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Design, Analysis and Manufacturing of Disc Brake Rotor

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Abstract:- A Brake is a mechanical device which is used to slowing or stopping a moving object or preventing its motion. Present work deals with structural and thermal analysis of disc brake rotor of a vehicle. Heat generation and dissipation of disc brake rotor is analysed. Further analysis is carried out to check heat flux and temperature distribution by changing thickness and material. Two thicknesses 5mm and 6mm and two materials namely Stainless Steel and Gray Cast Iron are considered for analysis in the present work. CATIA V5R20 is used for the design and ANSYS 15.0 is used for the analysis of disc brake rotor. The objective of this work is to compare temperature distribution and heat flux of disc brake rotor of two different materials. After obtaining the analysed results the manufacturing of the rotor for the best results is carried out using CNC machine.

Keywords: Structural analysis, Thermal analysis, Stainless Steel, Gray Cast Iron, CNC machine

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I INTRODUCTION

A brake is a device by means of which artificial frictional resistance is applied to moving machine member, in order to stop the motion of a wheel. The brake disc is typically manufactured from cast iron, however in some cases it is made up of composites, and it is connected to wheel hub. The caliper having brake pads is mounted on the rotor. In order to stop the vehicle the brake pads must forced towards the disc. The force applied on brake pads is generally in three ways such as hydraulic, pneumatic and mechanical.

Friction causes the disc and connected wheel to slow or stop. Brakes convert motion into heat, and if the brakes get too hot, they become less effective and this phenomenon is called as brake fade. Disc brake development and it’s utilize began in European nation in 1890’s. Disc brakes provide higher stopping performance. A brake consists of a cast iron disc clamped to the wheel center and a fixed housing is mounted on brake disc called as caliper**.**

1.1 Braking Requirements

The brakes should be sturdy enough to stop the vehicle with in minimum distance in an emergency. The driver should have good control over the vehicle throughout braking and therefore the vehicle should not skid. The brakes should have smart opposing fade characteristics i.e. their effectiveness mustn't decrease with constant prolonged application. The brakes ought to have good anti fade properties.

1.2 Problems In Disc Brake

Discs are damaged in three ways scarring, cracking, and excessive rusting. During the brake operation, the frictional heat is mostly cut in pads and disc, and an uneven temperature is distributed on the disc could induce severe thermo elastic distortion of the disc. The thermal distortion of a flat surface into a highly deformed state called as thermo elastic transition.

Continuous application of brake develops more frictional heating and it results bulging. Due to this pressure between brake pad and disc is increases and hot spots are formed on the disc. These hot spots leads to cracks on the disc, this can be referred to as thermo elastic instability.

The thermo elastic instability development increases with increase in rotating speed of the disk. This region where the contact load is targeted reaches extremely high temperatures that cause weakening the braking performance. Due to high temperatures thermally distorted hot spots are formed on the rotating disc, Theses hot spots under the brake pads cause low frequency vibrations.

II. LITERATURE REVIEW

Dixit, Beohar and Bal et al, [1] stated that the important tool for optimum designs for disc brake is stochastic signomial geometric programming. This program involves in probability of constraint equations, for the approach of realistic design. These equations are established for the design of disc in light passenger vehicles. Walter et al, [2] deals with the disc brake torque, brake roughness, vehicle response and rotor distortion. The new method has being suggested for analysis and measurement techniques of disc brake operational aspects and design. Pigozzi G. and Ceretto E.[3] investigated on design, analysis and testing of two-way proportioning for achieving better braking in a turn. They discussed about the optimization of braking performance, efficiency, stopping distance and experimentation procedures to obtain these parameters. Limpert [4] gives detailed information about technical aspects on design and safety of brake disc. He discussed in detail about functions, fundamentals, design, performance and safety of an automotive braking system in his research. From the design book he followed the fundamentals associated to design and performance. Erwin R. D. and Winkler C.B.[5] investigated on the influence of brake efficiency of wheel backup based on the probability. By this literature we can avoid the wheel lockup by the values of brake efficiency. It also suggests if the efficiency of braking falls below 80% then occurrence of lockup increases rapidly on wet surfaces. Limpert [6] experimented on the thermal performance of automotive disc brakes. The temperature evolved and heat flux generated with illustrated are discussed. The improvements of thermal performance are considered in this work.

