

Parametric Optimization of Coupled Thermal and Structural Analysis of a Brake disc Using Finite Element Analysis

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Abstract. The objective of this work is to conduct parametric optimizations for the performance of a ventilated brake disc manufactured from structural steel using Finite Element Analysis (FEA) to assess the structural and thermal performance of the brake disc while being subjected to coupled braking loads. The focus of the study is to investigate the response of critical parameters; thermal gradients, applied mechanical stresses, applied contact stresses, and deformation occurring during the braking cycle. Three key geometric parameters (rib thickness, hole diameter, and slot radius) were systematically varied leading to a full factorial design of (126) varying design configurations being created. The main goal was to minimize deformation of the brake disc, while simultaneously improving brake disc structural integrity, safety, and service life. The effects of coupled thermal-structural loading were incorporated into the FEA simulations to best simulate real-world operating conditions. Design Point 28 was determined to be the optimal design configuration from the (126) different designs evaluated.

1. Introduction

The brake disc is a crucial part of the car brake system since it converts the kinetic energy of the vehicle into heat via its friction interface, which requires a high dissipation capacity. The braking system is subject to three major issues: the formation of thermal cracks, loss of material in the brake disc, and reduction in braking performance. The correct design of brake discs requires engineers to analyse the coupling of thermal loads with contact stresses and their effect on the structural behaviour of the brake disc.

Today's transportation needs call for faster speeds, heavier loads, and less energy consumption, making it increasingly important to have brake discs that are both lightweight and high-performing. In emergency braking at high speeds, heavy friction induces enormous heat that will lead the structure of a brake disc to rapid temperature increase and

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severe thermal shock due to high thermal load. Such overheating results in poor braking efficiency and increased frictional loss, possibly leading to failure, with severe damage to property. Therefore, the development of ventilated brake discs with superior wear resistance, high-temperature endurance, and low weight, as well as studies regarding the effects of surface temperature rise on their structure, becomes quite important for safety improvement and the assurance of high reliability in high-speed automotive and rail applications.

Brake discs work under severe conditions, such as rapid temperature alterations, cyclic loads, high contact stresses at the interface of brake pads, and are prone to fatigue failure. Advanced simulation techniques, such as FEA, have helped to a great degree in predicting these effects and improving the design of the disc by parametric optimization. The objective of this research is to carry out a coupled thermal-structural analysis using FEA and optimize key parameters such as disc rib diameter, ventilation hole diameter, and slot radius. Structural steel is selected due to its high strength-to-weight ratio, cost-effectiveness, and abrasion resistance.

A coupled thermal-structural simulation will be made of a vented disc brake with Ansys in order to analyse the influence of temperature on strength. It reproduces the real braking situation in thermal gradient, deformation, contact stress and equivalent stress at high temperature. It is explained that the parametric optimization of rib thickness, hole diameter, and slit radius helps in achieving dimension that promotes deformation, stress reduction which thus increases strength, thermal stability and braking efficiency. Contribution in reinforcement of formulation for the heat-resisting-determined brake plate with high heat resistant and inhibiting thermal cracking even if used at a high speed and heavy load.

Kulkarni et al. [1] conducted a coupled thermal and structural analysis of a brake disc made from a silicon carbide–reinforced aluminium metal matrix composite using ANSYS. Their study examined temperature distribution, deformation, and von Mises stress to evaluate how well the material performs under braking conditions. The findings showed that the AMMC brake disc is capable of effectively handling both heat generation and mechanical loads during braking.

Manjunath and Suresh [2] performed individual thermal and structural analyses of a disc brake to study temperature distribution, stress, and deformation. Their work highlighted the importance of material selection in the thermal performance of the brake disc. However, their work did not involve coupled simulation or design variation. The current our paper extends this by using coupled analysis and exploring geometric optimization.

Park et al. [3] has conducted an investigation into the effect of hole and slot geometry on thermal and structural performance of ventilated brake discs by using coupled analysis on ANSYS. Their study was primarily aimed at geometrical shape optimization for improved heat dissipation. Although they considered slit and hole variations, the current study goes a step further by systematically varying hole diameter, slot radius, and rib thickness for enhanced performance improvement.

