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Analysis and Comparison of Design and Material of Ventilated Disc Brakes Using Ansys

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Abstract : Vehicles have proved to be one of the most important inventions of mankind. With time, the vehicle development process has started giving more and more importance to the safety and comfort aspects of the passengers and driver. This has become all the more important due to better speed and acceleration being achieved with new designs. Modern vehicles can accelerate much faster than their past counterparts, and hence, require better technologies to decelerate them proportionally. Due to these requirements, disc brakes have become a standard feature in modern vehicles to reduce stopping distance. Upon application of brakes, the disc undergoes thermal and structural stresses, which may cause the brakes to fail in slowing down or stopping the vehicle if they become too hot. The disc's design, thickness, and material have a significant impact on the heat dissipation rate. Therefore, this study emphasizes the importance of selecting suitable materials and designing efficient disc rotors that are capable of dissipating heat quickly. This study aims to compare the different designs and materials for discs and hence arrive at the most optimal solution to this life threatening and large scale problem.

***IndexTerms* - Ansys, SolidWorks, Thermal Analysis, Ventilated Disc Brake**

I. Introduction

The brake system is a vital component of an automobile that plays a crucial role in reducing the speed of a vehicle. It works by converting the frictional energy due to rubbing between disc and brake pads into heat energy. There are several types of brakes used in the automobile industry, but the most commonly used ones are based on the principle of friction as explained. These brakes comprise a stationary (brake pad) and a moving part (disc), which work together to wear out the moving part and slow down the vehicle. The kinetic energy of the automobile is converted into heat energy. One subtype of frictional brakes is the disc brake, which is widely used in modern vehicles.

A disc braking system has a rotating disc that is attached to the vehicle's axle or wheel-hub and moves along with the wheels. A brake caliper is attached to the disc. The disc is held in place between the two rubber pads on the caliper to ensure that they do not touch the disc during normal operation. When the driver presses the brake pedal, the braking fluid pushes the calipers forward, causing them to grip the disc plate from both sides and bring it to a stop. As the disc is connected to the vehicle, it brings the vehicle to a halt too.
Since disc brakes absorb a high amount of heat generated through friction to stop the vehicle, their design is an extremely crucial factor in determining the safety and usefulness of a vehicle. Disc brakes are subjected to a lot of forces and pressure, so the material used in their manufacturing needs to bear mechanical stresses, centrifugal forces, thermal loads, and tensile forces. Generally, cast iron and ceramic composites are used for manufacturing disc brakes because of their mechanical and thermal properties, which enable them to withstand the mentioned loads. In this research paper, gray cast iron, aluminum alloy, and stainless steel will be compared for the manufacturing of disc brakes. The properties of these materials are explained below-

1.1 MATERIALS USED

1.1.1 STAINLESS STEEL

Stainless steel contains steel and 10-30% chromium too. Chromium is present because it aids in resistance from corrosion and heat. Stainless steel is classified into the following types - ferritic, austenitic, duplex, martensitic, and precipitation-hardening. Properties of stainless steel are-

1.1.1.1 Melting Point: Stainless steel has high melting points, which are in the range of 1400°C - 1530°C. This makes Stainless steel a good choice for brake rotors. Hence, we use them in this comparison analysis.

1.1.1.2 Corrosion: Corrosion resistance for stainless steel can be increased by increasing chromium content to more than 11%, adding a minimum of 8% nickel, and molybdenum addition.

1.1.1.3 Wear: Stainless steel is prone to wear and galling. This can cause breaking or complete seizure of the moving components, which is the disc. It can be prevented by using stainless steel with dissimilar materials like bronze and a few others.

In this study, we have used SS-410 because it is a martensite stainless steel. It hardens on heat treatment and has high chromium content. This results in good corrosion resistance properties.

1.1.2 GREY CAST IRON

The grey cast iron contains graphitic microstructure. Due to the presence of graphite, it forms a grey-coloured fracture and thus it is called Grey CI. It has high specific heat capacity and high thermal conductivity and thus it is used in making Disc brake rotors. It is composed of 2.5 to 4% carbon by weight, 6 to 10% graphite by volume, and 1 to 3% silicon by weight.
Properties of Grey Cast Iron are-

1.1.2.1 Gailing and wear resistance: Grey Cast Iron has the property of self lubrication and thus provides good gailing and wear resistance.

1.1.2.2 Heat Dissipation: Due to its excellent damping capacity property, energy is absorbed and further converted into heat.

1.1.2.3 Corrosion Resistance: Good corrosion resistance is provided by the silicon present in the Grey Cast Iron.

1.1.3 ALUMINUM ALLOY

Aluminum is present in the highest proportion and is the dominant metal across all aluminum alloys. Typically magnesium, copper, tin, nickel, zinc, and silicon are the alloying elements used along with aluminum. Alloys containing cerium are also being developed for high-temperature automotive applications, for eg rotor discs.
Properties of Aluminum alloys are -

1.1.3.1 Corrosion Resistance: Good corrosion resistance properties are provided by silicon present in the Aluminum alloys.

1.1.3.2 Heat Dissipation: Aluminum is a very good heat reflector as well as heat conductor and is therefore an excellent choice for heat exchanger applications.

1.1.3.3 Wear Resistance: Hard ceramic particles can be added on aluminum bases to improve wear resistance of the metal or alloy.

We have used aluminium alloy with SiC particles which forms a metal-matrix composite for our analysis.

1.2 TYPES OF DISC BRAKE

1.2.1 Flat Disc Brake: It is a normal flat disc design that has surface area for the brake pad to hold on. It does the job of braking but it has a short life compared to other types of disc brakes. This type of brakes is not used much in present vehicles but in the past was used in smaller vehicles very frequently.

1.2.2 Ventilated Disc Brake: This type of disc is used in most types of modern vehicles. They can withstand much more load and can also provide more braking power to the vehicle. This disc brake has a ventilated design for better heat dissipation while braking. This increases the life of the disc brake and also increases the structural strength, which makes it a more safe option.

1.3 TYPE OF GROOVES/SLOTS

1.3.1 Drilled Disc: A disc plate that has holes drilled into its surface to increase surface area which helps in better heat dissipation. This also helps in reducing the weight of the disc brake due to material removal.

1.3.2 Slotted Disc: In this type of disc, instead of drilling holes, slots are made in the disc for the purpose of heat dissipation. The advantage of creating these slots is that it does not affect the heat resistance property of the disc. Sometimes a combination of both drilled and slotted can also be used.

For the purpose of this research study, we have used a combination of drilled and grooved design.

