RT&A, No 3 (58)
Volume 15, September 2020

Composite Disc Brake Design and Analysis

Malyala Sathya Sai Dattu[1] Shaik Nayeem[2]

•

[1,2,] *Department of Mechanical Engineering, Godavari Institute of Engineering and Technology, Rajahmundry, Andhra Pradesh, India.*
Email: malyaladattu670@gmail.com

Abstract

Brakes are the major components of the automobiles which are used to reduce the speed of the vehicle or to hold in the desired position by ceasing the motion of the vehicle. During braking, due to vehicle kinetic energy of the vehicle and the mechanical forces applied on the Disc leads to a temperature rise of the contact pairs of the discs results in heat dissipation. This project aims to select the best design of a Disc brake using the TOPSIS method and to develop a design of composite Disc and develop a methodology to check the durability under thermo-mechanical cyclic stresses. Initially, 5 models of the discs having various types of vents are selected and their durability was analyzed and the best Disc geometry was selected by using the ranking method, TOPSIS. The best-selected Disc design was analyzed with cast iron (Fe) and Titanium - cast iron metal matrix composite (Ti – Fe MMC) to sustain harsh working conditions. The Ti – Fe composites were prepared numerically by using MSC Digimat. The designed composite Disc brake is analyzed with existing material (Fe) and proposed Ti – MMC with Ti particle reinforcements in 5%, 10%, 15%, and 20% volume, for its sustainability using FEA and the results are compared and validated. The design of the composite brake is carried out in Solidworks Part Design and the thermo-mechanical analysis is carried out in ANSYS. From the results of thermal coupled with mechanical FE analysis (thermo-mechanical FEA) it is found that the Ti – Fe MMC 20% composite disc brake can work at temperatures up to 1050 K whereas the grey cast iron disc brake can only function up to 548 K.

Keywords: FEA, Disc brake, Composite, Ti- Fe MMC, Thermo-mechanical

I. Introduction

Among the automobile safety components, the braking system plays a vital role. The braking system deaccelerates the vehicle providing control over the speed of an automobile. It is also used to bring the driving speeds to the desired value. The kinetic energy of the wheel is converted into thermal energy through friction by using a friction braking system in which employs friction pads and rotating discs [1] Under the same operating conditions, Disc brakes have less wear compared to drum brakes. The linear relationship between the brake pad coefficient of friction and braking torque is the major advantage in the Disc brakes [2].

Disc brakes show prominent merits compared to drum brakes which made them a common braking system in light trucks and passenger cars. Brake friction materials employ high friction coefficient materials and are used in friction linings and brake pads. Braking materials should absorb a high amount of heat without showing any adverse braking performance [3]. Hence, the selection of braking material depends on the braking application. Thermal effects play a predominant role in the wear and tear of the braking systems. So, the thermo-structural analysis helps in finding out the thermo-mechanical behavior of the braking system.

The energy dissipated results in the temperature rise ranging from 200° C to 850° C which results in the micro – deformations due to frictional forces in the contact regions. As a result, when the vehicle travel at high speed the wear and tear of the rotating parts especially the brake rotors will be high resulting in a decrease in its life. This study aims at reducing the damage to Disc brake due to thermal and mechanical loads by using the Ti – Fe composite Disc brake.

II. Methodology

A. Disc Working Parameters

The four-wheeler vehicle weighing 855 kgs with weight transfer of 60:40 percentage on front and rear axle during braking is assumed. Table 1 represents the working parameters and their associated values used in this study which are imparted from the work of D Karan et al.

Tab.1-Disc Working Parameters

Parameter	**Unit**	**Value**
Average braking power	Watt	16531.96
Final breaking power	Nm/sec	1053.78
Heat flux	W/m^2	57217.8
Braking force	MPa	2.454
Braking torque	Nm	101.76
Convective heat transfer coefficient	W/m^2K	106.18

B. Ti-Fe MMC Properties

The mechanical properties for Ti – Fe MMC are obtained with the help of MSC Digimat. The analysis type used is Thermomechanical. Fe is in the matrix phase and Ti is in the inclusion phase (reinforcement). The mechanical properties are obtained for different volume fraction after simulations and are listed in Table 2.

