

Computational Study on Structural and Thermal Behavior of Aircraft Disk Brake Rotor for Different Materials

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ABSTRACT

Brakes are one of the most significant safety systems in an aircraft. The rotor will be exposed to large stresses which result in surface cracking, overheating of brake fluid, seals and other components during the braking process. Thus, one of the main tasks for the design of braking system is to reduce the stress, deformation and surface temperature of the brake rotor. This can be achieved by choosing the right material which will undergo the least thermal stresses. In this research a detailed study of structural and thermal analysis is carried out for disc brake rotor of DHC-6 Twin Otter with different materials. The objective of this research is to provide an efficient material for disc brake rotor which can dissipate heat generated during braking at faster rate and also being structurally safe. The materials chosen for the study are Mild Steel, Grey cast iron, Stainless steel, Carbon-carbon composite and Aluminum silicon carbide MMC. From the structural and thermal analysis it was found that the aluminum silicon carbide MMC disc brake rotor exhibits the superior performance against other materials with a mass of 2.37 Kg, deformation of 0.043617 mm, maximum stress of 167.91 MPa, maximum temperature of 250.85 °C and heat flux of 5.2043 W/mm². The mass, stress, deformation and temperature developed in the aluminum silicon carbide MMC rotor is less than the original stainless steel rotor by 61.3%, 3.66%, 6.9% and 35.6% respectively. Similarly, the aluminum silicon carbide MMC rotor provides better heat dissipation as compared to original rotor due to an increment in heat flux by 15.26%.

INDEX TERMS Disc brake, Rotor, Stress, Deformation, Heat flux, Temperature

I. INTRODUCTION

All modern aircraft are fitted with a braking system to assist in slowing and stopping when on the ground. Brakes are fitted to the main landing gear but not generally to the nose or tail wheel.

Any moving aircraft contains kinetic energy by virtue of its motion. The faster the aircraft moves the higher is its momentum or kinetic energy. This energy is proportional to the square of the aircraft's speed. Most brakes use the principle of friction to convert this kinetic energy into heat energy. The brakes must therefore store and dissipate all this heat into the surroundings before subsequent braking stages to have a good braking efficiency.

The large frictional forces generated during braking cause the pads to wear and so careful inspection and maintenance of the system is required to ensure the brakes continue to operate as designed. Brakes are usually hydraulically actuated, but in some cases may be operated through a mechanical actuation system.

This research work deals with the structural and thermal analysis of aircraft disc brake rotor for different materials. Both static structural and thermal analysis are performed to carry out the research. The heat dissipated along the brake disc surface during the periodic braking occurs via

conduction, convection and radiation. The findings of this research provide a useful design tool to improve the performance of disc brake.

The DHC-6 Twin Otter owned by Nepal Airlines was used for this research. The de Havilland DHC-6 Twin Otter is an all metal, high wing, twin-engine, short takeoff and landing (STOL) aircraft. The aircraft is highly maneuverable, rugged in design and can be flown at speeds from 80 to 160 knots. However, the landing speed of the aircraft is taken as 58 kt i.e. 107 km/hr. The aircraft provides total 22 seats for people i.e. 19 seats for passengers, 1 for pilot, 1 for co-pilot and 1 for crew. The maximum take off weight of the aircraft is taken as 5670 kg.

The information on the disc brake rotor used in the DHC-6 Twin Otter rotor is shown in the table 1:

Table 1 Information of disc brake rotor of DHC-6 Twin Otter

Rotor Outer Diameter	176.53 mm
Rotor inner Diameter	123.53 mm
Rotor Thickness	10.922 mm
Single Brake Lining Area	3212 mm ²
Number of Brake Lining	8
Maximum Pressure	4.1 MPa

The main objective of this work is to perform structural and thermal analysis of aircraft disc brake rotor for different materials to provide greater performance.

Rotor disc of disc brake was analyzed by using new materials to improve braking performance and provide greater stability to the aircraft. An attempt has been made to investigate the composite material which is lighter than mild steel or stainless steel and has good Young's modulus and density properties. The structural and thermal analysis of Disc brakes for different materials was performed and the results were compared.

