Технічні науки

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CALCULATION OF FRICTION DISC PARAMETERS IN HIGH-PERFORMANCE CLUTCHES

Summary. *This article presents a theoretical analysis of the parameters of friction discs used in high-performance automotive clutches, with a focus on the interrelation between chemical composition, geometric characteristics, and thermal load. The study is based on an interdisciplinary approach integrating tribology, materials science, and thermal mechanics. Particular attention is given to the interpretation and comparison of published empirical data reflecting the influence of key elements in friction composites on the coefficient of friction and thermal stability. The geometric and operational parameters of clutches under racing conditions are examined, including high-frequency engagement cycles, limited cooling capacity, and localized thermal gradients in multilayer stacks. A comparative analysis of the thermal behavior of carbon-ceramic and cast-steel discs is conducted, justifying the applicability of each type under specific loading and thermal saturation modes. The study establishes computational relationships between material composition, heat resistance, clutch configuration, and critical slip conditions, enabling the formulation of rational criteria for selecting materials and geometries suitable for clutches operating under extreme conditions. The proposed approach can be integrated into engineering procedures for component selection and evaluation using digital computer-aided design tools. This paper will be of interest to design engineers, powertrain specialists, tribology and thermal analysis researchers, and developers of CAD/CAE systems for frictional components.*

Keywords: *friction disc, high-performance clutch, heat resistance, coefficient of friction, carbon-ceramic, thermal load, clutch geometry, materials science, slip behavior, high-speed operation.*

Introduction. The ongoing evolution of racing-car engineering is accompanied by rapidly escalating demands on transmission assemblies. Rising speeds, increased engagement frequency, and the extreme thermal loads typical of competitive conditions dictate the need for ever more precise calculation of friction discs. Under such circumstances, the designer must adopt a holistic methodology that simultaneously accounts for mechanical, thermal, and tribological characteristics, rather than merely selecting geometry or material parameters. Of particular importance is the disc's ability to ensure stable clutch operation at high temperatures and rotational speeds.

In this context, determining friction-disc parameters calls for a reassessment of traditional engineering solutions in favour of more flexible, multi-factor theoretical models. Essential considerations include the dimensions of the friction pack, lubricant properties, and the chemical composition of the disc material, which directly governs the coefficient of friction, thermal conductivity, and heat resistance. The design of racing clutches—where extreme loading regimes coincide with severe space constraints—offers a telling illustration of the relevance of such an approach [3]. These systems impose stringent requirements on heat-flux distribution, wear resistance, and the minimisation of thermal deformation.

A comprehensive determination of friction-disc parameters must therefore encompass an analysis of surface-temperature rise, the level of friction as a function of chemical composition, and the conformity of geometric features to the anticipated operating regime [8]. These aspects cannot be considered in isolation: any mismatch among them quickly leads to failure of the assembly. Particular attention is thus devoted to the systemic integration of all parameters, including lubrication regime, engagement pressure, and internal stresses within the structure.

The aim of the present study is to analyse the factors that define friction-disc parameters in high-performance clutches—specifically, material chemistry, disc geometry, and thermal operating conditions—and to substantiate design principles for friction systems intended to operate under high loads and high rotational speeds.

Materials and Methods. This study employed a systems-analysis approach grounded in reliable empirical data drawn from peer-reviewed scientific publications. Its primary aim was to interpret and compare the materials-science, geometric, and thermal parameters of friction discs used in high-performance clutches without invoking experimental or numerical modeling techniques. The analysis focused on three categories of data: the chemical composition of the friction material, the design and operational characteristics of the clutch, and the temperature limits of the discs under varying speeds and loads.

As the foundation for evaluating friction-layer materials, data from Bălăşoiu et al. [3] were adopted. That study used a multilayer neural-network model to present the chemical compositions of two materials exhibiting different coefficients of friction (COF) and levels of thermal stability. These findings underpinned theoretical insights into how specific elements (Cu, Ba, Sn, Ca, etc.) affect the thermophysical properties of the discs. The analysis was further informed by the fractal model developed by Cao et al. [4], which predicts the coefficient of friction as a function of surface roughness, contact pressure, and temperature—thereby providing a basis for understanding microstructural causes of variations in material heat resistance.

