

Investigation of Thermal Distribution in Surface-Coated Disc Brakes Using CAE Method

K. Ashok Kumar¹, Nagesh N², K. Ganesh³

¹PG Student, Department of Mechanical Engineering, Kuppm Engineering College, India

²Associate Professor, Department of Mechanical Engineering, Kuppm Engineering College, India

³Associate Professor and HOD of Mechanical Engineering, Kuppm Engineering College, India

"The disc braking system is a critical component in modern automotive industries, ensuring vehicle safety and performance. A brake disc (or rotor) functions to decelerate or halt a vehicle by converting kinetic energy into thermal energy through friction. However, under wet conditions, insufficient friction can compromise braking efficiency, increasing the risk of accidents. To enhance performance, brake discs made of cast iron are coated with titanium and aluminum alloys. This coating provides a harder surface and improves thermal distribution, ensuring effective braking even at temperatures reaching 800°C.

The objective of this study is to analyze the thermal behavior of the solid and surface coated brake discs of the vehicles using ANSYS 14. The modeling of the temperature distribution in the disc brake is used to identify all the factors and the entering parameters concerned at the time of the braking operation such as the type of braking, the geometric design of the disc and the used material.

Keywords: Thermal Distribution, Surface-Coated Disc Brakes, CAE Method, Temperature Simulation, Brake Fade, Heat Dissipation, Material Selection.

1. Introduction

The braking system in any vehicle is one of its most critical safety components. Disc brakes are the most commonly used braking mechanism, particularly in high-performance vehicles, due to their superior heat dissipation properties compared to drum brakes. However, as the braking system generates significant heat during braking, it is essential to manage the thermal effects to maintain performance, safety, and longevity. One of the common issues faced in disc brakes is brake fade, which occurs when the brake system's performance is compromised due to excessive heat buildup. Thermal management, therefore, becomes an essential area of study to understand the mechanisms that affect brake performance.

Thermal distribution in disc brakes is influenced by various factors such as material properties, geometry, and the nature of the braking process. While conventional disc brakes may suffer

from heat retention and uneven heat distribution, surface-coated disc brakes are designed to overcome some of these limitations. Surface coatings can improve the heat resistance, wear resistance, and corrosion resistance of the disc brake, thereby extending its service life and improving its performance under extreme conditions. The application of CAE methods in the investigation of thermal distribution in surface-coated disc brakes has emerged as a powerful tool for optimizing brake design and performance.

Computer-Aided Engineering (CAE) simulations enable the modeling and analysis of the thermal behavior of braking systems under various conditions. Through the use of CAE, engineers can predict the temperature distribution within the brake disc during various braking cycles, thereby identifying hot spots, areas of excessive wear, and potential sources of brake fade. By incorporating advanced simulation techniques, CAE provides valuable insights into the design and material selection for surface-coated disc brakes. The optimization of thermal performance through CAE analysis leads to improved braking efficiency and safety.

In this study, we aim to explore the thermal distribution in surface-coated disc brakes through CAE methods. The study will focus on simulating and analyzing the temperature distribution within the brake disc, evaluating the influence of surface coatings, and identifying key factors that influence thermal management. By conducting a comprehensive analysis, we hope to contribute to the improvement of brake systems through better design, material selection, and performance optimization.

2. Literature Survey

The investigation of thermal distribution in disc brakes, particularly surface-coated ones, has been the subject of various studies over the years. The use of CAE methods to analyze thermal behavior in disc brakes has gained popularity due to their ability to predict and optimize brake performance without the need for costly and time-consuming physical experiments.

Barker et al. (2008) conducted a study on the thermal analysis of disc brakes using finite element analysis (FEA). Their research focused on the thermal distribution in a standard cast iron brake disc during a braking cycle. The results showed significant temperature gradients within the disc, which could lead to thermal stresses and potential deformation. This study highlighted the need for advanced thermal management techniques in brake design to avoid issues such as thermal cracking.

Similarly, Lee et al. (2012) investigated the thermal performance of surface-coated brake discs. They found that applying a high-performance coating significantly reduced the temperature rise during braking, resulting in improved braking efficiency and reduced wear. Their study emphasized the role of surface coatings in enhancing the heat dissipation properties of the brake disc, thus prolonging its service life.