Prajapati and Prajapati [4] performed thermal and structural analysis of an automotive brake disc using ANSYS Workbench. They evaluated temperature distribution, equivalent stress, and deformation under braking conditions. The study demonstrated the use of FEA for predicting brake disc behaviour. Their analysis was based on a standard disc geometry without any design modifications.

Pateriya et al. [5] analysed the thermal and structural performance of a brake disc under simulated braking conditions. They assessed temperature distribution, equivalent stress, and deformation. The study made a comparison of different materials that included cast iron and carbon-carbon composites. It highlighted material selection as a management factor for thermal and mechanical loads.

Jaiswal et al. [6] carried out structural and thermal analyses of the disc brake using SolidWorks for modelling and ANSYS for simulation. The effects of materials like cast iron and aluminium alloys on temperature distribution, thermal stress, and deformation were examined. The study included how braking heat has an effect on the mechanical stability. It further emphasized that material selection plays an important role in thermal management.

Narayana et al. [7] carried out a finite element analysis of both solid and ventilated disc brake configurations was performed using ANSYS. Thermal performance in temperature distribution, thermal stress, and structural deformation under braking loads was analysed for the comparative study between the disc types. It could be observed from the result that ventilated discs had higher rates of heat dissipation with lower generated stresses compared to solid discs. Again, this points toward thermal efficiency due to geometric design in brake systems.

While literature reports of coupled thermal-structural analyses for brake discs are available, most of these studies lack parametric optimization. This research uniquely combines FEA-based coupled analysis with parametric design optimization in order to investigate ways of enhancing the thermal and structural performance of the brake disc. The paper would determine the best geometry that minimizes stress and deformation during braking.

2. Methodology

The Parametric optimization of coupled thermal and structural analysis of a disc brake, in this study followed a systematic, simulation-based approach. The methodology was designed to cover key stages including geometric modelling, material selection, meshing, boundary condition application, parameters optimization analysis, post-optimization evaluation, Stress and Contact Stress assessment, ensuring a thorough analysis of the component's performance. The workflow of the analysis in Ansys workbench is shown in Fig. 1.

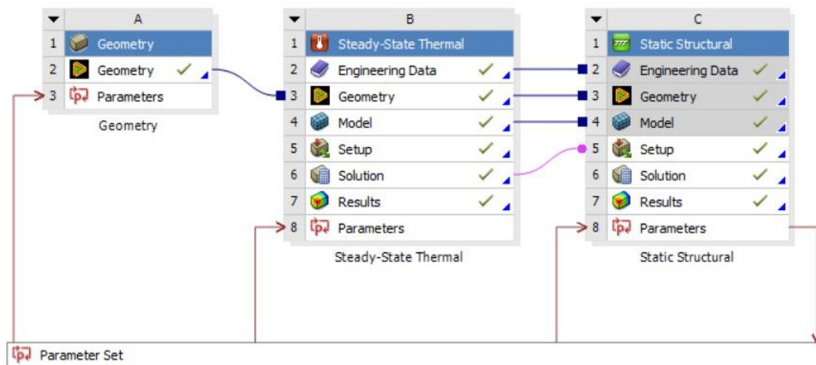


Fig. 1. Method of analysis in Ansys workbench.

In this study, the coupled thermal-structural analysis is done using Ansys for finding the structural behaviour under the effect of the Thermal Loads. A 3D model in SolidWorks is designed with predefined parameters such as dimensions and geometric constraint. The model is imported into Ansys through the geometry module and made compatible for further analysis. The imported model is transferred to the Steady-State Thermal module in Ansys. Application of thermal boundary condition such as Convection & Temperature constraint is applied in the model. Solve the thermal analysis and obtain the temperature distribution and the heat flux results indicating how the heat is transferred inside the Structure. These are then evaluated for thermal gradients and overall heat dissipation efficiency. The temperature result obtained from the steady-state thermal analysis is mapped to the Structural module in Ansys. In the Structural module, appropriate boundary conditions such as fixed supports, Pressure, rotational velocity, moment and constraints are applied. The structural analysis is then solved for finding the effect of Stress distribution, Contact stress, wear and deformation due to thermal Conditions. The same workflow is followed for the 126 combinations of parametric design points and the result gets evaluated.

