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Numerical Investigation on Composite Fabricated Disc Brake Rotor

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ABSTRACT
Nowadays, manufacturers fight to develop flashy cars without compromising safety. The most important aspect of high-speed vehicles lies in their braking system. As a result, several types of research are being conducted to enhance the disc brake quality. Brake discs often use gray cast iron because of its high friction properties and low cost of production, despite its low level of corrosion and wear resistance. In order to solve this issue, several investigations are being undertaken on brake discs for different materials. A steady-state thermal analysis of a disc brake made of carbon-carbon composites and aluminum silicon carbide metal matrix composites has been carried out. The materials are selected to dissipate heat at a very rapid rate. For improving brake stability, optimization of heat transfer rate is a major issue. In this analysis, the temperature fields of the disc are evaluated for one second of braking time using a steady state thermal analysis. The front face of the model is heated to a temperature of 80 °C. A convection load between 22°C and 80°C is applied to the inner surface for 1 second. The whole FEA analysis of the rotor is carried out on ANSYS 2021 R1. From the analyses, it is found that the rotor made of carbon-carbon composite performs better than the aluminum-silicon carbide MMC fabricated rotor regarding some parameters like stress, strain, heat flux and so on. For instance, maximum stress developed in carbon-carbon composite rotor was 248.67 MPa, which is less than the AMC composite rotor's 287.07 MPa. Moreover, the heat fluxes generated in the carbon-carbon composite and aluminum-silicon carbide MMC rotor were 6.1×10^{-4} and 6.6×10^{-4} respectively. Hence, there is no dissidence that a carbon-carbon composite rotor is more suitable for braking application.

Keywords: Braking system, Heat transfer, Rotor analysis, ANSYS design modeler

1. Introduction

These days, personal mobility is crucial. Cars are becoming more accessible, efficient, and secure thanks to innovation. Modern, lighter vehicles are taking the place of big, heavy ones. Energy and material output must be increased when resources become more limited. Safety components should be enhanced without increasing bulk or cost. Braking systems are essential for auto safety. The car's brakes stop or slow it down. Both disc and drum brakes are offered. Disc brakes exist in a variety of designs. It often operates hydraulically. Friction is created when calipers squeeze pads up against a disc or rotor. As a result, automobiles slow down. Stronger brakes are needed when vehicle speed increases. Brakes must be made lighter and more efficient by manufacturers. The choice of materials is crucial.

Composite materials are macroscopic combinations of constituent parts that maintain their properties. In comparison to alloys or single components, certain composite materials are tougher and stronger. Composite materials improve the consistency, durability, and dependability of brakes. N. Adriaan created an in-vehicle brake system temperature model that can estimate the temperature of the brake system [1]. The Detection of the possibility of brake fluid evaporation is analyzed by Abu-Bakar et al. [2]. A. Belhocine et al. analyzed the thermal behavior of the complete and vented brake discs of vehicles using the computer code ANSYS. The temperature distribution model of the disc brake is utilized to determine all the variables and input parameters that influence the braking operation [3]. A FEM model was created by Y. Patil et al. for contact analysis. This article explains how to use general-purpose of finite element analysis tools to investigate equivalent (von-Mises) and thermal stresses at the disc-to-pad interface [4]. P. Chakrapani et al. outlined the mechanical properties of aluminum metal matrix composites [5]. M.J. Denholm discussed aluminum metal matrix composite rotors and drums [6]. Banakar et al. studied the mechanical properties of carbon fiber-reinforced epoxy resin composites. This experiment was conducted to collect property data for material specifications [7]. V.D. Prasada et al. investigated the properties of basalt fiber-reinforced polymer composite[8]. R.K. Kumaar et al. created a carbon fiber and epoxy resin-based brake rotor. In addition, this article explains the model's finite element analysis [9]. Using time-dependent equations, H. Mazidi et al. established a mathematical model to quantitatively address the heat conduction challenges associated with disc brake components (Pad and Rotor) [10]. V.M.M. Tilak et al. aimed to create a hybrid composite material with improved Young's modulus, yield strength, and density while being lighter than cast iron. The results of a transient thermal elastic analysis of disc brakes were compared [11]. Using both transient and complex modal analysis, H. Xing built and evaluated a disc braking system for a passenger automobile. Natural frequencies are determined via complex modal analysis [12]. F. Talati et al investigated the disk's controlling heat equations as transient heat equations with time- and space-dependent heat production [13]. S.P. Jung et al. investigated a fundamental finite element model consisting of a disc and two pads. The TEI phenomenon was demonstrated by rotating the disc at a steady speed of 1,400 revolutions per minute [14]. K. Calzada et al. have utilized both experimental and computational modeling approaches. The analysis of fibers oriented at 0, 45, 90, and 135 degrees relative to the direction of tool motion yields various failure hypotheses for each orientation [15].

