Coupled Thermal and Structural Analysis of Brake Disc Rotor Manufactured from Aluminum Metal Matrix Composite (AMMC) reinforced with Silicon Carbide

Apoorv S. Kulkarni, Kiran C. Hegade, Omkar V. Karale & Parth S Joshi
B. E. Students, Department of Mechanical Engineering, Trinity College of Engineering and Research, Pune, India

Abstract: *The motive of undertaking the project of "Coupled Thermal and Structural Analysis of Brake Disc Rotor manufactured from AMMC" is to study and evaluate the performance of brake disc rotor under severe braking conditions. A brake is a device by means of which an artificial frictional resistance is applied to a moving machine member in order to stop the motion of the machine. Generally, cast iron is used to manufacture brake disc rotor, but AMMC is selected considering crucial advantages of the AMMC over cast iron material. AMMC refers to a class of light weight high performance Aluminium centric material systems. As silicon carbide is added in the AMMC as a reinforcement, it reinforces the overall mechanical and thermal properties of the AMMC. The objective of coupled analysis is to investigate the temperature distribution and heat flux across the brake disc and to couple its effects with structural analysis to check the validity of the disc brake rotor under thermal and structural load. The model of the brake disc rotor is developed by using solid modelling software Creo Parametric 2.0. Further the analysis is done by using ANSYS Workbench.*

Keywords: *Disc Brake, Coupled Thermal and structural analysis Creo Parametric, AMMC, Silicon Carbide, ANSYS Workbench*

1.Introduction

In today's growing automotive field the competition for better performance is growing enormously. The importance of good braking system is not only for safety but also for staying competitive and improving performance of the system. 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 friction pad held in position by retaining pins, spring plates. The passages are so connected to one another for bleeding. Each cylinder contains rubber-sealing ring between the cylinder and piston. Due to application of brakes on the car disc brake rotor, heat generation takes place due to friction and this temperature so generated has to be conducted and dispersed across the disc rotor cross section. An investigation into usage of new material is required which improve braking efficiency and provide greater stability to the vehicle.

1.1 Brake Disc Rotor

The Disc Brake discs are commonly manufactured out of grey cast iron. The SAE maintains a specification for the manufacture of grey cast iron for various applications. For Normal car and light truck applications the SAE specification is J431 G3000 (superseded to G10). This specification dictates the correct range of hardness, chemical composition, tensile strength and other properties necessary for the intended use. Some racing cars and airplanes use brakes with carbon fiber discs and carbon fiber pads to reduce weight. Wear rates tend to be high and braking may be poor until the brake is hot. It is investigated that the temperature distribution, the thermal deformation and the thermal stress of automotive discs have quiet close relations with car safety; therefore, much research in this field has been performed.

1.2 Aluminium Metal Matrix Composite (AMMC)

The term "composite" broadly refers to a material system which is composed of a discrete constituent distributed in continuous phase, and which derives its distinguishing characteristics from the properties of constituents, from the geometry and architecture of constituents and from properties of the boundaries between constituents. Composite materials are usually classified on the basis of the physical or chemical nature of the matrix phase e.g. polymer matrix, metal-matrix and ceramic composites. In AMCs one of the constituents is Aluminium/ Aluminium alloy which forms percolating network and is termed as matrix phase. The other constituents are embedded in this Aluminium/ Aluminium alloy matrix and serve as reinforcement, which is usually non-metallic and commonly ceramic such as SiC and Al2O3. The properties of AMCs can be tailored by varying the nature of constituents and their volume fraction.

The major advantages of AMCs compared too unreinforced materials are as follows,

- Greater strength
- Improved stiffness
- Reduced density (weight)
- Improved high temperature properties
- Controlled thermal expansion coefficient
- Thermal/ heat management
- Enhanced and tailored electrical performance
- Improved abrasion and wear resistance
- Control of mass (especially in reciprocating applications)
- Improved damping capabilities.

There has been interest in using Aluminium based metal matrix composites for brake discs and drum materials in recent years. While the friction and wear of AMMCs were high speeds and loads the behavior could be greatly improved beyond that of iron discs, given the correct match of pad and disc material.

1.3 Reinforcement of Silicon Carbide

Silicon Carbide is the only chemical compound of carbon and silicon. It was originally produced by a high temperature electro-chemical reaction of sand and carbon. Silicon carbide is an excellent abrasive and has been produced and made into grinding wheels and other abrasive products for over one hundred years. Today the material has been developed into high quality technical grade ceramic with very good mechanical properties.