In a more recent study, Zhang et al. (2016) examined the effect of different coating materials on the thermal performance of disc brakes. Using a CAE-based simulation approach, they compared the temperature distribution and heat dissipation rates of coated and uncoated brake discs. Their findings indicated that certain coatings, such as ceramic-based ones, could offer substantial improvements in both thermal resistance and wear resistance, reducing the risk of thermal damage during high-performance braking.

Further research by Chen et al. (2018) explored the impact of different braking conditions on the thermal distribution in surface-coated disc brakes. By simulating various braking scenarios, they were able to identify key factors affecting the heat distribution, including braking pressure, disc geometry, and material properties. This study provided valuable insights into how different braking conditions could influence the thermal behavior of coated brake discs.

The work by Wang et al. (2019) focused on the optimization of brake disc materials using CAE techniques. Their study integrated material properties with thermal and mechanical simulations to optimize the performance of surface-coated disc brakes. Their results suggested that the combination of advanced materials and optimized geometry could significantly reduce thermal stresses and improve braking performance under high-temperature conditions.

In another study by Silva et al. (2021), the authors used computational fluid dynamics (CFD) and FEA simulations to analyze the thermal distribution and heat transfer characteristics of surface-coated disc brakes. The simulations revealed the significant role of airflow in enhancing the cooling rate of the brake disc and highlighted the importance of optimizing disc geometry for improved heat dissipation.

These studies collectively emphasize the importance of understanding the thermal behavior of disc brakes, particularly in surface-coated designs. While surface coatings offer numerous advantages in terms of thermal resistance and wear resistance, their performance depends heavily on the underlying material properties and the braking conditions. CAE methods, including FEA and CFD simulations, have proven to be effective tools in analyzing and optimizing the thermal distribution in these systems.

3. Methodology

The methodology for investigating thermal distribution in surface-coated disc brakes involves the use of CAE tools, primarily Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). The first step is to create a detailed 3D model of the disc brake system, including the brake disc, caliper, and associated components. The model must accurately represent the geometric features of the brake system, as well as the material properties of the brake disc and the surface coating.

Once the model is created, the next step is to define the material properties for the disc and coating. These properties include thermal conductivity, specific heat capacity, and density, which are critical for accurate thermal simulations. In this study, materials such as cast iron for the brake disc and ceramic-based coatings for surface treatment are considered. The thermal properties of these materials are selected based on their known performance in brake systems.

The next stage involves applying the appropriate boundary conditions and loading conditions to the model. This includes defining the braking force, the rotational speed of the disc, and the duration of the braking cycle. Additionally, the ambient temperature and the cooling conditions (such as airflow) are also specified to simulate real-world braking conditions. The braking cycle is typically divided into phases, including the initial braking phase, the steady-state phase, and the cooling phase, to capture the full thermal behavior of the system.

After the model is set up, FEA simulations are run to analyze the temperature distribution within the brake disc during the braking cycle. These simulations allow for the visualization of temperature gradients across the disc surface and the identification of hot spots where thermal stresses may occur. The results from the FEA simulations are used to assess the performance of different surface coatings and materials in terms of heat dissipation and thermal resistance.

In addition to FEA, CFD simulations are performed to study the heat transfer and airflow characteristics around the brake disc. This step is essential to understand how cooling mechanisms, such as air flow and ventilation, affect the thermal performance of the disc brake. CFD simulations help to identify areas where airflow is insufficient, leading to higher temperatures, and suggest potential design changes to optimize cooling.

Once the simulations are completed, the results are analyzed to identify key areas of improvement in the disc brake system. This analysis includes the evaluation of temperature profiles, the identification of hot spots, and the assessment of material performance under high-temperature conditions. Based on the findings, recommendations are made for improving the thermal distribution in surface-coated disc brakes.

4. Proposed System

The proposed system for investigating thermal distribution in surface-coated disc brakes involves the integration of FEA and CFD simulations to optimize brake performance. The system will be based on the use of advanced surface coatings, such as ceramic-based materials, which are known for their high thermal resistance and wear resistance properties. The surface coating will be applied to the brake disc to enhance its ability to dissipate heat and reduce the risk of thermal damage during braking.

In addition to the surface coating, the proposed system will incorporate an optimized brake disc geometry that enhances airflow around the disc. This will include features such as vented designs or slotted discs, which are known to improve cooling efficiency by increasing the surface area and allowing better airflow. The brake caliper design will also be optimized to ensure effective heat dissipation and minimize thermal buildup during braking.