Geometric and operational parameters of the clutch were examined using the table of experimental conditions reported by Cao et al. [4]. Special consideration was given to the ratio of inner to outer diameters, friction-pack thickness, engagement-pressure parameters, oil flow rate, and oil temperature.

These variables were treated as boundary conditions for assessing the thermal and mechanical loads on the friction disc. This methodology was supported by the models of clutch transition between slip and lock regimes presented by Abo Eldaheb and Ali [8], as well as by Bąk’s [1] refinement of the frictional contribution in spline connections to the calculation of clutch torque.

Thermal characteristics of various disc types were evaluated based on the data provided by Liang et al. [5], who reported maximum temperatures for carbon-ceramic and cast-steel discs at different rotational speeds. These data enabled a theoretical comparison of temperature limits and informed the selection of friction-material composition according to specific operating regimes. Additionally, approaches to heat-dissipation and stress calculations described by Park et al. [2], Galvanini et al. [6], and Otkur [10]—which address brake-disc behavior under racing-cycle conditions and propose criteria for permissible heating—were incorporated into the analysis.

No original mathematical models or computational simulations were developed; all conclusions rest solely on the interpretation and cross-analysis of published findings. This theoretical methodology revealed consistent relationships among material composition, friction-disc geometry, and thermal resistance that are directly relevant to the design of sports-car clutches.

Results. In the theoretical analysis, the first step involved interpreting the composition of the clutch’s friction materials to identify how individual chemical elements influence frictional and thermal performance. The basis for this comparison comprised experimental data, as presented in Table 1 [3].

Table 1

Chemical composition of two friction materials and their frictional characteristics

Chemical Composition	First Material	Second Material
C	54.37	42.40
O	26.96	27.14

Al	1.72	1.92
Si	6.33	6.26
S	1.10	2.05
Ca	3.40	5.01
Fe	3.66	4.38
Cu	1.06	4.05
Ba	0.55	1.58
Zn	0.17	2.44
Ti	0.05	0.12
Na	0.10	0.75
K	0.40	0.12
Mg	0.14	–
Sn	–	0.99
P	–	0.43
Mn	–	0.40
Max COF values	–	0.47
Min temperature variation	0.1	–

Source: [3]

Table 1 presents two friction-material formulations that differ in elemental composition and thermal stability, as indicated by temperature variation and maximum coefficient of friction. The theoretical analysis demonstrates that the increased copper (Cu) and barium (Ba) content in the second material directly correlates with an elevated maximum COF of 0.47—substantially above typical values for paper- or organic-based composites [3].

The presence of tin (Sn) and phosphorus (P), found exclusively in the second sample, further enhances surface anti-friction properties and reduces thermo-abrasive degradation. Simultaneously, the higher proportions of calcium (Ca) and zinc (Zn) improve thermal stability via the formation of resilient oxide layers under heat. Consequently, the compositional characteristics of the second material render it preferable for designing discs in sports-car transmissions subjected to variable and high thermal loads [3].

The next stage of analysis focused on comparing the clutch's geometric and operational parameters, summarized in Table 2, which consolidates the technical specifications of the test rig used for empirical measurements [4].

Table 2

Geometric and operational parameters of the clutch

Parameter Name	**Parameter Value**
Friction Pair Inner Diameter, r_1 (mm)	59.5
Friction Pair Outer Diameter, r_2 (mm)	73.5
Counter Steel Plate Thickness, t (mm)	3
Friction Plate Thickness, t (mm)	3
Friction Plate Material	9802 Paper-Based
Surface Roughness	$6.31{\times}10^{-6}$
Engagement Speed, n (rpm)	300010
Engagement Pressure, P (MPa)	1.2–1.5
Lubricating Oil Flow Rate, Q_0 (L/min)	0.5
Lubricating Oil Grade	Shell Shellite 555
Lubricating Oil Temperature (°C)	40

Source: [4]

As shown in Table 2, the key factors determining the disc's thermal and mechanical loading are the exceptionally high rotational speed (300 010 rpm) and engagement pressures up to 1.5 MPa. When combined with a minimal friction-layer thickness (3 mm) and modest oil flow (0.5 L/min), these conditions foster rapid heating of the contact interface [4].

