Thermal Analysis of Disc Brake Made of Different Materials

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Abstract

Brake disc rotor is an important component of disc brake assembly which is used to decelerate or stop the vehicle. When brakes are applied the temperature of the brake disc increases and is subjected to thermal stresses. So a careful design and material selection is necessary to avoid the premature failure of the disc brake. An attempt is made to analyse the brake disc using analytical as well as finite element analysis for its temperature as well as thermal stress distribution. Four different materials were selected for this purpose namely cast iron, maraging steel, Aluminium metal matrix composites and E-Glass. By using vehicle specifications the parameters like brake torque, heat flux and single stop temperature were calculated. Maximum temperatures were calculated for all the materials using analytical method as well as finite element analysis. Maximum principal stresses were also calculated using both analytical as well as finite element analysis. The results obtained were compared and found that ALMMC has less temperature and less stress. So it is concluded that ALMMC is the most appropriate material among all four material selected for brake disc.

Keywords — *Brake disc; Material selection, Analytical analysis, Finite element method. .*

I. INTRODUCTION

One of the most important active safety features of automobile is a disc brake assembly which is located on the front axle. Brake disc rotor is the important component of the disc brake system. For safe driving the brake system is to be good enough to provide safe and repeatable stopping. Brake pads which are made up of friction materials are to be pressed against disc rotor on both sides hydraulically by using brake caliper device. When friction pads are pressed against the disc, the kinetic energy of the vehicle gets converted into heat and the vehicle gets decelerated. The heat generated dissipates into surroundings. So brake systems work with the principle of converting kinetic energy of the vehicle into heat through friction acting between brake pads and the rotor. So the efficiency of the brake system depends on the amount of friction between the pads and the rotor and how well the generated heat gets dissipated into surroundings failing which may lead to the failure of the brake system due to overheating and thermal stresses developed thereby. Brake system assembly includes the parts like calliper, piston and cylinder, pads and rotor [1,2].

II. MATERIAL OF ROTOR DISC OF DISC BRAKE

Greenhouse gas emission from the vehicle is the major challenge faced by automotive industries. Lighter the vehicle, lesser will be the fuel consumption. With reduction in fuel consumption leads to reduced greenhouse gas emissions. An every effort is made by automotive industries to reduce the weight of the vehicles by using low weight materials for the construction various parts of the vehicle. The usage of aluminum which is a well-known low weight material increased in automobile manufacturing industries. Reduction in the weight improves fuel economy and reduces emissions. Composite materials provide good strength t weight ratio. Aluminum alloy based metal matrix composites with ceramic particulate can be used for disc rotor of a disc brake system [3,4].

Composite material reinforcement has shown great promise for such applications. Aluminum based composite materials having a lower density and higher thermal conductivity as compared to the conventionally used gray cast iron. If the aluminum composite materials are used in brake system a weight reduction of 50 – 60% can be expected. Also it is observed that these composite materials have the potential to perform better under severe service conditions like higher speed, higher load etc. which are increasingly being encountered in modern automobiles. Since brake disc or rotor is a crucial component from safety point of view, materials used for brake systems should have stable and reliable frictional and wear properties under varying conditions of load, velocity, temperature and environment, and high durability. There are several factors to be considered when selecting a brake disc material [5]. The ability of brake disc material to withstand high friction and abrasive wear is the important criteria. The brake disc must have enough thermal storage capacity to prevent distortion or cracking from thermal stress until the heat can be dissipated. This criteria is very crucial in repeated stops from high speeds but not so important in single stop. Commonly grey cast iron is used for the construction of the disc brake rotors[6]. The SAE specifications are to be followed for the manufacture of grey cast iron for various applications. SAE specification J431 G3000 (superseded to G10) is used for normal car and light truck applications 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 or grabby until the brake is hot. The temperature distribution, the thermal deformation and the thermal stress of automotive disc brake have quite close relations with car safety.

When the brakes are applied by pressing the friction pads on to the disc rotor, heat generates due to friction and this heat flux flux has to be conducted and dispersed across the disk rotor cross section. The condition of braking is very much severe and thus the thermal analysis has to be carried out.

The thermal structural stability of the disc brake is influenced by the thermal and elastic property of material properties, rate of hydraulic pressure applied on pad and the basic design for the disc rotor.