3. Data Collection

The brake geometry was created in SolidWorks according to the specified design dimensions, as shown in Figure 2, and the completed model was exported in IGES format for direct import into ANSYS Workbench with defined parameters. The imported geometry used for analysis is presented in Figure 3, while the detailed specifications of the disc brake are summarized in Table 1. Disc brakes are commonly manufactured from materials such as grey cast iron, aluminium alloys, and structural steel; in the present study, structural steel was selected for the brake disc, and its mechanical and thermal properties are provided in Table 2.

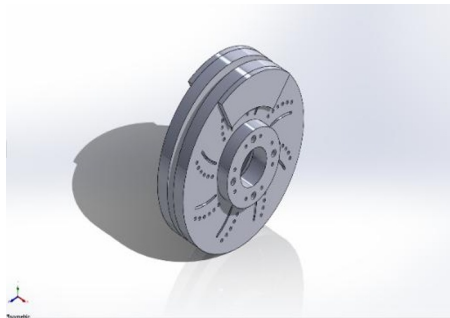


Fig. 2. 3D model of disc brake

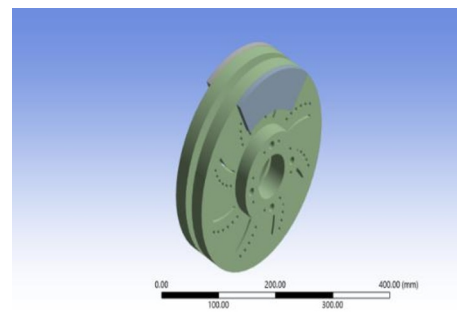


Fig. 3. Geometry of brake in Ansys

Table 1. Disc brake specification.

Parameters	Values
Weight of disc	3 kg
Diameter of rotor	298 mm
Rotational velocity	74.01 rad/s
Torque	52 Nm
Co- efficient of friction	0.25

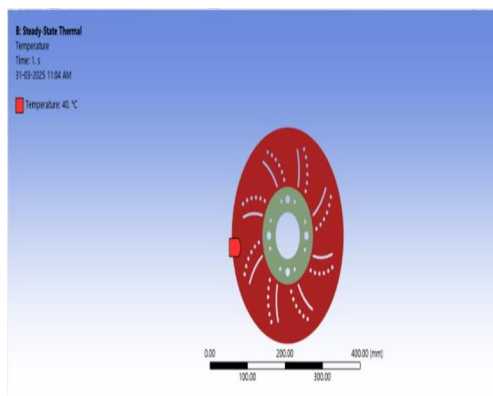
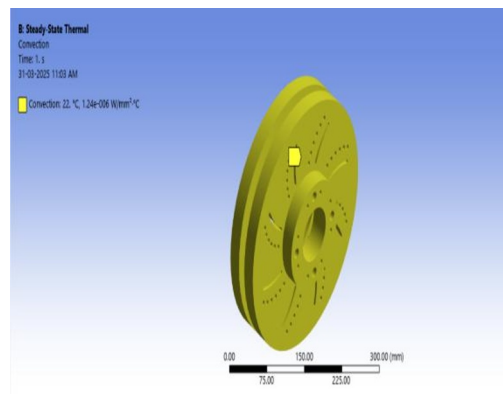
Table 2. Material properties for structural steel.