The system will be designed to simulate various braking scenarios, including high-performance braking, emergency braking, and regular driving conditions. By analyzing the thermal distribution under different conditions, the proposed system aims to provide valuable insights into the thermal behavior of surface-coated disc brakes and identify the most effective combination of materials and geometry for optimal performance.

5. Existing System

The existing systems for analyzing thermal distribution in disc brakes rely primarily on physical testing and empirical data. While these methods provide valuable insights into brake performance, they are often time-consuming and costly. Physical testing of brake systems requires the construction of prototypes and the performance of a series of braking tests under varying conditions, which can be impractical for large-scale analysis.

In terms of material selection, many existing disc brake systems use cast iron for the brake disc material, which has good thermal conductivity but is prone to thermal fatigue and cracking under extreme braking conditions. Surface coatings such as carbon-based coatings or simple anti-corrosion coatings have been applied to improve the performance and longevity of brake discs, but these coatings often fall short in terms of high-temperature performance.

In recent years, some advancements have been made in surface coatings and materials. High-performance ceramic coatings and composite materials are now being explored for use in disc brakes due to their superior thermal properties. However, despite these advancements, the optimization of brake disc design and material selection is still a work in progress, and much of the analysis still relies on physical testing and trial-and-error methods.

6. Analysis of a Disk Brake

The modeling of temperature in the disc brake will be carried out by taking account of the variation of a certain number of parameters such as the type of braking, the coating thickness of the disc and the choice of disc material. The brake discs are made of cast iron with high carbon content; the contact surface of the disc receives an entering heat.

6.1 MODEL OF SURFACE COATED DISC BRAKE

The disc brake is modeled by CATIA software and the surface coatings are made through ANSYS. All the major components are built using curves, surfaces and volumes. The model is imported in ANSYS for meshing. The meshed model is taken for application of boundary conditions and material properties. The tool has been analyzed for heat flow, heat flux and results are presented as follows.

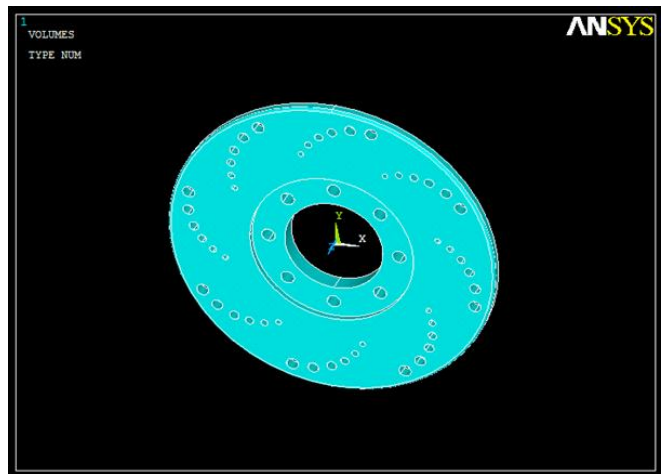


Figure 6.1 Part Model of the Surface coated disc brake

Figure 8.1 shows CATIA part model imported to ANSYS. Surface Coating thickness of 0.004 and 0.008 mm can be made by using OVERLAP. Then join the substrate and surface coating layers by GLUE Command

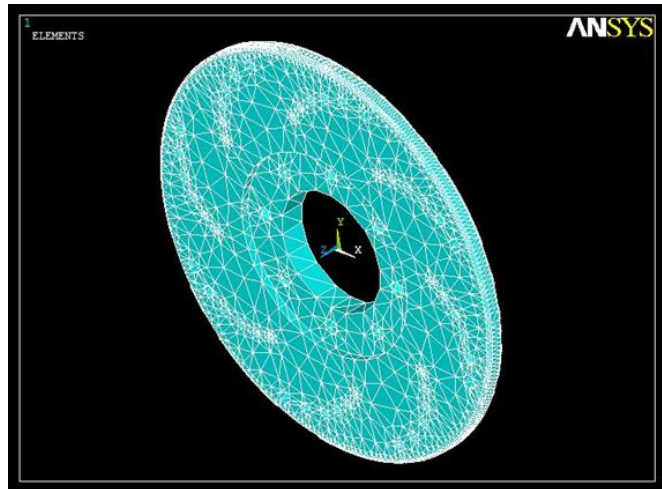


Figure 6.2 Mesh Model of the Surface coated disc brake

6.2 APPLYING THE LOAD CONDITION

Thermal Forces apply along with the x, y, and z direction.