Tab.2- Ti-Fe MMC Properties

Ti - Volume fraction (ϕ)	**Ti- Fe MMC Youngs Modulus (GPa)**	**Ti- Fe MMC Poisons Ratio**	**Ti- Fe MMC Shear Modulus (GPa)**	**Ti- Fe MMC Density (kg/m^3)**	**Ti- Fe MMC Yield Stress (Mpa) (σ_Y)**
0.05	81.506	0.25929	32.362	6850	154.45
0.1	83.037	0.26355	32.859	6700	157.9
0.15	84.594	0.26779	33.363	6550	161.35
0.20	86.179	0.27202	33.875	6400	164.8

The thermal properties for Ti – Fe MMC are obtained by using linear rule of mixtures prosed by Pac and Cho in the year 1981. Table 3 represents the thermal properties of the materials considered in thhis study. The linear rule of mixtures equations are as follows:

$$Property_{Composite} = (\phi)^* (Property_{Reinforcement}) + (1-\phi)^*(Property_{Matrix})$$

Thus,

$$k_{Ti-Fe\ MMC} = (\phi)^* (k_{Ti}) + (1-\phi)^*(k_{Fe}) \quad (1)$$

$$CTE_{Ti-Fe\ MMC} = (\phi)^* (CTE_{Ti}) + (1-\phi)^*(CTE_{Fe}) \quad (2)$$

Where, k = thermal conducticvity (W/mK)
CTE = coefficeint of thermal expansion (10^{-6}/K)
ϕ = volume fraction of reinforcement

Tab.3-Ti-Fe Properties

S. No	Material	ϕ	$1-\phi$	k (W/mK)	CTE (10^{-6}/K)
1	Ti-Fe MMC 5%	0.05	0.95	38.85	10.895
2	Ti-Fe MMC 10%	0.1	0.9	37.7	10.79
3	Ti-Fe MMC 15%	0.15	0.85	36.55	10.68
4	Ti-Fe MMC 20%	0.20	0.80	35.4	10.58

C. Disc Brake Design

The design of brake discs was carried out in Solidworks part design. Five discs with various geometric features on the swept area were designed. The model I Disc is a solid Disc with a pitch circle diameter 100 mm and swept area of Disc pad is located at a distance of 58 mm from the Disc center. The Disc sept area is 18400 mm^2. Model II. III, IV, and V are made from Model I geometry. The five models are shown in fig 1 (a) to 1 (e).

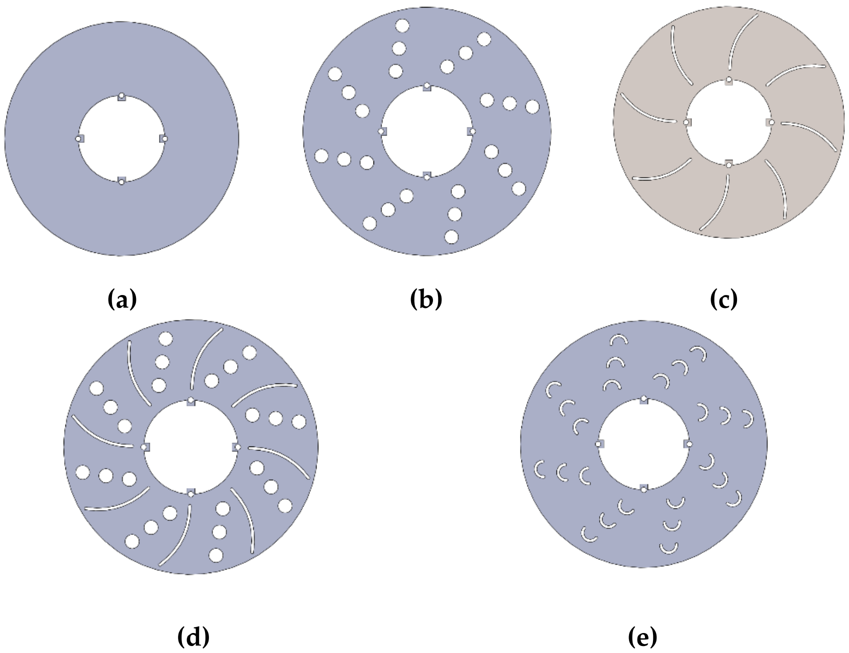


Fig 1: Schematic model of (a) Disc Model I (b) Disc Model II (c) Disc Model III (d) Disc Model IV (e) Disc Model V