II. LITERATURE REVIEW

Lemi Abebe presented a paper on thermal analysis of disc brakes made of multiple materials – Cast Iron(CI), E-Glass Fiber, Maraging Steel, and AL-MMC. By comparing the FEA results and analytical results, values were found to be similar and were not much different. In both cases, it was observed that the pattern of variation of temperature is the same. [1]

Manjunath TV examined vented and solid disc rotors in order to assess the effects of temperature increase, deflection, and stress field. It revealed that compared to a solid disc, the vented CI disc underwent 8% less deformation, 31.47% more temperature decrease, and 22.5% less stress. [2]

V. Naveen assessed the braking abilities of several disc rotors. It was determined that the rotor's shape and manufacturing material had a direct impact on braking efficiency. [49]

Ali Belhocine did a study on the thermal analysis of a full and vented disc delivered. Three different forms of CI—the AL-FG 25, FG 20, and FG 15—were studied. It was investigated how the braking mode affected the thermal behavior of disc brakes. It shown that radial airflow is crucial for disc rotor cooling, which has an impact on braking effectiveness. [3]

Sumit Satope found that cast iron and stainless steel had quite different maximum temperature rises. Thus, it was determined that the optimum material to make disc brake rotors out of is cast iron. Its disadvantage is that metal corrodes when exposed to moisture and cannot be utilized in two-wheelers as a result. [4]

Shah Alam compared two types of rotors (i) without holes and (ii) perforated. The maximum temperature after 50 seconds is lower for the perforated disc than it is for a plain disc, indicating that it is more effective. [5]

Yashwardhan Chouhan's study on the static thermal and structural performance of disc brakes states that the disc deforms more at the outer radius and generates significant strains on the disc bowl. The solid disc had more deformations than the vented disc, it was discovered. In comparison to a solid disc, a ventilated disc offers a better distribution of temperature. [6]

Dr Swastik Pradhan worked on the strain properties of various materials and found that following structural steel in terms of strain are stainless steel, grey cast iron, titanium, copper, and aluminium alloy The least stressful material is aluminium alloy, which is followed by stainless steel and grey cast iron. In the majority of the circumstances, stainless steel and grey cast iron retained their average values. Rotor discs have been discovered to attain temperatures of up to 300°C. [7]

Y Chandna conducted a transient thermal study using AlSiC Composite Disc Brake. The results showed that a ventilated cast iron disc performs worse than a ventilated composite disc under repeated braking situations. [8]

Durgesh Kaiwart tried to lighten the weight of braking disc rotors. The analysis used titanium alloys and AlNiCo alloys. Total strain, stress, and deformation were within acceptable ranges. [15]

Rolan Siregar undertook a study on the highest temperature obtained on disc rotors. It was discovered that there was a maximum 49 °C discrepancy between the front and rear brake temperatures. [48]

A. Phaneendra contrasted disc brake rotors made of carbon ceramic, cast iron and aluminium alloy. Cast iron is preferred for standard autos because it has a low maximum temperature and is widely accessible. The highest maximum temperature was reached by carbon ceramic, but it dispersed the most heat and was lighter than the others. [46]

AM Ismael investigated the heat distribution of solid, vented, and vented and drilled disc brake rotors. The disc with vents and drilling outperformed the other two discs. [47]

C. Radhakrishnan contrasted grey cast iron (CI) with Ti550 alloy on measures of thermal efficiency, . It was determined that Ti 550 was superior to the other.[21]

MD Rajkamal examined SS, CC composite, CI discs & compared them to vanadium discs. In terms of overall structural strength, it was discovered that the vanadium disc outperformed the competition.[23]

III. MOTIVATION

Every year, India sees over 400,000 road accidents resulting in more than 173,000 deaths, with brake failure being a major contributor. This poses a significant threat to the safety of passengers in faulty vehicles as well as bystanders on the road. It is for this reason that we have undertaken a study on the analysis of disc brakes.

Despite advancements in the automotive industry, with more refined engines, increasing power figures, and emerging fuel sources, braking systems have been neglected. It is important to note that a vehicle capable of achieving high speeds must also be able to come to a stop quickly and safely. As Mechanical Engineering students specializing in Automotive Engineering at Delhi Technological University, we feel a sense of responsibility towards the industry, and have chosen to focus our research on the braking system of automobiles.

Our study specifically focuses on ventilated disc brakes, an area that has seen little research. Through this study, we aim to identify potential issues in the design of disc brakes and improve their efficiency in dissipating heat, reducing stopping distance, and increasing safety. Our ultimate goal is to develop reliable and efficient braking systems that can enhance the safety of drivers, passengers, and bystanders on the road.

IV. RESEARCH GAP

Compared to a solid disc rotor, a ventilated disc rotor is known for its greater efficiency. While previous research has mainly focused on traditional disc brakes, there has been limited study on the benefits of ventilated disc brakes. Therefore, we aimed to address this gap by analyzing the performance of various materials used in the manufacturing of ventilated disc brakes. Our findings will serve as a valuable resource for both academic and industrial communities, providing a more detailed understanding of this technology and increasing confidence in its practical use. Overall, this study highlights the need for continued research and development in the field of ventilated disc brakes, as they offer significant potential for improving the safety and performance of modern vehicles.

V. METHODOLOGY

5.1 COMPUTER-AIDED MANUFACTURING AND AUTOMATED TESTING PROGRAMS

Manufacturing that incorporates computer software and equipment run by computers is known as computer-aided/computer-integrated manufacturing. By efficiently optimising the manufacturing process, it aids in the manufacturing phase. It also includes computer-aided design, a technique that aids in developing the component utilising software on a computer. It aids in error detection and lowers waste in industrial operations. Numerous sectors now utilise CAM/CAD because it helps with final component manufacture and part visualisation. Because these techniques are more effective and accurate, several automated testing programmes are also used in the modern era to meet client expectations with regard to quality. They support the testing of the component without requiring manual testing, saving both time and resources.

5.2 MODELING

Solidworks 2020 is used for the disc brake rotor's CAD modeling. The disc's size follows industry standards for produced disc rotors. In this research study, three distinct designs have been compared. Different pillar ventilation methods are used in each design. Three different materials were used to analyse each of these designs in order to determine the ideal mix for use in the market.

The disc's design affects how much heat a disc braking system can dissipate. The disc's dimensions, including its diameter, thickness, surface area, etc., are all extremely important. The pillar system or disc vanes in a vented disc might have different lengths or be angled. S. Sarkar et al.'s study [37] found that angled or radial vanes modify the airflow within the ventilated disc, improving heat dissipation. The disc's dimensions are shown in Figure 1.