II. LITERATURE REVIEW

2.1 Numerical Modelling for Thermal Analysis

The first law of thermodynamics indicating the thermal conservation of energy as a summation of rate of increase of energy and net heat flux density gives: (A.Belhocine, 2013)

$$\rho C_p \left(\frac{\partial T}{\partial t} + \{v\}^T \{L\} T \right) + \{L\}^T \{Q\} = P \quad (2.1)$$

In our case there is not an internal source ($P=0$), thus, Equation (2.1) is written as:

$$\rho C_p \left(\frac{\partial T}{\partial t} + \{v\}^T \{L\} T \right) + \{L\}^T \{Q\} = 0 \quad (2.2)$$

With,

$$\{v\} = \begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} \quad (2.3)$$

$$\{L\} = \begin{Bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{Bmatrix} \quad (2.4)$$

Where, ρ = density

C_p = heat capacity at constant pressure

v = vector speed of mass transport

v_x = vector speed of mass transport along x axis

v_y = vector speed of mass transport along y axis

v_z = vector speed of mass transport along z axis

T = temperature

t = time

Q = heat flux density

P = Internal heat generation

Fourier's law (2.2) can be written in the following matrix form:

$$\{Q\} = -\{K\}\{L\}T \quad (2.5)$$

With,

$$\{K\} = \begin{bmatrix} k_{xx} & 0 & 0 \\ 0 & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{bmatrix} \quad (2.6)$$

Where,

K = conductivity matrix

k_{xx} = thermal conductivity along x axis

k_{yy} = thermal conductivity along y axis

k_{zz} = thermal conductivity along z axis

As material is assumed to be isotropic, we assume $k_{xx} = k_{yy} = k_{zz}$

By combining Eq 2.2 and 2.5

$$\rho C_p \left(\frac{\partial T}{\partial t} + \{v\}^T \{L\} T \right) = \{L\}^T \{K\} \{L\} T \quad (2.7)$$

By developing Eq (2.7)

$$\begin{aligned} \rho C_p \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) \\ = \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{xy} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_x \frac{\partial T}{\partial z} \right) \end{aligned} \quad (2.8)$$

The initial heat flux q_o entering the disc is calculated by the following formula (Reimpe, 1998)

$$q_o = \frac{1 - \phi}{2} \frac{m g v_o z}{2 A_d \epsilon_p} \quad (2.9)$$

Where, m = mass of vehicle, v_o = velocity, g = acceleration due to gravity, A_d = area where brake experiences, ϵ_p = Factor load distribution on the disc surface, ϕ = rate distribution of the braking forces, z = Braking effectiveness

2.2 Mathematical calculation for the Braking Force

The forces action on disc brake rotor during the application of brake via brake pad are shown on given figure. (Swapnil R. Abhang, 2014)

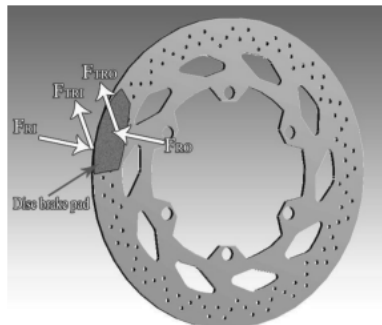


Figure 1 Forces action on Disc Rotor Sources

Inner Tangential force between pad and rotor (Inner face), F_{TRI}

$$F_{TRI} = \mu_1 \cdot F_{RI} \quad (2.10)$$

Where F_{RI} = Normal force between pad brake and rotor (inner)

μ_1 = Coefficient of friction

Then,

$$FRI = P_m / 2 A_p \quad (2.11)$$

Where, P_m = Pressure applied.

A_p = Area of brake pad

b) The outer tangential force between pad & rotor (outer face), F_{TRO} In this case, F_{TRO} equal F_{TRI} because same normal force and same material.

$$F_{TRO} = F_{TRI} \quad (2.12)$$

Here, the assumption is made that frictional force is applied by brake pad on the disc rotor with the equal coefficient of friction.

c) Then Total force (F_T)

$$F_T = F_{TRI} + F_{TRO} \quad (2.13)$$

d) Brake Torque (BT)

$$BT = F_T * R \quad (2.14)$$

Where, R = Radius of rotor disc.

III. RESEARCH METHODOLOGY

The study for this research work mainly includes the following steps:

1. Identification of Problem

Nepal Airlines were using the mild steel disc rotor for their DHC-6 Twin Otter. The discs used to get damaged frequently in one of four ways: scarring, cracking, warping and rusting. Over the time, the material of the disc brake was changed to stainless steel. The stainless steel rotor is found to be more durable than mild steel rotor. However, no research has been carried out by Nepal Airlines on the change in static structural and thermal parameters after modifying material from mild steel to stainless steel. Also, this research focuses on finding another material for the manufacturing of disc brake that provides superior results in performance.

