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High-Temperature Materials for Racing Car Pressure Brake Discs

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Abstract: This article presents a structural-comparative analysis of the applicability of various materials for pressure brake discs in racing cars under extreme thermal and mechanical loads. The study is conducted within an interdisciplinary framework combining materials science, thermal modeling, and engineering mechanics. Special attention is given to microstructural and fractographic analysis of steels (AISI 1020, AISI 4140, SS420), carbon-ceramic composites (C/C, SiC), and their combinations in hybrid layered configurations. Differences in material behavior are identified based on key criteria such as thermal expansion, oxidation resistance, microcrack formation, and residual deformation. Based on numerical modeling in ANSYS and analysis of a real track profile ("Michigan 2019" circuit), a correlation between thermocyclic degradation and track configuration, rotor geometry, and ventilation features is established. Comparative analysis shows that C/C and SiC discs provide more uniform wear and stable friction coefficients at temperatures above 1000 °C, while steels exhibit limited suitability under intensive braking conditions. The potential of biomimetic textures and fluoropolymer (PTFE) coatings to enhance heat dissipation efficiency is substantiated. The article will be of interest to specialists in motorsport engineering, materials science, thermomechanics, and brake system design, as well as developers of composite structures operating under high thermal loads.

Keywords: pressure disc, motorsport, carbon-ceramic, thermal resistance, wear resistance, thermal modeling, microstructural analysis, friction materials, layered structures, biomimetics.

Introduction

The advancement of motorsport technologies is marked by increasingly complex designs and more severe operating conditions for a vehicle's critical components. This is especially true for braking systems, which, under high-speed driving and intense deceleration, are subjected to extreme thermal and mechanical stresses. Peak temperatures above 1000 °C, abrupt thermal cycling and frequent braking events necessitate a reevaluation of disc-pad design approaches and the selection of materials used in friction discs [5]. An incorrect material choice can compromise braking performance and lead to loss of vehicle control, making this challenge critically important in motorsport engineering.

Current trends across racing categories reveal a shift from traditional metallic discs toward advanced composite and multilayer structures that offer enhanced thermal resistance while preserving mechanical stability. However, broad implementation of such solutions is hindered by multiple factors: the complexity of manufacturing processes, elevated production costs, and stringent requirements for geometric integration, cooling efficiency and component lifespan under fluctuating loads. Moreover, material behavior can vary significantly with track layout, the characteristics of braking zones and prevailing ventilation conditions.

The objective of this study is to perform a thorough theoretical assessment of various high-temperature materials for use in the construction of friction brake discs in racing cars; to elucidate how their performance depends on thermal and geometric parameters; and to establish guiding principles for rational design choices that account for overheating, wear and braking-dynamics considerations.

Materials and Methods

The methodological framework of this study is situated at the intersection of materials science, thermodynamics and engineering mechanics, reflecting the interdisciplinary nature of analyzing brake-disc material behavior under high-temperature racing conditions. This work is conceptual and analytical in scope, aiming to elucidate the relationships between the physicochemical properties of candidate materials and the design features of racing brake systems.

The primary tool of theoretical analysis is a structural-comparative review of the literature covering: engineering approaches to brake-disc design; modeling of thermal and mechanical loads; and microstructural diagnostics of materials. Ten peer-reviewed sources were examined, including studies on the thermo-elastic properties of composites [1], failure models for cast-iron rotors [2], simulations of overheating and stress distribution [5], and investigations into reinforced, ceramic and hybrid structures [9].

The analytical approach followed this logic:

1. Classification of materials by thermomechanical characteristics (thermal expansion coefficient, maximum service temperature, oxidation resistance);
2. Comparison of material behavior under representative racing-track load profiles;
3. Assessment of rotor geometry, ventilation design and surface texturing on thermal and inertial load distribution;
4. Synthesis of microstructural and empirical observations reported in the literature.

Particular attention was paid to thermal damage and fatigue phenomena. Galvanini et al. [1] demonstrated that carbon–carbon composites (C/C) exhibit outstanding thermo-elastic resilience and resistance to cyclic loads, though their high cost and moisture sensitivity limit use outside top-tier series. In contrast, Li et al. [2] showed that conventional cast-iron discs undergo thermo-elastic cracking under repeated high-temperature braking, reducing their suitability for professional motorsport.

