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Design and Analysis of Vented Disc Brake Rotor

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Abstract

Brakes are one of the most significant safety systems in an automobile. In the braking process, the rotor will be exposed to large stresses which result in surface cracking, overheating of brake fluid, seals and other components. Therefore one of the main tasks of the braking system is to reduce the surface temperature of the brake rotor. This can be achieved by choosing the right material which will undergo the least thermal stresses. In this paper a detailed study of structural, thermal analysis for vented with cross-drilled holes disc brake rotor of Audi A6 is done, for providing an efficient material for disc brake rotor which can dissipate heat generated during braking at faster rate and also being structurally safe, like Grey cast iron, Stainless steel, Aluminum silicon carbide MMC, carbon ceramic matrix, E-Glass fiber, Titanium alloy, Aluminum alloy, Aluminum metal matrix composite. The results obtained are observed and analyzed for optimization.

Keywords: Braking system, Disc Brake Rotor, Thermal, Structural Analysis, CATIA V5, ANSYS WORKBENCH 16.2.

I. INTRODUCTION

The disc brake is a wheel brake which slows the rotation of the wheel by the friction caused by the pushing brake pads against a brake disc with a set of calipers. The brake rotor is connected to the wheel and axle. To stop the wheel, the friction material mounted on a brake caliper, is forced mechanically, hydraulically, pneumatically or electromagnetically against both sides of the disc. Friction causes the disc and wheel to slow down. The function of brakes is based on the law of conservation of energy. In this process, the brakes absorb either kinetic energy of the moving member or the potential energy given up by objects being lowered by hoists, elevators, etc.[1,2,3] The energy absorbed by brakes is dissipated in the form of heat to the surrounding atmosphere. The brakes efficiency decreases with an increase in temperature which is a phenomenon known as brake fade.

1.1 *Principle of Braking system*

When a certain amount of force is applied on the brake lever or pedal, the push rod which is connected through the lever or pedal to master cylinder piston transmits the force to it, this movement allows the master cylinder piston to slide and push the return spring inside the bore of the master cylinder which generates pressure in the reservoir tank to flow over it into the brake hosepipes. [6,7] A secondary seal ensures that the brake fluid from escaping to another side. Then the fluid enters into cylinder bore of caliper assembly via brake hosepipes and pushes the caliper piston or multiple pistons, at this time the piston ring rolls with the piston, then the caliper piston pushes brake pad. This movement causes brake pads to apply force on the brake disc which creates friction force and opposes the rotational motion of the brake disc/rotor. In this way, a disc brake system contributes to stop or slow down a vehicle.

Generally, regenerative braking and friction braking system are commonly used in vehicles. A friction brake generates frictional forces when two or more surfaces rub against each other. Based on the design configuration, vehicle friction brakes can be grouped into drum and disc. [7, 8]. A brake disc is a solid body; the area of contact between disc and pads determines the amount of frictional force can be generated.

Disc brake rotors can be vented or non-vented. The vented type has two discs or rotors connected to one another, vented disc rotors have larger surface area while non-vented disc brakes have a single disc with a relatively smaller surface area. [4,5] Also, depending on the performance required and amount of heat to be dissipated, the vented with cross-drilled disc brake rotor consist of drilled holes through the entire disc thickness which dissipates the heat generated at a faster rate and these are widely used in automobile braking system for improved cooling [1].

Rotor disc of disc brake is analyzed by using new materials to improve braking efficiency and provide greater stability to a vehicle. An attempt has been made to investigate the suitable hybrid composite material which is lighter than cast iron and has good Young's modulus, and density properties. Aluminum metal matrix composites and High Strength Glass Fiber composites have promising friction and wear behavior as a Disk brake rotor. The transient thermos-elastic analysis of Disc brakes in repeated brake applications has been performed and the results were compared [12, 13, 14]. Finally, conclude that the suitable material for the braking operation is S2 glass fiber and all the values obtained from the analysis are less than their allowable values and brake Disc design is safe based on the strength and rigid criteria.

Disc-style brakes development and use began in England in the 1890s. The first caliper-type automobile disc brake was patented by 1890s. The first caliper-type automobiles disc brake was patented by Frederick William Lanchester in his Birmingham UK factory in 1902 and used successfully on Lanchester cars. Compared to drum brakes, disc brakes offer better-stopping performance, because the disc is more readily cooled. A disc brake consists of a cast iron disc bolted to the wheel hub readily cooled [9, 10, 11]. A disc brake consists of a cast iron disc bolted to the wheel hub and a stationary housing called caliper. The caliper is connected to some stationary part of the vehicle like the axle casing or the stub axle as is cast in two parts each part containing a piston. In between each piston and the disc, there is a friction pad held in the position by retaining pins, string plates, etc. passages are drilled in the caliper for the fluid to enter or leave each housing. The passages are also connected to another one for bleeding. Each cylinder contains rubber-sealing ring between the design of disc brake rotor by Mit Patel [2], Mansi Raval, Jenish Patel. The main purpose of this study is to analysis the thermos mechanical behavior of the brake disc during the braking phase.

