Design Optimization Method for Drilled and Slotted Brake type Rotors

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Abstract – *Brake rotor has been contributing nearly 26 kg of the weight of wheel assembly, and most of the researches are focused on changing materials of brake rotors but less has been done to change its design without hampering the performance characteristics. The study proposes a method by which the weight of drilled and slotted type brake rotor can be reduced without change in performance or minimal change in performance. In this study we have designed a standard drilled and slotted brake rotor of cast iron and performed thermal and structural analysis. The results obtained were used to perform topology, where we analysed the unwanted material that can be removed without affecting the performance of the rotor. A new design is created which has 11% less mass than of the initial design. For this design optimization we used design and analysis software – Solidworks and ANSYS.*

Key Words: FEA analysis, Brake Rotor design, ANSYS, Thermal and Structural analysis, Topology

1.INTRODUCTION

Brake plays a major role not only for stopping of the vehicle but also for the safety of passengers. So, when it comes to designing of Brake rotors, they are designed to withstand high temperatures and mechanical loads due to braking actions. During the braking process as the brake paddle is pressed, the braking fluid flows through the braking lines to master cylinder, where the piston is pushed to transfer the fluid pressure equally to the wheels of the vehicle. As the fluid pressure is reached to the braking calipers, then the pads press the braking rotor to stop wheel or to decelerate them. In this process the brake disc absorbs kinetic energy of the vehicle and dissipate it in the form of heat. This heat is either given out in surrounding air or water which is circulated in brake drums, so that excessive heating does not takes place.

The efficient braking depends on pressure between braking surfaces, velocity of the vehicle, coefficient of friction between braking surfaces, projected area where braking occurs, ability to dissipate heat and brake lining materials. The material is selected based on high coefficient of friction with minimum wear rate, high heat resistance and dissipation capacity, sufficient mechanical strength and no effect of oil or moisture.

Disc brake rotors are designed to be durable, self-cleaning ability and light in weight. There are several types of Disc rotor brakes that have specialized characteristics depending on the application. They vary based on their geometry, heat absorption and dissipation rate. Also, disc brakes are generally considered better than drum brakes because of effective management of heat, better performance in wet conditions, better stopping ability, and less stopping distance. In addition, disc brakes are easy to service as it contains less parts than drum brakes. However, due to increased weight of disc brake rotors the fuel efficiency and vehicle performance is reduced (as the overall mass of the vehicle is increased). Hence, to tackle this many research had been already done on brake rotor materials where several Aluminium alloys or carbon composite materials are used. While, other researches focused on optimizing the heat dissipation by incorporating different designs. They are as follows:

A. Types of Disc Brakes:

Flat-brake disc provides an excellent contact between braking pads and rotor, also it's smooth. These discs are usually found on small light weight vehicles as they are easily machinable at low cost. However, after a prolonged use they damage the pads of braking calipers as they accumulate dust, and the heat, gases do not dissipate efficiently from these brake discs. Hence, it causes high wearability of brake and decreases life cycle of braking pads, which may further cause failure of brakes.

Vented- brake disc dissipates the heat more efficiently compared to flat type. This brake has a sandwiched structure, where the vanes/spokes are between the two discs. As they rotate the greater inflow of air takes place through it causing them to cool easily compared to the others. However, these rotors are quite heavy due to the increased mass of vanes, but they work efficiently in dissipating heat to the surrounding. Hence, heat stresses are very well managed in this braking rotor.

Drilled – brake disc has holes on the disc through which they are easily cooled. They provide good out flow of residual gases, heat and dust particles through them, thus preventing debris or other build-up materials to accumulate on it. Structural integrity of the disc remains same even though the holes are drilled, but as most of the heat flows through these holes, chances of cracking and warping are very rare.