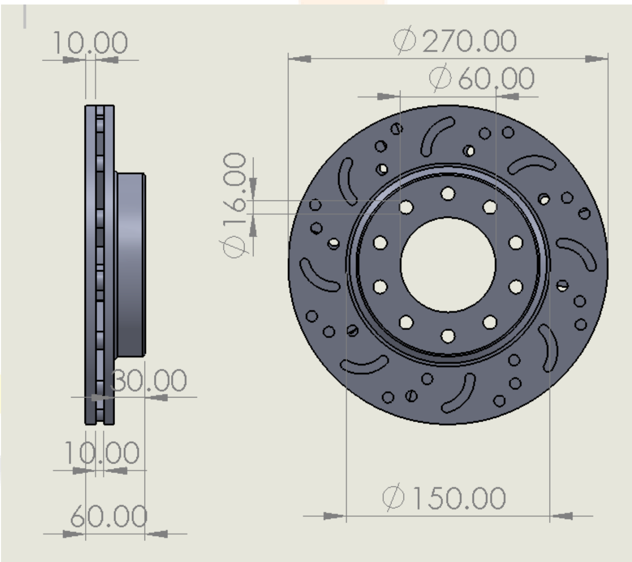

fig. 1 - dimensions of ventilated disc brake

Figure 2-6 shows the three pillar designs in 3d models:

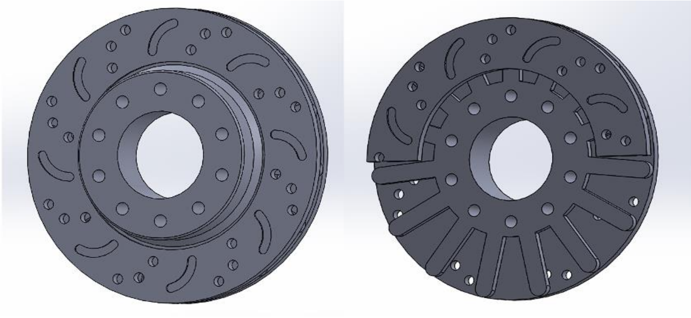

fig. 2 - section view of straight pillar disc brake

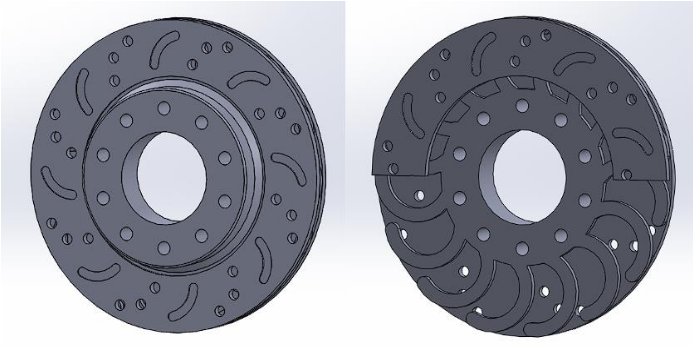

fig.3 - section view of radial pillar disc brake

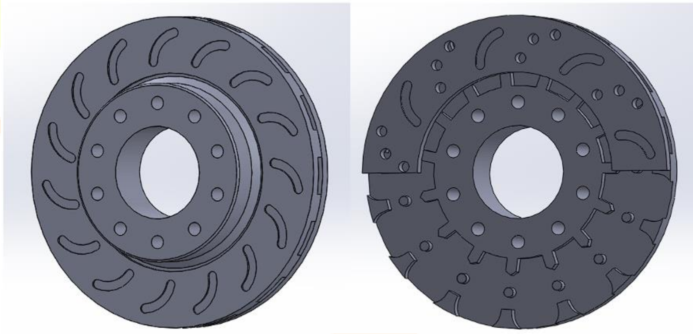

fig. 4 - section view of segmented pillar disc brake

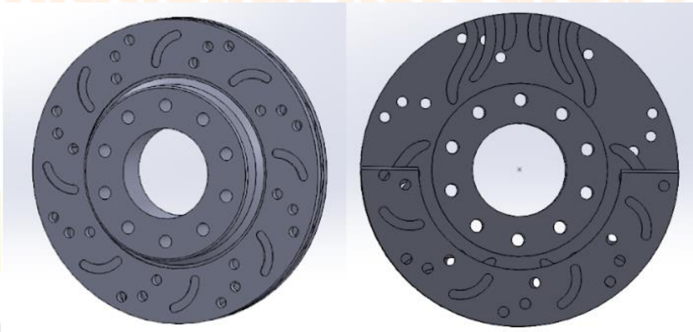

fig. 5 - section view of wave pillar disc brake

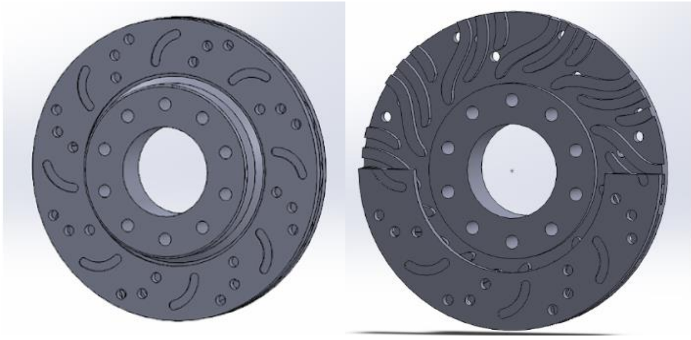

fig. 6 - section view of mirror wave pillar disc brake

5.3 GEOMETRY

For steady-state thermal analysis, CAD disc brake models are created in SolidWorks 2020 and loaded into Ansys Workbench. Two plates in direct contact make up the disc brake unit.

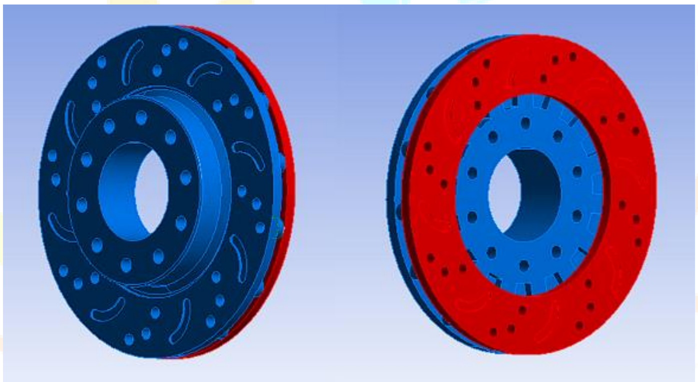

fig. 7 - components of disc brake

The hub plate (blue plate), which is different in each assembly, has a unique pillar design. As a result, the disc rotors have different masses. The mass property data for each pillar design and brake disc rotor material is provided in Table 1.

table 1 - mass of disc (in kg)

Material	Aluminium Alloy	Gray Cast Iron	Stainless Steel
Straight Pillar	1.12	2.91	3.13
Radial Pillar	1.13	2.93	3.16
Segmented Pillar	1.08	2.80	3.01
Wave Pillar	1.12	2.92	3.14
Mirror Wave Pillar	1.08	2.82	3.03

5.4 MESHING

The geometric model is divided into smaller sections called meshes, and each mesh represents a finite element. To achieve precise findings, we used fine meshing on the model. Because the components in a finer mesh are smaller and can capture stress or temperature gradients across the model, fine meshing requires more time and memory than coarse meshing but produces results that are more accurate. An automated process creates the mesh. The number of nodes and elements are shown in Table 2, and the mesh size is shown in Table 3.

table 2 - number of nodes in each disc

Disc Type	No. of Nodes	No. of Elements
Straight Pillar	188462	107259
Radial Pillar	190896	111340
Segmented Pillar	170442	96154
Wave Pillar	151455	84714
Mirror Wave Pillar	162840	91225

table 3 - mesh sizing properties used

Sizing	
Use Advanced Size Function	Off
Relevance Center	Fine
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	High
Transition	Fast
Span Angle Center	Fine
Minimum Edge Length	4.549e-002 mm

5.5 BOUNDARY CONDITIONS

In Ansys Workbench 16.0's steady-state thermal module, the initial and boundary conditions for thermal analysis are added. The regions where the boundary conditions are used are depicted in Figure 8 below. The findings of the analysis are determined by the boundary conditions. All designs and materials employ the same boundary conditions. The disc's initial temperature is assumed to be 22°C.