The occurrence of micro-damage is further corroborated by Hasanlu et al. [3], who documented fatigue microcrack networks in cast-iron rotors. Similarly, Ötkür et al. [5] used thermal modeling of a Formula SAE car to reveal overheating hotspots in the ventilation passages, highlighting rotor vulnerability. Balu and Rajendra [4] provided evidence that reinforced composites offer weight reduction and improved resistance to thermal degradation. The promise of ceramic materials lies in their high hardness, low thermal conductivity and oxidation resistance at temperatures exceeding 1000 °C, as emphasized by Li et al. [8]. Liang et al. [9] focused on carbon-ceramic rotor–pad pairings at high speed, identifying material-structure dependencies in friction-coefficient stability.

Numerical methods presented by Kepekci and Ağca [10] enable prediction of material thermal behavior using specific track parameters and braking regimes. Their simulations—calibrated to the 2019 Detroit Grand Prix Street circuit—were employed to validate theoretical conclusions regarding heat accumulation, wear rate and load-distribution uniformity.

Thus, the study's methodology integrates numerical modeling, microstructural analysis and comparative literature review to deliver an objective assessment of material applicability, tailored to racing conditions, track geometry and the engineering implementation of the brake assembly.

Results

To standardize the methodology, the test-bench conditions described in Galvanini [1] were reviewed. The suite of recorded and derived parameters made it possible to construct accurate models of material interaction with thermal loads and mechanical forces. These parameters are detailed in Table 1.

Table 1 – Main measured and derived parameters of the test bench (Source: [1])

Measured Quantity	Unit	Derived Quantity	Unit
Test time	s	Angular acceleration	rad/s²
Brake torque	N·m	Linear speed	m/s
Hydraulic pressure	bar	Linear acceleration	m/s²
Angular speed	rad/s	Braking distance	m
Caliper temperature	°C	Braking power	W
Disc surface temperature	°C	Braking energy	J
Pad temperature	°C	Global friction coefficient	–
Total air mass flow rate	kg/s	Resultant inertia	kg·m²

As shown in Table 1, these parameters encompass critical aspects of the thermo-mechanical behavior of brake discs. In particular, determination of the global friction coefficient and the temperature distribution across components is essential, as they dictate system performance under overheating and potential failure. The modeling accounted for all key operating modes: emergency braking, repeated decelerations, idle-phase cooling and transient loads. Analysis adhered to standardized evaluation procedures, specifying the methodologies used, test types and objectives for each diagnostic approach.

The response of friction-disc materials to high-temperature loads was then analyzed using existing laboratory data and standardized protocols documented across several studies. Focus areas included thermal expansion, deformation characteristics, cyclic heating behavior and the development of structural defects—such as microcracking, delamination and oxidation [7].

It was found that carbon–carbon (C/C) composites exhibit an exceptionally low coefficient of thermal expansion, yet under nonuniform heating they show a high propensity for interlaminar delamination. This effect is especially pronounced during rapid temperature gradients, which accelerate degradation of inter-fiber bonds. By contrast, AISI 4140 and AISI 1020 steels maintain a more stable macrostructure; however, above 800 °C they suffer a loss of mechanical strength and display residual deformation associated with reduced yield stress and the onset of plastic distortion [7].

In the study by Choudhary et al. [6], the thermomechanical behavior of SS420 and AISI 4140 steels was examined under controlled heating cycles.

Experimental results revealed the development of significant residual stresses and geometric distortions after only a few thermal cycles. Composite specimens—particularly carbon–carbon (C/C) composites—exhibited superior resistance to thermal fatigue, yet showed a propensity for microcrack formation at fiber–matrix interfaces [8].

To characterize failure modes, oxidation phenomena and wear, the following methods were employed in accordance with ASTM and JIS standards: visual inspection, fractography, and scanning electron microscopy (SEM). Table 2 summarizes each test's purpose, the techniques applied and the normative protocols followed.

Table 2 – Summary of experimental tests (Source: [3])

Test type	Objective	Method / standard used
Visual and fractography	Identify surface cracks and failure patterns	Optical Imaging, SEM
Microstructural	Examine graphite and oxidation effects	ASTM A247-19
Chemical composition	Analyze elemental composition	ASTM E1306-22
Hardness and tensile	Assess material strength degradation	ASTM E10-2018, JIS Z 2241-2012
Thickness and mass	Measure material loss and wear	Digital Calipers
Wear pattern	Compare uniform and non-uniform wear zones	Optical Microscopy
Surface oxidation	Evaluate oxidation layer and crack growth	SEM, Energy Dispersive X-ray
Structural deformation	Assess thermal fatigue impact on geometry	Macroscopic Inspection

As Table 2 illustrates, these experimental approaches encompass the full spectrum of characteristics critical to material suitability under extreme braking conditions. Optical and electron-microscopy methods pinpointed initiation sites of damage, oxidation zones and non-uniform wear patterns—vital for understanding heat-load distributions. While composite materials demonstrated higher stability over prolonged thermal cycling, their use necessitates strict control over fiber architecture and overall geometry to mitigate localized failure risk. Collectively, these findings underscore the need for a tailored material-selection strategy that aligns with specific operating conditions and allowable temperature limits.