Manjunath T.V. Dr. Suresh P.M [4], the disc brake is a device for slowing or stopping the rotation of the wheel. Repetitive braking of the vehicle leads to heat generation during each braking event. Transient thermal and structural analysis of the rotor Disc of disk brake is aimed at evaluating the performance of disc brake rotor of a car under severe braking conditions and thereby assisting in the disc rotor design and analysis.

II. METHODOLOGY

The methodology involves the technology utilized for performing the designing and analysis of the object.

- Design of disc brake rotor
- Material selection
- Analysis of disc brake rotors.
  - Static structural analysis
  - Steady state thermal analysis
  - Transient thermal analysis
- Evaluating results from the analysis.
- Comparing the results of different materials for different iterations.

2.1 *Design of disc brake rotor:*

Designing of vented disc brake rotor using the ISO standard dimensions of Audi A6 car in CATIA V5 as shown in fig.1 and table.1.

Table.1: Dimensions of the disc brake rotor

Parameter name	Parameter value (units)
The outer diameter of the disc rotor (D_r)	0.288 (m)
The inner diameter of the disc rotor	0.135 (m)
Hole diameter	0.068 (m)
The thickness of vented with drilled holes disc rotors	0.025 (m)
Drilled hole diameter	0.010 (m)
Mass of the vehicle (M)	1600 (Kg)
Top Speed (V)	33 (m/sec)
Rim diameter	0.4318 (m)
Wheel diameter (D_w)	0.8318 (m)
Caliper piston diameter (D_p)	0.044 (m)
Coefficient of friction (μ)	0.7

Nomenclature:

g	Acceleration due to gravity (m/sec^2)
R	Radius of the tyre (m)
r	Radius of the rotor (m)
N	Speed (rev/sec)
m_d	Mass of the disc (Kg)
C_p	Specific heat (J/Kg-K)
ΔT	Change in temperature (Kelvin)

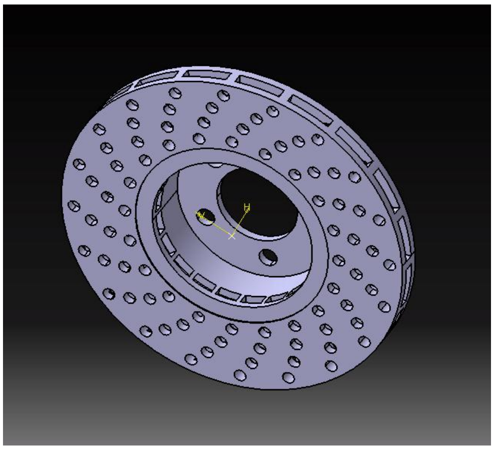

Fig.1: Vented with cross-drilled holes disc brake rotor

***Calculations*:**

i. *The kinetic energy of vehicles:*

KE= $(M*V^2)/2$ = 888711.12 (Joules)

ii. *Stopping distance of vehicle*:

The max frictional force F=μ*M*g =10987.2 (Newton)
Considering the coefficient of friction (μ) for all materials as 0.7
Deceleration of the vehicle a=F/M=6.8 (m/sec^2)
Time taken to stop the vehicle t=V/a=4.9~5 (sec)
The obtained maximum speed of the vehicle is 33.33 m/sec, so the distance covered by the vehicle in 5 seconds is 166.6 (m)
Now, considering the reaction time of the driver
Total stopping distance (S_d) = (V* reaction time) + (V^2/ (2*μ*g))
Therefore the average stopping time = 165 (m)

iii. *Braking force:*

Braking force is also known as the braking power of a vehicle. The following process calculates the exact force required to stop the vehicle within minimum stopping distance or minimum stopping time.
Tangential braking force (F_b) = KE/S_d= 5386.128 (Newton)
Tangential force on each wheel (Ft)= F_b /4 = 1346.532 (Newton)
Braking torque on wheel (T_w) = Ft*R= 850.7389 (Newton-m)

iv. *Effective rotor radius (Re):*

Effective rotor radius (Re) = (r)-(D_p/2) = 0.122 (m)
Braking torque on disc T_b = T_w*R/r= 847.64 (Newton-m)
Clamping force (C) = T_b /(2*μ*Re)= 4962.76 (Newton)
Force is acting on each side of the rotor by caliper piston is 4962.76 (Newton)
Velocity (V)= π*D_w*N (m/sec)
Angular velocity (w) = 2* π*N= 79.116 (rad/sec)

v. *Heat flux (HF):*

In the braking system, the mechanical energy is transformed is characterized by heating of the disc and pads during the braking phase. The energy dissipated in the form of heat can rise in temperature from 300ºC to 800ºC. Considering the thermal conductivity of brake pads is smaller than the disc and the heat produced will be completely absorbed by the brake disc, the heat flux emitted by this surface is equal to the energy generated by friction.