D. FEA Analysis

To select the best geometric model from the five-disc models a thermo-mechanical analysis is carried out using the ANSYS workbench module under the working parameters represented in Table 1. Steady-state thermal analysis and thermo-mechanical fatigue analysis are done and the obtained results are taken to select the best by using TOPSIS methodology. The boundary conditions applied are as follows:

- Ambient temperature: 295.01 K
- The moment on the disc: 101.01 N-m
- Heat flux: 57216.621 W/m^2
- Convection film coefficient: 106.181 W/m^{2}K
- The cutoff limit for infinite cycles: 10^7 cycles

The thermo-mechanical analysis is a coupled steady-state thermal and static – structural analysis. These two interfaces must be coupled in ANSYS workbench as represented in Fig 2 for the selection of best geometry and represented in Fig 3 for the selection of best geometry. The mesh details are tabulated in Table 4. The analysis is carried out using the specified boundary conditions and with structural steel as a material.

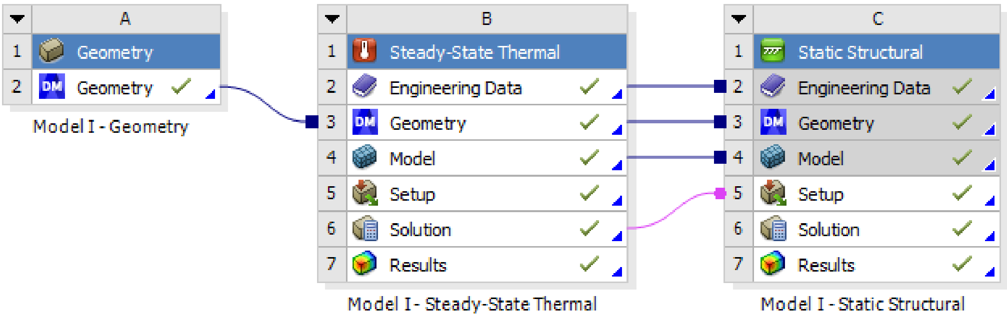


Fig 2: ANSYS Thermo-mechanical coupled FEA for selection of best geometry

Tab.4 – FEA Analysis

Parameter	Value
Elements	54564
Nodes	275785
Element size	2

E. TOPSIS Methodology

The best geometric model from the five-disc models and best Ti – Fe MMC composition is selected by using TOPSIS (Technique of Order Preference Similarity to the Ideal Solution) which is a straightforward MCDA (Multiple-criteria decision analysis) method. The method is based on finding an ideal and an anti-ideal solution and comparing the distance of each one of the alternatives to those. The method as follows:

Step-1: Calculate Normalised Matrix

$$\overline{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}}$$

Step-2: Calculate weighted Normalised Matrix

$$V_{ij} = \bar{X}_{ij} \times W_j$$

Step-3: Calculate the ideal best and ideal worst value

Step-4: Calculate the Euclidean distance from the ideal best

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+ \right)^2 \right]^{0.5}$$

Step-5: Calculate the Euclidean distance from the ideal worst

$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^- \right)^2 \right]^{0.5}$$

Step-6: Calculate Performance Score

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

III. Results

A. Geometry influence on the disc life

The thermo-mechanical FE analysis is conducted under the boundary conditions discussed in section II-D on the five models and the results obtained are used for the best geometric model by using the TOPSIS method. The results of thermomechanical FE analysis are tabulated in Table 5.