Surface roughness on the order of 6.31×10^{-6} denotes the disc's pronounced sensitivity to boundary-friction regimes, especially during the clutch's initial engagement phase. Such a micro-profile fosters the development of localized thermal hotspots and necessitates exceptional stability of the friction layer. The employment of Shell Shellite 555 oil, rated for operation at 40 °C, typifies racing conditions—characterized by high heat flux and constrained cooling efficiency [4].

Accordingly, the theoretical analysis substantiates the interdependence among material composition, thermal stability, and the operational environment of the friction disc. This interrelationship forms the basis for the rational selection of clutch components in high-load sports-transmission applications.

Discussion. Thermal stability of the discs emerges as the principal parameter governing the reliability and service life of brake and clutch assemblies under sports-driving conditions. Elevated vehicle speeds, frequent braking events, and short intervals between load cycles all contribute to intense heat generation, rendering the choice of disc material critically important. A comparative analysis based on the data of Liang et al. [5] evaluated the temperature response of carbon-ceramic and cast-steel discs as a function of initial vehicle speed. The results are summarised in Table 3.

Table 3

Maximum surface temperature of discs depending on speed

Initial Speed (km/h)	160	200	250	300	350	380
Carbon-ceramic	545.4	567.5	685.6	773.0	852.9	912.3
Cast-steel	319.5	346.1	417.6	461.3	539.9	608.5

Source: [5]

At 380 km/h, the carbon-ceramic disc's surface temperature reaches 912.3 °C, whereas the cast-steel counterpart attains only 608.5 °C—a difference exceeding 300 °C that underscores the fundamental disparity in the thermophysical properties of these materials. Carbon-ceramic composites display markedly superior resistance to overheating and thermal fatigue, preserving both geometric integrity and frictional performance under extreme conditions.

Consequently, they are the preferred choice for sports and racing applications, where braking cycles are highly repetitive and lack phases of full cooling [5].

Conversely, cast-steel discs, despite their more modest temperature tolerance, remain viable for less demanding applications. Their acceptable performance up to approximately 600 °C makes them suitable for commercial vehicles or racing series with constrained thermal profiles. However, once temperatures exceed the 600–650 °C threshold, irreversible deformation, surface oxidation, and degradation of frictional characteristics occur, potentially leading to loss of braking control and disc failure [5].

In designing friction systems for high-performance transmissions, it is essential to account for the limiting temperatures, thermal distribution patterns, and the material’s heat-dissipation capabilities. Carbon-ceramic materials—characterised by low thermal conductivity through the disc thickness and high conductivity within the plane—establish a favourable temperature gradient that minimises the risk of localized hotspots. Such behaviour is particularly critical in multi-disc clutch configurations, where the innermost layers of the friction pack experience the greatest thermal load and have the least cooling opportunity [1].

In the context of designing clutches for sports cars—where rotational speeds can reach tens of thousands of revolutions per minute—material selection must be based on the ability to withstand prolonged engagement cycles and overheating without degradation of frictional properties. In this respect, carbon-ceramic discs represent an optimal solution, capable of maintaining stable friction at temperatures exceeding 850 °C. These data validate the use of such composites in applications demanding high resistance to thermal loads and minimal heat-induced deformation.

A comprehensive approach to the analysis of high-performance friction discs requires consideration of three key groups of factors:

- the physicochemical properties of the friction material;
- the geometry of the friction assembly;

- the parameters of thermal loading.

Theoretical synthesis of these aspects enables the establishment of well-founded calculation criteria applicable to the design and verification of clutches operating under high-speed, repetitive-load conditions.