Reinhard et.al. [7] deals with the temperature induced from friction of disc brakes are determined. The results and concepts of friction temperature of disc brakes are known by experimentation. Yoshio et.al. [8] investigated on the high thermal conductivity of cast iron for disc brake rotor. The experimentation gives the idea of new material and they analysed the non study state of thermal conductivity and thermal stresses of new material developed. The resultant temperature and their analysis through finite element methods are presented.

Krosnar et.al. [9] investigated on the cast iron material for the disc brake for future. The experimentation gives the brief understanding about the cast iron material used for disc brake and its requirements, composition and properties of material of disc brake. Graham et.al. [10] discussed the effect of metallurgy on wear and friction characteristics of cast iron disc brake. The friction and wear characteristics of four GCI's and the difference between the characteristics are presented in his work. Karthik et.al. [11] deals with the properties of the brake system of automotives. By his work the idea about the material selection and various treatments applied to disc brake combination are noticed. They also compare the performance of the designs of disc brake rotor.

III. METHODOLOGY

3.1 Design of Disc Brake Rotor

For the design of disc brake rotor Catia V5R20 is used. The disc with dimensions 120 mm radius and 5 mm thickness has designed. Figure1 shows the design of disc, designed in CATIA with different modules.

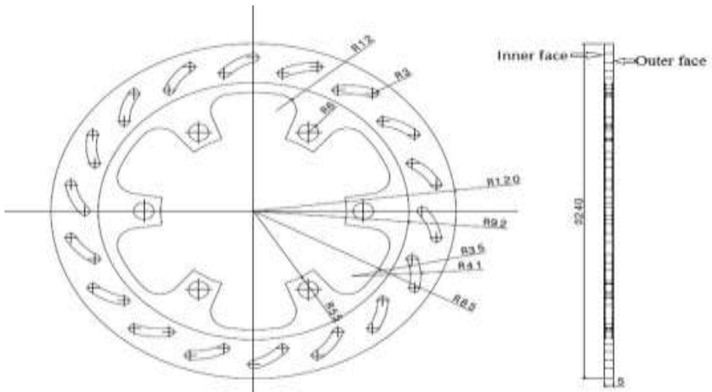

Fig 1 2D Design of disc

3.2 Material

At present scenario, commercially used materials for disc brake rotor are Cast Iron, Reinforced Carbon–Carbon or Ceramic matrix composites etc. In the present study Gray Cast Iron and Stainless Steel are two materials chosen for analysis. Mechanical properties of Grey Cast Iron and Stainless Steel are shown in table 3.1.

Table I Mechanical properties of Gray Cast Iron and Stainless Steel

S No	Properties	Gray Cast Iron	Stainless Steel
1	Young's modulus(E)	125e3 MPa	193e3 MPa
2	Poisson's ratio	0.28	0.31
3	Material density	7200 kg/m³	7750 kg/m³
4	Thermal conductivity (k)	52 w/m °c	15.1 w/m °c
5	Specific heat capacity	586 J/kg °c	420 J/kg °c

3.3 Calculations Of Disc Brake

While carrying out structural analysis and steady state thermal analysis, we come across below mentioned terminology and calculations.

Tangential force: A force which acts on a moving body in the direction of a tangent to the path of the body is called as Tangential force. Unit for tangential force is Newton. Two tangential forces acting on the disc are F_{TRI} (tangential force between rotor inner face and brake pad) and F_{TRO} (tangential force between rotor outer face and brake pad) respectively.

F_{TRI} = $\mu . F_{RI}$
μ = Coefficient of friction = 0.5
F_{RI} = P / 2 × A
So, F_{TRI} = $\mu \times F_{RI}$
F_{TRI} = $0.5 \times 0.5 \times 1 \times 10^6 \times 2000\times10^{-6}$
F_{TRI} = 500 N

Brake Torque (T_B): : It can be obtained by multiplying total tangential force and radius of brake point from centre. It is represented by T_B. Units for brake torque are N-m. Formulae for brake torque is given below

T_B = F_T. R

(Where F_T is Total tangential forces i.e. F_{TRI} + F_{TRO} = 500+500= 1000 N, R is the radius of the disc)

So, T_B = 1000 × 120 × 10-3
T_B = 120 N-m

Heat flux: Heat flux is defined as the amount of heat transferred per unit area per unit time from or to a surface. Units for heat flux are KW/m ^{2}.