Tab.5 – Thermo-mechanical FE analysis

Model	**Temperature (k)**	**Total Deformation (mm)**	**Factor of Safety (NA)**	**Von Mises Stress (Mpa)**
I	581.69	0.26635	0.5918	222.9
II	599.7	0.27926	0.6757	221.2
III	574.64	0.23864	1.2781	144.6
IV	573	0.21745	1.2939	145.8
V	581.49	0.26448	0.9475	199.6

The steps involved in the TOPSIS are discussed in section II-E and the results are tabulated in Tables 6, 7, and 8. Table 6 shows the weightage and Table 7 shows the normalized matrix. Table 8 shows the remaining steps involved in the TOPSIS method and ranks.

Tab.6 - Weightage

Weightage	**Non-Beneficial**	**Beneficial**	**Beneficial**	**Beneficial**
	0.35	0.25	0.25	0.15
Parameter	Temperature	Total Deformation	Factor of Safety	Von Mises Stress

Tab.7 – Normalized matrix results

Model	**Temperature (k)**	**Total Deformation (mm)**	**Factor of Safety (NA)**	**Von Mises Stress (Mpa)**
I	0.446836357	0.468572033	0.26435	0.5244
II	0.460671085	0.491283747	0.30182	0.5206
III	0.441420764	0.419823653	0.57088	0.3403
IV	0.440160966	0.38254548	0.57794	0.3431
V	0.446682723	0.465282265	0.42322	0.4696

Tab.8- TOPSIS Results

Model	Temperature (k)	Total Deformation (mm)	Factor of Safety (NA)	Von Mises Stress (Mpa)	Si+	Si-	Pi	Rank
I	0.156392725	0.117143008	0.06609	0.0787	0.0786	0.0353	0.31	5
II	0.16123488	0.122820937	0.07546	0.0781	0.0694	0.0395	0.3625	4
III	0.154497267	0.104955913	0.14272	0.051	0.0329	0.0775	0.7017	1
IV	0.154056338	0.09563637	0.14448	0.0515	0.0385	0.0787	0.6719	2
V	0.156338953	0.116320566	0.1058	0.0704	0.0401	0.049	0.5499	3

By following the TOPSIS method the Model III has the Pi value of 0.7017 which is greater than all the remaining models. So, Model III disc geometry is considered in the design of the Ti- Fe MMC composite disc.

B. Influence of volume fraction of reinforcement on the disc life

The thermo-mechanical FE analysis is conducted on the brake disc Model III under the boundary conditions discussed in section II-D and by using the metal matrix composites discussed in Table 3 of section II-B and the results obtained are tabulated in Table 9.

Tab.9 – TOPSIS Results

S.No	Material	T (K)	Displacement (mm)	Strain (mm/mm) (ϵ)	Von Mises Stress (Mpa) (σ_V)
1	Grey Cast Iron	576.64	0.20321	$7.0959e^{-004}$	77.386
2	Ti-Fe MMC 5%	576.64	0.19952	$7.0129e^{-004}$	56.671
3	Ti-Fe MMC 10%	576.64	0.20424	$7.0978e^{-004}$	58.422
4	Ti-Fe MMC 15%	576.64	0.19712	$6.9097e^{-004}$	57.951
5	Ti-Fe MMC 20%	576.64	0.19531	$6.8381e^{-004}$	58.425