Slot and groove- disc brakes- are generally found on trucks and all-terrain vehicles, they have the same working principal just like a drilled disc brake. Instead of holes, grooves are made on the disc to allow the flow of heat, gases and the foreign particles. The profile of the slots is made in the similar direction to the rotation of the wheel, these allows better friction between brake pads and disc. However, it also causes noise as the grooves rub the pads of the brake caliper.

Slotted and holed- brake discs are composite of slot type and hole type brake discs. Their application is mostly found in high-speed vehicles or racing cars. They work in both dry and wet conditions very effectively. However, the manufacturing cost is high for this type of rotors. They are very efficient in dissipating heat to the surrounding with less chattering noise. More holes reduce the noise of the rotor and allows better heat flow, while slots provide better flow of residual particles like mud, dust, or debris generated by friction or rubbing of pads.

Dimpled- disc brakes are seen along with slot and holed brake type, to reduce weight without change in performance slot and holed type, dimpling is done.

Wavy edge- disc brakes are modern braking discs that provide good contact between the disc and pad of the rotor. They also provide most efficient heat flow, but the cost is high. Hence, they are only used in high end cars.

B. Materials used in Disc Brakes:

Factors which are taken into account for selection of brake rotor material is based on ability to sustain high frictional force, minimal abrasive wear, high stiffness to sustain conditions of sudden braking, high strength, good thermal conductivity and dissipation rate, good corrosion resistance, and low weight. Moreover, the factors such as ease of manufacturability and cost are also taken into consideration. The brake disc material should have sufficient heat storage capacity, so that it could sustain cracking and distortion.

Most of the rotors used are manufactured from galvanized cast iron due to its low cost, ease of manufacturability, and recyclability. However, the use of aluminium alloys is increasing to reduce the weight of vehicles. This composite is matrix composites (MMC's) reinforced with ceramics to provide good strength, with lower density and high thermal conductivity. Another, type of material used includes composite of cast iron with titanium, which provides good strength, but decreases the coefficient of friction [3]. Other composites are based on aluminium, silicon and carbon-carbon based, which are generally used in sports cars where performance is key criteria. Al2O3-TiC is aluminium composite which is costliest, but have light weight and good strength.

Cast irons are widely used braking material nowadays. They are classified as: gray, nodular, vermicular, malleable and white [3]. These type of cast irons are obtained from pig iron, manganese iron, chrome iron and nickel irons [3]. The alloys containing molybdenum, vanadium are used to provide good strength. Therefore, the gray cast iron alloys used have different chemical compositions, cooling rates, microstructures with different ferritic or pearlitic matrices.

Table: 1: Properties of Materials for brake rotor [8]

Material	Properties				
	Compressive Strength (MPa)	Friction Coefficient (μ)	Wear rate ($x10^{-6}$ mm^3 /Nm)	Specific Heat Cp (KJ/ KgK)	Density (g/cc)
Gray Cast Iron	1293	0.41	2.36	0.46	7.20
Titanium Matrix Composite	1300	0.31	8.19	0.51	4.68
Aluminium Matrix Composite 1	406	0.35	3.25	0.98	2.7
Aluminium Matrix Composite 2	761	0.44	2.91	0.92	2.8
Alpha Beta Titanium Alloy	1070	0.34	246.3	0.58	4.42

2. Methodology

A) Assumptions

1) The dynamic weight transfer during braking on the front and rear axle is 60:40 percent of the total vehicle weight respectively. [4]
2) All the four wheels will come to rest when brakes are applied and the condition of slip is also considered.
3) We have calculated the forces on sedan car having weight of 880 Kg.
4) The kinetic energy of vehicle is dissipated in the form of thermal energy. [4]
5) Ambient temperature is assumed to be constant at 27°C and the convection and radiation is taking place through air.
6) The thermal conductivity of material is uniform throughout the process. [5]
7) The vehicle has constant deceleration when coming to rest. [4]