Heat flux generated in disc brake rotor is calculated for existing and modified designs of disc brake rotor, calculations are as below

Specific Heat Capacity (Cp) of Gray Cast Iron and Stainless Steel are 586 and 420 J/kg ^{0}c respectively.

Time taken to stop the vehicle is 5 seconds

Developed Temperature difference is 15^0 c

Rubbing surface area of existing and modified discs are 0.017 and 0.016m^2 respectively.

Heat flux calculations for existing disc brake rotor of Gray Cast Iron:

Mass of disc (m) = 0.8 kg
Heat generated (Q) = m × Cp × ΔT Joules
= 0.8 × 586 × 15 = 7032 J
Heat Flux (q) = Heat Generated /Second /area
= 7032 /5 / 0.017
= 82.729 KW/m ^{2}

Heat flux calculations for existing disc brake rotor of Stainless Steel:

Mass of disc (m) = 0.9 kg
Heat generated (Q) = m × Cp × ΔT Joules
= 0.9 × 420 × 15 = 5670 J
Heat Flux (q) = Heat Generated /Second /area
= 5670 /5 / 0.017
= 66.705 KW/m^2

Heat flux calculations for modified design of Gray Cast Iron (t=5mm):

Mass of disc (m) = 0.803kg
Heat generated (Q) = m × C_p × ΔT Joules
= 0.803 × 586 × 15 = 7058.77 J
Heat Flux (q) = Heat Generated /Second /area
= 7058.77 /5 / 0.016
= 88.327 KW/m^2

Heat flux calculations for modified design of Stainless Steel (t=5mm):

Mass of disc (m) = 0.8kg
Heat generated (Q) = m × C_p × ΔT Joules
= 0.8 × 420 × 15 = 5040 J

Heat Flux (q) = Heat Generated /Second /area
= 5040 /5 / 0.016
= 63 KW/m^2

Heat flux calculations for modified design of Gray Cast Iron (t=6mm):
Mass of disc (m) = 0.9519kg
Heat generated (Q) = $m \times C_p \times \Delta T$ Joules
= 0.9519 × 586 X 15 = 8367.201 J
Heat Flux (q) = Heat Generated /Second /area
= 8367.201 /5 / 0.016
= 104.590 KW/m^2

Heat flux calculations for modified design of Stainless Steel (t=6mm):
Mass of disc (m) = 1.026 kg
Heat generated (Q) = $m \times C_p \times \Delta T$ Joules
= 1.026 × 420 × 15 = 6454.98 J
Heat Flux (q) = Heat Generated /Second /area
= 6454.98 /5 / 0.016
= 80.687 KW/m^2

3.4 Analysis

Analysis of disc brake rotor is carried out in ANSYS 15.0 software. Static structural and steady state thermal analysis are carried out for existing and modified disc. In static structural analysis, deformation and equivalent stresses of disc are calculated and in steady state thermal analysis the heat flux and temperature is calculated. This analysis is done for the best combination of disc brake rotor.

3.4.1 Static Structural Analysis

A static structural analysis determines the displacements, stresses, and strains in elements caused by masses that don't induce inertia and damping effects. The static structural loads are applied in Ansys. The types of loading that may be applied in a very static analysis include:
1 Forces and pressures
2 Fixed supports.
3 moment.