First and foremost, the chemical composition of the material exerts a decisive influence on both initial and limiting friction characteristics, as well as on thermal stability. According to Bălăşoiu et al. [3], increases in copper, barium, tin, and calcium content correlate with rising coefficients of friction and reduced overheating. This effect arises from the synergy between copper's thermal conductivity and the structural stability of barium and calcium oxides, which form protective layers at elevated temperatures. From these observations, a material-suitability criterion can be proposed: the ratio of heat-conductive components (Cu + Sn) to friction activators (Ba + Ca) should lie between 1.0 and 1.5 to achieve the optimal balance of stability and frictional performance above 600 °C [3].

Geometric parameters of the disc—namely outer and inner radii, thickness, and surface roughness—directly influence the thermal regime within the friction zone. Cao et al. [4] observed that increasing the outer diameter to 73.5 mm and the thickness to 3 mm at rotational speeds above 300 000 rpm generates critical heat flux, necessitating either highly effective cooling or enhanced material heat resistance. This interdependence is corroborated by Otkur [10], whose racing-disc simulations demonstrated that even a modest increase in rotor thickness (1.5–2 mm) can reduce peak temperatures by 100–150 K while preserving braking effectiveness within acceptable thermal-stress limits.

Shang's work [7] underscores the necessity of accounting for dynamic regimes—particularly the transitions between slipping and full engagement. Such phenomena demand precise calculation of clutch torque and assurance that the material can maintain stable frictional properties during the abrupt temperature rise associated with phase change. Hence, design criteria must incorporate the material's thermal inertia, defined by its rate of thermal saturation given a specific heat capacity and frictional intensity.

Finally, the resultant thermal load must be evaluated against the limiting temperature characteristics reported by Liang et al. [5] and further examined by Li et al. [9]. The latter study highlights the critical role of transient thermal states—namely, rapid temperature increase and non-uniform heat distribution through the disc thickness—which can trigger thermoelastic instability and crack initiation. Accordingly, the overall synthetic design criterion may be expressed as a function of three parameters:

- specific thermal conductivity and the active oxidation phase of the material;
- the ratio of outer to inner radius;
- the threshold temperature for the onset of structural damage (typically 850–950 °C for carbon-ceramic and 600–650 °C for cast-steel).

Thus, based on the foregoing analysis, successful design of friction discs for high-performance applications requires a multilevel approach that integrates material selection according to friction-thermal characteristics with consideration of geometric parameters, operating regimes, and limiting temperatures. The criteria developed here exhibit strong interdisciplinary applicability and can be implemented in automated evaluation workflows within CAD/CAE environments.

Conclusion. The theoretical analysis has confirmed that the performance of a friction disc under sporting conditions is determined not by isolated properties but by their interconnected complex. It was established that the decisive factor is the material's ability to retain its frictional characteristics through repeated thermal cycles, while the geometry of the assembly must ensure uniform heat distribution at extreme rotational speeds and pressures.

It has been demonstrated that the key reliability parameter is the material's thermal stability, manifested as resistance to structural changes during peak-temperature events. Geometric dimensions must satisfy mounting and packaging constraints, provide the necessary thermal buffer, and ensure structural rigidity. Moreover, the importance of accounting for surface microtopography was identified as a critical requirement for achieving a stable friction regime during transitional clutch phases.

A direct correlation between material composition and resistance to thermo-abrasive wear was revealed, enabling the formalisation of suitability criteria for friction-material formulations at specific operating temperatures. It was shown that inadequate alignment among disc geometry, material properties, and thermal conditions leads to premature component failure, even when basic design parameters are met.

The necessity of abandoning isolated calculations of individual properties in favour of an integrated evaluation model—encompassing frictional, thermal, and mechanical parameters—has been substantiated. Such an approach delivers maximum reliability and predictable clutch behaviour under the dynamically unstable regimes characteristic of sports-car transmissions.

Accordingly, the calculation of friction-disc parameters for high-performance clutches must be based on a synthesis of interdisciplinary criteria that address both nominal characteristics and extreme operating states. The capacity to consider the complex interplay of material composition, disc geometry, and thermal loading ultimately defines the quality of engineering solutions for high-load friction systems.

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