B) Calculations

Table: 2: Vehicle and Brake Rotor Specification

Sr.No	Parameters	Values
1	Pedal ratio $(L_2/L_1)/\,l_p$	6.2:1
2	Bore diameter of master cylinder (b_{mc})	28 mm
3	Caliper piston diameter (b_p)	54 mm
4	Velocity of Vehicle (V_v)	120 Kmph =33.33m/s
5	Constant deceleration while braking	9.09 m/s^2
6	Weight of vehicle (W)	880 kg
7	Tire slip(s)	0.07
8	Outer effective Diameter of Brake Disc(D)	286mm
9	Inner effective Diameter of Brake Disc(d)	222mm
10	Pedal lever efficiency (η_p)	0.8
11	Initial mass of rotor (m_d)	6.89 kg
12	Material	Gray Cast Iron
13	Specific heat of Cast Iron (C_p)	462 J/kg.K
14	Room ambient Temperature $(t_{initial})$	27˚C
15	Density of Cast iron	7200 kg/m^3
16	Young's Modulus of Cast Iron	125 GPa
17	Thermal Conductivity of Cast Iron	52 W/mK
18	Height	52.6mm
19	Minimum Thickness	8.2mm
20	Nominal Thickness	23.8mm
21	Number of Vanes	32
22	Diameter of Tire	28 in

- *Brake pedal force* (F_{bp})

Average force applied by driver to brake pedal = 70lbs = 312N

F_d = For emergency braking it can be= 90lbs = 400N

$$F_{bp} = F_d \times \frac{L_2}{L_1}$$

$$F_{bp} = 400 \times \frac{6.2}{1}$$

$$F_{bp} = 2480N$$

- *Master Cylinder pressure* (P_{mc})

$$P_{mc} = \frac{F_{bp}}{A_{mc}}$$

$$A_{mc} = \frac{\pi b_{mc}^2}{4} = \frac{\pi \times 28^2}{4} = 615.75mm^2$$

$$P_{mc} = \frac{2480}{615.75} = 4.027\ N/mm^2$$

- *Force by caliper piston* (F_{cal})

$$F_{cal} = P_{mc} \times A_{cal}$$

$$A_{cal} = \frac{\pi b_p^2}{4} = \frac{\pi \times 54^2}{4} = 2290.22mm^2$$

$$F_{cal} = 4.027 \times 2290.22 = 9222.72N$$

- *Clamp load by caliper* (F_{cl})

$$F_{cl} = F_{cal} \times 2$$

$$F_{cl} = 9222.72 \times 2 = 18445.45N$$

- *Force on brake pads* $(F_{friction})$

$$F_{friction} = F_{cl} \times \mu_{bp}$$

For dry condition, $\mu_{bp} = 0.4$

$$F_{friction} = 18445.45 \times 0.4 = 7378.18N$$

- *Stopping time* (t)

Deceleration of vehicle (a) = 9.09 m/s^2

$$t = \frac{V_v}{a} = \frac{33.33}{9.09} = 3.66\ sec$$

Stopping distance (SD)

$$SD = \frac{V_v^2}{2a} = \frac{33.33 \times 33.33}{2 \times 9.09} = 61.11\ m$$

- *Average braking power* (q_o)

$$q_o = \frac{k(1-s)V_v.a.w}{2}$$

Tire slip (s) is a ratio of difference between vehicle forward speed and circumferential speed to vehicle forward speed. [6]

$$q_o = \frac{1(1-0.07) \times 33.33 \times 9.09 \times 880}{2} = 123.975\ KW$$

$$(q_{eff}) = q_o \times 0.6 \times 0.5 \times 0.5 \times 0.88$$

Where,

0.60 = weight distribution on front wheels

0.50 = since one front brake rotor is considered

0.50 = since one side of the rotor is considered

0.88 = 12% heat lost (heat lost coefficient)

