Thermal analysis of brake disc of an automobile

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Abstract One of the most effective protective features of modern vehicles is the braking system. The brake absorbs kinetic energy of the rotating parts (Wheels) and dissipates this energy into the surrounding atmosphere in the form of heat energy. Disc brake is the recent trend in automobile which dissipates the heat faster than the conventional brakes but if hard braking is done, thermal stresses in the brake disc are induced, leading to excessive heat generation, which further produces distortion and thermal cracking of the disc leading to disc failure. The main objective of this work is to compare four different materials viz. Aluminium Alloy, Ceramics, Grey Cast Iron and Titanium Alloy for disc brake and to identify the most suitable material for brake disc. The model of disc was prepared using the dimensions of an existing Maruti car and its transient state analysis is done using SOLIDWORKS. After the analysis the value of heat flux distribution and von-Mises stress for the selected profile was 1.577e+05 W/m² and 7.920e+09 N/mm² for Aluminium alloy, 4.358e+05 W/m² and 9.806e+09 N/mm² for Ceramics, 9.747e+05 W/m² and 1.218e+10 N/mm² for Grey Cast Iron and 9.224e+05 W/m² and 8.292e+09 N/mm² for Titanium alloy. It was noted that the heat flux dissipation is more and von-Mises stress is less for the Grey Cast Iron and it is suitable for the manufacturing purpose.

Keywords: Brake disc, Material Selection, Solidworks, Finite Element Method, Numerical Analysis.

1. Introduction The most essential protective features of motor vehicles are brakes. Brakes are designed to slow and stop the wheel’s rotation. Braking pads on both surfaces are mechanically driven against the rotor or disc to avoid the movement of the wheel. They are necessary for all vehicles to work securely.

In short, brakes transform the car’s kinetic energy into heat energy, thus slowing its velocity. Brake fade is the decrease in stopping power that can occur, generally in high load or high-speed conditions, after repeated or continuous brake application. Heat build-up, subsequent changes and
reactions in the components of brake system cause brake fade and can be encountered in drum brakes and disc brakes. Via appropriate equipment, material design and selection, as well as good cooling, these fades can be minimised to a greater extent.

Disc brake is a type of brake that uses callipers to force the stationary pads to secure the spinning disc by causing friction. The mechanism of the disc brake is to delay or stop the motion or revolution of the wheels. When the interruption is over, the vehicle’s kinetic energy is converted into heat energy, which is then dissipated into the surrounding atmosphere in the form of heat.

There is an increase in temperature due to the formation of frictional heat on the disc and pad interface, resulting in brake failure, premature wear and vaporisation of the brake fluid and failure of the bearing when the temperature reaches the critical value of the material in question. This form of fault has a major effect on braking performance. In today’s evolving and advanced automotive industry, disc brakes have holes or vents which increase heat dissipation from the rotor by increasing the surface area available for heat transfer. At a high rotational speed, these holes or vents often provide higher airflow. Some of the authors have done their job in the past to improve the efficiency of the disc brake in terms of heat dissipation and dissipation of heat. Lee and Yee et al \cite{1} noticed that the varying temperature distribution on the frictional pad surface induces thermal distortion generally known as coning, and this is responsible for the effect of judder and the variation in disc thickness. Mesut Duzgun et al \cite{2} investigated the thermal characteristic of ventilated brake discs and cross-slotted with side groove disc rotor was found to be superior than cross drilled and cross-slotted disc rotors. With ventilation applications, heat generation on solid brake discs of grey cast iron material has reduced to a maximum of 24%. However, thermal stress formations were higher with ventilated brake discs when compared to those with solid discs. Saiz et al \cite{3} investigated the thermo-mechanical behaviour of different brake rotors under extreme working condition i.e., a very hard (fading) test to evaluate the temperature distribution, stresses and strains. The disc rotor of curved-vanes was considered to be the best solution. Limpert et al \cite{4} performed experiments on disc brakes and concluded that the radiation contribution to total heat dissipation is less than 5% of the total heat dissipation under standard braking conditions, while the radiation contribution rises and becomes as much as 33% of the total heat transfer at a higher temperature. Koetniyom et al \cite{5} performed temperature analysis on brake discs under severe operating conditions and found that the physical shape of vehicle brake discs played an important role in determining the temperature characteristics, including the overall brake capacity. Belhocine et al \cite{6} used SOLIDWORKS simulation software for studying the thermal actions of the dry contact between the brake pad discs at the time of the braking operation. Temperature distribution was obtained by the transient thermal analysis. Sarkar et al \cite{7} investigated and examined the temperature distribution of the
rotor disc and used FEA analysis to measure the crucial temperature in the course of operation. The static thermal evaluation has been achieved on the disc rotor to assess and examine their overall performance, and the temperature distribution was analysed thinking about cooling parameters. Kammerdtong et al \cite{8} tried to relate the interaction between mechanical and thermal effects with disc motions and heat induced by friction and concluded that temperatures on the disc surface varied at each point over the time from finite element analysis, suggesting the uneven dissipation and variations in temperature on each side of the disc. Hence, inconsistent contact between disc and pad could affect material deformation. Telang A et al \cite{9} reported that, friction coefficient of AL-MMC is 25-30\% times more and its thermal conductivity is about two or three times higher as compared to that of cast iron. Also, an MMC disc could be 60\% lighter than an equivalent cast iron disc. M.A. Maleque et al \cite{10} developed the material selection method in-order to determine the optimum material for the brake disc system application using digital logic system. In this study, cast iron, Aluminium alloy, Titanium alloy, ceramics and composites were assessed for material performance specifications and alternative solutions. The critical attributes in the process were mechanical properties, including compressive strength, coefficient of friction, wear resistance, thermal conductivity, specific gravity and cost, and it demonstrates the composite aluminium metal matrix as the perfect candidate material for brake disc system. Venkatramanan et al \cite{11} investigated and analysed the temperature distribution of brake disc at some point of operation using SOLIDWORKS Simulation and finished the thermal evaluation, and additionally calculate the heat flux and temperature of the disc brake model. Hemraj Nimhal et al \cite{12} found that due to its mechanical and material characteristics, the use of non-vented disc made up of ceramic material can be seen to be the right material for future.