2. Literature Review

A basic information about the brake history, types of brakes, method of brake actuation, types of brake mechanism has been well studied in order to gain the detail information of disc brake rotors. The high preferences are given to the journals and research articles relating to the design, structural and thermal analysis of disc brake rotors.

The information and knowledge gain from the different literature reviews has benefited to make the clear assumption and detail mathematical calculations required to be input while simulating the results. This also provides basic ideas about the dependency of the brake performance of disc brake rotor on the deformation, temperature variation on disc rotor generated due to friction, disc rotor dimensions and the various made up material. The simulation techniques and the process and expected outcomes of different research articles and journals has been carefully studied to predict the positive result of this thesis work as well.

3. Design

3D CAD model have been drafted using solid works software to carry out the thesis work analysis. The dimension of the original disc brake rotor was measured using component maintenance manual and vernier caliper. First 2D of the disc rotor was drafted then 3D CAD model was obtained by extruding 2D sketch. The Boolean operation like subtract command was used to create ventilated holes on disc and holes were equally distributed by using 3D array command on software.

4. Material Selection

Based on the essential properties of disc brake rotor, following materials were selected for the research.

- a. Mild Steel
- b. Stainless Steel
- c. Grey Cast Iron
- d. Carbon Carbon Composite
- e. Aluminum Metal Matrix Composite (AL-MMC)

5. Finite Element Modeling

The 3D CAD model was divided into number of small elements of tetrahedron shape to carry out the structural and thermal analysis. Mesh independent test was performed to choose the number of elements for analysis. The graph illustrating resultant value and number of cells in simulation is the easiest technique to verify for a mesh independent solution. Number of elements was plotted along X-axis and corresponding value for stress was plotted along Y-axis. After the mesh independence analysis, 107892 elements were chosen for analysis since further refinement in the mesh would have only increased the computational time.

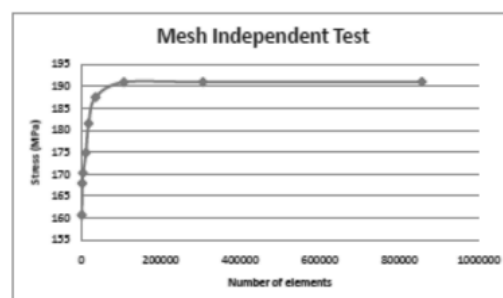


Figure 2 Mesh Independent Test

6. Structural Analysis

For the static structural analysis of the disc brake rotors, the criteria of deformation and stress developed during the braking condition was selected. The compressive braking forces, applied pressure and torque developed were calculated analytically. The formula to calculate these values

were taken with reference to the different journals and articles relating to the design and optimization of disc brake rotors.

7. Thermal Analysis

During the application of the brake, the kinetic energy is converted into heat energy rising the temperature on the surface of the disc rotors. The performance of the disc rotors depends on the temperature distribution and the quantity of the heat flowing through its cross sectional per seconds which is termed as heat flux. Hence, the temperature and heat flux are chosen as the analysis criteria for the thesis work. For the initial boundary condition, initial heat flux is calculated analytically and the model is assumed to be at 26°C. Similarly, the heat is also assumed to be dissipated through convection and radiation as well. The more the heat flux capacity of the disc rotors the more superior performance it will deliver.

8. Result Interpretation

After these analyses, the results obtained of disc rotors for all materials are compared to each other in terms of deformation, stress, temperature distribution and heat flux. The results obtained are interpreted in details so that the optimum material becomes easy to choose for this thesis work. The results are the basis to evaluate the degree of performance of disc rotor for different materials.

9. Selection of best material

From the results obtained, the best material is selected as the final design for the thesis work among the five discs rotors materials. The final design should meet the criteria of the objective in terms of structural and thermal analysis. In other words, the final selected material should exhibit less deformation, less stress, less temperature and maximum heat flow than the original disc rotor.

Many assumptions were also made to simplify the analysis as follows:

- The kinetic energy on the disk braking surface is converted into thermal or heat flow.
- The material on the disk is considered standard and isotropic.
- The field is symmetrical in all axes.
- Inertia and physical forces are negligible during the study.
- The disk remains stress-free before braking action take place.
- In this experiment, the ambient temperature and initial temperature are set at 26 ° C
- All potential other disk brake loads are disregarded.