$(q_{eff}) = 123.975 \times 0.6 \times 0.5 \times 0.5 \times 0.88$

$= 16364.7$ Watt

- *Brake power* (P)
  $P = \frac{(q_{eff})}{t} = \frac{16364.7}{3.66} = 4471.22\ \mathrm{Nm/sec}$
- *Heat Flux* = $\frac{\text{Power}}{\text{Area}}$
  Swept area of disc rotor = $\frac{\pi}{4}(D^2 - d^2)$
  = $\frac{\pi}{4}(0.286^2 - 0.222^2)$
  = $0.0255\mathrm{m}^2$
  Heat Flux = $\frac{4471.23}{0.0255} = 175.342\ \mathrm{KW/m^2}$
- *Braking Pressure* (P_b)
  $P_b = \frac{1}{A_{mc}}[\frac{F_d}{2} \times l_p \times \eta_p]$
  $P_b = \frac{1}{615.75}[\frac{400}{2} \times 6.2 \times 0.8]$ = 1.61 MPa

  Considering 2 cylinders, so force on each cylinder
  $F_c = [\frac{400}{2} \times 6.2 \times 0.8]/\ 2$ = 496N

- *Braking Torque* = $2F_c.\mu_{bp}.R_m$

  $R_m = \frac{2}{3}\left[\frac{D^3 - d^3}{D^2 - d^2}\right]$=0.2553 m

  Braking Torque = $2F_c.\mu_{bp}.R_m$

  = 2 ×496 × 0.4× 0.2553
  = 101.3 Nm
- *Kinetic Energy (K.E)* = $\frac{Mv_v^2}{2} = \frac{880 \times 33.33^2}{2}$= 488.791 KJ
- *Heat generation* (H_g) = $m_d.C_p.\Delta t$
  488791 = 6.89 × 462 × Δt
  $\Delta t = 139.60^{\circ}\mathrm{C}$
  139.60 = $t_{final} - t_{initial}$
  139.60 = t_{final} - 27°C
  $t_{final} = 166.6^{\circ}C$

In this paper, we have assumed a car at a speed of 120Kmph applying brake and stopping in single stop. At first the standard model of drilled and slotted type rotor is created to perform analysis using ANSYS 19, where we performed structural and steady state thermal analysis to study the temperature distribution, heat flow, stress analysis and deformation caused in brake rotor.

Later on, the topology function was used to remove the material from non-functional area of the rotor, which helped us to understand the areas from where material can be jotted down. After studying these areas, a new design was created and analyzed for performance.

3. Geometry

The model of drilled and slotted type brake rotor is designed using SolidWorks. In this, a model was created by taking into consideration that most of the area is exposed to the convection which will take place naturally (by air). Moreover 32 vanes are provided to dissipate the heat rapidly.

The holes are drilled so that proper heat flow through them takes place and minimum thermal stresses are generated within the body to avoid condition of warping and cracking. Rounded holes are useful because the stress distribution occurs uniformly around the surface, and as there are no sharp edges the chances of cracking are reduced. The grooves are provided on the surface of brake rotor to allow the outflow of debris and particles generated by friction between pad and rotor.

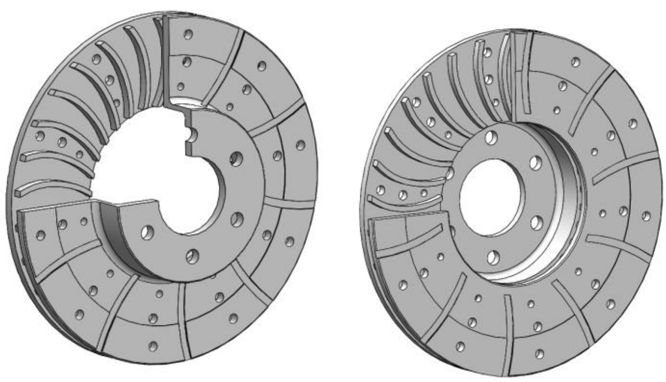


Fig -1: Section view of Drilled and slotted type Rotor

The modification in geometry of rotor can cause change in thermal and structural output and thus effect the area of rotor, flow pattern of air, and other values used for analysis. So, the effective areas of braking are not changed throughout the analysis.