1.1 Research Gap

Most of the research is carried out using single disc profile with different materials but the parameters for analyses are generally less. The main aim of the work is, to investigate the thermal characteristics of the disc brake materials. Disc brakes are usually made up of cast iron or the composites of ceramics. In this numerical analysis the comparison of different materials of a disc brake such as Titanium alloys, Aluminium alloys, Ceramics, and Cast Iron with different parameters is studied.

2. Research Methodology

A problem in disc brake arises due to uneven stress and heat dissipation during braking; rusting, cracking, poor stopping, noise and vibrations, and they depend on the properties of materials which is used in the brake disc.

The models are prepared on SOLIDWORKS and analysed on SOLIDWORKS Simulation software for transient state thermal analysis for four different materials i.e. Titanium alloys, Aluminium alloys,
Ceramics, and Cast Iron using the Finite Element Method (FEM). The procedure involved in the transient thermal analysis consists of:

1. Design the model using SOLIDWORKS.
2. Obtaining the solution by initiating the initial boundary condition like initial temperature, heat flux, and generated heat power in SOLIDWORKS Simulation Software.
3. Reviewing the results.

3. Finite Element Method (FEM) A tool for the numerical solution of various engineering problem is the finite element analysis method. The main reason of auto meshing is to provide stable, easy-to-use meshing software that simplifies mesh generation. The model used must be divided into a number of small parts known as finite elements. FEM is more preferable because of:

   i.) Precise reflection of the complex geometry.
   ii.) Inclusion of property of dissimilar material.
   iii.) Easy representation of the solution.
   iv.) The capture of the specific impacts/effects.

   After meshing, the profile model gets discretized into small fragments which are called as nodes. Thus, the boundary conditions get applied to every node. All the profiles have meshed for the further investigation of the heat dissipation through the brake disc.

   Meshing details of the profile is as follows and is shown in figure 1.

   ![Meshing of profile](image)  

   **Figure 1:** Meshing of profile.
Table-I Meshing Details of Profile

| Sr. No. | Parameter            | Value          |
|---------|----------------------|----------------|
| 1.      | Total Nodes          | 16748          |
| 2.      | Total Elements       | 7624           |
| 3.      | Mesh Size            | 4 mm           |
| 4.      | Mesh Type            | Solid mesh     |
| 5.      | Maximum Aspect Ratio | 19.847         |

4. Design and Analysis

Disc brakes are usually made up of cast iron or the composites of ceramics. In this numerical analysis the comparison of different materials of a disc brake such as Titanium alloys, Aluminium alloys, Ceramics, and Cast Iron with different parameters is studied.

4.1 Specifications and Input Parameters for Disc Brake

The specifications, input parameters and material properties are defined correctly to study and analyse the performance of disc brakes and for the analysis, it is assumed that the wheels do not skid during working condition.

Table-II Input Parameters

| Sr. No. | Input                              | Values          |
|---------|------------------------------------|-----------------|
| 1.      | Diameter of Inner Disc             | 170 mm          |
| 2.      | Diameter of Outer Disc             | 340 mm          |
| 3.      | Hub Diameter                       | 68 mm           |
| 4.      | Hole Diameter                      | 8 mm            |
| 5.      | Disc Thickness                     | 5 mm            |
| 6.      | Mass of vehicle                    | 1250 kg         |
| 7.      | Maximum Velocity                   | 38.89 m/s       |
| 8.      | Coeff. of friction between rotor and pads (μbp) | 0.31 |
| 9.      | Coeff. of friction between rotor and pads (μrt) | 0.62 |
| 10.     | Deceleration of vehicle            | 6.076 m/s²      |
The table below lists the important properties of different materials which are to be taken into consideration while selecting the material.

