTRODUCTION

Friction brakes convert kinetic energy into heat while maintaining stable friction, low wear, and structural integrity under highly transient thermal cycles [1,2]. Materials for brake discs are therefore designed not only for mechanical strength and stiffness but also for tribological compatibility with brake pad materials, corrosion resistance under realistic environmental exposure, and predictable thermophysical behaviour across temperature ranges that can locally exceed several hundred degrees Celsius [3,4]. For many years, grey cast iron (GCI) has been the main material used for brake discs, thanks to its advantageous graphite structure, good vibration damping, and low manufacturing cost. However, as the demands for lighter weight, higher durability, and better environmental performance continue to grow, research has shifted toward exploring new base materials, surface technologies, and rotor designs [4,5].

Current research on brake disc materials brings together several areas of engineering and a range of analytical methods. It focused on how the microstructure influences tribological performance in metallic rotors, where the shape of the graphite and the composition of the metal matrix play key roles in maintaining stable friction and controlling wear mechanisms [6]. Researchers have quantified the relationships between material properties, heat transfer behaviour, and braking duty cycles using thermophysical characterization and numerical modelling [3]. To achieve improved thermal stability, oxidation resistance, and reduced fade under extreme braking conditions, advanced ceramic and carbon–ceramic composite materials such as carbon/carbon–silicon carbide (C/C–SiC) are under optimization [7]. In the case of the GCI rotors, surface engineering technologies such as conversion coatings, thermal spraying, and physical vapor deposition have improved wear resistance, decreased corrosion, and reduced particulate emissions. [4]. Additionally, optimization of rotor geometry, particularly through ventilated vanes and cross-drilled configurations, increases convective heat transfer and minimizes thermal gradients. [8,9]. Process-level interventions such as cryogenic treatment have further demonstrated potential to refine microstructural features, relieve residual stresses, and improve wear performance under cyclic thermal loading [10]. The environmental dimension, including non-exhaust particulate emissions, corrosion by-products, and end-of-life impacts, now plays a decisive role in material selection. These factors increasingly reshape how performance is evaluated, shifting the focus toward real-world operating conditions and the overall life-cycle impact of brake disc materials [11–14].

This study consolidates current research across multiple domains, analysing the interdependence between material constitution (phase composition and morphological features), processing routes such as thermal and cryogenic treatments, and surface characteristics, including coatings and topography. Particular attention is given to how these factors interact with disc architecture and system-level thermal fields during braking. The objective is to establish a coherent framework that bridges laboratory-derived material parameters with operational performance phenomena such as frictional fade, thermal cracking, hot-spot formation, acoustic response, and particulate emission behaviour.

2. METHODOLOGICAL APPROACH

This section outlines the methodological framework adopted for the present synthesis, which consolidates experimental findings, modelling insights, and engineering analyses from recent literature. The approach is qualitative and interpretive rather than experimental, aiming to integrate convergent results across multiple research domains relevant to brake disc materials. The paper focuses on publications and technical reports addressing tribological behaviour, thermophysical properties, surface engineering, and environmental performance of braking systems and covers several complementary domains: the microstructure - dependent tribological behaviour of grey cast iron (GCI) and alternative metallic alloys [6]; thermo-physical property evaluation, including thermal conductivity, specific heat, and diffusivity, under transient braking conditions [3]; and the development of advanced ceramic and carbon–ceramic composite systems for high-temperature stability and low fade performance [7,15]

Additional attention has been directed to corrosion and wear-resistant surface coatings, as well as to system-level thermal and CFD investigations of ventilated and cross-drilled rotors, which link geometry to convective cooling and thermal stress development [4,8,16]. Process-level enhancements, such as cryogenic treatment, have been investigated for their potential to refine microstructural features and enhance wear resistance. Additionally, increasing attention has been directed towards environmental aspects, particularly wear debris formation and non-exhaust particulate emissions [10,11].

This paper highlights recurring trends identified across independent investigations, emphasising the consistent relationships between microstructure, thermal response, and tribological stability. Increasingly, eco-performance considerations are being integrated into both the design philosophy and the evaluation criteria for brake disc materials, reflecting a broader shift towards sustainable engineering practice.

Table 1 shows a comparative overview of representative material and system-level properties relevant to brake disc performance. The compiled parameters include density, thermal conductivity, friction coefficient, maximum operating temperature, and qualitative trends in particulate emissions and relative cost. These comparative data form the foundation for subsequent analysis and for evaluating material-specific design trade-offs.

From the comparison in Table 1, several trends become apparent. Grey cast iron (GCI) remains the reference material for conventional automotive rotors, combining moderate thermal conductivity, high damping capacity, and low cost. Laser-cladded or ceramic-coated GCI variants demonstrate improved corrosion and wear resistance with only marginal changes in thermal properties.