It is used in abrasives, refractoriness, ceramics and numerous high-performance applications. The material can also be made an electrical conductor and has applications in resistance heating, flame igniters and electronic components. Silicon carbide is composed of tetrahedral of carbon and silicon atoms with strong bonds in crystal lattice. This produces a very hard and strong material.

The properties of silicon carbide are described as follows. Mechanically, silicon carbide has low density, high strength, high hardness as well as high elastic modulus. Thermal properties of silicon carbide are also excellent as it has low thermal expansion, high thermal conductivity and excellent thermal shock resistance. Also it has superior chemical inertness.

As silicon carbide is added in the AMMC as a reinforcement, it also reinforces the overall properties of the AMMC. It improves the mechanical properties of the AMMC, it increases the strength and hardness of the composite. And also it improves the thermal conductivity and thermal shock resistance of the material.

2. Mathematical Modelling of Brake Disc Rotor

In the aspect of car accident prevention, the braking performance of vehicles has been a critical issue. The rotor model forces are calculated for the car moving at velocity 27.77 m/s and following is the calculation procedure.

Data:

1) Mass of the vehicle = 1300 kg
2) Initial velocity (v) = 27.77 m/s (100 kmph)
3) Brake rotor diameter = 0.215 m
4) Axel weight distribution = 35% on each side (γ) = 0.35
5) Input driver force = 150N
6) Pedal ratio = 5:1
7) Diameter of master cylinder (d_m) = 25.4 mm
8) Area of mater cylinder (A_m) = $5.16*10^{-4}$
9) Brake line pressure (P_c) = 1453488.37 Pa
10) Caliper piston diameter (d_p) = 38.1 mm
11) Area of caliper (A_c) = $1.15*10^{-3}$ m^2
12) Coefficient of friction of pad (μ)= 0.47
13) Effective radius (D_e) = 0.145 m

1. **Clamping Force**

Clamping force (N) = 2*μ* force on caliper

Force on caliper = P_c*A_c* 2 (2 Pistons)

= $1453488.37*1.15*10^{-3}$

= 3343 N

Clamping Force (N) = 2* 0.47* 3343

= 3142.42 N

2. Braking Torque

Braking Torque (T_b) = $N*R_e$

= 3142.42*0.0725

= 227.82 Nm

3. Braking Distance

Work Done = Clamping Force*x

x = Distance travelled by the vehicle before it comes to rest

Kinetic energy of the vehicle = ½ $m*v^2$

m = Mass of the vehicle = 1300 kg

v = velocity of the vehicle = 100 km/h = 27.77 m/s

In order to bring vehicle at rest

Work done = Kinetic energy

$N*x = ½*\gamma* m*v^2$

$x = m*v^2 / 2*N$

$$= \frac{0.35*1300*27.77^2}{2*3142.42}$$

= 55.83 m

4. Stopping time

$$\text{Stopping time } (t) = \frac{2*x}{v+v_f}$$

$$= \frac{2*55.83}{27.77+0}$$

= 4.02 sec

5. Kinetic Energy

Kinetic Energy (K.E) = $½ *\gamma*m*(v-v_f)^2$

$= ½ *0.35*1300*(27.77-0)^2$

=175441.83 J

6. Braking Power

$$\text{Braking power } (P_b) = \frac{K.E}{t}$$

$$= \frac{175441.83}{4.02}$$

= 43642.24 Watt

7. Heat Generated

Heat Generated = Total Kinetic Energy

= 175441.83 J

8. Rubbing Area

Rubbing Area = $\pi/4 * (D-D_e)^2 * 2$

$= \pi/4 * (0.215-0.145)^2 * 2$

$= 7.6969 * 10^{-3}\ m^2$

9. Heat Flux

Heat Flux = Heat Generated / Time / Rubbing Area

$= 175441.83 / 4.02 / 7.6969 * 10^{-3}$

= 5670106.96 Watt/m^2

10. Maximum Temperature

Single stop temperature rise is the temperature rise due to single braking condition.

$$T_{max} = \frac{0.527 * q * \sqrt{t}}{\sqrt{(\rho*C*K)}}$$

T_{max} = maximum disc temperature (ºC)

q = Heat flux (W/m2)

t = Break on time (sec)

ρ = Density of disc brake material (Kg/m3)

C = Brake disc specific heat capacity (J/Kg/K)

K = Brake disc thermal conductivity (W/mK)

T_{amb} = Ambient temperature (ºC)

$$= \frac{0.527 * 5670106.96 * \sqrt{4.02}}{\sqrt{(2698.9 * 836.8 * 181.6}} + 20$$

= 315.83 ºC

11. Fade stop temperature rise

The temperature rise after repeated stopping can also be approximated, although so many variables exist, it is suggested that it is only used for basic optimization work.

