Experimental Investigation on Thermal Characteristics of Helical Grooved Disc Brake

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Abstract

This study investigates the thermal characteristics of helical grooved disc brakes to enhance heat dissipation, reduce thermal stress, and improve braking efficiency. Helical grooves machined into the rotor surface increase airflow, promote even heat distribution, and minimize brake fade. Finite element analysis (FEA) is conducted using ANSYS to evaluate stress distribution, temperature rise, and deformation across various materials. Comparative analysis of experimental and analytical results indicates that AISI 1213 exhibits the lowest von Mises stress, making it suitable for stress-sensitive applications, while AISI 1020 demonstrates high rigidity with minimal deformation. The findings highlight the effectiveness of helical grooved disc brakes in optimizing thermal and mechanical performance for high-performance and heavy-duty applications.

Keywords: Helical grooved disc brake, heat dissipation, thermal stress, brake fade, finite element analysis, von Mises stress, deformation, AISI materials, ANSYS simulation.

1. INTRODUCTION

One kind of disc brake that has helical (spiral-shaped) grooves drilled into the rotor surface is called a helical grooved disc brake. By improving the braking system's mechanical and thermal performance, these grooves help to mitigate common problems like wear, brake fade, and heat accumulation. Helical grooved disc brakes are very useful in high-performance and heavy-duty applications, such sports vehicles, large trucks, and industrial machinery, due to its design and operation.

Helical grooved disc brakes enhance the surface area of the brake rotor, which significantly improves heat dissipation. The spiral grooves carved into the rotor's surface allow heat to transfer from the rotor to the surrounding air more efficiently. In high-performance situations when considerable friction-induced heat accumulation may occur, this increased surface area is especially crucial for swiftly dispersing the heat generated during braking. The grooves also help to increase airflow around the rotor when it warms up.

By encouraging even heat dispersion throughout the rotor surface, helical grooved disc brakes are very good in lowering thermal loads. Conventional flat rotors frequently distribute heat unevenly, resulting in thermal hotspots—areas where heat builds up more quickly than in other places. As the rotor expands unevenly during braking, these hotspots may cause structural damage including warping or thermal cracking.

Brake fade, a common problem when the braking system overheats, can be avoided with helical grooved disc brakes, which greatly improves brake performance. When brake pads and rotors lose their capacity to provide enough friction due to high heat, brake fade occurs, decreasing the efficiency of braking.

Because they reduce direct contact between the brake pads and the rotor surface, the helical grooves in disc rotors are essential for lowering rotor wear. These grooves contribute to a more uniform wear pattern by more evenly distributing braking forces throughout the rotor, which lowers the total wear rate of the brake pads and the rotor.

The helical grooves not only lessen noise but also lessen vibration when braking. Braking systems frequently experience vibration, particularly in high-performance cars that use strong braking forces and decelerate quickly. These vibrations, which cause the steering wheel or brake pedal to tremble and make the braking system less predictable, can have a detrimental effect on both driver comfort and braking effectiveness. By guaranteeing a more seamless interface between the brake pad and rotor, the grooves help to reduce these vibrations. They aid in the more uniform distribution of braking forces, avoiding uneven contact that can result in uncomfortable or jerky movements. The grooves improve performance and the entire driving experience by creating a more solid and constant contact surface, which reduces vibrations.

1.1. Significance of the Study

The significance of this study lies in its potential to enhance the thermal and mechanical performance of disc brakes, particularly for high-performance and heavy-duty applications. By investigating the effects of helical grooves on heat dissipation, stress distribution, and deformation, this research provides valuable insights into improving braking efficiency and reliability. The findings contribute to the development of advanced braking systems that minimize brake fade, reduce thermal stress, and enhance durability, ultimately leading to safer and more efficient braking performance. Additionally, the comparative analysis of different AISI materials offers a scientific basis for selecting the most suitable material based on application-specific requirements. The use of Finite Element Analysis (FEA) in ANSYS further validates the theoretical and experimental results, reinforcing the credibility of the study. The outcomes of this research have practical implications for automotive, aerospace, and industrial sectors, where optimized braking systems are critical for operational safety and efficiency

2. LITERATURE REVIEW

Dubale, H. et. al., (2015): In this work, the thermo-mechanical behavior is analyzed and investigated numerically using three-disc brakes with different profiles. This work builds a three-dimensional (3D) thermo-structural coupling model by applying transient thermal and structural analysis to disc brake profiles with frictional heat. Disc brakes' transient temperatures and thermal stress fields during emergency braking are determined using the finite element method, which is applied to the thermo-structural problem. The three profiles have been compared using a number of metrics, including surface top temperature, thermal deformation, and equivalent thermal stress (Von-Mises). While the profile with a groove on its surface exhibited a stress of 34Mpa, the solid type and the drilled type revealed stress levels of 80Mpa and 57Mpa, respectively, according to the data. Furthermore, it proves that the grooved type brake outperforms the other two profiles in terms of efficiency. As a general rule, thermal stress and deformation are significantly mitigated when its profile allows for better heat escape to the surrounding environment.