Structural analysis procedural steps are given below

Step 1: Importing Geometry

Fig 2 Imported geometry

Step 2: Meshing

Fig 3 Mesh model

Step 3: Applying Structural boundary conditions

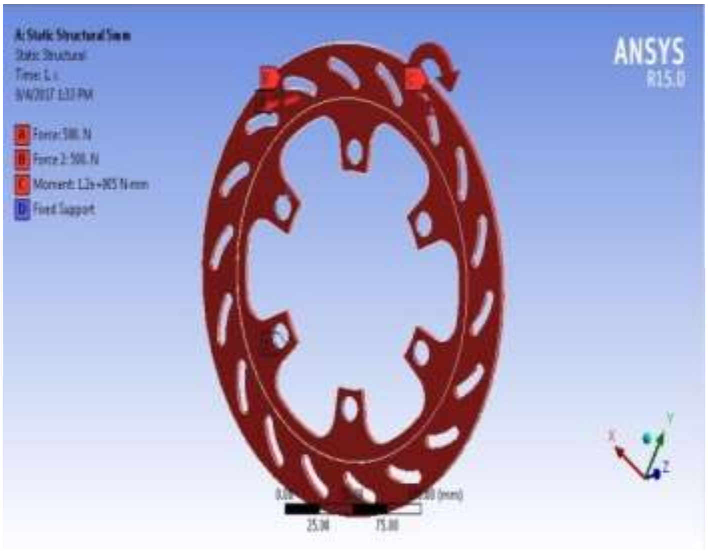

Fig 4 Applied boundary conditions

Step 4: Solutions

Effect of deformation and equivalent stresses on modified disc

Effect of equivalent stress on modified disc of grey cast iron with 5mm thickness, the maximum stress of 11.563 MPa is at clamping holes and minimum stress of 0.035909 MPa is developed at brake pad contact area. Figure 5 shows the equivalent stresses of modified disc.

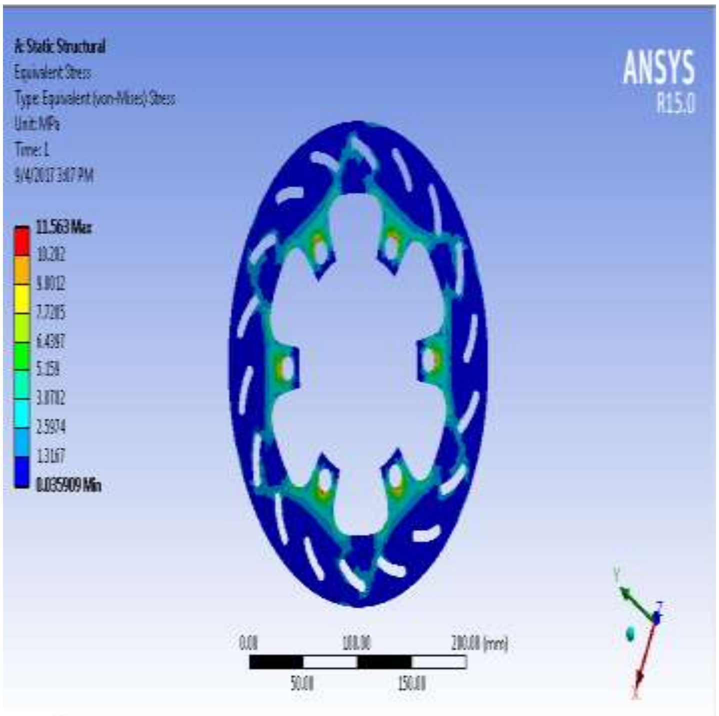

Fig 5 Equivalent stresses of modified disc of Gray cast iron with 5mm thickness

Effect of deformation on modified disc of grey cast iron with 5mm thickness, the maximum deformation of 0.0032829 mm is at extreme end of the disc and minimum deformation of 0 mm is at clamping holes. The red and blue color indicates maximum and minimum deformation respectively. Figure 6 shows the deformation of modified disc.

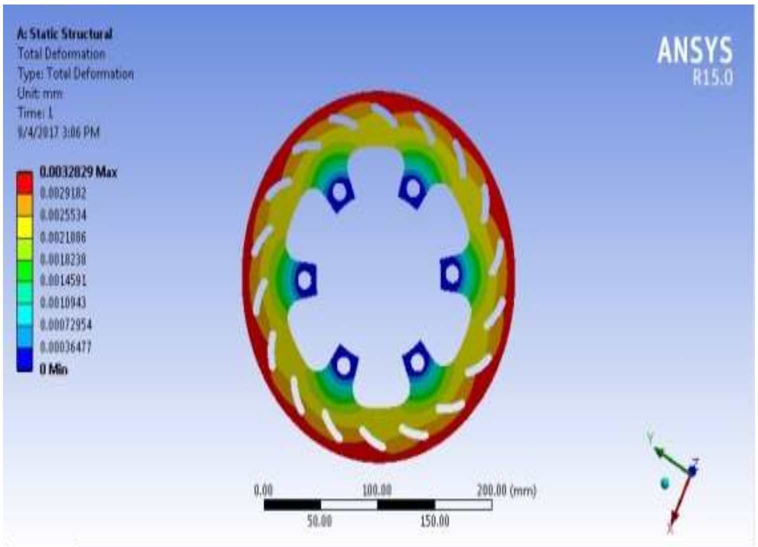

Fig 6 Deformation of modified disc of Gray cast iron with 5mm thickness

3.4.2 Steady-State Thermal Analysis

A steady-state thermal analysis calculates the consequences of steady thermal loads on the element. Thermal analysis is to observe temperatures, thermal gradients, heat flow rates, and heat fluxes in an object that are caused by loads that don't vary over time. Heat flux and heat generated in various cases considered are tabulated in the table II for easy reference.