The heat generated when applying braking action on the disc brake (H_g) = kinetic energy = 888711.12 (Joules)
$H_g = m_d * C_p * (\Delta T)$
As KE entirely converted for 5 seconds the power produced will be P=KE/t = 177742000.224 (W)
Considering 60% of the mass of the vehicle on the front wheels, the power on each front rotor is P =26661 (W)
Heat flux = (P/t)/A = (26.661/5)/A= $2*(\pi/4)*((D_r)^2-(D_r - D_p)^2)$
= 145291.5531 (W/m^2)

2.2 *Material selection:*

The materials used for the analysis of vented with drilled holes disc brake rotor.

Table.2: Material properties

Material	***Density (Kg/m^3)***	***Young's modulus (GPa)***	***Poisons ratio***	***Thermal conductivity (W/m-K)***	***Specific heat (J/Kg-K)***
Grey cast iron	7200	110	0.28	54.5	586
Stainless steel	7750	190	0.3	26	500
Carbon ceramic composite	1800	95	0.31	40	755
Titanium alloy	4620	96	0.36	7.3	570
Aluminum alloy	2700	71	0.33	190	900
Aluminum metal matrix	2765.2	98.5	0.33	181.65	836.8
Aluminum silicon carbide MMC	3000	192	0.25	160	0.74
E-Glass	2580	72.3	0.22	1.3	81

2.3 *Analysis of disc brake rotor:*

After designing disc brake rotors in CATIA V5 the profiles is imported to ANSYS WORKBENCH 16.2 for further analysis such as static structural analysis, and transient thermal analysis.

2.3.1 *Static structural analysis:*

Static analysis is performed over a structure when the loads and boundary conditions remain stationary and do not change over time; it is assumed that the load or field conditions are applied gradually.

- *Meshing*

Meshing is done with relevance center 0.1 and fine element size. The elements used for meshing of the solid, vented and vented with cross-drilled disc rotors are tetrahedral three- dimensional elements with 10 nodes (iso-parametric). In this simulation, the meshing is refined in the contact zone (disc pad), this is important because in this zone the temperature varies significantly.

- *Boundary conditions*

Table 3: Static structural analysis boundary conditions

Frictional force	4962.7634 Newton
Rotational velocity	79.116 rad/sec

- *Solving model*

Once the conditions are applied, the model is solved for three factors:

a. Total deformation
b. Equivalent stress
c. Equivalent elastic strain

2.3.2 *Steady-state thermal analysis:*

A steady-state thermal analysis determines the temperature distribution and other thermal qualities under steady state loading conditions is a situation where heat storage effects varying over a period of time can be ignored.

- *Meshing*
  Meshing similar to static structural analysis.

- *Boundary conditions*
  The following table gives a brief description of the initial boundary conditions applied on the disc rotor (vented with drilled holes) for the steady-state thermal analysis.

Table 4: Steady-state thermal analysis boundary conditions

Heat flux (W/m^2)	145291.553233
Film convective heat transfer coefficient (W/m^2-K)	38.11
Radiation	22-27 ^{0}C or 295-300 Kelvin

- *Solving model*
  Once the conditions are applied, the model is solved for three factors:
  a. Temperature
  b. Total heat flux
  c. Directional heat flux

2.3.3 *Transient thermal analysis:*

The transient thermal analysis determines the temperature and other thermal quantities that vary over time; the temperature from the transient thermal analysis is used in the computation of structural analysis for thermal stress heat transfer applications. A transient thermal analysis follows basically the same procedure as a steady state thermal analysis [11].

- *Meshing*
  Meshing similar to static structural analysis.

- *Boundary conditions*
  The following table gives a brief description of the initial boundary conditions applied on the disc rotor (vented with drilled holes), for the transient thermal analysis.