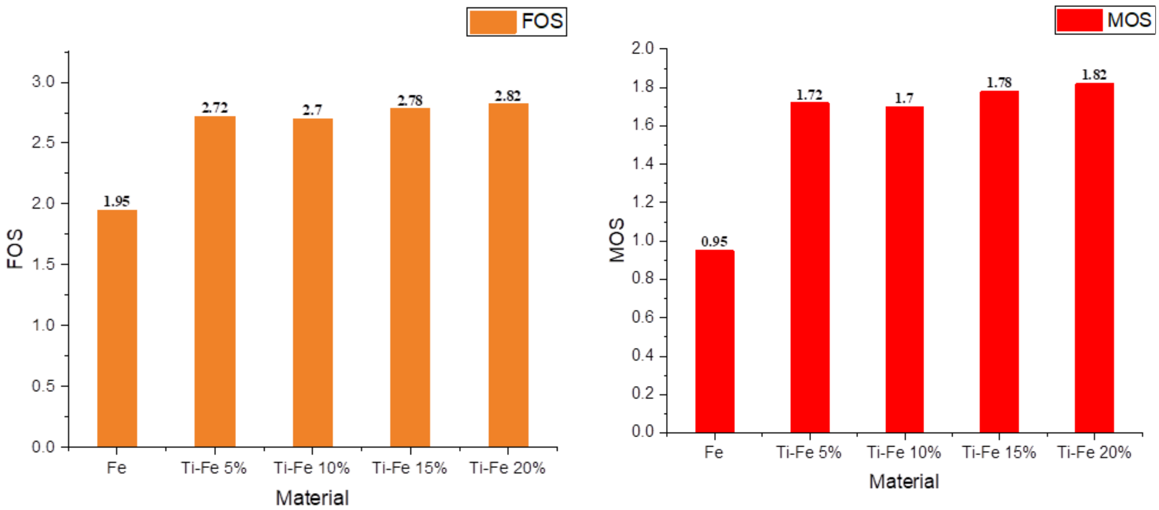
The factor of safety is calculated by using "Distortion energy theory with Von Mises Stress." The factor of safety and margin of safety is calculated by using the following equations and are tabulated in Table 10. The plots are shown in fig 4 and fig 5.

$$FOS = (\sigma_Y / \sigma_V)$$
$$MOS = FOS - 1$$

Where FOS = Factor of Safety
MOS = Margin of Safety
σ_Y = Material Yield Stress
σ_V =Von Mises Stress

Tab.10- Results of FOS & MOS

S.No	Material	Yield Stress (Mpa) (σ_Y)	Factor of Safety FOS = (σ_Y/ σ_V)	Margin of safety MOS = FOS – 1
1	Grey Cast Iron	151.1	1.95	0.95
2	Ti-Fe MMC 5%	154.45	2.72	1.72
3	Ti-Fe MMC 10%	157.9	2.70	1.70
4	Ti-Fe MMC 15%	161.35	2.78	1.78
5	Ti-Fe MMC 20%	164.8	2.82	1.82



(5) (6)

Fig: (5) FOS and **(6)** MOS results plot for materials specified in Table 10

The TOPSIS results are tabulated in Tables 10, 11, and 12. Table 11 shows the weightage and Table 12 shows the normalized matrix. Table 13 shows the remaining steps involved in the TOPSIS method and ranks.

Tabl.11- Weightage

Weightage	**Non-Beneficial**	**Beneficial**	**Beneficial**	**Beneficial**
	0.35	0.25	0.25	0.15
Parameter	Temperature	Margin of Safety	Factor of Safety	Displacement

Tab.12- TOPSIS Results

Material	Temperature (k)	Margin of Safety (NA)	Factor of Safety (NA)	Displacement (mm)
Grey Cast Iron	0.447213595	0.26116549	0.333581	0.45459735
Ti-Fe MMC 5%	0.447213595	0.47284698	0.465303	0.446342519
Ti-Fe MMC 10%	0.447213595	0.46734876	0.461881	0.456901544
Ti-Fe MMC 15%	0.447213595	0.48934165	0.475567	0.440973523
Ti-Fe MMC 20%	0.447213595	0.50033809	0.482409	0.436924405

Tab.13 – Ranking of TOPSIS

Material	Temperature (k)	MOS (NA)	FOS (NA)	Displacement (mm)	Si+	Si-	Pi	Rank
Grey Cast Iron	0.156524758	0.06529137	0.083395	0.068189603	0.07	0.003	0.036	**5**
Ti-Fe MMC 5%	0.156524758	0.11821175	0.116326	0.066951378	0.008	0.062	0.883	**3**
Ti-Fe MMC 10%	0.156524758	0.11683719	0.11547	0.068535232	0.01	0.061	0.862	**4**
Ti-Fe MMC 15%	0.156524758	0.12233541	0.118892	0.066146028	0.004	0.067	0.943	**2**
Ti-Fe MMC 20%	0.156524758	0.12508452	0.120602	0.065538661	0.003	0.07	0.959	**1**