Density	7850 kg/m ³
Young modulus	200 Gpa
Thermal conductivity	50 W/m. K
Specific heat	420 J/kg. C
Poisson's ratio	0.3

Grey cast iron, aluminium alloys, and structural steel are widely used in disc brakes due to their strength, thermal stability, wear resistance, and good manufacturability under severe braking conditions. Grey cast iron is popular for its excellent thermal conductivity, high damping capacity, and natural resistance against wear and thermal cracking. Aluminium alloys are preferred in lightweight or high-performance systems since they reduce overall mass and enhance heat dissipation, although needing coatings due to lower wear resistance. Structural steel, the material of choice in this work, presents a strong balance of high strength, good thermal capacity, and structural rigidity that will enable it to bear coupled thermal-mechanical loads without excessive deformation. It also provides consistent material properties, good machinability, and cost-effectiveness, making it ideal for parametric optimization with variable geometries.

Thermal boundary conditions

In the study, these thermal boundary conditions were set up to simulate the process of heat generation and dissipation during braking. A 40 °C thermal gradient was applied to one side of the brake disc to simulate the local thermal load at the frictional contact face, as illustrated in fig 4. This boundary condition serves as the leading heat source of the disc and is responsible for initiating the propagation of temperature rise through material. All other outside surfaces were provided with natural convection boundary conditions and have been shown in fig 5 for the heat loss to surroundings. The convective heat transfer coefficient was borrowed from the ANSYS stagnant-air simple database, representing slow-moving ambient airflow usually exist when the disc cools in a passive fashion.

**Fig. 4.** Temperature Gradient.**Fig. 5.** Convection Boundary.

Structural Boundary condition

A fixed support is applied at one end of the disc pad as shown in fig 6, while a uniform pressure of 1 MPa is applied at the other end of the brake pad shown in fig 7. Simultaneously, both torque and rotational velocity are applied in the same direction along the brake rotor shown in fig 8, inducing rotational motion and the displacement occurs due to these forces. The X-axis, which corresponds to the direction of rotation, is set to be free, and the other direction get arrested to avoid directional deformation. Along that the frictional contact is applied on brake pad and the surface of disc in contact region with coefficient of 0.25 were shown in fig 9.

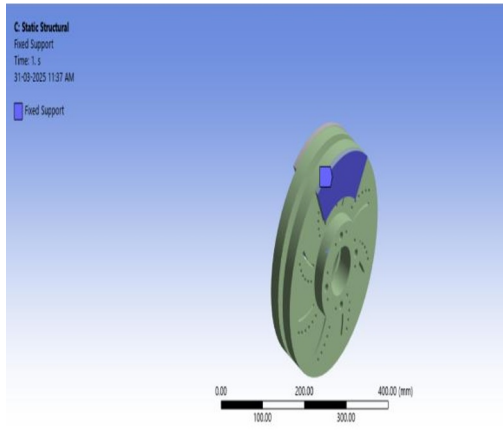


Fig. 6. Fixed supports on the outer face of pad.

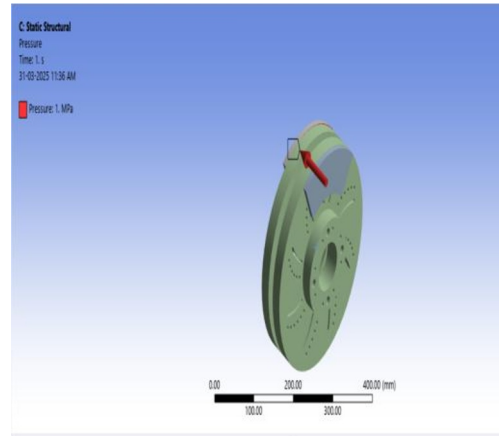


Fig. 7. Pressure applied on inner face of pad.

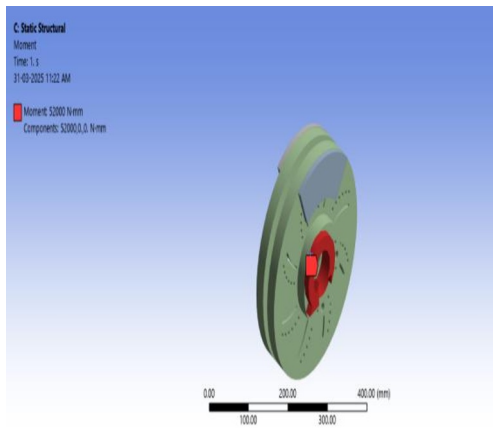


Fig. 8. Moment is applied on the brake disc.