4. Analysis

A) Structural Analysis

Fixed support is applied to the fastening area which attaches brake rotor to hub, hence reducing one degree of freedom of the body. The brake force of 7378.18 N is applied on the brake rotor where the brake pads will rub the brake rotor. The load applied includes a moment of 101.3 N-m on one side of disc, having circular cross section. This will be applied in opposite direction of rotation of wheel, as the brake will decelerate the vehicle. The angular velocity of wheel is 93.74 rad/s for vehicle at speed of 120Kmph. This is applied in the same direction of vanes profile, through which inflow of air will happen.

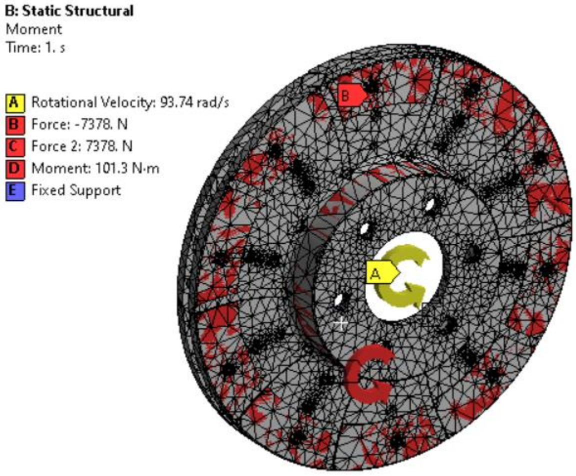
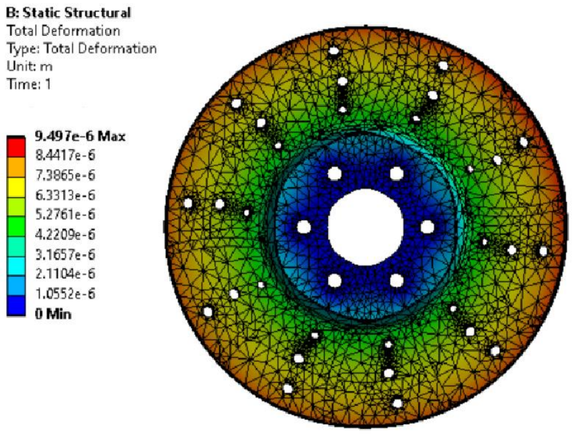


Fig -2: Applied forces on brake rotor



Tabular Data

	Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1	1.	0.	9.497e-003	6.2327e-003

Fig -3: Results obtained after solving structural analysis

The maximum deformation of 0.009 mm is occurring on the outer surface where the pads apply force to rotor and the least deformation is taking place, near the area around fixed support. The deformation is decreasing from outer surface towards hub area and similar trend is seen at the back side of rotor. However, the equivalent stress concentration goes on increasing from center of the rotor and becomes zero on outer periphery.

B) Steady State Thermal Analysis

The thermal analysis was carried under atmospheric conditions at 295 K or 22˚C, where the rotor dissipates heat by means of convection and radiation to surrounding. Heat flux of 175.342 KW/m2 is applied on circular cross section where the disc will come in contact with the piston cylinder [4]. Heat transfer is taking place by conduction, convection and radiation shown in figure. The thermal conductivity is taken as 52 W/mK as the disc is made of Gray Cast iron.