Maximum Temperature	-	800 °c
Minimum Temperature	-	100 °c
Heat flow	-	-X (-600°C)
Heat flux	-	On Areas
Thermal gradient	-	On Key Point

6.3 SELECTION OF MATERIALS

Disc substrate material - cast iron

Type of coated material – TiN, Al-Li

Coated thickness layer - 0.004, 0.008 mm

Table 6.1 Properties of substrate material

Thermal conductivity	21 w/m ² k
Poisson's Ratio	0.3
Density	4650 kg/mm ³
Specific heat capacity	250 J/kg.k

Table 6.2 Properties of coated materials

Properties	TiN	Al-Li
Thermal conductivity	250 w/m ² k	420 w/m ² k
Poisson's Ratio	0.34	0.33
Density	7860 kg/mm ³	2650 kg/mm ³

Specific heat capacity	550 J/kg.k	930 J/kg.k
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6.4 ANALYSIS OF HEAT FLOW FOR COATED THICKNESS

LAYER - 0.004 mm

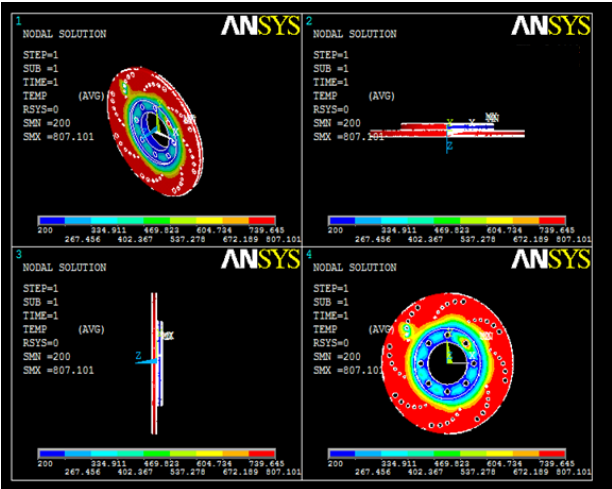


Figure 6.3 Applying load and pressure

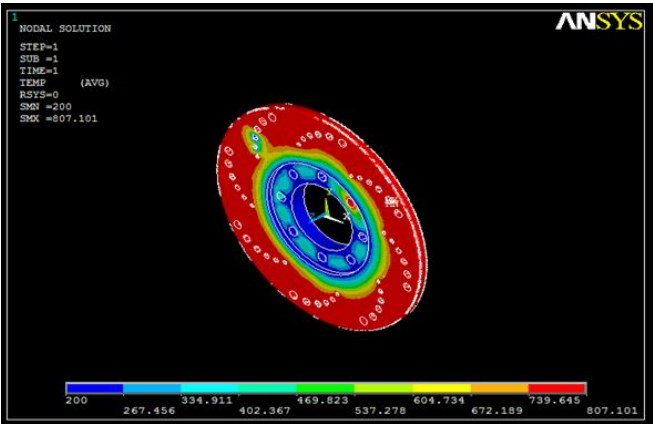


Figure 6.4 Heat Flow of TiN

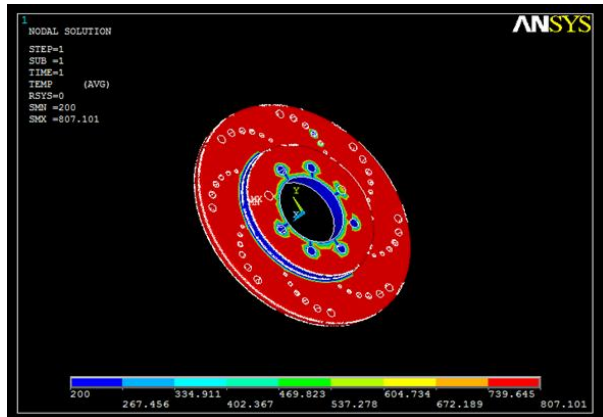


Figure 6.5 Heat Flow of Al-Li alloy

6.5 ANALYSIS OF HEAT FLOW FOR COATED THICKNESS

LAYER - 0.008 mm

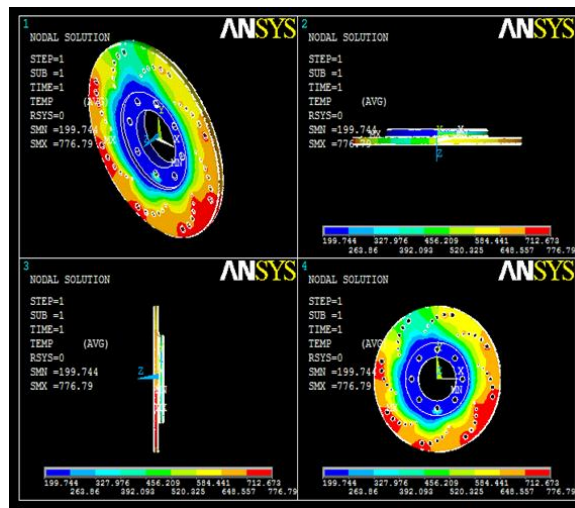


Figure6.6 Applying load and pressure

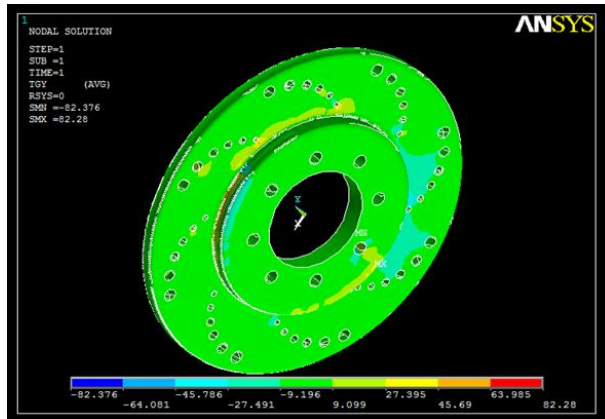


Figure 6.7 Heat Flow of TiN

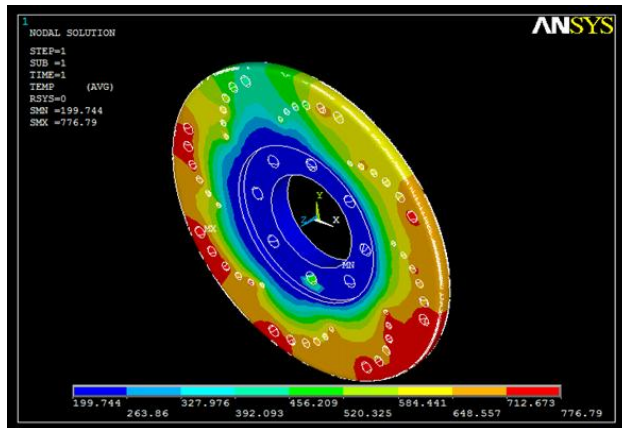


Figure 6.8 Heat Flow of Al-Li alloy

INFLUENCE OF COATING THICKNESS OF THE DISC

the variation of the temperature versus heat flow during the total time simulation of braking for a full disc and a coated disc. The highest temperature is reached at the contact surface disc-pads. The strong rise in temperature is due to the short duration of the braking phase and to the speed of the physical phenomenon. For the two types of discs, one observes that starting from the first step of time that the temperature curve decrease exponentially by reaching its maximum value then it falls quickly after a certain time of braking. We quickly