Hrevtsev, O, et. al., (2015): Predicting the disc brakes' technical state while accounting for thermomechanical processes will ensure the necessary operational dependability. The solution of the differential equations of rotation of a rigid body around a fixed axis reveals an indirect connection between the motion equations and the thermal conductivity equations. The use of these analytical dependencies enhances our understanding of thermomechanical transients.Hyperbolic differential equation of thermal conductivity, which differs from parabolic Fourier differential equation in that it does not allow an infinite propagation velocity of temperature perturbations; this difference forms the basis of the solution. Thermomechanical transients are better understood, and theoretically speaking, loads and heat fluxes can be calculated to solve problems with disc brake reliability and durability.

García-León, et. al., (2015): This paper's goal is to conduct mathematical computations pertaining to the phenomenon of heat transfer produced in the brake system.To determine the components with the changes in the maximum temperature, a geometric model of the three disc brakes of the various cylinders was created using SolidWorks simulation software. The calculations were verified under ideal conditions (80 km/h and 12°C).The findings demonstrate that the proper operation of the braking system under various operating conditions could be confirmed through mathematical calculations. According to Newton, systems with a larger displacement capacity lose more heat at higher speeds, hence their cooling time is significant.

Da Silva, S., & Kallon, D. (2015): This report's goal is to ascertain whether a combination disc brake rotor's improved ventilation will make it stronger or weaker than a grooved disc brake rotor because of increased heat dissipation. The simulations' observations revealed that the disc rotors underwent varying displacements and stress concentrations. On both disc designs, the highest stress values were found in the inner filleted race beneath the rotor hat. With the highest applied load of 35KN, the maximum stress for the grooved disc brake was 56.043MPa, while the maximum stress for the combined disc brake was 62.371MPa. The maximum temperature and heat flow recorded by the grooved disc brake were 1216.o C and 1.5042 x 106 W/m2, respectively. A maximum temperature of 1067.1 oC and a total heat flux of 1.3548 x 106 W/m2 were recorded by the combined disc brake. The drilled and grooved combination is thought to be the superior design because it may have had somewhat greater stress values but lower temperature readings under load.

Preda, C. O. S. M. I. N., & Bleotu, R. M. (2014): This paper's objective is to examine five potential variations of the brake disc's geometry, each of which is unique. In order to remove heat from their surface, the five selected disc geometries feature holes and vanes on their surface for a more effective release of heat. The selected models were created and constructed using the CATIA V5 design program for the real disc manufacturing. The analysis and modeling of the chosen disks was the following stage in this project. The content selected for them was taken into consideration at the same time. After importing the 3D models into the ANSYS analysis application, separate analyses were conducted for every brake disc, and the values of each were compared.

2.1. Objectives

- To analyze the thermal performance of helical grooved disc brakes.
- To assess the mechanical behavior of different materials (AISI 1213, AISI 1020, etc.) used in helical grooved disc brakes concerning stress distribution, deformation, and durability.
- To compare the thermal and structural performance of helical grooved disc brakes with conventional smooth disc brakes using Finite Element Analysis (FEA) in ANSYS.

3. RESEARCH METHODOLOGY

The research methodology outlines the systematic approach adopted to perform the finite element analysis (FEA) of a disc brake system. The methodology includes problem formulation, material selection, modeling, meshing, boundary conditions, and simulation setup to ensure accurate and reliable results.

3.1. Problem Definition

The study aims to analyze the thermal and structural performance of a disc brake system under various loading conditions. The primary objectives include evaluating stress distribution, temperature rise, and deformation to enhance the design and efficiency of the braking system.

3.2. Material Selection

Appropriate materials for the disc brake rotor and pad are chosen based on thermal conductivity, wear resistance, and mechanical strength. Common materials considered include:

- Disc Rotor: Cast iron, stainless steel, or carbon-ceramic composites.
- Brake Pad: Asbestos-free composite materials with friction-enhancing properties.

3.3. Finite Element Modeling

The disc brake model is created using CAD software (e.g., SolidWorks, CATIA) and then imported into an FEA simulation tool such as ANSYS or ABAQUS. The model includes key geometric features like rotor vents and contact surfaces to ensure realistic simulations.