Lightweight systems such as aluminium-matrix composites (Al-MMCs) and titanium alloys achieve significant mass savings but exhibit lower heat capacity and reduced thermal conductivity, leading to steeper thermal gradients and potential fade under repeated braking. Ceramic-matrix and carbon–ceramic composites (C/C–SiC) show outstanding high-temperature strength and minimal fade. However, their production cost and acoustic harshness limit large-scale adoption.

The table also reflects a clear trade-off between density and heat dissipation: high-conductivity materials like Al-MMCs cool rapidly but store less heat, whereas ferrous systems absorb and distribute heat more uniformly. Furthermore, materials incorporating coatings or composite architectures tend to reduce particulate-matter emissions (PM/PN trends) by stabilising wear mechanisms at the pad–disc interface. Overall, the data underscore the balance required between mechanical robustness, thermal management, and environmental performance in modern brake disc design.

3. RESULTS AND DISCUSSION

3.1. Ferrous substrates

Grey cast iron remains a strong reference for passenger-car rotors due to its graphite flake morphology, which confers contact damping, compliant tribological behaviour with organic brake friction material, and a self-lubricating effect at asperity contacts. Tribological studies linking rotor microstructure to brake pad friction material interactions indicate that flake size, distribution, and matrix pearlite/ferrite ratios affect both friction stability and wear scar morphology, especially during transitions from boundary to mixed lubrication with third-body debris [6]. Wear mapping of cast irons confirms that pearlitic matrices resist micro-ploughing and fatigue crack initiation better than ferritic-rich matrices at equivalent hardness. However, the graphite network can both arrest and re-seed cracks depending on lamellae continuity [5]. Additional data on thermal shock against graphite morphology corroborate the sensitivity of grey iron to flake-induced stress concentrations [17]. Thermophysical data underscore why GCI remains practical: moderate thermal conductivity and relatively high volumetric heat capacity allow discs to absorb peak thermal loads without excessive localised temperature spikes, thereby stabilising friction and minimising thermal shock [3]. Cryogenic processing has been explored as a low-cost performance lever, refining carbide distributions and potentially transforming retained austenite in alloyed irons. The results point to improved wear resistance and a reduction in crack-initiation sites under repeated thermal cycling [10,18,19]. Complementary, the microstructure links have been reported when surface treatments and finishing alter near-surface residual stresses and oxide films, further tuning brake squeal tendency and dusting behaviour [20].

3.2. Non-ferrous and light-alloy

Weight reduction encourages exploration of aluminium-matrix composites and titanium-based alloys, but both face tribological and thermal issues. Aluminium matrix composites require hard, thermally stable reinforcements and a special countermaterial. Recent work using boron-doped titanium dioxide (TiO_2) reinforcements has shown promising friction stability and wear resistance in disc specimens, depending on the quality of the reinforcement dispersion and interfacial bonding [21]. Titanium offers an attractive specific strength and corrosion resistance. However, its low thermal conductivity and tendency to galling require special friction materials to avoid adhesive wear and temperature run-up in severe decelerations [22]. Comprehensive analyses of disc failure mechanisms underline the critical influence of microstructural configuration on the evolution of thermal gradients during high-energy braking [2].

3.3. Ceramic and carbon–ceramic composites

C/C–SiC and associated ceramic systems exhibit exceptional high-temperature strength retention and oxidation resistance. They also show low fade in high-energy brake cycles and stable friction characteristics over extended cycles. Their microstructure, which comprises carbon fibres in a ceramic matrix, supports crack deflection and controlled energy dissipation. This produces wear characterised by fine debris rather than large spalls and mitigates thermomechanical fatigue [7,15]. Recent reviews have reported on advances in the processing methods and application domains of C/C and C/C–SiC composites. These advances have focused on improving manufacturing processes and reducing production costs [23,24].

3.4. Coating and surface engineering

Protective and functional coatings on GCI rotors prevent corrosion in environments with high chloride content, improve wet brake performance, and reduce wear debris.

Table 1. *Comparative thermo-physical, mechanical, and tribological characteristics of typical brake disc materials from literature*

Material	Density (g/cm³)	k (W·m⁻¹·K⁻¹)	μ (–)	T_{max} (°C)	PM/PN trend	Relative cost	Ref.
GCI (uncoated)	≈7.2	46–54	0.35–0.45	700	High	Low	[4–6,27]
GCI + WC laser facing (WC–LC)	≈7.2	≥50	0.40–0.50	750	Moderate to Low	Medium	[28,29]
GCI + Al_2O_3 hard coating (PVD/CVD thermal spray)	≈ 7.2	≈ 50	0.38–0.45	750	Lower than GCI	Medium	[26,30]
Steel rotor (martensitic)	≈ 7.8	35–45	0.35–0.45	800	Moderate	Low–Medium	[31,32]
Al-MMC (Al–SiC)	2.6–2.9	120–170	0.40–0.50	500	Low	High	[21,33]
Al-MMC + PEO ceramic coating	2.6–2.9	≥ 160	0.38–0.43	500	Low	High	[34,35]
Ti-6Al-4V (engineered surface)	≈ 4.4	6–7	0.35–0.60	600	Low	Very High	[22,36]
C/SiC composite 2.5D/3D)	2.0–2.4	20–60	0.30–0.50	≥ 1000	Very Low	Very High	[7,37,38]
Hybrid C/SiC on aluminium carrier	≈ 2.0 + 2.7	> 40	0.30–0.50	> 1000	Very Low	Very High	[37,39]
SiC (full-ceramic, sintered/HP)	3.1–3.2	120–320	0.30–0.45	≥ 1400	Very Low	Very High	[23,37]