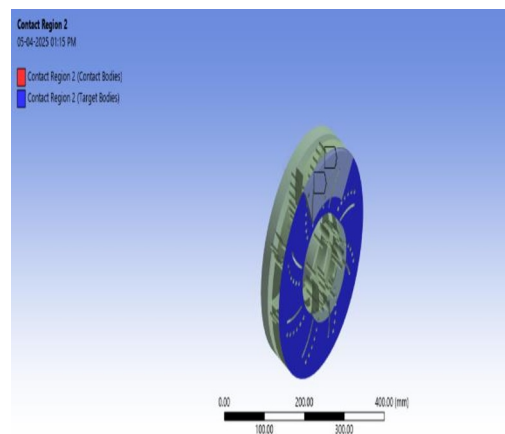


Fig. 9. Contact region between Pad and face.

Parametric optimization in Ansys involves systematically changing the design parameters of a model in search of the best possible solution to achieve a given objective; typically, this is performed for improved performance, cost reduction, or to satisfy certain engineering constraints. Given various design variables, in most cases dimensions, in this study, three design parameters were varied systematically across 125 different combinations of design

points. For each of these combinations, equivalent stress, total deformation, and contact stress were assessed, providing an idea of how such factors change with the varying parameters. Parametric table were shown in Table 3.

Table 3. Parametric data from Ansys

Design point	P1	P2	P3	P4	P5	P6
DP 0	10	6	2	0.041253	156.0949	4.962786
DP 1	12	6.8	2.8	0.040964	152.381	5.538227
DP 2	12	6.8	3.6	0.040918	152.898	5.191572

[P1,P2,P3] -Input variable [P4,P5,P6] – Results P1 -Circular rib diameter vary with range [10-20] with interval of 2 mm were shown in fig 10, P2 - Hole diameter vary with the range [6-10] with interval of 0.8 mm were shown in fig 11, P3 - slot radius vary with the range [2-6] with interval of 0.8 mm were shown in fig 11, P4 -Total deformation in mm P5 - Equivalent stress in MPa P6 - Contact stress in MPa.

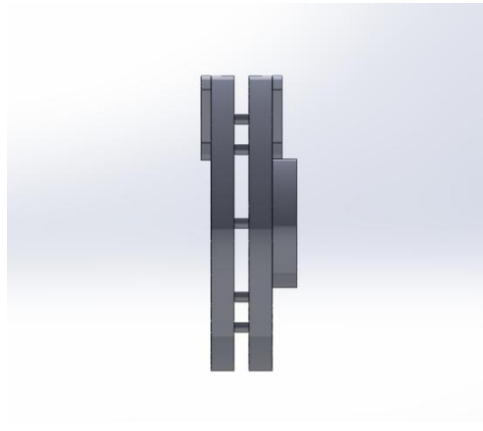


Fig. 10. Circular rib diameter.

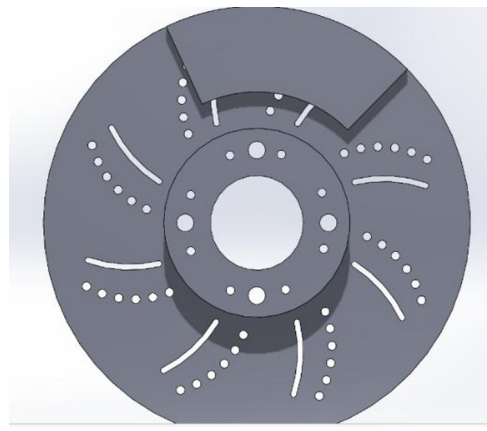


Fig. 11. Hole diameter and slot radius.