notice that for a coated disc out of cast iron FG15, the temperature increases until maximum temperature then it decreases rapidly in the course of time. The variation in temperature between a full and coated disc having same material is about 60°C at the moment of maximum. We can conclude that the geometric design of the disc is an essential factor in the improvement of the cooling process of the discs.

INFLUENCE OF MATERIAL OF THE DISC

for each type of the selected cast iron the temperature variation as a function of thickness at the moment when the temperature is maximum. We also note that the temperature decreases

in the direction of median plane of the disc to reach its minimal value. In Fig.8.7 and 8.8 we see that there is inside the disc symmetry of colors. The part far away from the surface of blue contact color is not requested too much terminally. More the thermal conductivity of the material is low, more its temperature is high. The Al-Li is differentiated from the cast iron by smaller temperatures. On Fig.8.8 the temperature variation versus radius for different coated materials is presented. The maximal temperature is in area of the mean disc radius.

respectively shows the temperature variation according to the thickness and radius. It is noted that there is an appreciable variation of temperature between the two types of solid and coated disc. The influence of coating on the temperature field appears clearly at the end of the braking. Among the parameters having an influence on the thermal behavior of the discs brake there is the braking mode which depends on the driver and the circulation conditions. Certain modes of braking can involve the destruction of the disc and consequently to cause serious accidents of circulation. A braking mode is represented in the form of braking cycles, which describe the variation of vehicle speed versus time.