VI. RESULTS AND DISCUSSION

4.1 Structural Analysis

The stress and deformation developed due to the application of braking force is calculated under structural analysis for all the materials.

Figure 4 Deformation analysis on mild steel disc rotor

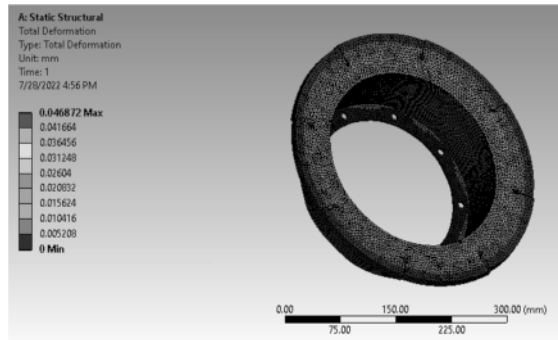


Figure 6 Deformation analysis on stainless steel disc rotor

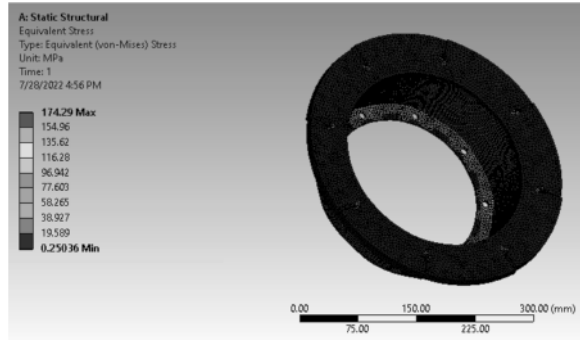


Figure 7 Stress analysis on stainless steel disc rotor

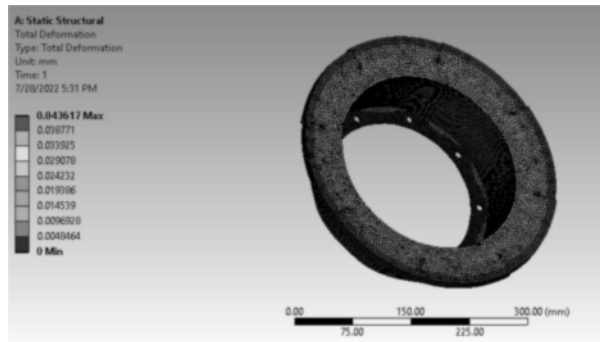


Figure 3 Deformation analysis on Aluminium Silicion Carbide MMC disc brake rotor

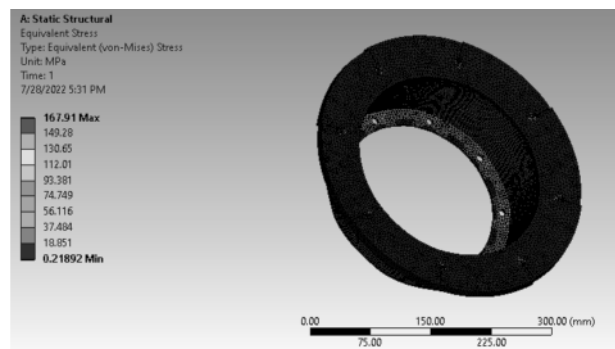


Figure 13 Stress analysis on Aluminium Silicion Carbide MMC disc brake rotor

4.2 Thermal Analysis

The temperature distribution and heat flux was studied under the thermal analysis for different materials.