Some of the thermally most important properties of disc brake rotor are as follows:-

- Ability to store the heat generated which is known as thermal capacitance. It depends on density and specific heat. Thermal capacitance plays important role during short braking. It is also important during initial braking process.
- Ability to redistribute thermal energy which is termed as Thermal conductivity. During long and low intensity braking, the peak temperature is largely depends on the disc material’s conductivity. However, the thermal conductivity has a little effect during short braking.
- Thermal expansion coefficient (related to location of friction contact due to the thermal deformation) affects the tendency towards hot spotting and thermal disc thickness variation (DTV) generation. The temperature gradients of the disc brake can cause to temporary DTV owing to the uneven thermal expansion of the material

Here for thermal analysis we have considered 4 rotor disc materials cast iron, maraging steel , Aluminum metal matrix composites, & E -glass fiber. Following material Properties were selected for the modified Disc Brakes.

A. *Cast Iron and its Properties*

Cast iron usually refers to grey cast iron, but identifies a large group of ferrous alloys, which solidify with a eutectic. Iron accounts for more than 95%, while the main alloying elements are carbon and silicon. The amount of carbon in cast iron is the range 2.1-4%, as ferrous alloys with less are denoted carbon steel by definition. Cast irons contain appreciable amounts of silicon, normally 1-3%, and consequently these alloys should be considered ternary Fe-C-Si alloys. Here graphite is present in the form of flakes. Disc brake discs are commonly manufactured out of a material called grey cast iron.

Cast iron which comes under a group of iron-carbon alloys contains carbon greater than 2%. The alloy constituents affect its color when fractured: white cast iron has carbide impurities which allow cracks to pass straight through; grey cast iron has graphite flakes which deflect a passing crack and initiate countless new cracks as the material breaks.

Carbon (C) and silicon (Si) are the main alloying elements, with the amount ranging from 2.1–4 wt% and 1–3 wt%, respectively. Iron alloys with less carbon content are known as steel. While this technically makes these base alloys ternary Fe–C–Si alloys. Since the compositions of most cast irons are around the eutectic point of the iron–carbon system, the melting temperatures closely correlate, usually ranging from 1,150 to 1,200 °C (2,100 to 2,190 °F), which is about 300 °C (572 °F) lower than the melting point of pure iron.

B. *Maraging Steels and its Properties*

Maraging steels (a portmanteau of "martensitic" and "aging") are steels (iron alloys) that are known for possessing superior strength and toughness without losing malleability, although they cannot hold a good cutting edge. *Aging* refers to the extended heat-treatment process. These steels are a special class of low-carbon ultra-high-strength steels that derive their strength not from carbon, but from precipitation of intermetallic compounds. The principal alloying element is 15 to 25 wt. % nickel. Secondary alloying elements, which include cobalt, molybdenum, and titanium, are added to produce intermetallic precipitates,. Original development (by Bieber of Inco in the late 1950s) was carried out on 20 and 25 wt.% Ni steels to which small additions of Al, Ti, and Nb were made; a rise in the price of cobalt in the late 1970s led to the development of cobalt-free maraging steels.

C. ALMMC(Aluminum metal matrix composites) and its Properties

A metal matrix composite (MMC) is composite material with at least two constituent parts, one being a metal necessarily, the other material may be a different metal or another material, such as a ceramic or organic compound. When at least three materials are present, it is called a hybrid composite.

Aluminum is the most popular matrix for the metal matrix composites (MMCs). The Al alloys are quite attractive due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, high thermal and electrical conductivity, and their high damping capacity. Aluminum matrix composites (AMCs) refer to the class of light weight high performance aluminum centric material systems. The reinforcement in AMCs could be in the form of continuous or discontinuous fibers, whisker or particulates, in volume fractions ranging from a few percent to 70%. In the last few years, AMCs have been utilized in high-tech structural and functional applications including aerospace, defense, automotive, and thermal management areas, as well as in sports and recreation. There has been interest in using aluminum based metal matrix composites for brake disc and drum materials in recent years. While much lighter than cast iron they are not as resistant to high temperatures and are sometimes only used on rear axles of automobiles because the energy dissipation requirements are not high as compared to front axle. While the friction and wear of ALMMC 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 [12].