### Table- III Properties of Materials

| Sr. No. | Features                  | Aluminium Alloy | Ceramics | Gray cast iron | Titanium Alloy |
|---------|---------------------------|------------------|----------|----------------|----------------|
| 1.      | Mass density (Kg/m3)      | 2700             | 2300     | 7200           | 4480           |
| 2.      | Poisson's ratio           | 0.33             | 0.22     | 0.27           | 0.31           |
| 3.      | Thermal conductivity (W/m- k) | 200             | 1.4949   | 45             | 7.8            |
| 4.      | Specific Heat (J/kg-K)    | 900              | 877.96   | 510            | 530            |

### 4.2 Calculations

Total force produced to stop the car while braking,

\[ F = m \times a \]

\[ a = \text{deceleration as a result of braking} = \mu rt \times g = 6.076 \text{m/s}^2 \]

\[ F = 1250 \times 6.076 = 7595 \text{ N.} \]

Torque required to stop the vehicle,

\[ T = F/4 \times Rw \]

\[ = 337.6 \text{ N-m.} \]

#### 4.2.1 Heat flux calculation for Aluminium alloy

Specific Heat Capacity (\( cp \)) = 897 J/kg °C

Heat generated \( Q = m \times cp \times \Delta T \)

\[ Q = 0.80 \times 897 \times 20 = 14352 \text{ J} \]

\[ Q = 14352/4=3588 \text{ Watt} \]

Area of Disc = \( \pi \times (R^2 - r^2) \)

\[ = \pi \times [(0.170)^2 - (0.085)^2] \]

\[ = 0.06805 \text{ m}^2 \]

Heat Flux = Heat Generated/area

\[ = 3588/0.06805 = 52725.93 \text{ W/m}^2 \]
4.2.2 Heat flux calculation for Ceramics

Specific Heat Capacity (\(c_p\)) = 850 J/kg °C
Heat generated \(Q = m \times c_p \times \Delta T\)
\[Q = 0.80 \times 850 \times 20 = 13600 \text{ J}\]
\[Q = 13600/4 = 3400 \text{ Watt}\]
Area of Disc = \(\pi (R^2 - r^2)\)
\[= \pi \times [(0.170)^2 - (0.085)^2]\]
\[= 0.06805 \text{ m}^2\]
Heat Flux = Heat Generated / area
\[= 3400/0.06805 = 2498.16 \text{ W/m}^2\]

4.2.3 Heat flux calculation for Grey Cast Iron

Specific Heat Capacity (\(c_p\)) = 447 J/kg °C
Heat generated \(Q = m \times c_p \times \Delta T\)
\[Q = 0.80 \times 447 \times 20 = 7152 \text{ J}\]
\[Q = 7152/4 = 1788 \text{ Watt}\]
Area of Disc = \(\pi (R^2 - r^2)\)
\[= \pi \times [(0.170)^2 - (0.085)^2]\]
\[= 0.06805 \text{ m}^2\]
Heat Flux = Heat Generated / area
\[= 1788/0.06805 = 29405.47 \text{ W/m}^2\]

4.2.4 Heat flux calculation for Titanium alloy

Specific Heat Capacity (\(c_p\)) = 634 J/kg °C
Heat generated \(Q = m \times c_p \times \Delta T\)
\[Q = 0.80 \times 634 \times 20 = 10144 \text{ J}\]
\[Q = 10144/4 = 2536 \text{ Watt}\]
Area of Disc = \(\pi (R^2 - r^2)\)
\[= \pi \times [(0.170)^2 - (0.085)^2]\]
\[= 0.06805 \text{ m}^2\]
Heat Flux = Heat Generated / area
\[= 2536/0.06805 = 37266.71 \text{ W/m}^2\]
5. Result and Discussion

Finite element analysis is performed on disc brake for four different materials such as Aluminium alloy, Ceramics, Grey Cast Iron and Titanium alloy. Analysis illustrates the heat flux distribution, von misses stress and temperature distribution on brake disc for four different materials, and the comparison of all the materials on the basis of above parameters. All the work is classified under following cases:

5.1 Analysis Result

All the work of analysis is classified under following cases:

Case 1: Heat flux and stress generated for Aluminium alloy.
Case 2: Heat flux and stress generated for Ceramics.
Case 3: Heat flux and stress generated for Grey Cast Iron.
Case 4: Heat flux and stress generated for Titanium alloy.
Case 5: Comparison for heat flux and stress generated for all the materials.