$$\Delta T = \frac{P * t}{\rho * C * v}$$

$$= \frac{43642.24 * 4.02}{9698.9 * 836.8 * 7.039 * 10^{-4}}$$

$$= 110.3\ ^{o}C$$

3. Software Modelling of Brake Disc Rotor

The geometric model of the disc was created using software Creo Parametric 2.0. The solid model is shown in the Figure

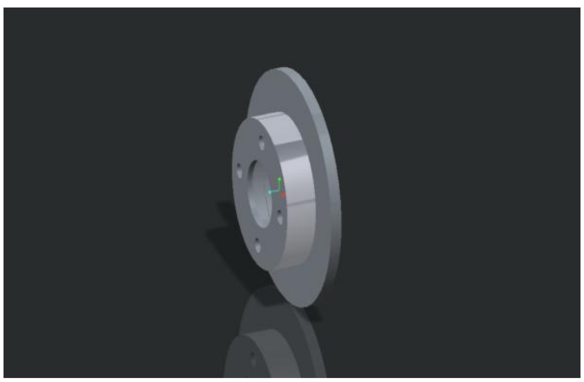

Figure 1: Design of the brake disc rotor

4. Finite Element Analysis

The finite element method is a powerful tool to obtain the numerical solution of wide range of engineering problem. The method is general enough to handle any complex shape or geometry, for any material under different boundary and loading conditions. The generality of the finite element method fits the analysis requirement of today's complex engineering systems and designs where closed form solutions of governing equilibrium equations are usually not available. In addition, it is an efficient design tool by which designers can perform parametric design studies by considering various design cases, (different shapes, materials, loads, etc.) and analyze them to choose the optimum design.

The method has gained increased popularity among both researchers and practitioners. The basic concept of finite element method is that a body or structure may be divided into small elements of finite dimensions called "finite elements". The original body or the structure is then considered, as an assemblage of these elements connected at a finite number of joints called nodes or nodal points.

Figure 2: Meshing of the brake disc rotor

4.1 Thermal Analysis

A Thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities are:

1. The temperature distributions
2. The amount of heat lost or gained
3. Thermal fluxes

4.1.1 Types of Thermal Analysis

1. A Steady State Thermal Analysis determines the temperature distribution and other thermal quantities under steady state loading conditions. A steady state loading condition is a situation where heat storage effects varying over a period of time can be ignored.
2. A Transient thermal analysis determines the temperature distribution and other thermal quantities under conditions that vary over a period of time.

Due to the application of brakes on the car disc brake rotor, heat generation takes place due to friction and this temperature so generated has to be conducted and dispersed across the disc rotor cross section. The condition of braking is very much severe and thus the thermal analysis has to be carried out.

In this study transient thermal analysis is performed because the application of the brakes on any vehicle is also a function of time. The brakes are applied for several seconds to a moving vehicle until it comes to halt. In a standard braking test brakes are applied to a moving vehicle at 100km/h until it stops

Imperial Journal of Interdisciplinary Research (IJIR)
Vol-2, Issue-6, 2016
ISSN: 2454-1362, http://www.onlinejournal.in

and the braking time and stopping distance are measured. In transient thermal analysis the temperature variation and the heat flux variation are analyzed across the area of the brake disc rotor.

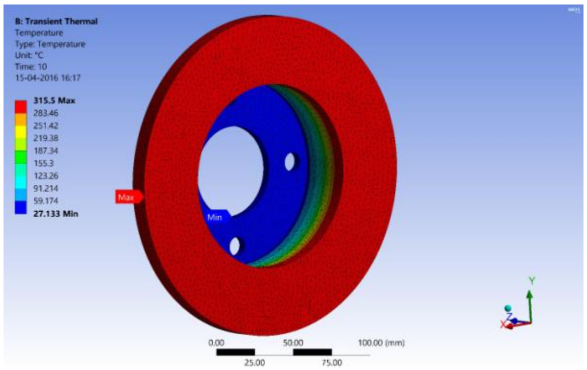

Figure 3: Temperature distribution

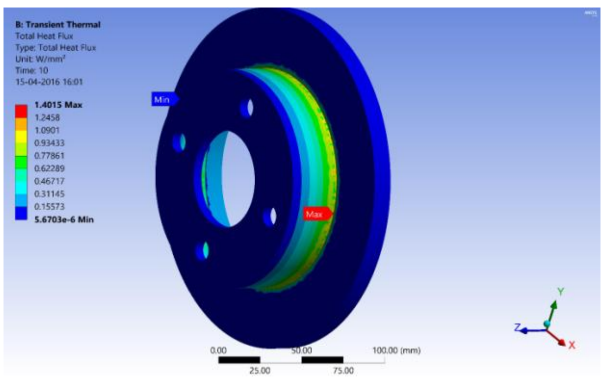

Figure 4: Heat flux distribution

4.2 Structural Analysis

Structural analysis is the most basic application of finite element analysis.