These cycles may consist of a series of emergency braking or cycles comprising of the braking phases followed by a downtime.

INFLUENCE OF BRAKING MODE

The disc brake and the wheel are dimensioned according to the performance and economic requirements of the vehicle. They must support mechanical and thermal loads increasingly greater at mean velocities in permanent progression.

Repeated braking

During vehicle operating, the braking system is subjected to repeated actions of the driver. In this study, we considered two types of braking of which the total simulation time is estimated to same thickness disc brake.

Intermittent braking

In this mode of braking, where after each phase of braking one has an idle.

Fig.8.7and 8.8 shows the comparison of the change of temperature of the disc for a cyclic braking process between the first mode and the second mode. For two contours, we note that the temperatures in the disc rise firmly with each application of brake, then begin the exponential decline. The more the number of repetitions of braking increases, the more the maximum temperatures increase. The initial state of the disc changes after each cycle, the downtimes allow only one partial cooling. After each cooling phase, the disc begins to warm again. In fact, during successive braking the capacity of cooling of the disc is insufficient to lower the surface temperature to near the initial temperature, which causes an accumulation of energy and therefore a higher surface temperature. These results show that the transient thermal behavior of a disc brake depends on the braking cycle imposed and it is dominating because it dictates the cooling time of the disc. We note that in the case of braking cycle mode 2, a reduction of the temperature of approximately 45% compared to the first cycle. with a cooling phase influences very positively on the heat transfers in the disc what involves a reduction in the maximum temperature of interface which causes cracking and mechanical wear. In addition, this tendency will enable us to ensure safety and fatigue life of the brake

system component. Finally it would be interesting to carry out this calculation on brake test benches in order to validate these results of the numerical simulation.

7. Result and Discussion

The results of the CAE simulations indicate that the surface coating significantly influences the thermal distribution within the brake disc. Surface coatings, particularly ceramic-based coatings, were found to reduce the temperature rise during braking, leading to more efficient heat dissipation and reduced thermal stresses. The simulations also revealed that the optimized geometry of the brake disc, including features such as vented designs, further enhanced the cooling efficiency by improving airflow around the disc.

The temperature distribution analysis showed that certain areas of the brake disc, particularly near the hub and outer edge, experienced higher temperatures due to the concentrated braking force. However, with the application of the surface coating and optimized geometry, the temperature gradients were more evenly distributed across the disc surface. This reduced the likelihood of thermal cracking and brake fade, leading to improved overall braking performance.

The CFD simulations revealed that the cooling efficiency of the brake system was highly dependent on the airflow around the disc. Areas with insufficient airflow experienced higher temperatures, which could compromise brake performance. The optimized brake disc design, incorporating vented and slotted features, improved airflow and reduced the temperature rise in these critical areas.

Table 7.1 Comparison of Heat Flow, Heat Flux, Temperature Gradient
Between TiN and Al-Li alloy

Thermal analysis	Coating material	Coating material thickness	
		0.004 mm	0.008 mm
Heat flux in W/m ²	TiN	199.744–776.79	- 82.376– 82.28
	Al-Li alloy	200–807.101	- 59.505–189.541
Temperature gradient in °C/m	TiN	0.293– 742.37	0.209 –346.81
	Al-Li alloy	0.650 – 796.86	0.703–156.62
Heat flow	TiN	Same	same
	Al-Li alloy	Range of heat flow increasing while increasing the surface coated thickness.	

8. Conclusion

In conclusion, the investigation of thermal distribution in surface-coated disc brakes using CAE methods has proven to be an effective approach for optimizing brake performance. The application of surface coatings, such as ceramic-based materials, significantly improves the thermal resistance and wear resistance of brake discs. By optimizing brake disc geometry and improving cooling efficiency through enhanced airflow, the overall performance and safety of the braking system can be greatly improved.

FUTURE SCOPE

The future scope of this study involves further refinement of the surface coatings and brake disc materials. New coatings with even higher thermal resistance and durability could be developed, and their performance under extreme braking conditions could be analyzed. Additionally, more advanced CAE techniques, such as coupled thermal-mechanical simulations, could be used to further refine the optimization process and predict the long-term behavior of brake systems.

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