Tab.14- Maximum Operating Temperatures for Grey Cast Iron and Ti-Fe MMC models

S.NO	Materials	MOS	Initial Temperature (Ti)	MOS*Initial Temperature
1	Grey Cast Iron	0.95	576.64	547.808
2	Ti-Fe MMC 5%	1.72	576.64	991.820
3	Ti-Fe MMC 10%	1.70	576.64	980.288
4	Ti-Fe MMC 15%	1.78	576.64	1026.419
5	Ti-Fe MMC 20%	1.82	576.64	1049.484

Tab.15- Temperature difference based on Margin Of Safety

S.NO	Materials	MOS	Initial Temperature	Grey Cast Iron Temperature	ΔT= (MOS* Initial Temperature)- Grey Cast Iron Temperature
1	Grey Cast Iron	0.95	576.64	576.64	-28.83
2	Ti-Fe MMC 5%	1.72	576.64	576.64	415.18
3	Ti-Fe MMC 10%	1.70	576.64	576.64	403.64
4	Ti-Fe MMC 15%	1.78	576.64	576.64	449.77
5	Ti-Fe MMC 20%	1.82	576.64	576.64	472.84

By following the TOPSIS method the Ti-Fe MMC 20% has Pi value of 0.959 which is greater than all the remaining composites. From this, we can state that the Ti-Fe MMC 20% can be used in the preparation of composite disc brakes. The post-processing images of the Model III disk with Ti-Fe MMC 20% composite are shown in fig 6, fig 7 and fig 8.

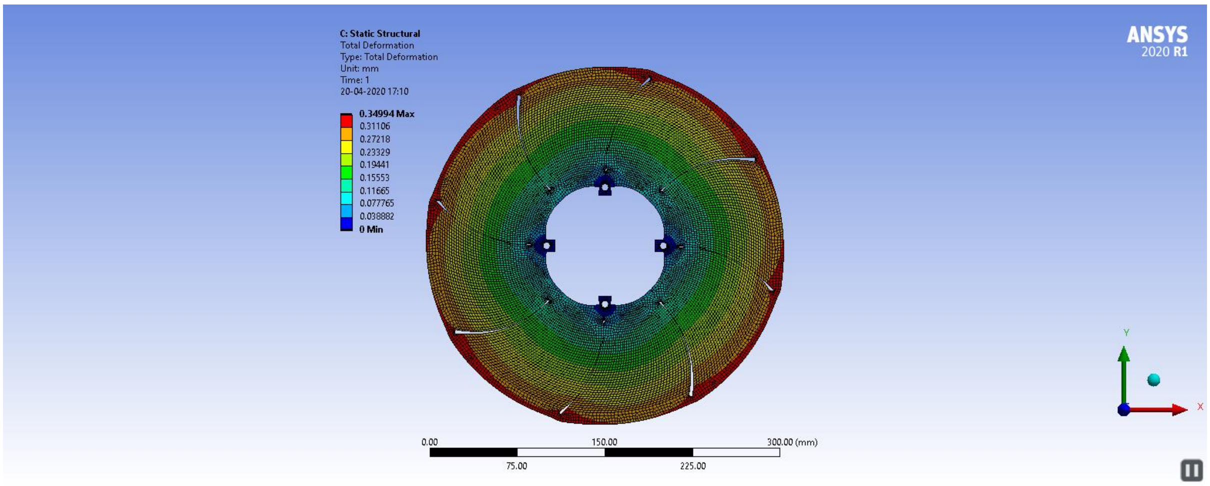


Fig 6: ANSYS Thermo-mechanical total deformation contour of Ti-Fe MMC 20% composite disc