Structural analysis has a wide application in mechanical and electrical engineering. The part of structural analysis in structural failures in mechanical engineering deals with the reasons of for failure of objects and fix objects which fail to perform. The structural failures in mechanical engineering is classified into two types, static failures and fatigue failures. The static structural failure is related; when a force being applied on the object which is analyzed either breaks down or gets deformed depending on the criterion which is set for failure.

The fatigue structural failure on the other hand is when an object fails after a number of loading, unloading cycles. The reasons for imperfections could be a few; such as imperfections in design of objects, minutes such as microscopic cracks on the surface, which grow slightly with each cycle until it becomes large enough to cause ultimate failure. Failure in the context to structural analysis is not defined when a component breaks but when a component fails to work as it was intended to.

Structural analysis in mechanical engineering is used by mechanical engineers to check whether the design is safe under required loading conditions.

4.2.1 Static Structural Analysis

A static structural analysis calculated the effects of steady loading condition on a structure, while ignoring inertia and damping effects such as those caused by time varying loads. A static analysis can however include steady inertia loads (such as gravity and rotational velocity), and time varying load that can be approximated as static equivalent loads (static equivalent wind and seismic loads).

The structural analysis on the brake disc rotor is performed to check the validity of the component under the actual conditions such as caliper pressure acting on the brakes and the deformation and stresses are found out.

It is very difficult to exactly model the brake disc. There is always a need of some assumptions to model any complex geometry. The assumptions are always made depending upon the details and the accuracy required in modeling.

Assumptions made for static structural analysis:

1. The analysis is done taking the distribution of the braking torque between the front and rear axle is 70:30
2. Brakes are applied on all the four wheels.
3. The kinetic energy of the vehicle is lost through the brake discs i.e. no heat loss between the tyres and the road surface and the deceleration is uniform.
4. The disc brake model used is of solid type and not the ventilated one.

Displacement in axial direction on flange is constrained in one side of the disc.

4.3 Coupled Thermal and Structural Analysis

A coupled thermal and structural analysis is done to check he factor of safety of the material or the component under thermal as well as structural loading conditions.

The brake disc rotor is loaded both thermally as well structurally, i.e. when brakes are applied due to the friction between brake pads and disc thermal loads are induced and due to the application of force by the brake pads on the rotor, axial forces are exerted by the pads on the brake disc rotor. Also due to the inertia of the vehicle between the time of application of the brakes till the vehicle comes to rest, torsional forces are also applied on the brake disc rotor.