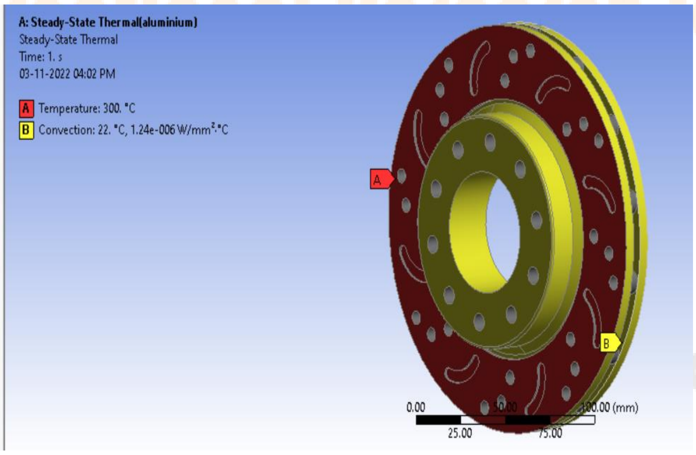

fig. 8 - boundary condition application area

table 4 - step control

Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled

The analysis's step controls are displayed in Table 4. The disc is predicted to reach a maximum temperature of 300°C. Since the geometrical surface is exposed to the atmosphere for heat dissipation, the convection boundary condition is also applied there and stagnant air data is used for the film coefficient. [49]