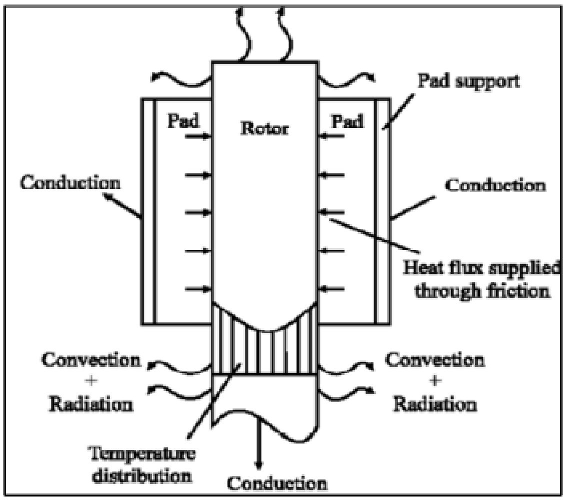


Fig -4: Modes of heat transfer in brake rotor. [10]

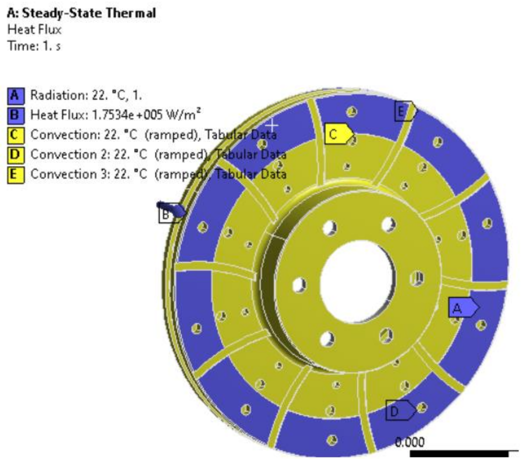
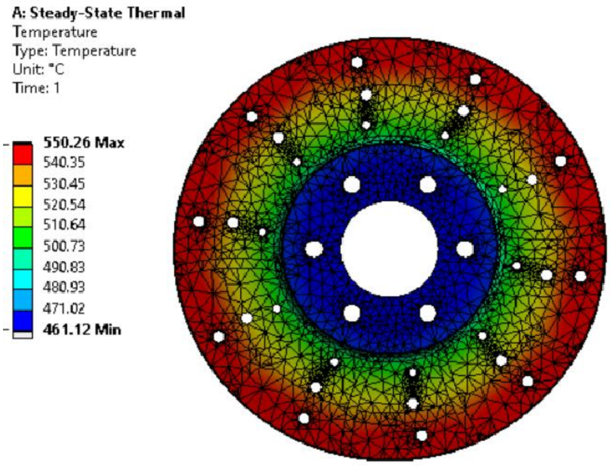


Fig -5: Applied flux on brake rotor



Tabular Data

	Time [s]	Minimum [°C]	Maximum [°C]	Average [°C]
1	1.	461.12	550.26	524.37

Fig -6: Results obtained after solving thermal analysis

The maximum temperature was seen on the functional area of rotor which stays in contact when brakes are applied, it was 550°C. It kept on decreasing as we moved to the center of the disc as the heat was flown out by means of holes, vents and other surfaces which came in contact with air as the disc rotated. Similarly heat flux was observed to be maximum on middle area which is non-functional and accompanies only during heat dissipation.

C) Topology Optimization

Topology optimization is tool that seeks to identify the best material distribution within the body in given constraints.

For, this optimization our objective is to minimize the weight of brake rotor without disturbing or making minimal change in temperature and deformation values obtained. For, this analysis we are using 'Topology Optimization', module available in ANSYS-19. The initial weight of rotor was observed to be 6.89 kg, which sums up-to approximately 27 kgs for four rotors.

Firstly, for performing analysis we have defined our functional and non-functional areas shown in figure below.

We have defined first functional area near fastening locations where the hub will attach the brake rotor. Second functional area is fixed where the brake caliper will apply braking forces to decelerate the vehicle. In these areas there will be no change in material distribution. The non-functional area in our analysis can be seen in blue colour, where material removal will occur without effecting the temperature and deformation significantly. We have set the percentage of mass retain to be 75% as our response constraint.