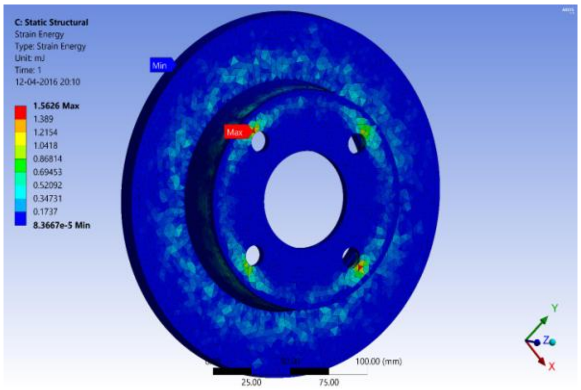

Figure 5: Strain energy in the brake disc rotor

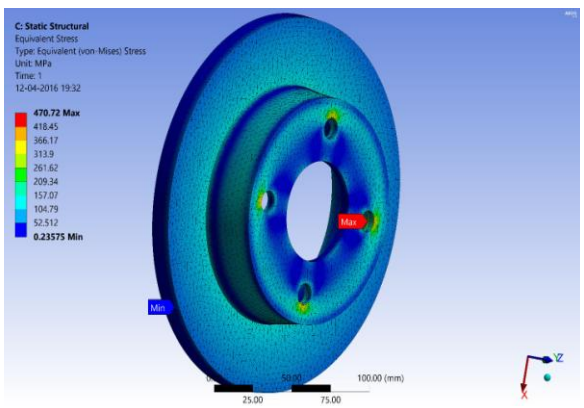

Figure 6: Equivalent stress in the brake disc rotor

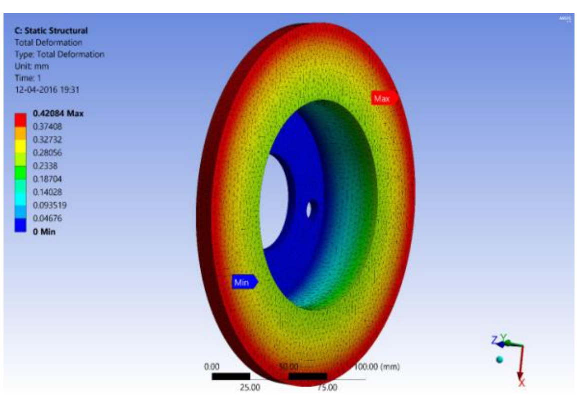

Figure 7: Total Deformation in the brake disc rotor

5. Conclusion

In order to improve the braking efficiency and provide greater stability to vehicle. An investigation was carried out and the suitable hybrid composite material, Aluminium Metal Matrix Composite which is lighter than cast iron and has good Young's modulus, Yield strength and density properties. The low weight, the hardness, the stable characteristics also in case of high pressure and temperature and resistance to thermal shock.

The following conclusions are drawn from the present analysis

- Coupled Thermal and Static structural analysis was carried to check the validity of the component.
- The Temperature distribution and Heat flux distribution is plot with respect to time.
- The maximum heat flux was observed to be 1.4015 W/mm^2
- The maximum Von Mises stress was observed to be 470.72 MPa.
- The maximum deformation was observed to be 0.42084 mm
- The brake disc design is safe based on the Strength, Rigidity and Thermal Criteria.
- It is safe to say that Aluminium Metal Matrix Composite can be used to manufacture an automobile brake disc rotor.

6. References

[1] K. Sowjanya, S. Suresh, "Structural Analysis of Disc Brake Rotor", International Journal of Computer Trends and Technology (IJCTT) – volume 4 Issue 7- July 2013, PP 2295-2298.

[2] Manjunath T V, Dr Suresh P M, "Structural and Thermal Analysis of Rotor Disc of Disc Brake", International Journal of Innovative Research in Science, Engineering Technology, volume 2, issue 12 – December 2013, PP 7741-7749.

[3] K Naresh Babu, T. Siva Krishna, "Structural Design and Thermal Analysis of Car Disc Brake Rotor", International Journal of Advanced Engineering Research and Studies, E-ISSN2249-8974.

[4] Guru Murthy Nathi, T N Charyulu, K Gowtham, P Satish Reddy, "Coupled Structural/ Thermal Analysis of Disc Brake", International Journal of Research in Engineering and Technology, volume: 01, Issue 04 – December 2012, PP 539-553.

[5] Swapnil R. Abhang, D. P. Bhaskar, “Design and Analysis of Disc Brake”, International Journal of Engineering Trends and Technology, volume 8 Number 4 – Feb 2014, PP 165-167.

[6] Ishwar Gupta, Gaurav Saxena, Vikas Modi, “Thermal Analysis of Rotor Disc of Disc Brake of BAJA SAE 2013 Car Through Finite Element Analysis”, International Journal of Engineering Research and Applications, ISSN 2248-9622.

[7] Anudeep B. Naga Sunil. B, “Design and Couple Field Analysis of Aircraft Disc Brake Rotor”, International Journal of Engineering Research and General Science, volume 3, Issue 4, Part-2, July-August 2015, PP 316-323.

[8] M K Surappa, “Aluminium Matrix Composites: Challenges and Opportunities”, Sadhna Vol.28, Parts 1 & 2, February/April 2003, PP 319-334.

[9] P. O Babalola, C. A Bolu, A. O Inegbenebor, K. M Odunfa, “Development of Aluminium Matrix Composite: A review”, Online International Journal of Engineering and Technology Research, volume 2, April 2014, PP 1-11.

[10] Manoj Singla, D. Deepak Dwiwedi, Lakhvir Singh, Vikas Chawla, “Development of Aluminum Based Silicon Carbide Particulate Metal Matrix Composite”,Journal of Minerals & Materials Characterization & Engineering, volume 8, No. 6, PP 455-467, 2009.

[11] Kok M., “Production and Mechanical Properties of Al_2O_3 particle-reinforced 2024 aluminium alloy composites”, Journal of Material Processing Technology, volume 161, 2005 PP 381-387.

[12] Dr. Karnik Madhuri G., Sonawane Parushuram M., Kulkarni Swanand R., “Effect of Graphite Addition on the Mechanical Properties of Stir Cast Particulate Aluminium Metal Matrix Composite Reinforced with Alumina and Silicon Carbide.