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K.M. Ghauri et al. described the SiC/Al composite that is produced by reinforcing several SiC compositions [16]. The purpose of P. Grze's study was to investigate the temperature fields generated by a solid disc brake during emergency braking [17]. H. Jawahar analyzed the steady-state behavior of a grey cast iron F12801 disc brake rotor [18]. V. Thiruvengadam analyzed the temperature distribution in a composite disc brake rotor. He accomplished this by employing steady-state thermal analysis [19]. R.R. Pind et al. investigated thermocoupled disc brakes [20].

The principal objectives of this numerical study are to investigate the temperature of different thermocoupled disc brakes comprised of carbon-carbon composite and aluminum silicon carbide MMC. The stress and strain of thermo coupled disc brakes will also be investigated.

2. Materials

Disc brakes are often constructed from grey cast iron or stainless steel. They are widely used due to their low cost and outstanding mechanical properties. Carbon-carbon composites and aluminum metal matrix composites are more suitable for high thermal conductivity and low weight.

Table 1 Significant Property of the Composites

Property	Carbon-Carbon Composites	Aluminum Silicon Carbide Composites
Elasticity, GPa	125	192
Poisson Ratio	0.25	0.25
Density, kg/m^3	7100	3000
Conductivity, W/mK	54.5	160
Specific Heat, J/gK	586	0.74

Carbon-carbon composite: Carbon-carbon composites consist of carbon fiber encased inside a carbon matrix. It has the maximum heat conductivity of any comparable material, is very durable, and is stiffer than aluminum. It is extremely fatigue resistant. Additionally, it has a broad range of CTE. Carbon fiber is preferred over other materials due to its low thermal expansion in situations where minor movements might be harmful.

Aluminum Silicon Carbide MMC: The matrix phase of aluminum metal matrix composites (AMC) is an aluminum alloy, whereas the reinforcement is integrated into this matrix. Aluminum Silicon Carbide MMC is a composite material made of a matrix of aluminum with particles of silicon carbide. The type and volume fractions of the component phases dictate the characteristics of AMC. For automotive applications, a vast number of manufacturers choose them. They are lightweight and possess high heat conductivity.

3. Numerical modelling

This investigation focused on a single circular disc brake. ANSYS design modeler was used to create the CAD model. The units used were millimeters.

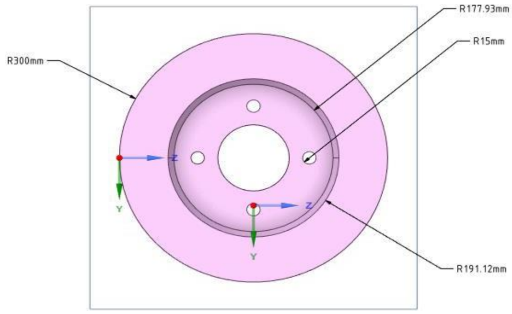
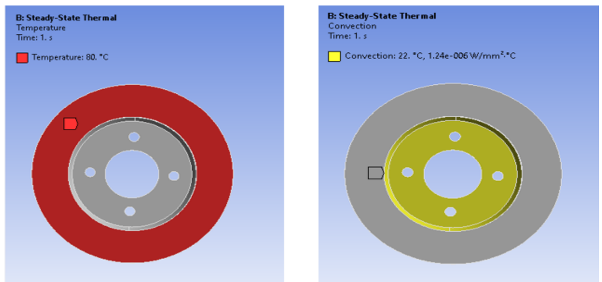