Table II heat flux and heat generation values

	Heat generation (Q in Joules)	Heat flux (q in KW/m^2)
Existing disc (Stainless Steel)	5670	82.729
Existing disc (Gray Cast Iron)	7032	66.705
Modified disc (5mm , Stainless Steel)	5040	63
Modified disc (5mm , Gray Cast Iron)	7058.77	88.327
Modified disc (6mm , Stainless Steel)	6454.98	80.687
Modified disc (6mm , Gray Cast Iron)	8367.20	104.590

Thermal analysis procedural steps are given below

Step 1: Importing Geometry

Fig 7 Imported geometry

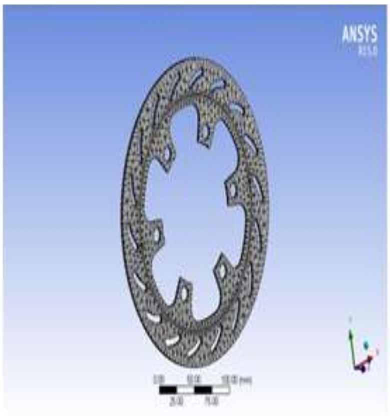

Fig 8 Mesh model

Step 2: Meshing

Step 3: Applying Thermal boundary conditions

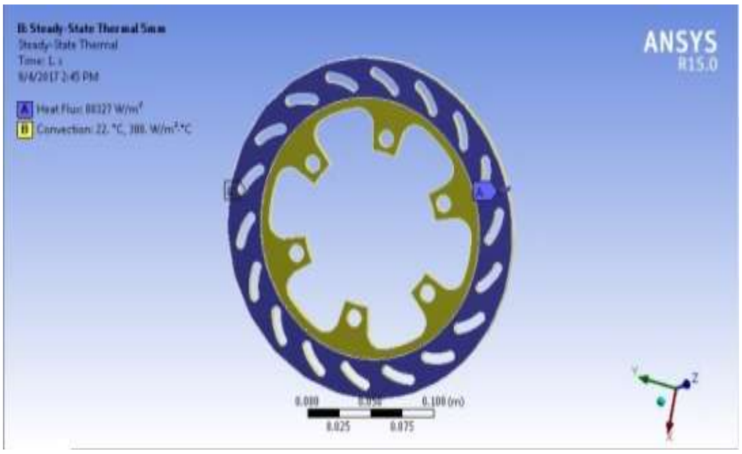

Fig 9 Applied boundary conditions

Step 4: Solution

Effect of temperature and heat flux on modified disc

Effect of temperature on modified disc of grey cast iron with 5 mm thickness, the maximum temperature of 563.62 °C is developed at brake contact point that is at end of rotor and minimum temperature of 94.806 °C is at clamping holes. Red and blue color indicates maximum and minimum temperatures as shown in below figure. Figure 10 shows the temperatures of modified disc.

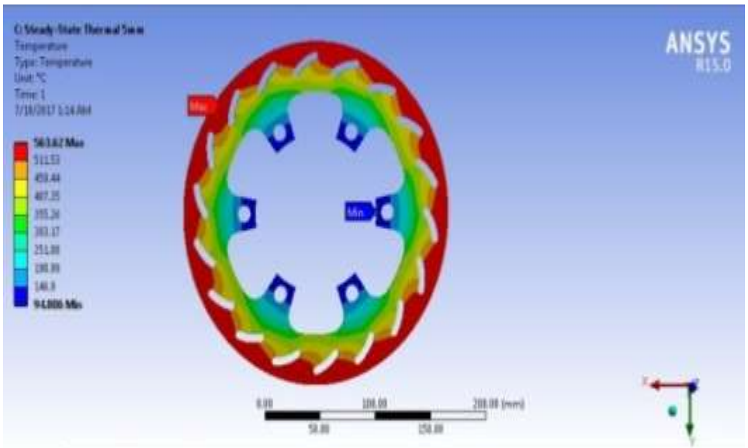

Fig 10 Temperatures of modified disc of Grey cast iron with 5mm thickness

Effect of heat flux on modified disc of grey cast iron with 5 mm thickness, the maximum heat flux of 1.0298 W/mm^2 is generated at brake pad contact point and minimum heat flux of 0.0023396 W/mm^2. Red and blue color in the figure indicates maximum and minimum heat flux values respectively. Figure 11 shows the heat flux of modified disc.