VI. RESULTS AND DISCUSSION

6.1 Design-1 (Straight Pillars)

6.1.1 Aluminium Alloy

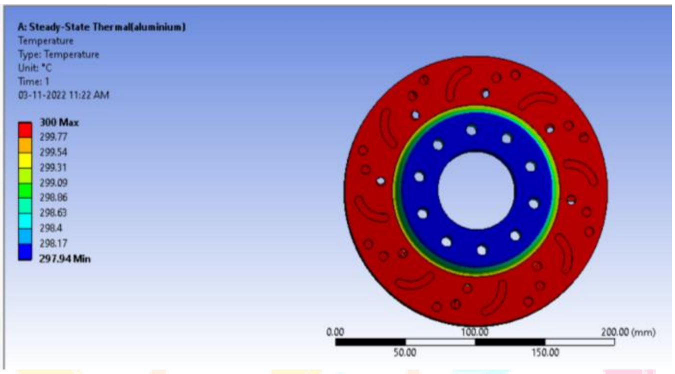

fig. 9 - temperature distribution

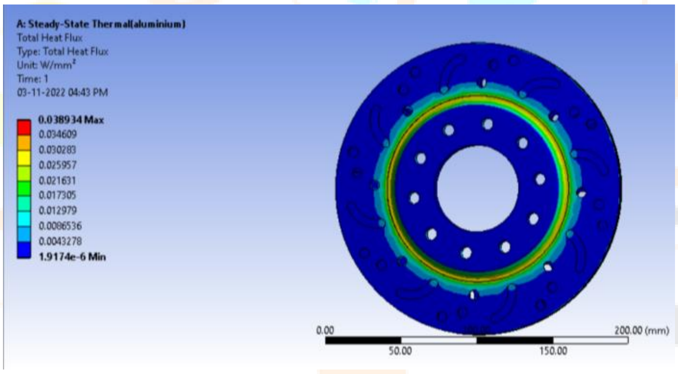

fig. 10 - total heat flux

6.1.2 Gray Cast Iron

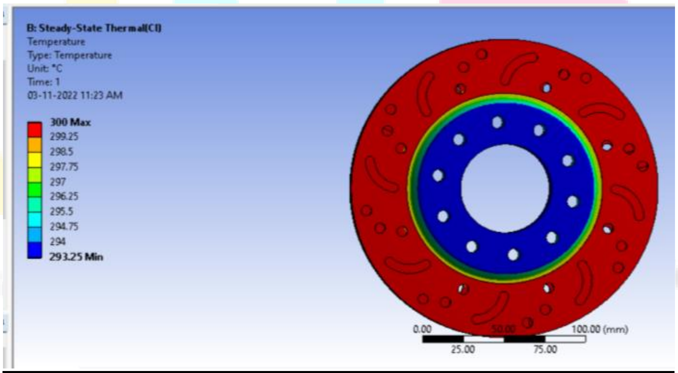

fig. 11 - temperature distribution

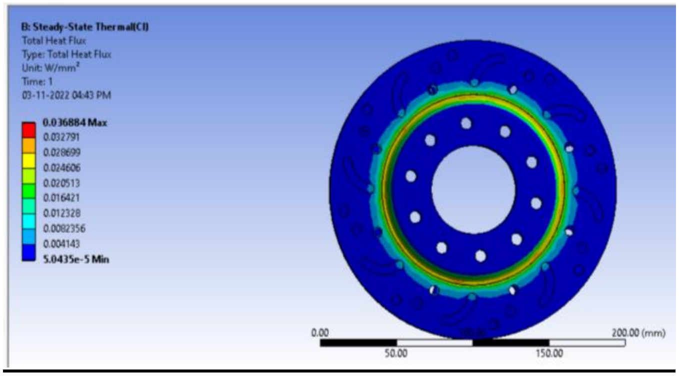

fig. 12 - total heat flux

6.1.3 Stainless Steel

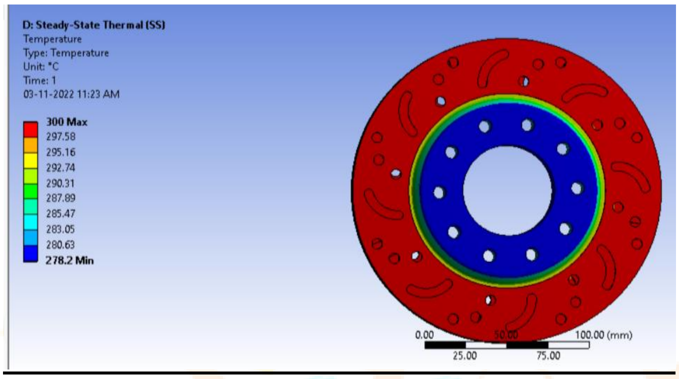

fig. 13 - temperature distribution

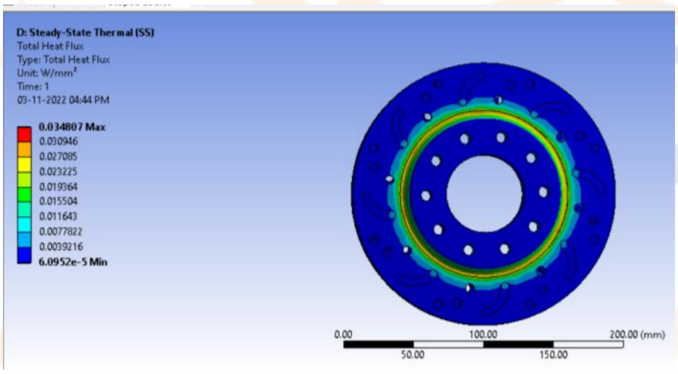

fig. 14 - total heat flux

6.2 Design-2 (Radial Pillars)

6.2.1 Aluminium Alloy

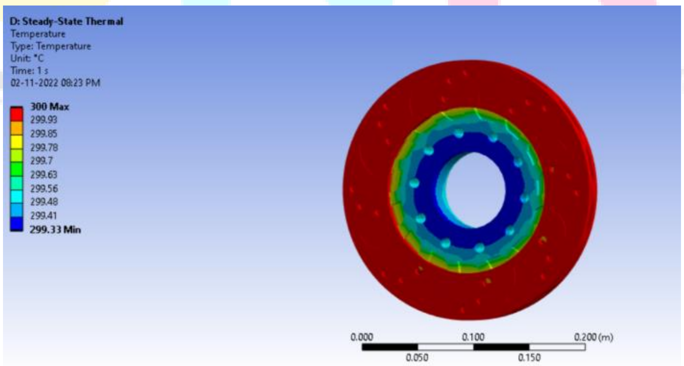

fig. 15 - temperature distribution

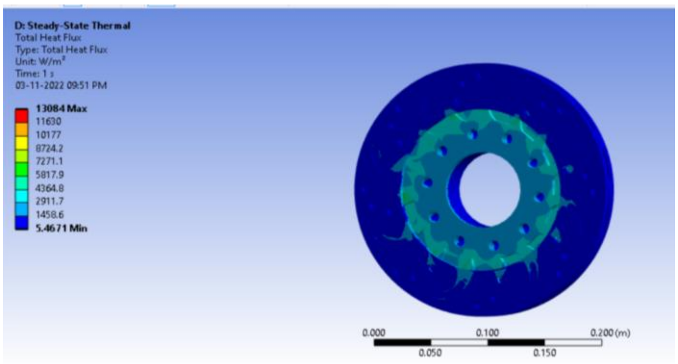

fig. 16 - total heat flux

6.2.2 Gray Cast Iron

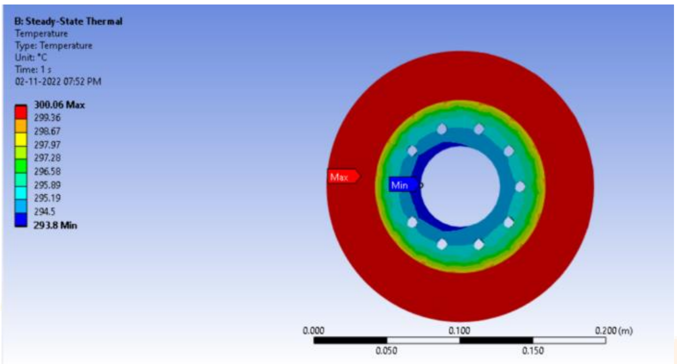

fig. 17 - temperature distribution

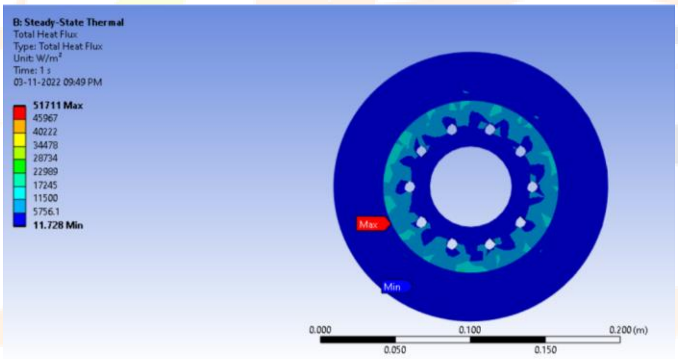

fig. 18 - total heat flux

6.2.3 Stainless Steel

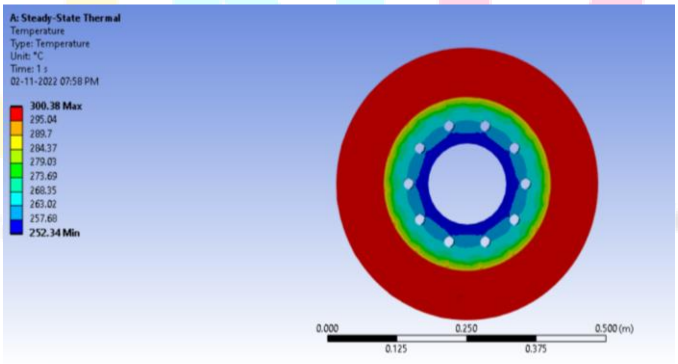

fig. 19 - temperature distribution

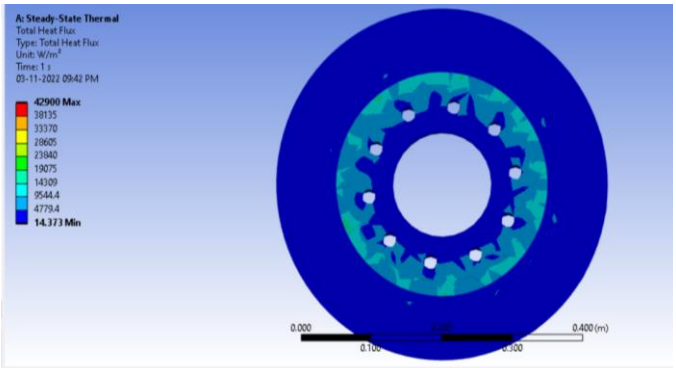

fig. 20 - total heat flux

6.3 Design-3 (Segmented Pillars)

6.3.1 Aluminium Alloy

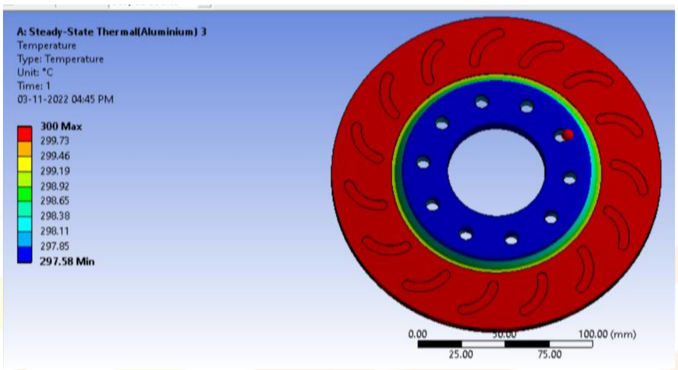

fig. 21 - temperature distribution

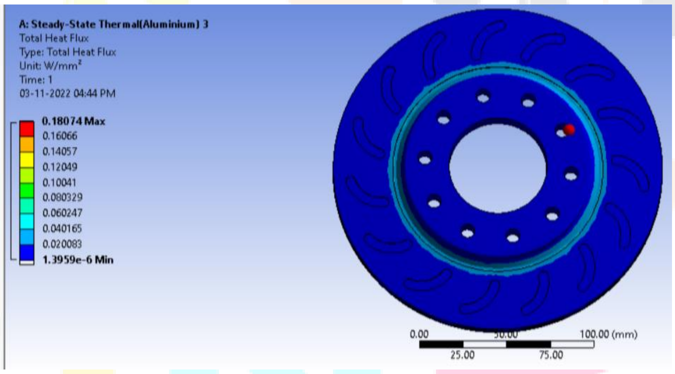

fig. 22 - total heat flux

6.3.2 Gray Cast Iron

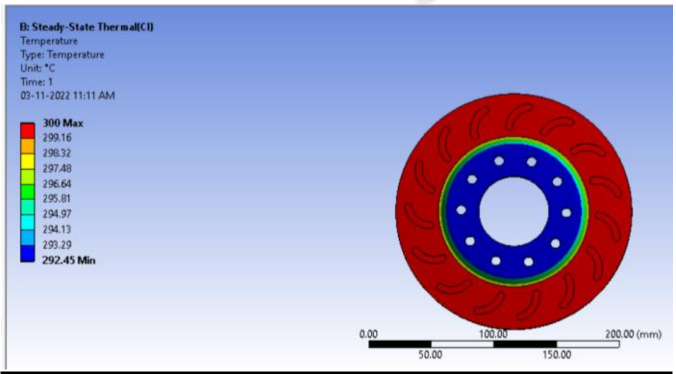

fig. 23 - temperature distribution

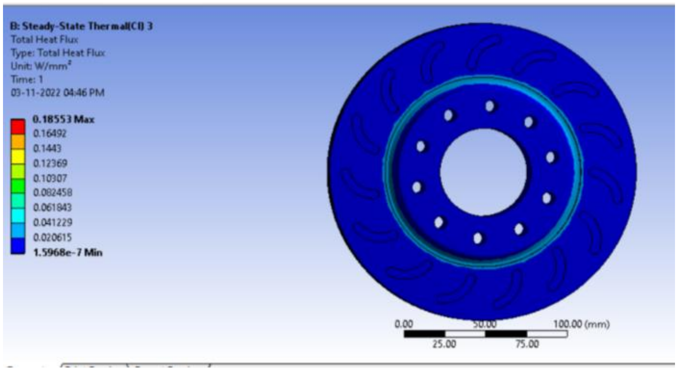

fig. 24 - total heat flux

6.3.3 Stainless Steel

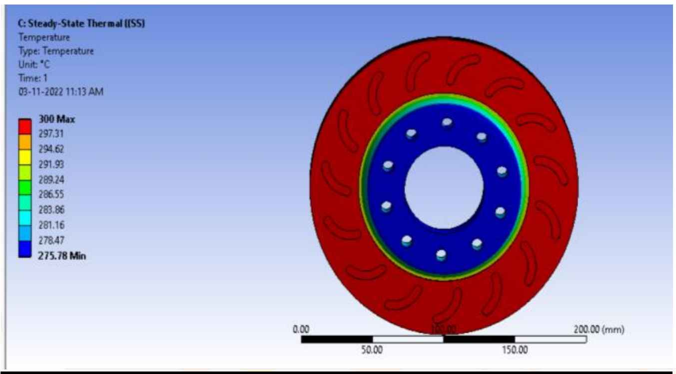

fig. 25 - temperature distribution

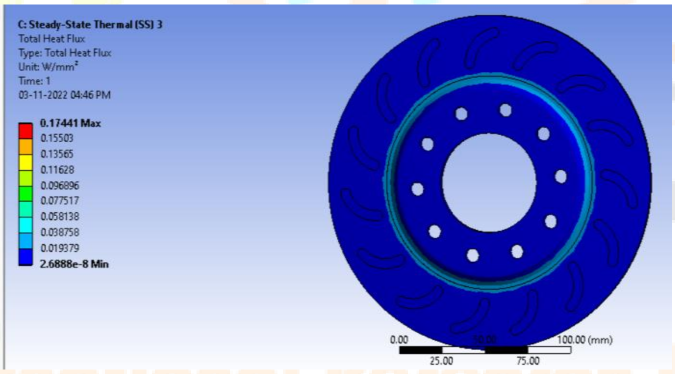

fig. 26 - total heat flux

6.4 Design-4 (Wave)

6.4.1 Aluminium Alloy

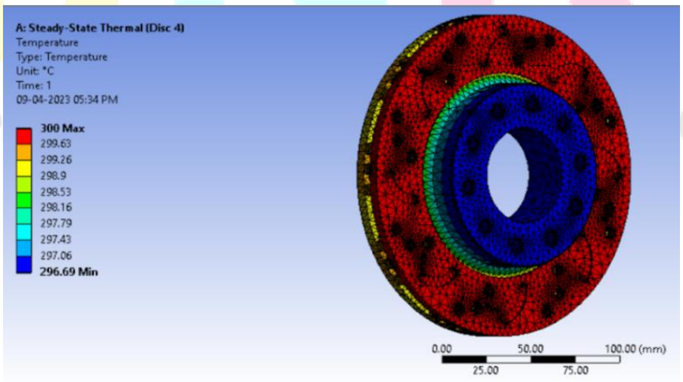

fig. 27 - temperature distribution

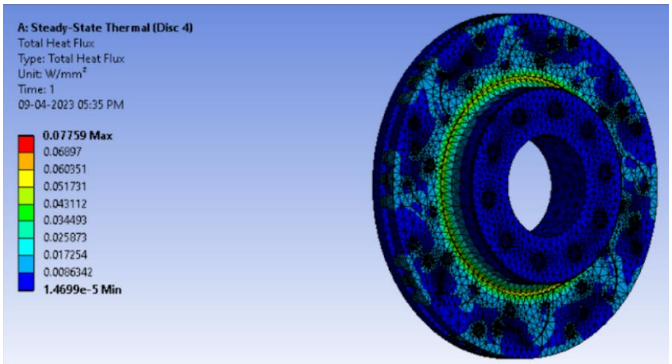

fig. 28 - total heat flux

6.4.2 Gray Cast Iron

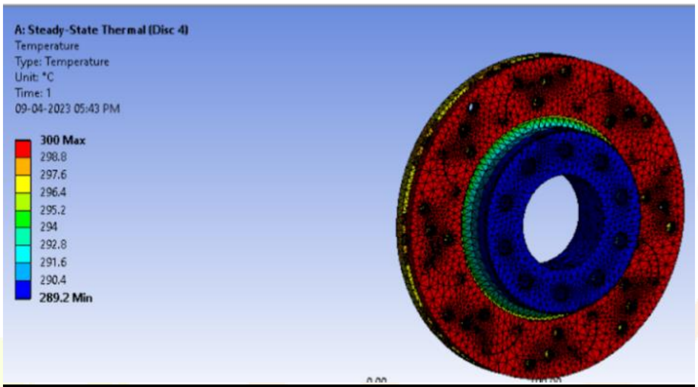

fig. 29 - temperature distribution

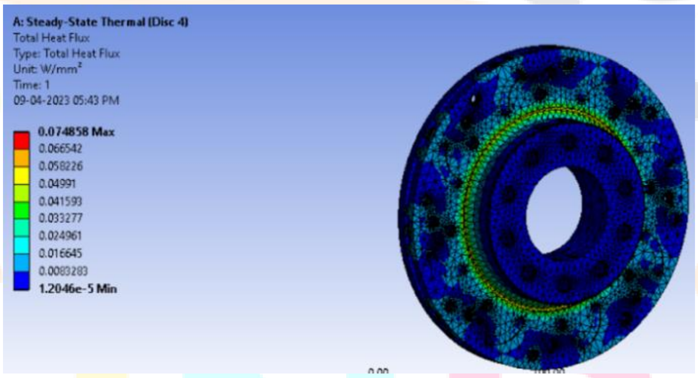