Fig.1 Geometry of disc brake

When the profile is rotated around its horizontal axis, a disc-shaped structure appears. The brake pads make contact with the outer disc surface in order to slow the vehicle. The outside section of the disc has a 300 mm radius. The total surface area is calculated. Four holes were bored into the inner disc in order to connect it to the wheel hub and allow it to rotate with the wheel.



(a) (b)

Fig.2 The temperature load on the (a) front face (b) inner face

The convectional heat load is applied to the model's inner faces in this case. The inner face is in direct contact with the surroundings. The convection coefficient of the film is temperature dependent in this case.

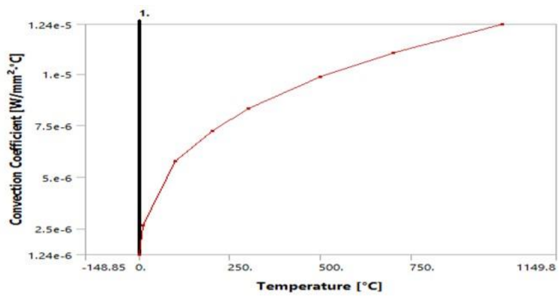


Fig.3 Convection coefficient vs. Temperature

This model was subjected to steady-state testing. When the brake pad and disc are applied, they generate heat. The rotor ingests heat. A portion of the rotor's heat is lost to the air. The rotor absorbs heat and must be cooled in order to preserve system equilibrium. Air convection dissipates heat from the pad-rotors. Also contributing to ambient heat is radiation. Previous studies showed that the transfer of radiated heat is minimal [21]. Radiation is therefore disregarded. Using a steady state and the physical characteristics of the materials, thermal calculations are performed, where initial temperature was 22 ^{0}C.

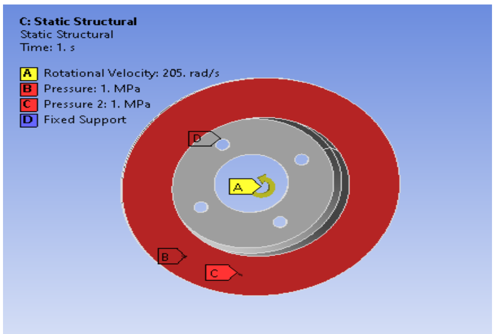


Fig.4 Boundary condition for static structural analysis

3. Results and Discussion

3.1 Mesh sensitivity test

Mesh sensitivity analysis is a critical step in numerical analysis. The primary goal of numerical analysis is to produce the most precise result in the least amount of time. Here, a varied number of meshing elements is placed on the model to test its sensitivity.

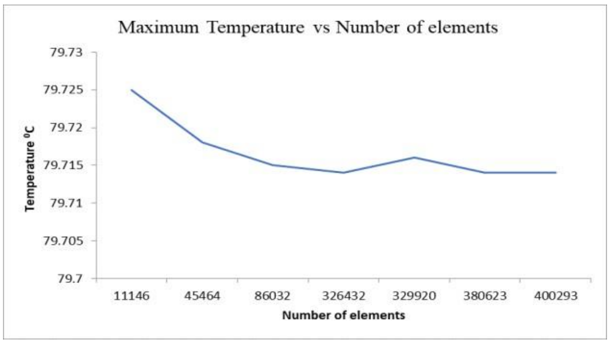


Fig.5 Maximum Temperature vs number of elements

As seen in the Fig.5, 11146 elements provide an imprecise result. From 11,000 to four million elements, precision increases. The findings for 326432 elements and 400293 elements are identical. Therefore, adding 400293 items will not accelerate processing. Therefore, 326432 is the ideal number of elements. We will examine this optimal element count.