4. Results and Discussion

4.1 Numerical Results

The parametric study identified the optimal design variables for an automotive brake disc, showing that an increase in the number of holes and ventilation slits improves heat dissipation. However, excessive enlargement of these features also led to higher stress concentrations and increased contact stress. To address this trade-off, an optimization approach was applied to determine suitable hole and slot dimensions that minimize both disc temperature and stress levels. The optimal configuration was obtained at Design Point 28, where the equivalent von Mises stress was 137.9636 MPa, the contact stress was 6.358161 MPa, the total deformation was limited to 0.0409495 mm, and the disc temperature was reduced by 4 degrees. The corresponding optimal design parameters are presented in Table 4.

Table 4. Optimum design point.

DP 28	14	6.8	4.4	0.040495	137.9636	6.358161
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4.2 Graphical Results

The fig 12 shows the values of equivalent stress, total deformation and contact stress for the 125 design points.

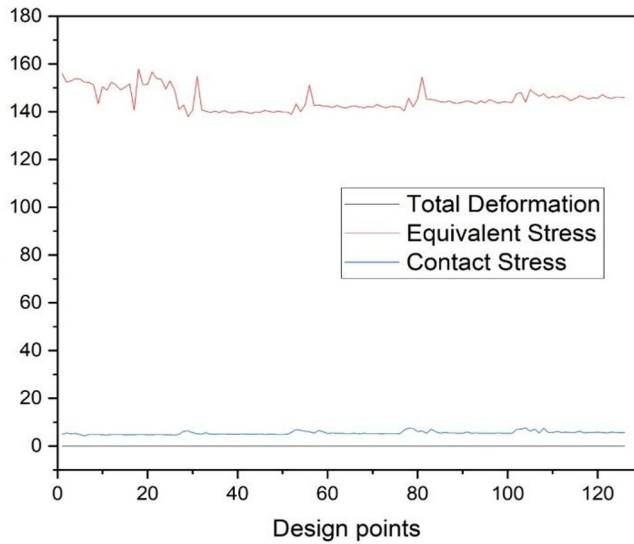


Fig. 12. Graph design points vs result.

The computed equivalent stress remains within the allowable limit, indicating that the brake disc design satisfies the required strength and stiffness criteria. The numerical results obtained from the coupled analysis, including temperature distribution, total deformation, equivalent stress, and contact stress, are illustrated in Figures 13 - 16.

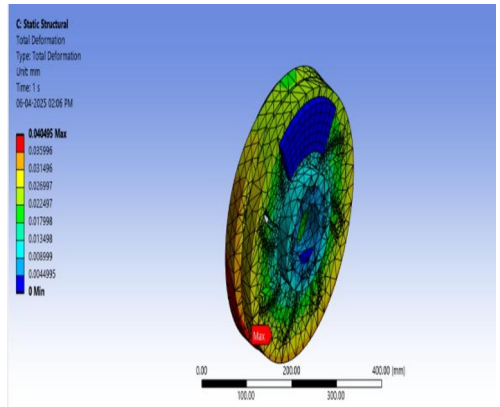
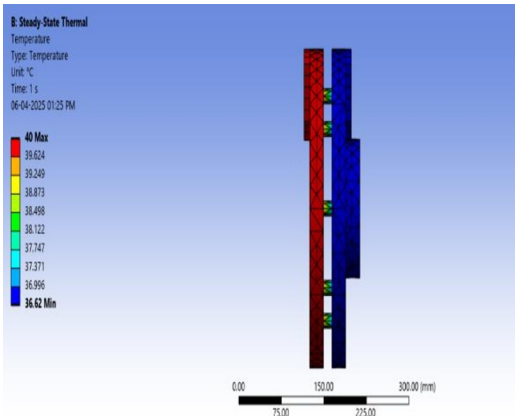