fig. 30 - total heat flux

6.4.3 Stainless Steel

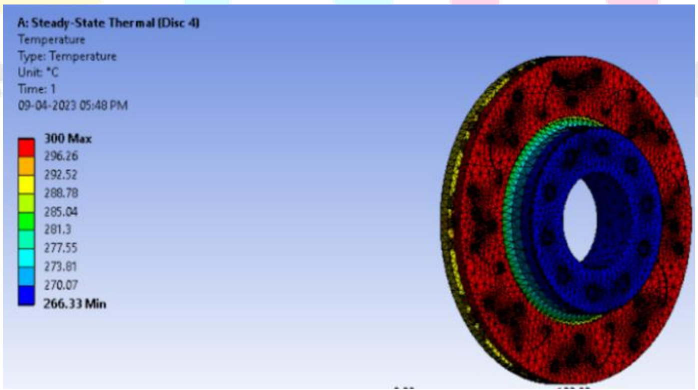

fig. 31 - temperature distribution

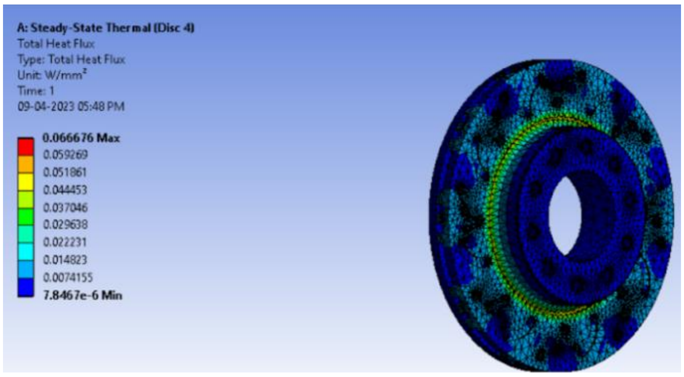

fig. 32 - total heat flux

6.5 Design-5 (Mirror Wave)

6.5.1 Aluminium Alloy

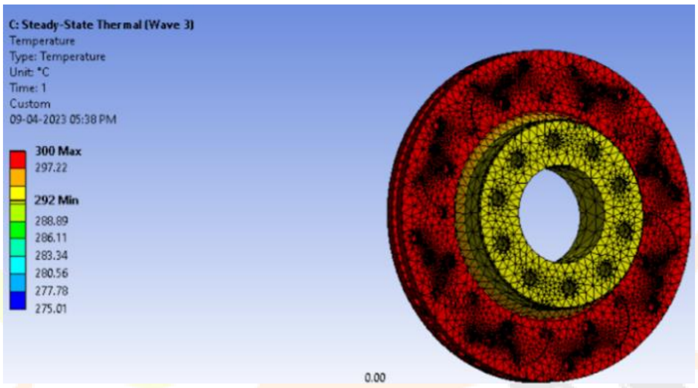

fig. 33 - temperature distribution

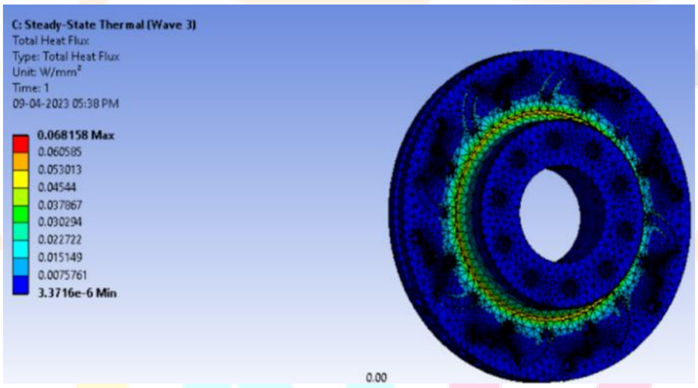

fig. 34 - total heat flux

6.5.2 Gray Cast Iron

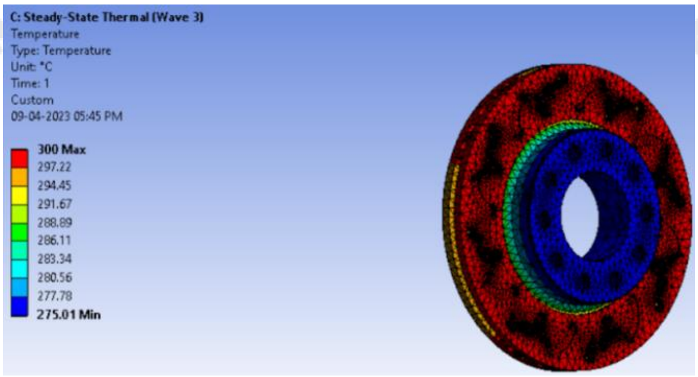

fig. 35 - temperature distribution

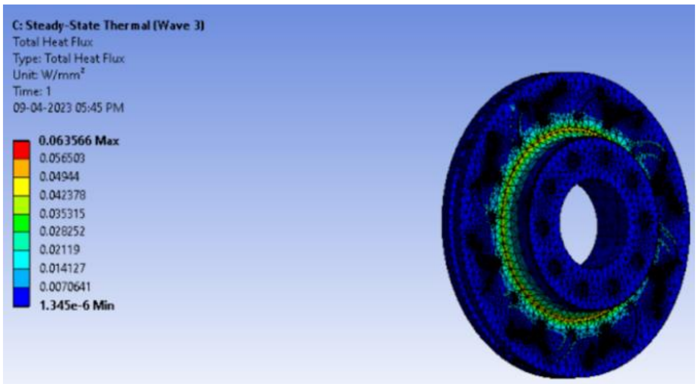

fig. 36 - total heat flux

6.5.3 Stainless Steel

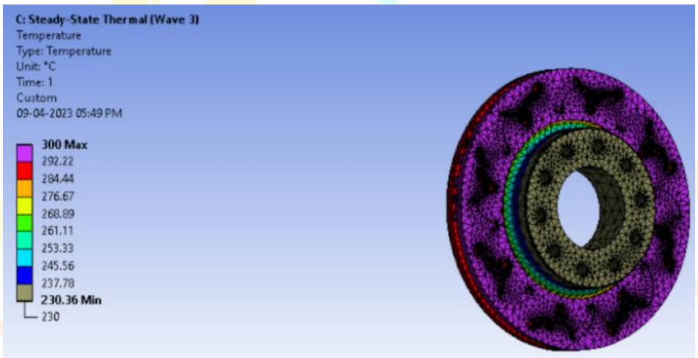

fig. 37 - temperature distribution

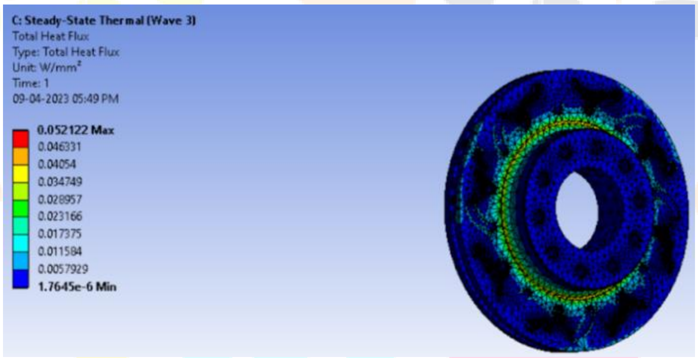

fig. 38 - total heat flux

table 5 - analysis results of temperature and heat flux

Disc Type	Material	Min. Temperature	Heat Flux (W/mm2)	
		(°C)	Min	Max
Straight Pillar	Aluminium Alloy	297.94	1.92E-06	0.038934
	Gray Cast Iron	293.25	5.04E-05	0.036884
	Stainless Steel	278.2	6.10E-05	0.034807
Radial Pillar	Aluminium Alloy	252.34	0.54E-05	0.013084
	Gray Cast Iron	293.8	1.17E-05	0.051711
	Stainless Steel	299.33	1.43E-05	0.042900
Segmented Pillar	Aluminium Alloy	297.58	1.40E-06	0.18074
	Gray Cast Iron	292.45	1.60E-07	0.18553
	Stainless Steel	275.78	2.69E-08	0.17441
Wave Pillar	Aluminium Alloy	296.69	1.46E-05	0.07759
	Gray Cast Iron	289.2	1.20E-05	0.074858
	Stainless Steel	266.33	7.84E-05	0.066676
Mirror Wave Pillar	Aluminium Alloy	275.01	3.37E-05	0.068158
	Gray Cast Iron	275.01	1.34E-06	0.063566
	Stainless Steel	230.36	1.76E-06	0.052122

The study involved the use of computational-simulation tools to analyze and compare the designs and materials of ventilated disc brakes. As with any study that involves the use of simulation tools, there are several practical or operational issues that were considered:

1. Availability of computational resources: High-performance computing systems and software licenses are necessary for the use of simulation tools like Ansys. As a result, before beginning the investigation, the availability of these resources was taken into account.