D. (Electrical)E-Glass Fiber and its Properties:

E-Glass or electrical grade glass was originally developed for standoff insulators for electrical wiring. It was later found to have excellent fiber forming capabilities and is now used almost exclusively as the reinforcing phase in the material commonly known as fiberglass.

The use of E-Glass as the reinforcement material in polymer matrix composites is extremely common. Optimal strength properties are gained when straight, continuous fibers are aligned parallel in a single direction. To promote strength in other directions, laminate structures can be constructed, with continuous fibers aligned in other directions. Fiber dimension and to some extent proper-ties can be controlled by the process variables such as melt temperature (hence viscosity) and draw-ing/spinning rate. The temperature window that can be used to produce a melt of suitable viscosity is quite large, making this composition suitable for fiber forming.

III. MODELING OF THE ROTOR DISC

As a first step a structural model of the brake disc with pads was prepared using CATIA software. 3-D model developed for the analysis is shown in the figure 1. The model developed was imported into ANSYS workbench. Thermal structural analysis was done on this model of simplified version of disc brake consisting of two main components brake disc and friction pads. These are the critical components which are subjected higher temperatures and thereby thermal stresses.

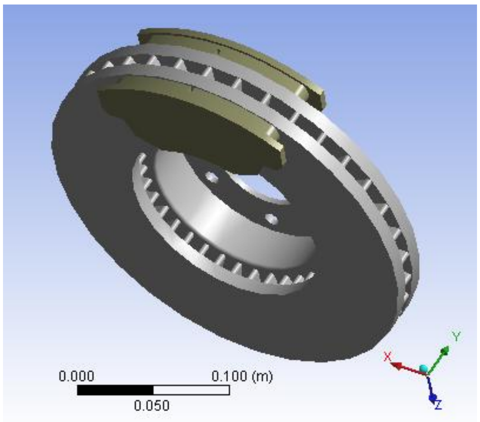


Figure 1 3D Model of 24 mm Disc brake

IV. RESULTS AND DISCUSSION

The results for temperatures and thermal stresses obtained by analytical method and finite element analysis are compared. The obtained data is given in the table 1 given below. It is observed that the results obtained for temperature distribution are almost similar for both methods. In the case of analytical calculation the temperature values are slightly higher. But the distribution pattern is almost the same. Similarly the values of thermal stresses also higher in case of analytical calculations than the analysis using ANSYS. Thermal stress values are also higher for analytical calculation compared to ANSYS analysis both compressive stresses as well as tensile stresses. It is observed that the similarity is maintained in both temperature distribution and thermal stress variation in both methods.

Table 1: Comparison of the Analytical and FEM Results of Brake Disc

S. NO	Material	Analytical Max. Temp °c	FEM Max. Temp °c	Analytical Max. principal Stress Mpa	FEM Max. principal Stress Mpa
1	Cast iron	185.41	167.56	197	140.42
2	Maragin g steel	363.62	306.89	211	154.35
3	ALMMC	166.85	148.97	186	129.24
4	E-Glass	411.74	375.37	242	185.81

A. Results of Thermal Analysis

Figure 2, Figure 3 and Figure 4 show the temperature Distribution for Grey Cast Iron Rotor Disc, maraging steel rotor disc and E-Glass rotor disc respectively, predicted by the FE analysis in brake application. In order to investigate the temperature and von Mises stress histories, surface of the disc is selected, because surface area is subjected to high temperature and stresses. These values are gradually reduced from outer edge to inner edge.