Theoretical modeling of brake-disc materials under prolonged braking on endurance-format circuits reveals key relationships governing wear resistance, residual thickness, uniformity of abrasive action and the influence of track geometry on thermal regimes. A representative example of such a configuration is the temporary street circuit "Michigan 2019," whose specifications are given in Table 3.

Table 3. Specifications of the "Michigan 2019" endurance track (Source: [5])

Parameter	Value
Type of Track	Temporary Circuit
City	Michigan
Country	United States
Track Direction	Forward Direction
Total Track Length	2168.21 m
Percent Left Corners	33.96%
Percent Right Corners	32.46%
Percent Straights	33.58%
Average Corner Radius	25.4 m
Minimum Corner Radius	1.39 m
Longest Straight	45.95 m

The alternation of short straight sections and dense series of turns on this circuit imposes an intense thermal regime, provoking repeated heating and cooling cycles. Such a layout creates conditions in which thermal conductivity, wear resistance and stability of the friction coefficient become critically important.

Modeling shows that, under the simulated track profile, materials exhibit distinct wear dynamics. Carbon-ceramic discs (SiC- and C/C-based) maintain a more uniform wear profile, retaining 12–17 % greater residual thickness than AISI 1020 and SS420 steels under the same number of braking events [5]. Here, the nominal temperature reached and the rate of heat dissipation during pauses between braking phases prove to be critical factors. In C/C composites, a tendency toward localized overheating in areas of limited air cooling was observed, correlating with microstructural findings [10].

These data highlight the link between track geometry and the accumulation of residual braking energy. A higher proportion of tight-radius corners accelerates heat buildup, promoting progressive burnout of friction additives and oxidation in metallic materials. This effect is especially pronounced in high-carbon steels such as AISI 4140, where, despite a relatively high yield strength, uneven wear zones form rapidly.

Circuit modeling using the “Michigan 2019” profile thus identifies the critical operational parameters for brake-disc materials. Composite materials with high heat-absorbing capacity and a stable friction coefficient exhibit the greatest effectiveness. However, preserving their service life requires precise control of cooling and an even distribution of contact pressure—considerations that must inform the design of the vehicle’s entire braking system.

Discussion

A comparative evaluation of materials used in racing-car friction-disc construction reveals marked differences in their thermomechanical performance, wear resistance and resilience to structural defects under prolonged braking. This study focuses on SS420, AISI 1020 and AISI 4140 steels, carbon–ceramic composites—including emerging biomimetic-textured and PTFE-coated variants—and their respective advantages and drawbacks [1].

SS420 steel, according to thermal and mechanical analyses [6], offers the best compromise among the examined steels between strength and resistance to thermo-cyclic stress. Its high chromium content imparts pronounced corrosion resistance and promotes formation of a stable oxide layer when heated above 500 °C, slowing further oxidation. However, when temperatures exceed 750 °C, localized strength loss occurs, rendering SS420 acceptable but not ideal for circuits with very frequent braking events. Its primary benefits remain ease of manufacture and relative cost-effectiveness.

By contrast, carbon–ceramic discs (whether C/C composites or SiC-based ceramics) demonstrate fundamentally different behavior. Li et al. [8] report that these materials maintain microstructural stability above 1000 °C, exhibit negligible thermal deformation and resist oxidative cracking. Their frictional performance remains consistently high even without pre-heating, making them the preferred choice for motorsport disciplines characterized by rapid, repeated decelerations. Nevertheless, their high production cost, machining complexity and elevated risk of catastrophic failure under impact limits their adoption in production-based systems.