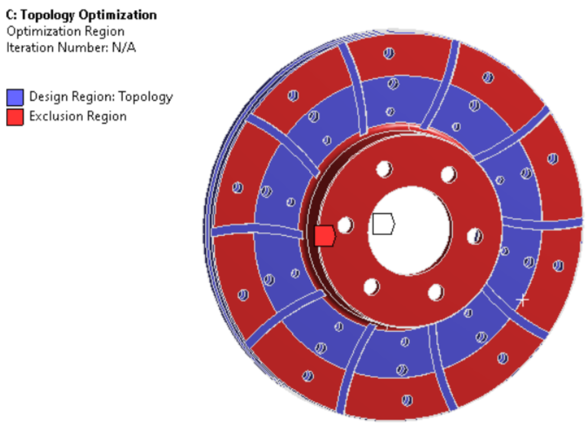


Fig -7: Functional (red) and Non-functional (blue) areas

Original Volume	9.5796e-004 m³
Final Volume	8.2971e-004 m³
Percent Volume of Original	86.612
Original Mass	6.8973 kg
Final Mass	5.9739 kg
Percent Mass of Original	86.612

Fig -8: Results obtained after Topology

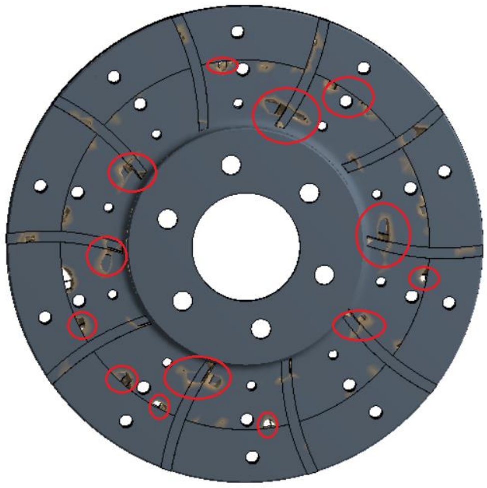


Fig -9: Front area from where material can be removed

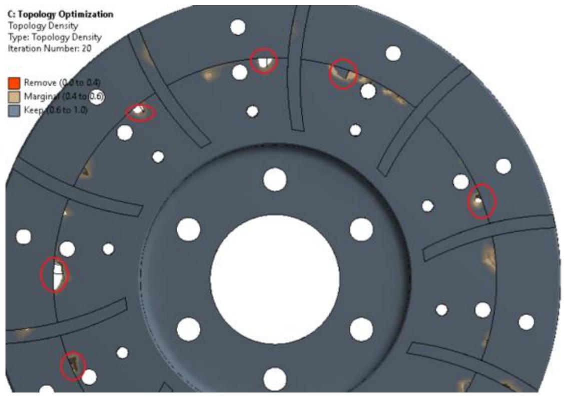


Fig -10: Rear area from where material can be removed

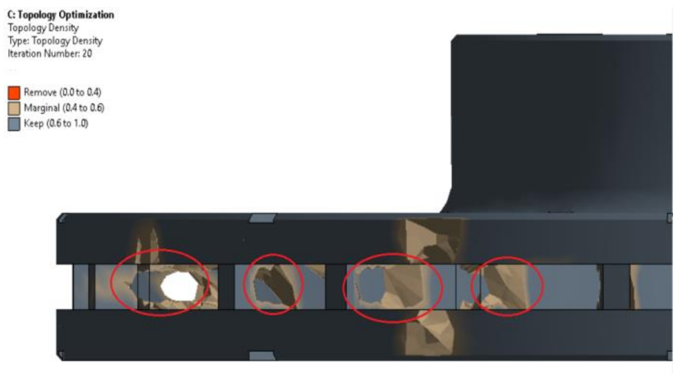


Fig -11: Vanned area from where material can be removed

A maximum reduction of 14% of the mass can be done to achieve similar results of temperature and deformation. However, reduction in every elemental mass is not possible due to manufacturing constraints. So, we were able to achieve 11% reduction.