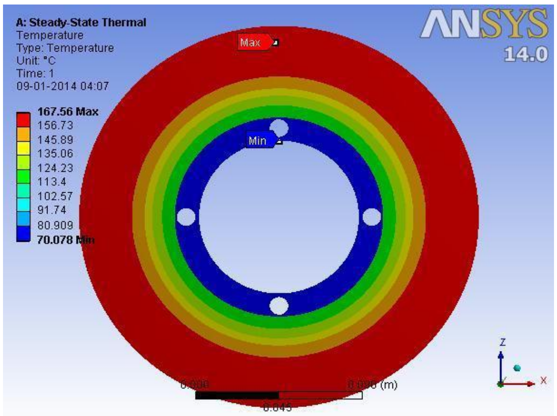
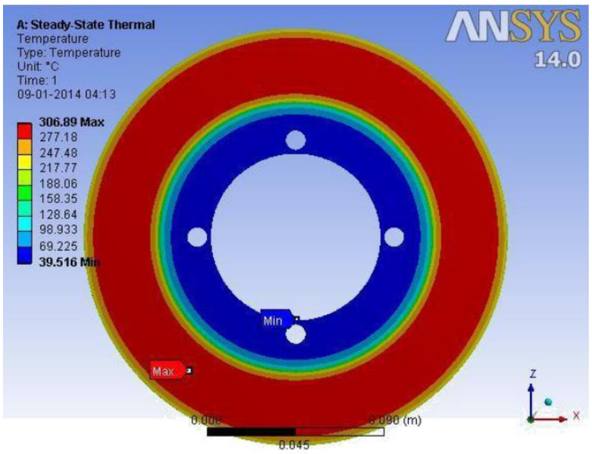


Figure 2 Temperature Distribution for Grey Cast Iron Rotor Disc



.Figure 3 Temperature Distribution for maraging steel Rotor Disc

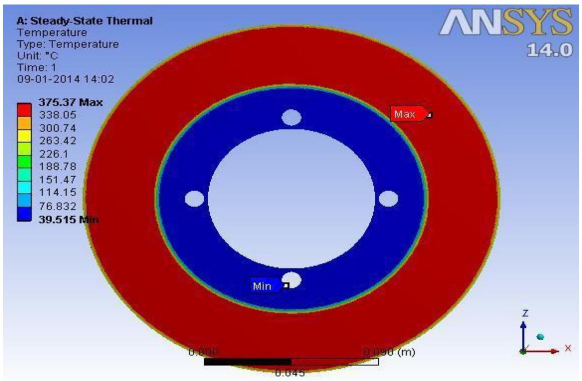


Figure 4 Temperature Distribution for E-Glass Rotor Disc

Table 2 Maximum and Minimum Temperatures of Disc Brake

S.No	Material	Max. Temp(˚C)	Min. Temp(˚C)
1	Grey Cast Iron	167.56	70.078
2	Maraging steel	306.89	39.516
3	ALMMC	148.97	98.316
4	E-Glass	375.37	39.515

The maximum and minimum temperatures obtained for all four materials are given in the table 2.

Thermal analysis was done after applying the braking force using friction between pads and disc for time duration of 5 seconds. The maximum temperature obtained in ALMMC rotor disc is at rubbing surface & is observed to be 148.97 ˚C. By comparing the different results obtained from FEA & analytical method it is observed that rotor disc of ALMMC is the best suitable rotor disc.

V. CONCLUSIONS

Disc brake rotor was analyzed for temperature and thermal stresses using analytical calculations and finite element analysis. A method of analytical calculation and Finite element analysis was given. A step by step procedure of finite element analysis was developed so that anybody can follow the methodology for similar analysis. The method developed in this work can be used to analyze temperature and thermal stress in sliding contact mechanical components. By comparing the analytical results and FEA results, it is found that the values are similar with no much difference. The pattern of variation of temperature is also observed to be the same in both cases. Generally the present study can provide a useful design tool and improve the brake performance of disk brake system.

Based on the results of analysis it is concluded that:

- All the values obtained from the analysis are less than their allowable values. Brake disk design is safe based on the strength and rigidity criteria.
- Braking torque, heat flux and single stop temperature rise are calculated with the help of vehicle specifications.
- Maximum temperature rise is calculated for four different materials, i.e. Gray cast iron, maraging steel ,ALMMC and E-Glass using both Analytical and FEA methods.
- Maximum principle stress obtained from FEA analysis for the material Gray cast iron, maraging steel, ALMMC and E-Glass are 140.42 MPa,

154.35MPa ,129.24MPa, , and 185.81 MPa respectively.

- From Analytical analysis the maximum principle stress obtained for the material Gray cast iron, maraging steel, ALMMC and E-Glass are 197MPa, 211MPa ,186MPa and 242MPa respectively.
- Comparing the results of temperature rise and stress field obtained from analysis it is observed that the values are less in case of ALMMC than the other materials.
- It can be concluded that aluminum metal matrix composite is the most appropriate material for brake disc.
- ALMMC is also of less weight giving better fuel economy and reduction in greenhouse gas emissions.

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