3.2 Validation

To validate this analysis initially, analysis of V. Thiruvengadam for Carbon-Carbon composite was analyzed using ANSYS 2021 R1 and then the accuracy was determined by comparing with his data [19]. The temperature distribution in the cylindrical surface of the disk is given below

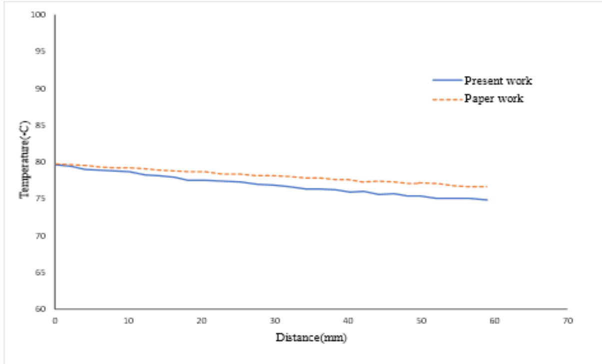
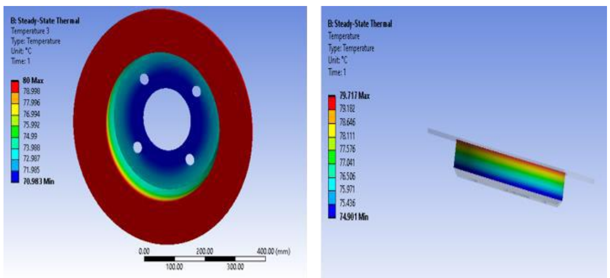


Fig.6 Comparative analysis of this simulation and reference result based on temperature against distance

From the inside to the outside, the temperature of the rotor hub rises. The inner hub of the rotor is heated, while the outer hub is cold. The outcome validates this. The variance seen between this simulation and the published findings is somewhere around 0% and 3%. This disparity is due to software limits. Our investigation was conducted using the student edition of ANSYS, which has fewer features than the previous version employed in the study.

4.3 Steady State thermal analysis

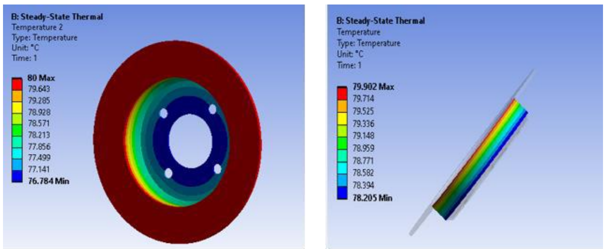
In this steady state thermal analysis of carbon-carbon composite, the starting temperature was determined by applying all boundary conditions. This investigation verified that that the outside portion of the rotor creates temperatures as high as 80℃, while the inner area produces temperatures as low as 70℃, which are below the melting point of the material. So the material is safe for this initial temperature analysis



(a) (b)

Fig.7 Analysis of Carbon-carbon composite (a) Initial (b) Final temperature

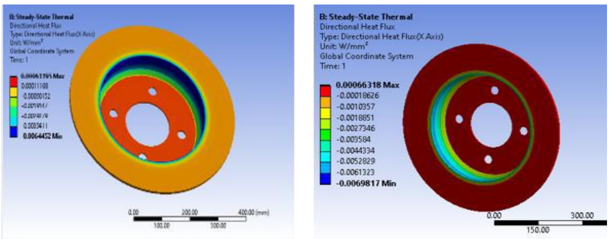
According to Fig.8 and Fig.9, the temperature flows from the inner side of the rotor hub to the outside side, hence the inner side has a higher temperature than the outer side. The heat flow is measured in direction x. The examination of directional heat flux provides information about the heat flux intensity on both the rotor and the rotor hub to prevent plastic deformation.