Table 5: Transient thermal analysis boundary conditions

Temperature	Step 22-800 ^{0}C or 295-1073 Kelvin
Film convective heat transfer coefficient (W/m^2-K)	From imported convection data (stagnant air-horizontal cyl)

- *Solving model*
  Once the conditions are applied, the model is solved for three factors:
  a. Temperature
  b. Total heat flux
  c. Directional heat flux

III. RESULTS

Comparing the results of the disc brake rotor for different materials:

Table 6: Summarized results

Type of material	***Static structural analysis***			***Steady state thermal analysis***			***Transient thermal analysis***		
	Total deformation (m)	*Equivalent elastic strain*	*Equivalent stress (Pa)*	*Temperature (Kelvin)*	*Total heat flux(W/m^2)*	*Directional heat flux (W/m^2)*	*Temperature (Kelvin)*	*Total heat flux (W/m^2)*	*Directional heat flux (W/m^2)*
Grey cast iron	1.5535 e^{-6}	2.9172e^{-5}	2.9003e^{+6}	1198.72	2.6018e^{+6}	1.0691e^{+6}	1223.45	6.417e^{+6}	2.3503e^{+6}
Stainless steel	9.7161e^{-7}	1.823e^{-5}	3.1657e^{+6}	1238.232	1.1056e^{+6}	0.47049e^{+6}	1223	3.6028e^{+6}	3.1489e^{+6}
Titanium alloy	9.9108e^{-7}	3.0532e^{-5}	2.6558e^{+6}	1227.31	1.4574e^{+6}	0.61276e^{+6}	1225.31	2.9663e^{+6}	1.9205e^{+6}
Al-alloy	9.2822e^{-7}	4.3639e^{-5}	2.7301e^{+6}	1161.63	4.9673e^{+6}	1.9977e^{+6}	1223.77	17.45e^{+6}	5.7453e^{+6}
Carbon ceramic composite	9.2176e^{-7}	1.7294e^{-10}	3.1897e^{+6}	1207.46	2.2035e^{+6}	0.91105e^{+6}	1223	0.5350e^{+6}	0.17955e^{+6}
Al-metal matrix composite	1.4508e^{-7}	7.0362e^{-6}	2.762e^{+6}	1160.58	5.0492e^{+6}	2.0297e^{+6}	1223.2	0.61689e^{+6}	0.20525e^{+6}
Al-silicon carbide MMC	3.2e^{-7}	1.7521e^{-5}	2.8972e^{+6}	1164.16	4.7714e^{+6}	1.9212e^{+6}	1223	0.61323e^{+6}	0.2041e^{+6}
E-Glass	1.0108e^{-6}	4.8e^{-5}	2.9835e^{+6}	1265.16	0.13e^{+6}	0.10534e^{+6}	1223.02	0.10673e^{+6}	4.4607e^{-4}

Static structural analysis: On applying of 4962.7634 Newton of load on disc brake rotor of different materials, the minimum deformation is found for aluminum metal matrix composite when compared with other materials.
Similarly, the strain and stress values are also in the desirable limits for rotor with aluminum metal matrix composite material.

Steady state thermal analysis: The heat generated should be dissipated at a faster rate. On comparing all materials, aluminum metal matrix composite generates the least temperature i.e. 1160.58 K or 887°C.
Similarly, higher heat flux of 5.0492e^{+6} (W/m^2).
The same kind of phenomenon is also observed in transient thermal analysis.

For the same amount of temperature generation, the heat flux for the vented with cross-drilled holes disc brake rotor with aluminum metal matrix composite material is high.
Here the Static structural, Steady-state and Transient thermal analysis of the profile is selected with an Aluminum metal matrix composite material is shown in figures below.

Static structural analysis:

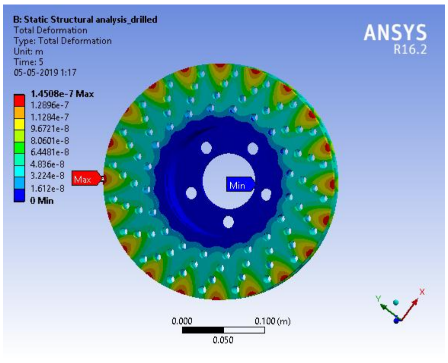

Fig.2: Total deformation

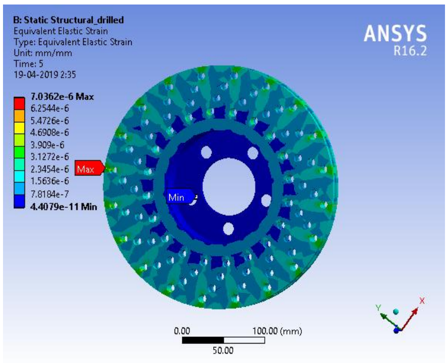

Fig.3: Equivalent elastic strain

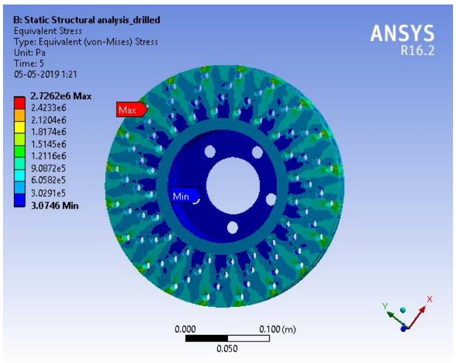

Fig.4: Equivalent stress

Steady state thermal analysis:

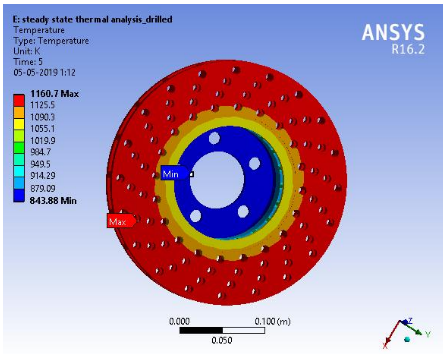

Fig.5: Temperature distribution

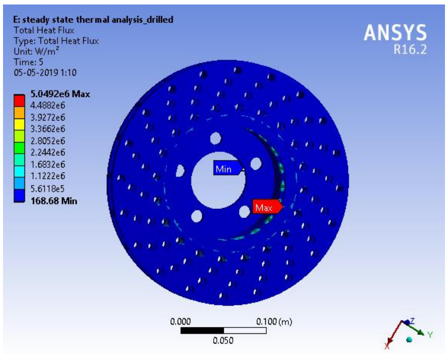

Fig.6: Total heat flux

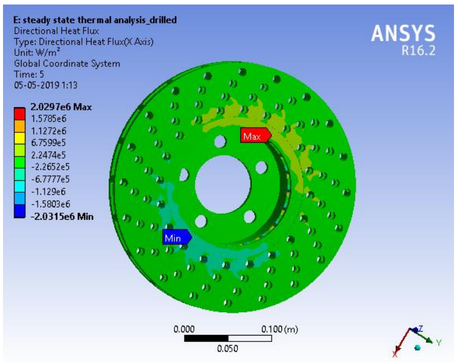

Fig.7: Directional heat flux

Transient thermal analysis:

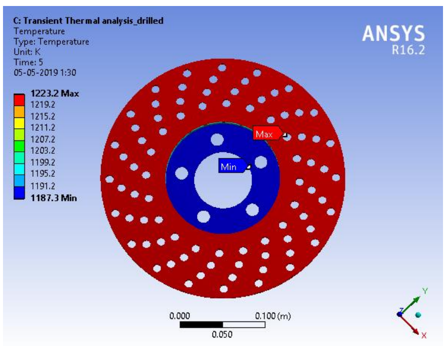

Fig.8: Temperature distribution

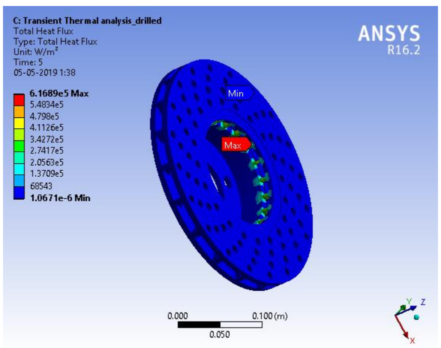

Fig.9: Total heat flux

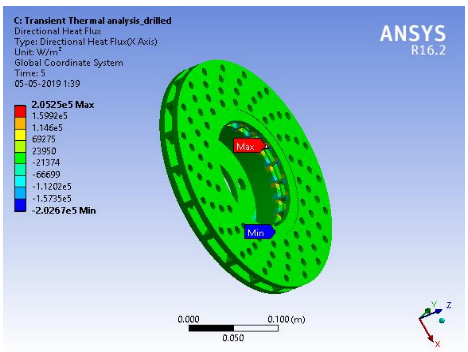

Fig.10: Directional heat flux

IV. CONCLUSION

The figures which are shown above reveals the thermal stress, strain concentration and deformations of the disc brake rotor with aluminum metal matrix composite material. From all materials which are taken into consideration, aluminum metal matrix composite will show the desirable results for disc brake rotor (vented with cross-drilled holes) which bares maximum thermal stresses induced due to friction between brake pad and surface of disc rotor and also dissipates the heat generated at a faster rate. So aluminum metal matrix composite material is preferred because of less deformation, high strain and stress along with high heat flux when compared with other materials.

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