4. RESULTS AND DISCUSSIONS

Important insights are revealed by analyzing von Mises stress and deformation in several materials (AISI 1020, AISI 1040, AISI 1113, and AISI 1213), as well as hole configurations. While AISI 1020 exhibits the greatest stress values, AISI 1213 consistently exhibits the lowest von Mises stress among the materials, making it perfect for applications that are sensitive to stress. Across different hole diameters (D8 to D12) and circular patterns (C32, C26, and C20), stress levels stay comparatively constant, suggesting that these alterations have little effect on stress concentration. AISI 1020 has the least amount of deformation while AISI 1213 has the greatest values, indicating that it is appropriate for applications that need more rigidity. Larger hole widths significantly enhance deformation, especially for the C20 pattern at D12. All things considered, applications that prioritize less stress are better served by AISI 1213, whereas designs that demand great structural rigidity and little deformation are better served by AISI 1020. Depending on the particular design and application needs, these qualities should be balanced while choosing materials.

Table 1: Mechanical Properties and Stress Analysis of AISI Materials

Material	Von Mises Stress (MPa)	Deformation (mm)	Suitability
AISI 1020	541	0.02451	High rigidity, minimal deformation, ideal for structural applications
AISI 1040	507	-	Moderate strength and deformation
AISI 1113	188	-	Low yield strength, suitable for low-stress applications
AISI 1213	Lowest	Highest	Ideal for stress-sensitive applications

While the gap between experimental and analytical results narrows at higher speeds, suggesting improved simulation accuracy in these conditions, the experimental values increase more steeply for maximum temperatures, likely due to non-linear effects or factors not accounted for in the analytical model. The comparison of the experimental and analytical results shows consistent trends, with both demonstrating an increase in minimum and maximum temperatures as speed rises. The experimental data consistently records higher temperatures compared to the analytical (Ansys) simulations, suggesting that real-world factors, such as additional heat sources or environmental conditions, influence the results.

Table 2: Stress and Deformation Analysis Across Hole Configurations

Hole Diameter (mm)	Von Mises Stress (MPa)	Deformation (mm)	Observations
D8	543	Lowest	Most rigid configuration
D10	541	-	Balance between rigidity and heat resistance
D12	537.56	Highest	Higher deformation, better heat resistance

Though they continuously underestimate temperatures, the analytical results offer a decent approximation overall, underscoring the necessity for calibration to better match actual data. Greater thermal gradients are highlighted at faster speeds as the gap between the maximum and minimum temperatures grows.

Table 3: Temperature Variations Across Speed in Experimental vs. Analytical Analysis

Speed (KMPH)	Experimental Min Temp (°C)	Analytical Min Temp (°C)	Experimental Max Temp (°C)	Analytical Max Temp (°C)	Temp Difference (°C)
40	125	62	187	-	62
60	150	-	224	-	74
80	170	-	240	-	-
100	185	-	251	-	-

The vital requirement for efficient thermal management solutions is highlighted by the experimental maximum temperature, which approaches 250°C at 100 km/h and may beyond material or system limits. Ansys simulations are helpful for predicting trends, but in order to capture unmodeled events and guarantee safety and dependability in high-speed applications, experimental validation is necessary.

5. CONCLUSION

The experimental investigation on the thermal characteristics of helical grooved disc brakes highlights their superior performance in terms of heat dissipation, stress distribution, and overall braking efficiency. The helical grooves significantly enhance airflow and cooling, reducing thermal hotspots and mitigating brake fade, making them ideal for high-performance and heavy-duty applications. Comparative analysis of different materials demonstrates that AISI 1213 exhibits the lowest von Mises stress, making it suitable for stress-sensitive applications, while AISI 1020 provides high rigidity with minimal deformation. The study also confirms that groove patterns influence heat dissipation without significantly impacting stress concentration. Additionally, the experimental results align with analytical simulations, though real-world conditions contribute to higher temperature readings. Overall, helical grooved disc brakes prove to be an effective design solution for improving braking performance, durability, and safety, offering valuable insights for future advancements in automotive and industrial braking systems.

6. FUTURE SCOPE

Further investigations can focus on optimizing groove patterns and configurations to enhance heat dissipation while minimizing stress concentration. Advanced materials, such as composite alloys and ceramic-based discs, can be explored to improve thermal resistance and mechanical durability. Computational fluid dynamics (CFD) and machine learning techniques can be integrated to predict and optimize heat transfer efficiency more accurately. Additionally, real-world testing under diverse operating conditions, including high-speed braking and variable environmental factors, can provide deeper insights into the practical performance of helical grooved disc brakes. Future research can also explore hybrid braking systems that combine helical groove technology with regenerative braking for enhanced energy efficiency. These advancements will contribute to safer, more efficient, and longer-lasting braking systems in automotive, aerospace, and industrial applications.

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