(a) (b)

Fig.8 Aluminum Silicon Carbide MMC (a) Initial (b) Final temperature

The surface which has contact with friction pad has highest temperature 80 ℃. On the other hand, the center surface has lowest temperature due to heat dissipation by convection



(a) (b)

Fig.9 Analysis for the directional heat flux for (a) Carbon-Carbon composite (b) Aluminum Silicon Carbide MMC

The heat flux is measured in the x direction. Due to conduction and convection highest directional highest heat flux is found in the inner surface in both materials. Highest heat flux of carbon-carbon composite is found 0.00061195 W/mm^{-2} which is less than the aluminum silicon carbide.

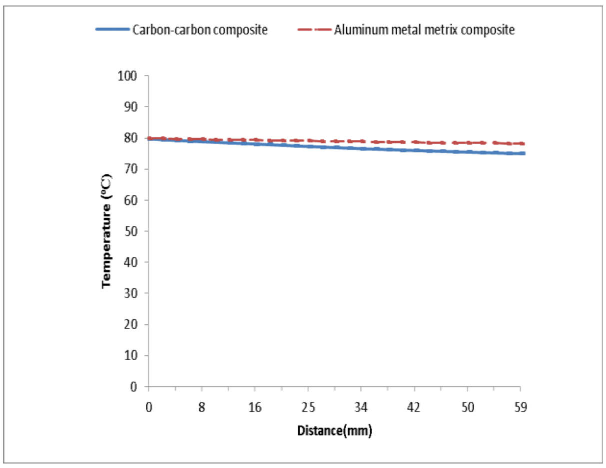
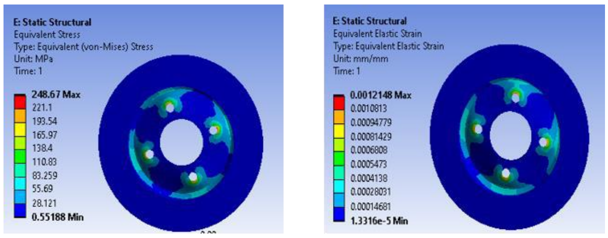


Fig.10 Temperature vs. Distance plot Carbon-carbon composite and AMC

From Fig.11 it is observed that temperature dissipated rapidly in carbon-carbon composite than Aluminum Silicon Carbide MMC. This is why as the distance from inner side of rotor hub increases the temperature decreases more in carbon-carbon composite.

3.3 Static structural analysis using Carbon-carbon composite

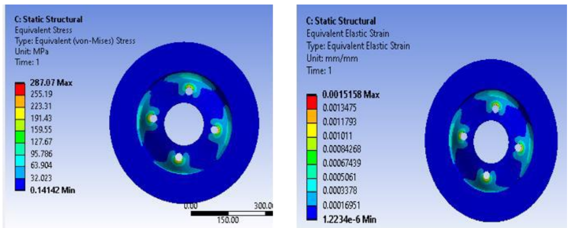


(a) (b)

Fig.11 Analysis for equivalent von-mises (a) stress (b) strain for Carbon-Carbon composite

The regions with the highest stress and strain are holes. Holes are stress concentrators. The maximum stresses are 248.67 MPa and strain is 0.0012148 mm/mm. Deformation is zero in the center and gradually increases toward the disc's periphery as a result of brake pads attaching and pushing on the disc.

3.4 Static Structural analysis using Aluminum Silicon Carbide MMC:



(a) (b)

Fig.12 Analysis for equivalent von-mises (a) stress (b) strain for Aluminium silicon carbide

Maximum stress and strain is respectively 287.07 MPa and 0.0015158 mm/mm which are both in hole region. Maximum deformation is found 0.21598 mm in outer edge.