From the results obtained we have highlighted the areas by red circles as shown in figure from where material removal can be done. Based on the analysis a new design was created by removing material. Structural and thermal analysis was performed again to verify the results and while doing analysis on modified design we kept the initial parameters same as above.

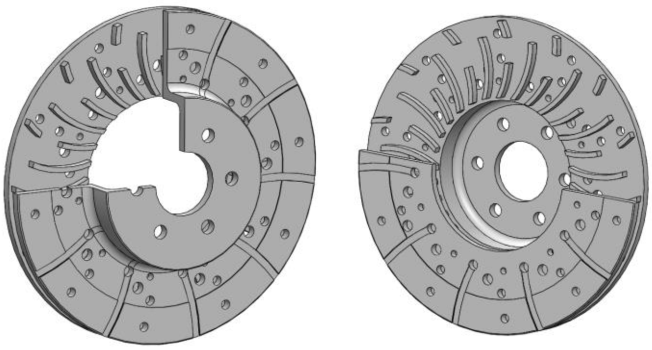


Fig -12: Section View of modified design of rotor

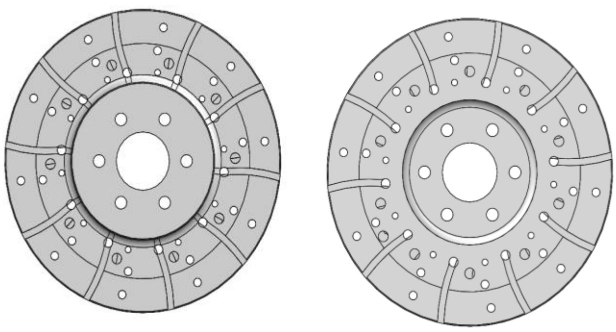


Fig -13: Front and back view of brake rotor

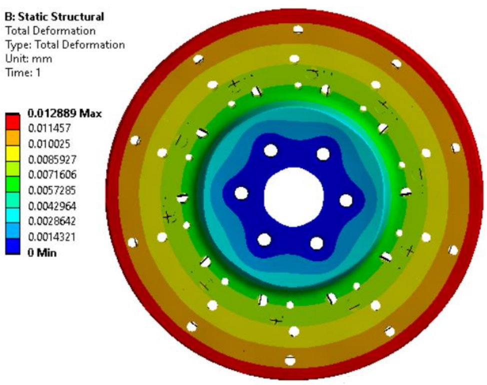


Fig -14: Static Structural Analysis of Modified brake rotor

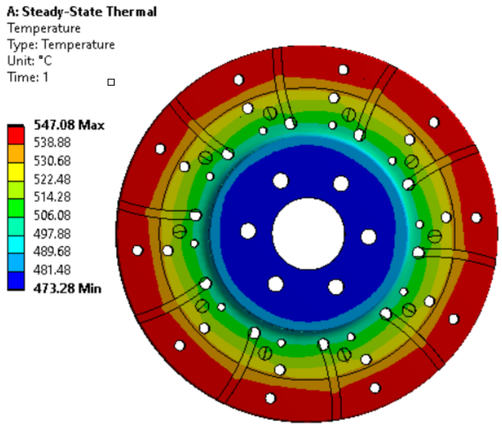


Fig -15: Steady State Thermal Analysis of Modified rotor

5. CONCLUSION

After performing analysis on modified rotor design, the weight of the slotted and drilled type rotor obtained is 6.15 kg, where 750 gm weight is jotted down from initial design. Moreover, the maximum temperature and maximum deformation after analysis is 547°C and 0.012mm respectively, which are similar to the readings obtained in earlier analysis. The heat flux and equivalent stresses generated are also nearly same. Therefore, from the analysis we conclude that the new design is within safe limits of brake design and this methodology can be used to perform analysis on other types of brake rotors and other automotive components.

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