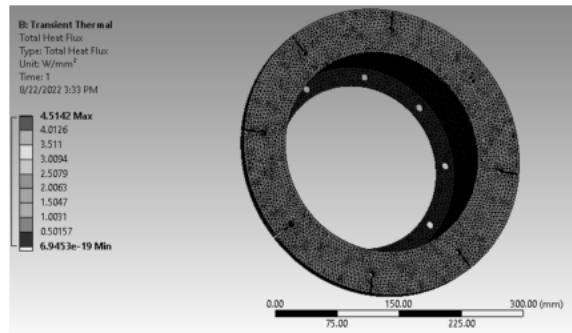


Figure 16 Heat flux analysis on stainless steel rotor

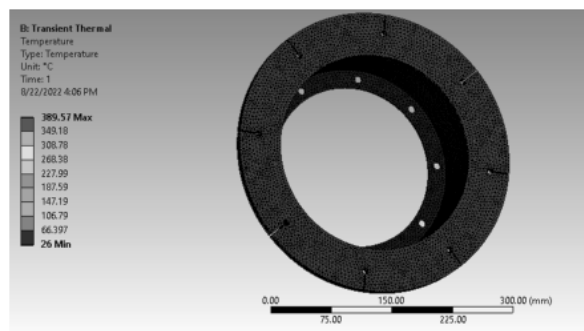


Figure 17 Temperature distribution on stainless steel rotor

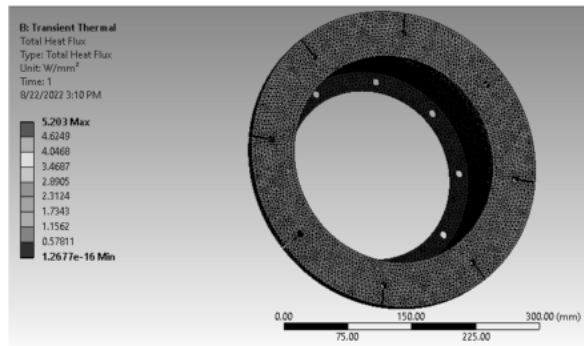


Figure 22 Heat flux analysis on aluminum silicon carbide MMC

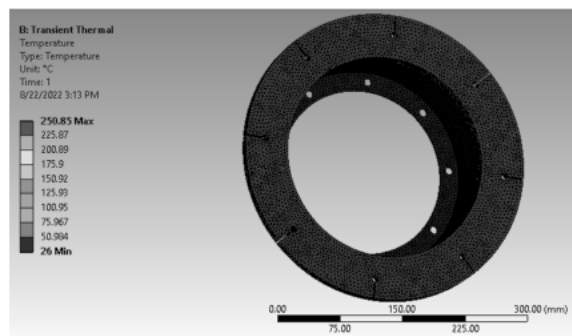


Figure 23 Temperature distribution on aluminum silicon carbide MMC

1.4 Comparison of all disc rotors

The results obtained from the analysis of all the disc rotors are presented in the table given below.

Analysis	Criteria	Mild Steel	Stainless Steel	Grey Cast Iron	Carbon-carbon composite	Aluminum Silicon carbide MMC
	Mass (Kg)	6.241	6.1225	5.688	1.422	2.37
Structural	Stress (MPa)	190.92	174.29	196.14	173.24	167.91
	Deformation (mm)	0.047005	0.046872	0.090866	0.044523	0.043617
Thermal	Temperature (°C)	379.52	389.57	405.09	414.53	250.85
	Heat Flux (W/mm ²)	4.8211	4.5142	4.864	5.3488	5.203

After reviewing all the disc rotors in terms of mass, stress, deformation, temperature and heat flux, aluminum silicon carbide MMC is selected as the best material for manufacturing the disc brake rotor in this aircraft. Aluminum silicon carbide MMC shows the best performance in terms of stress, deformation and temperature. However, carbon-carbon composite shows best performance in terms of mass and heat flux. But the aluminum silicon carbide MMC shows superior performance in terms of both mass and heat flux in comparison to other three materials.

VI. CONCLUSION

The study on the structural and thermal behavior of DHC 6 twin otter aircraft was successfully carried out in terms of mass, stress, deformation, temperature distribution and heat flux. The 3D model of disc brake rotor was developed in Solid works software and the simulation was performed using ANSYS software. After observing the results obtained from simulation, aluminum silicon carbide MMC was selected as the best material for manufacturing the disc brake rotor as it provided better heat dissipation with more heat flux than original disc rotor. Similarly, it showed less stress, deformation, temperature and mass than the original rotor.

The mass, stress, deformation and temperature developed in the aluminum silicon carbide MMC rotor is less than the original rotor by 61.3%, 3.66%, 6.9% and 35.6% respectively. Similarly, the aluminum silicon carbide MMC rotor provides better heat dissipation as compared to original rotor due to an increment in heat flux by 15.26%.

VI. RECOMMENDATION

This research has some limitations that provide opportunities for future studies to refine and narrow the scope. Some of the recommendations suggested for future studies to widen the scope of this thesis work are:

- Experimental analysis can be carried out for the better result validation and verification.
- The structural and thermal analysis can be carried out by varying the shape of ventilation holes of disc rotor.
- The cost analysis can be performed for manufacturing disc brake rotor for different materials.

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