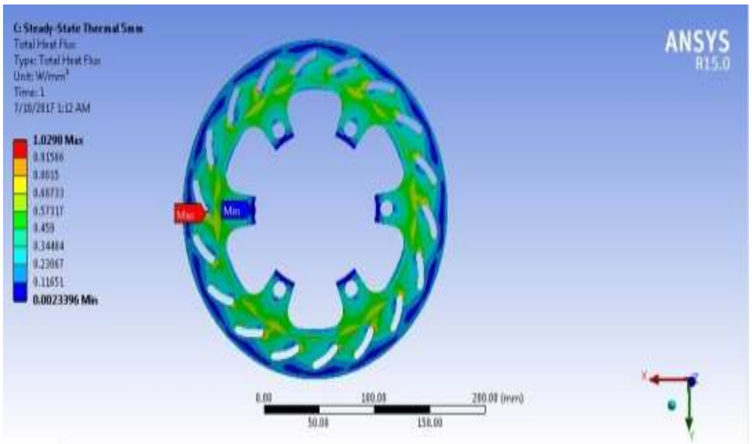

Fig 11 Heat flux of modified disc of Grey cast iron with 5mm thickness

3.5 Manufacturing

In this work manufacturing of disc having 5mm thickness is done by CNC vertical machine. The disc is manufactured according to the best results from the analysis.

Fig 12 Manufactured Disc

IV. RESULTS AND DISCUSSIONS

Structural analyses of existing and modified disc are compared with deformation and stresses are taking into consideration. Boundary conditions are applied for both existing and modified disc brake rotor to optimize results.Thermal analysis is performed for heat flux and temperature. Heat flux i.e. heat generated per seconds per unit area and convective heat transfer coefficient are applied to existing and modified disc brake rotor as boundary conditions. After applying boundary conditions, as a result temperature and heat loss per unit area are calculated for best material suitable for disc brake rotor. Following tabular column shows the structural and thermal analysis results:

Table III Results of structural and thermal analysis

	Material	Deformation (mm)	Von mises stress (MPa)	Heat Generation (J)	Heat flux (W/mm^2)	Temperature (°C)
Existing disc/Reference disc	Stainless steel	0.0016866	11.982	5670	0.5383	622.76
	Grey cast iron	0.0029268	12.082	7032	0.92713	554.07
Modified disc (5mm thick)	Stainless steel	0.0019102	12.629	5040	0.47389	547.35
	Grey cast iron	0.0032829	11.563	7058.77	1.0298	563.62
Modified disc (6mm thick)	Stainless steel	0.0015938	10.572	6454.98	0.4712	569.56
	Grey cast iron	0.0027664	10.633	8367.20	0.94688	553

It is observed that all the equivalent stress values obtained from structural analysis are less than the allowable stress value, so that the design is secure based on the strength and rigidity criteria.

Though heat generated in the case of Modified Disc made of stainless steel with thickness 5 mm is less than the heat generated in existing design of disc, the heat flux value is observed to be less than the disc with existing design made of grey cast iron. But in case of Modified disc with 5 mm thickness made of grey cast Iron, the heat generated is high and heat flux value is also observed to be high which results in high heat dissipation. Hence it is the finest probable combination of thickness and material for the current experimentation.

V. CONCLUSIONS

The following conclusions are drawn from the present work:

1. From the set of variables taken for the experiment, the best result among all is found at modified disc with 5 mm thickness of Gray Cast Iron material based on its high heat flux.
2. Maximum heat flux of 1.0298 W/mm^2 is produced in Gray Cast Iron with 5 mm thickness, hence the Gray Cast Iron with modified design is suitable for disc brake rotor.
3. By structural analysis all stresses are under allowable stress, but heat flux is more on the Grey Cast Iron with 5 mm thickness hence the combination is better for the disc brake rotor.

4. From the set of variables, the best results are found at deformation of 0.0032829 mm, stress at 11.563 MPa, heat flux at 1.0298 W/mm^2 and temperature at 563.62°C on Grey Cast Iron with 5mm thickness.

The disc brake rotor is manufactured according to the best results obtained.

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