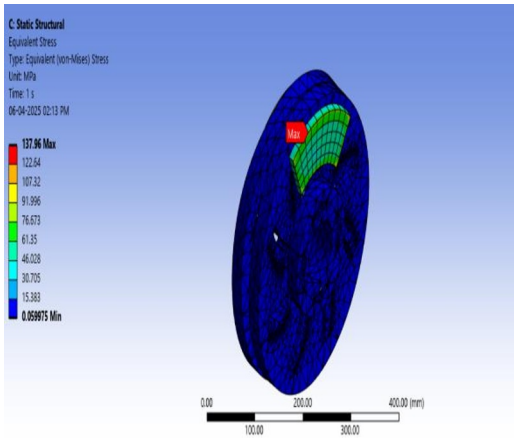
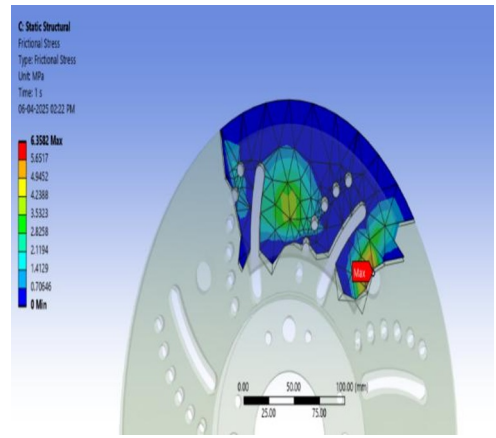
Fig. 13. Temperature distribution on brake disc.**Fig. 15** Equivalent stress of brake disc**Fig. 14.** Total deformation of brake disc.**Fig. 16** Contact Stress of brake disc

Fig. 14 illustrates the deformation pattern of the disc brake obtained from structural analysis, where the maximum displacement is concentrated near the region of outer edge.

Fig.16 result shows high contact stress at leading edge (6.3582MPa) compared to trailing edge, more stress causes the more wear occur at the leading edge This is mainly because of higher pressure occurred on the leading side when the disc starts to slide, when excessive contact stress can lead to increased wear, surface fatigue, and early crack initiation at the contact interface.

4.3 Proposed Improvements

In this paper, an optimized design of a ventilated brake disc was proposed by integrating the parametric modelling and coupled thermal-structural analysis using FEA in ANSYS. By considering the typical braking conditions, the optimization process aimed to minimize thermal distortion, mechanical, and contact stresses while maintaining structural integrity and improving heat dissipation.

A full factorial design of experiments was conducted, involving 125 unique combinations of three key geometric parameters—rib thickness, hole diameter, and slit radius. Each configuration was simulated under identical thermal and mechanical boundary conditions, representing realistic braking scenarios.

The optimal geometry design was finalized by optimization with a rib thickness of 14 mm, hole diameter of 6.8 mm, and slit radius of 4.4 mm. This resulted in the best performance parameters - total deformation of 0.0409495 mm, an equivalent (von Mises) stress of 137.9636 MPa and contact stress of 6.358161 MPa. It can be seen that these are much lower than for the non-optimized configuration, suggesting a higher resistance against thermal gradients and mechanical loading.

The optimum configuration enables the cooling air path to be effectively enhanced while providing sufficient strength to reduce hot spots and thermal fatigue. This reduction of contact stress is of particular benefit to the wear life of disc-pad interface and hence, for long-term performance and safety.

This optimization strategy is a successful and reliable design tool in the context of high-performance brake disc manufacturing. It is not only improving the performance of brake but also prolonging the life of components that has extremely important significance to automotive application, and especially in modern car, the thermal reliabilities and the structural stabilities of parts are increasingly required.

5. Conclusion

In this study, we built a finite element model to check how a ventilated brake disc holds up structurally and handles heat during real braking. We ran thermal-structural simulations in ANSYS R21, focusing on three geometric factors: rib thickness, hole diameter, and slot radius. We wanted to see how these changes affected stress, deformation, and how well the disc got rid of heat. The results showed that with the right dimensions, the disc deformed less and stress was more focused, plus it managed heat better. Overall, the study successfully achieved its objectives.

The novelty in this research is an integrated parametric optimization approach to brake disc design, combining thermal and structural considerations. The paper presents the systematic analysis of 125 configurations, offering a validated design framework that will enhance braking efficiency, reduce wear, and extend component life. These results provide useful insights for future development of high-performance, thermally efficient braking systems in the automotive industry.

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