A comprehensive review documents conversion coatings, thermally sprayed overlays, and PVD/CVD thin films that are designed to resist abrasion while maintaining pad compatibility. Particular attention is given to avoiding brittle interfaces and galvanic couples with aluminium carriers [4]. Additional studies indicate rapid progress in laser coating and environmentally friendly alternatives to hard chrome and galvanic methods for rotor protection [25][26].

3.5. Thermal management by geometry and system context.

Ventilated rotors with optimised vane geometries promote internal convection. Cross-drilled holes can also increase local heat transfer and remove gaseous reaction products from the brake pad–brake disc interface. These strategies both alter the temperature field and attendant thermal gradients. Controlled studies report that appropriately sized and positioned cross-drilled patterns increase cooling without unacceptably concentrating stresses, thereby moderating hot-spot formation. Poor patterning, by contrast, can intensify stress risers [8]. Numerical and experimental investigations indicate that the effectiveness of brake heat dissipation under repeated braking cycles is governed mainly by the rotor’s internal air pumping performance and the configuration of the external flow paths [16]. At the system level, factors such as transient braking behaviour, dwell time between stops, ambient airflow, and wheel-house aerodynamics have a strong influence on cooling performance. This indicates that material properties and rotor geometry need to be optimised together rather than treated separately [1]. Wu et al. developed a numerical model that incorporates pad wear and the progressive evolution of the contact interface during braking. Their study demonstrated that accounting for these effects produces temperature distributions that are much closer to experimental observations and significantly improves the prediction of hot band migration and localised frictional fade. This work confirms the strong coupling between wear processes and thermal behaviour in disc–pad systems [40]. Complementary geometry work on vane cross-sections demonstrates that rounded radial vanes influence internal flow structures and can reduce pressure drop penalties while sustaining high Nusselt numbers across the rotor channel [9].

3.6. Energy harvesting and system integration.

Coulibaly et al. investigated the integration of thermoelectric generators (TEGs) into vehicle brake rotors to recover part of the dissipated heat energy. Their simulations and experimental assessments demonstrated that a measurable amount of electrical power can be harvested during braking events without substantially reducing cooling efficiency. However, the study also revealed that TEG performance is constrained by the competition for available thermal gradients and by durability challenges arising from vibration and thermal shock loading [41].

3.7. Environmental considerations

Environmental analysis now extends beyond tailpipe emissions to non-exhaust sources such as brake wear particles. Material pairs that minimise abrasive fragmentation and suppress unstable third-body formation tend to reduce particulate generation. Composite and coated solutions show potential to limit mass loss and alter particle size distributions. However, trade-offs with noise, lining wear, and wet-condition friction must be considered [11]. Recent reviews and toxicology studies reinforce the regulatory importance of non-exhaust emissions from brakes and tyres, with evidence on particle size, composition, and health effects [12][42].

4. CONCLUSION

Recent developments in brake disc materials reflect a shift from single-property optimisation to system-level design, where materials, surfaces, and geometry co-work with the braking duty and environmental objectives. Within ferrous baselines, microstructure-aware foundry control and cryogenic/post-process treatments offer tangible improvements in wear resistance and friction stability without wholesale material substitution. For high-performance platforms, carbon–ceramic systems remain unmatched in thermal stability and fade resistance, with continuous gains in manufacturability and acoustic tuning. Thermal-management strategies, vane optimisation, cross-drilling, and wheel-house flow alignment must be co-designed with materials to mitigate hot spots and thermal cracking while sustaining cooling performance. Advances in modelling that incorporate evolving contact and wear states are essential to translate laboratory constants into predictive, duty-cycle-specific temperature fields.

From an environmental perspective, the pathway to lower non-exhaust emissions integrates: (i) material/lining pairs that stabilise the third body and reduce abrasive fragmentation; (ii) corrosion-resistant surfaces that limit rust-induced degradation and dusting; and (iii) durable architectures (including ceramics) that reduce lifetime rotor replacement rates.

Overall, the most promising route is a hybrid strategy: maintain GCI or carbon–ceramic platforms tailored to the duty, overlay robust coatings for environment-specific protection, and deploy geometry that maximises convective efficiency without introducing stress concentrators. Coupled experiments and high-fidelity, wear-aware simulations should serve as the backbone of future development, supported by life-cycle assessments that quantify environmental benefits in service rather than at material production alone.

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