2. Accuracy of simulation models: The validity of the findings depends heavily on the accuracy of the simulation models employed in the study. In order to verify that the simulation models utilized produce correct predictions, they were validated using experimental data.
3. Material characterization: The material properties of the brake materials used in the study were accurately characterized to ensure that the simulation accurately reflects the behavior of the materials.
4. Boundary conditions: To guarantee that the boundary conditions used in the simulation provide accurate results of an

actual working circumstances of the brake system, they were described carefully.

5. Careful interpretation of the data is necessary to make sure they are consistent with the physical behavior of the brake system and that they can be applied to practical design decisions.

VII. CONCLUSION

Table 5 displays the findings of the steady-state thermal analysis. Gray Cast Iron is the most common material used for manufacturing disc brakes. The mirror wave pillar design gives a temperature reduction of 25°C which is much more compared to the other designs wherein the temperature reduction is approximately 10°C for gray cast iron material. It is also discovered that the lowest temperature that will occur while braking in the mirror wave pillar design is 230.36°C for stainless steel material. Hence, the disc brake rotor with the mirror wave design has the greatest temperature reduction of approximately 70°C. It is also observed that the radial pillar performs better than the straight and segmented pillar. This is because the length of the pillars grows as they are constructed at an angle, increasing the surface area and helping in faster heat dissipation. The same principle is applied to wave and mirror wave designs. The vented disc of aluminum alloy with wave pillar design has the highest