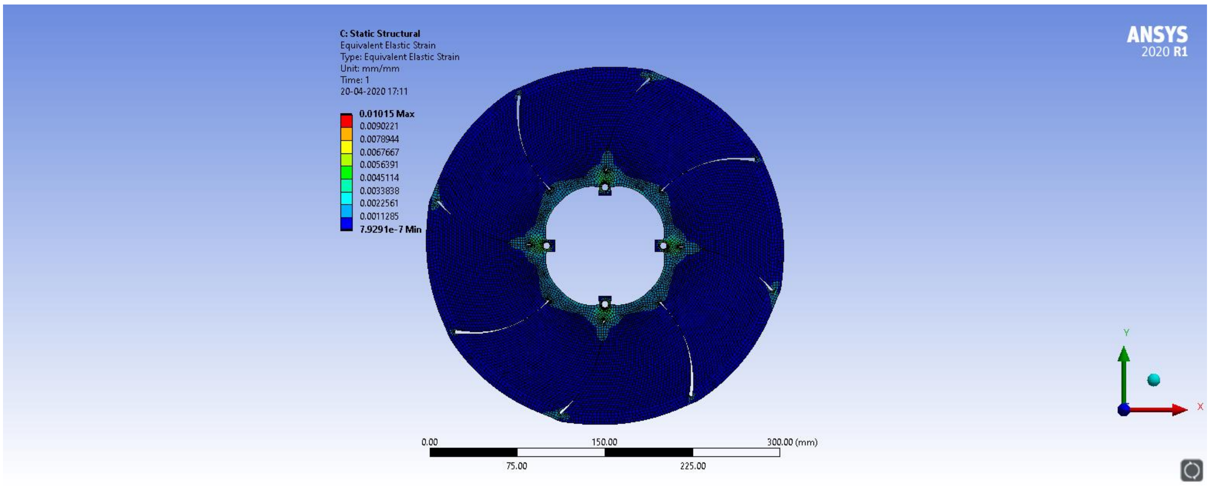


Fig 7: ANSYS Thermo-mechanical strain contour of Ti-Fe MMC 20% composite disc

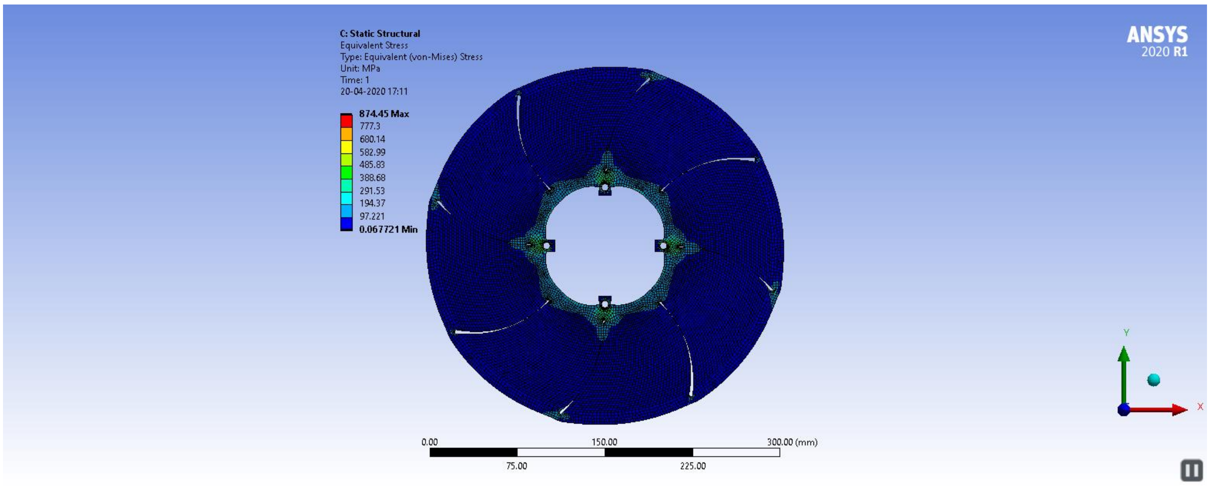


Fig 8: ANSYS Thermo-mechanical Von Mises stress contour of Ti-Fe MMC 20% composite disc