5.1.1 Heat flux and stress generated for Aluminium alloy.

The figure 2 shows the transient state thermal analysis and figure 3 shows the static analysis of disc brake made up of Aluminium alloy material where the maximum heat flux distribution is $1.577 \times 10^5$ W/m² and the maximum value of von-Mises stress induced is $7.92 \times 10^9$ N/mm². Figure 4 shows the variation of heat flux and stress with respect to time. During the analysis the maximum temperature produced on the brake disc corresponds to 291.4 °C.

![Figure 2: Heat flux for Aluminium Alloy.](image1)
![Figure 3: Stress generated for Aluminium Alloy.](image2)
5.1.2 Heat flux and stress generated for Ceramics. The figure 5 shows the transient state thermal analysis and figure 6 shows the static analysis of disc brake made up of Ceramic material where the maximum heat flux distribution is $4.358 \times 10^5$ W/m² and the maximum value of von-Mises stress induced is $9.806 \times 10^9$ N/mm². Figure 7 shows the variation of heat flux and stress with respect to time. During the analysis the maximum temperature produced on the brake disc corresponds to 476.8 °C.
5.1.3 Heat flux and stress generated for Grey Cast Iron. The figure 8 shows the transient state thermal analysis and figure 9 shows the static analysis of disc brake made up of Grey Cast Iron material where the maximum heat flux distribution is $9.747 \times 10^5$ W/m² and the maximum value of von-Mises stress induced is $1.218 \times 10^9$ N/mm². Figure 10 shows the variation of heat flux and stress with respect to time. During the analysis the maximum temperature produced on the brake disc corresponds to 320.2 °C.
5.1.4 Heat flux and stress generated for Titanium alloy. The figure 11 shows the transient state thermal analysis and figure 12 shows the static analysis of disc brake made up of Titanium alloy material where the maximum heat flux distribution is $9.224 \times 10^5$ W/m$^2$ and the maximum value of von-Mises stress induced is $8.292 \times 10^9$ N/mm$^2$. Figure 13 shows the variation of heat flux and stress with respect to time. During the analysis the maximum temperature produced on the brake disc corresponds to 474.7 °C.

![Figure 11: Heat Flux for titanium alloy.](image1)

![Figure 12: Stress Generated for titanium alloy.](image2)

![Figure 13: Variation of heat flux and stress vs time.](image3)

5.1.5 Comparison for heat flux and stress generated for all the materials. In this case comparison between all the materials is being made on the basis of their maximum heat flux, von-Mises stress and maximum temperature generation. Figure 14 shows maximum heat flux for materials and it is observed that the maximum heat flux is obtained for Grey Cast Iron which is $9.747 \times 10^5$ W/m$^2$. Figure 15 represents the von-Mises stress for materials and it is seen that the maximum stress is induced in ceramics which is $9.806 \times 10^9$ N/mm$^2$ and the minimum stress is induced in Grey Cast Iron which is $1.218 \times 10^8$ N/mm$^2$. Figure 16 shows the maximum temperature produced in brake disc and it is observed that the maximum temperature is produced in Ceramics which is 476.8 °C.
Conclusion From all the values recorded in analysis following conclusions are drawn:

1. Aluminium alloy has the maximum temperature of about 291.4 °C which is least as evaluated and compared in case of other materials. Also, the rate of heat dissipation is least for Aluminium alloy as compared to other materials and hence it is not a suitable material for brake disc.

2. Ceramics have minimum weight among other materials and the maximum temperature noted is about 476.8 °C which is highest as evaluated and compared in case of other materials but the rate of heat dissipation is low as compared to Grey cast Iron and Titanium alloy. Also, the stress induced in ceramics which is $9.806 \times 10^9$ N/mm$^2$ is maximum as compared to other materials. Hence, it is not a suitable material for brake disc.

3. Titanium alloy has maximum temperature of 474.7 °C which is more as compared to that of Aluminium alloy and Grey Cast Iron and it also has a maximum heat dissipation of $9.224 \times 10^5$ W/m$^2$ which is better as evaluated and compared in case of Aluminium alloy and ceramics. However, the induced stress in Titanium alloy is also very high and hence, it is not a suitable material for brake disc.

4. It was observed that the value of von-Mises stress induced in Grey Cast Iron is $1.218 \times 10^8$ N/mm$^2$ and is least among all the materials and hence it is a suitable material for brake disc in terms of induced stress.
5. Grey Cast Iron has maximum heat dissipation of $9.747 \times 10^5 \text{ W/m}^2$, which is highest as evaluated and compared in case of other materials and hence it is a suitable material for brake disc in terms of rate of heat dissipation.

Since, the rate of heat dissipation is maximum for Grey Cast Iron and the value of induced von-Mises stress is minimum for Grey Cast Iron. So, it is the most suitable material for manufacturing of brake disc.

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