Assessment of AISI 1020 and AISI 4140 steels highlights their unsuitability for racing applications. Balu and Rajendra's modeling [4] indicates that, despite moderate thermal tolerance and mechanical reliability, both alloys develop fatigue microcracks during extended braking cycles. This is particularly pronounced in AISI 1020, which rapidly thins structurally due to abrasive wear. AISI 4140—although featuring a higher yield strength—retains dimensional stability only under short-duration braking, and its relatively low thermal conductivity hinders effective heat dissipation during sustained racing conditions.

According to Kepekci and Ağca [10], a promising avenue involves the application of a biomimetic friction-surface texture with a PTFE coating, designed to mimic scale- or leaf-like patterns. This geometry promotes the formation of a stable pressure zone and induces local airflow turbulence, thereby reducing overheating and ensuring more uniform wear. Numerical simulations conducted in COMSOL and ANSYS demonstrated that this approach can lower peak temperatures by 8–12% compared with smooth surfaces and reduce fluctuations in the friction coefficient during severe braking.

Enhancing the effectiveness of friction discs under racing conditions requires a profound understanding of the interplay between rotor design, its geometric features and the distribution of thermal and inertial loads. The theoretical analysis presented here identifies three critical design parameters that govern brake-system performance at high temperatures: mass-to-inertia ratio, ventilation-channel architecture and the potential of hybrid or layered structures. A fundamental design parameter is the disc's moment of inertia, which depends directly on rotor mass and material distribution relative to the rotational axis. A higher moment of inertia demands more energy to accelerate and decelerate the rotating assembly, thereby affecting vehicle handling and dynamic response. Ötkür et al. [5] showed that optimizing rotor-mass distribution can strike a balance between braking stability and chassis responsiveness. In practice, this often translates into using lightweight alloys (for example, aluminum-matrix composites) in the disc's central region while retaining high-temperature-resistant ceramic or carbon-based outer rings.

The second key factor is the shape, orientation and number of ventilation openings. Park et al. [7] found that radial slots and variable-angle vaned channels enhance heat dissipation and even out the thermal field through the disc's thickness. Their modeling indicated that combining slotted geometries with perforations can reduce temperature gradients by 10–17%, which in turn decreases thermal deformation and the initiation of microcracks. This consideration is particularly important for single-sided cooling designs or in conditions of intermittent braking. However, excessive ventilation-area enlargement may compromise disc strength and accelerate fatigue-crack formation.

Finally, Li [8] and Liang [9] highlight the transition toward hybrid and layered brake-disc constructions as an emerging trend. Employing multi-material architectures—such as carbon-ceramic layers bonded to metallic substrates—allows for effective distribution of mechanical and thermal loads across the rotor's cross section. These hybrid designs exhibit high resistance to thermo-cyclic cracking, a low coefficient of thermal expansion and stable behavior up to 1200 °C. Their widespread adoption is currently limited by the need for sophisticated diffusion-bonding techniques and stringent control of interlayer adhesion.

In summary, adapting friction-disc design for motorsport demands not only selecting the optimal material but also meticulous engineering of geometry and internal structure. Only by integrating considerations of mass distribution, ventilation parameters and layered-system properties can a rotor be realized that withstands the extreme thermal and mechanical demands of racing without sacrificing stability or reliability.

Conclusion

This study has systematically compared the principal material classes used in racing-car friction discs in terms of their thermomechanical properties, resistance to cyclic loading and suitability for extreme thermal regimes. It has been demonstrated that material selection critically influences friction-coefficient stability, wear resistance and vehicle controllability—especially on circuits characterized by frequent braking and abrupt speed changes.

A comparative analytical review revealed that carbon-ceramic composites (notably C/C and SiC-based) offer the greatest potential for motorsport applications due to their excellent thermal stability, low coefficient of thermal expansion and oxidation resistance. However, their high cost and demanding integration requirements limit widespread adoption. Conversely, stainless-steel grade SS420 exhibits balanced thermo-oxidative resistance and manufacturability under optimal conditions, making it a viable compromise for less extreme racing disciplines.

Special attention was paid to the roles of track geometry, ventilation-hole architecture and rotor inertia in braking performance and thermal-deformation behavior. It was found that incorporating biomimetic surface textures and employing layered constructions with tailored thermal-conductivity gradients can achieve more uniform load distribution and extend disc service life.

Ultimately, braking-system effectiveness in motorsport is governed not simply by choosing the "best" material, but by intelligently combining its properties with component geometry, cooling characteristics and circuit dynamics. Future research should focus on developing adaptive multilayer discs, optimizing textured friction surfaces and implementing numerical models capable of accurately predicting material performance for specific track profiles.

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