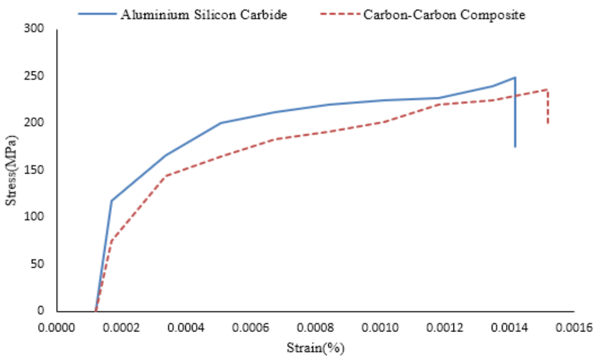


Fig.13 Stress vs. Strain

From this Fig.13 it is evident that the carbon-carbon composite has more strength than the other material. Hence, it has longer service life.

3.5 Comparison between the materials

Table 2 Comparison between the composite rotor properties

Property	Carbon-Carbon Composites	Aluminum Silicon Carbide Composites
Maximum temperature, ^{0}C	79.72	79.90
Directional heat flux, W/mm^2	0.00061195	0.00066318
Maximum stress, MPa	248.67	287.07
Maximum strain, mm/mm	0.0012148	0.0015158
Deformation, mm	0.210745	0.21598

Using a variety of mesh element sizes, the mesh dependence of this study has been evaluated, and it has been determined that this analysis is mesh independent. Carbon-carbon composite and Aluminum Silicon Carbide MMC were then subjected to steady-state thermal analysis. Initially, the temperature distribution on the cylinder's surface was analyzed. The temperature of carbon-carbon composites was discovered to be lower than that of aluminum-silicon carbide MMC. Carbon-carbon composite has an innermost section temperature of 74.091^{0}C, which is lower than Aluminum Silicon Carbide MMC (78.205^{0}C). Carbon-carbon composites create a maximum temperature of 79.717^{0}C. This material is better than Aluminum Silicon Carbide MMC (79.902^{0}C). In a similar fashion, the heat flux created by carbon-carbon composite is lower than that of Aluminum Silicon Carbide MMC. Then, structural static analysis was performed. At the hole regions, the highest levels of tension are seen. This arises because to the high stress concentration in hole locations. The carbon-carbon composite has a maximum stress of 248.67 MPa, which is less than the Aluminum Silicon Carbide MMC's 287.07 Mpa. As force is applied, the brake pad and brake disc contact area experience the most deformation. The maximum deformation of carbon- carbon composite is 0.0012148 mm, which is smaller than Aluminum Silicon Carbide MMC.

4. Conclusion

Brake disc made of aluminum silicon carbide-based metal matrix composite and carbon-carbon composite were subjected to both steady state thermal analysis and static structural analysis in this present study.
The outcomes of this analysis lead to the following inferences:

- The temperature and heat flux generated on the cylindrical surface of a carbon-carbon composite disc brake are lower than those of an aluminum metal matrix composite.
- Carbon-carbon composite-based brake disc create less deformation, stress, and strain than aluminum metal matrix composites.
- By comparing these, it can be concluded that rotor disc made of carbon-carbon composite is way better in bearing both thermal and structural loads as compared to the aluminum metal matrix composite.

However, there are a number of reasons why composite disk brakes are hard to implement in everyday automobiles. First of all, due to the high cost of high performance brakes, there is little demand for them. Since typical cars aren't driven at high speeds, less heat is produced by low friction. In turn, this makes the composite brakes significantly weaker and less effective, especially in colder weather. This weakness is caused by the composite's and matrix's thermal expansion. The material expands at various rates at different temperatures, which can lead to cracking on the brakes' surface. Recycling carbon fiber might be the answer to these problems. It would gradually decrease the cost of production of carbon-carbon composite rotors as well as cars. Moreover, some research has concluded that presence of PEI and PC in the carbon fiber reinforced composites can prevent the formation of micro-cracks. As a result, it is clear that a carbon-carbon composite rotor has a high potential in the near future if its drawbacks can be overcome.

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NOMENCLATURE

C_p	: specific heat at constant pressure, kJ・kg^{-1}・K^{-1}
H	: Hydraulic diameter, m
h	: Heat transfer coefficient, W/m^{2}·K
p	: pressure, kPa
T	: temperature, K
t	: Celsius temperature, ^{o}C
V	: volume, m^{3}