heat flux value (77590 W/m2), and the wave pillar design is also wherein the average heat flux for various materials is found to be at its highest. Heat dissipation will be greater due to the direct relationship between heat flux and the surface area available for heat transfer. It is also noted that for wave and mirror wave designs the heat dissipation is more compared to the other designs as the max value of heat flux is more. Stainless steel performed the best out of all the materials tested, achieving the lowest minimum temperature in the mirror wave pillar design (230.36°C). The two new designs show better temperature reduction and heat dissipation compared to the old designs.

VIII. FUTURE SCOPE

This research paper's goal is to determine how the choice of material and design affects the temperature distribution in a vented disc. Based on the thorough investigation done, we were able to compare the aforementioned designs and materials. We have not, however, conducted any additional investigation into any connected topics due to time and financial limitations. Future research could delve more deeply into the aerodynamics of the disc and examine how the airflow around it impacts its performance. There is also room to examine how changes in material, braking style, and disc design affect the disc's lifespan. This can also be used to suggest the best braking technique, which will benefit car owners by extending the life of the brake discs and benefit automakers by lowering owner maintenance costs.

IX. DECLARATION

9.1 Author contributions

All the authors participated equally in the analysis of the component.

9.2 Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

9.3 Availability of data and materials

The interested reader can contact the authors to access the analysis files.

9.4 Competing interests

The authors declare that they have no competing interests.

9.5 Acknowledgements

Not Applicable

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