IV. Conclusions

From the studies, we can say the geometric design of the disc plays a major role in the thermomechanical characteristics. The disc with vents supports the rapid cooling of the brake rotor and thereby facilitating faster cooling and reducing the weight which makes it usable for racing applications. From the study following can be concluded:

1. From the thermo-mechanical analysis, it can be seen that by using grey cast iron in the disk fabrication resulted in FOS of 1.95. Though the factor of safety is greater than 1 which implies the disk support the design load, the MOS is 0.95 which is a measure of requirement verification states that it may fail at the sudden rise in loads.
2. While the results of the thermo-mechanical analysis on the Ti – Fe MMC discs shows that the composite disc with Ti-Fe MMC 20% resulted in FOS of 2.82 and MOS of 1.82 which states that the design can sustain even there is a 1.82 times sudden rise in both thermal and mechanical loads than the designed loads.

From this, it can be seen that the Ti – Fe MMC 20% composite disc brake can work at temperatures up to 1050 K whereas the grey cast iron disc brake can only function up to 548 K. Therefore the aim of the study to design a composite disc rotor which can sustain high thermal loads is met by using Ti – Fe MMC composite discs.

Future Scope: The percentage of Ti reinforcement in Ti – Fe MMC composite discs should be based on the operating temperatures of the brakes. And before utilizing the Ti – Fe MMC composite discs in practical applications for the specific model of disc experimentations should be carried out before its application which is left as future scope.

References

[1] Aleksander Yevtushkendo, Michal Kuciej, "Temperature and Thermal Stresses in a pad/disc during braking", Elsevier, Applied Thermal Engineering 30 (2010) 354-359,2011, doi: 10.1016/j.applthermaleng.2009.09.015
[2] Ali Belhocine, Mostefa Bouchetara, "Thermal analysis of solid brake disc", Elsevier, Applied Thermal Engineering 32 (2012)59-67,2012, doi: 10.1016/j.applthermaleng.2011.08.029
[3] Fred Puhn, "Brake Handbook" (HP Books, U.S.A., 1985), ISBN: 0-89586-232-8.
[4] F. Talati, S.Jalalifar, "Investigation of heat transfer phenomenon in a ventilated disc brake rotor with straight radial rounded vanes", Journal of Applied Sciences, 8:3583-35922008, doi: 10.3923/jas.2008.3583.3592
[5] Guru Murthy Nathi, T N Charyulu, K. Gowtham, P. Satish Reddy, "Coupled Structural/ Thermal Analysis of Disc Brake", IJERT: 539-553, 2012, doi.org/10.15623/ijret.2012.0104004
[6] Giancarlo Genta, Lorenzo Morello, "The Automotive Chassis (Volume 1), Springer, 2009", ISBN: 978-1-4020-8674-8.
[7] Rudolf Limpert, "Brake Design and Safety" (S.A.E.Internationl, U.S.A., 1999), ISBN: 1-56091-915-9
[8] ANSYS (Version 15.0), ANSYS Meshing User's Guide, Computer Software, ANSYS Inc., Houston, USA, 2015.
[9] M. Boniardi, F.D'Errico, C.Tagliabue, G.Gotti, G.Perricone, "Failure analysis of motorcycle brake disc", Engineering Failure Analysis, 13 (2006) 933–945, doi:10.1016/j.engfailanal.2005.04.01.
[10] Daanvir Karan Dhir, Thermo-mechanical performance of automotive disc brakes, Materials Today: Proceedings, Volume 5, Issue 1, Part 1, 2018, Pages 1864-1871, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2017.11.287.

[11] Mahle Metal Leve S/A, Mahle International GmbH, "Cylinder Line and Cast-Iron Alloy", U.S. Patent 14/239,240, Oct 30, 2014.

[12] Julie A. Bannantine, Jess J. Corner, James L. Handrock, "Fundamentals of Metal Fatigue Analysis" (Prentince Hall, 1990), ISBN: 013340191X

Received: July 03, 2020
Accepted: September 15, 2020