DESIGN AND ANALYSIS OF Al/TiC MMCs FOR DISC BRAKE

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Abstract - *The research work aimed to increase the thermal properties and to reduce the weight of disc brake using suitable and reliable materials. Previous researchers were found that the AMMC (TiC reinforced) material has more corrosion resistance, thermal properties and less density compared to grey cast iron. The metal matrix composite materials are widely used in automotive engineering applications. In the present work, Aluminium alloy AA6082 as the matrix metal and Titanium carbide (TiC) particles (4, 8, and 12%) as reinforced material were fabricated by stir casting method and to investigate its suitability for the application on disc brakes. Mechanical and tribological properties are compared by using different chemical composition. Scanning Electron Microscope (SEM) is used to examine the tribological behaviour (wear) of the material. The structural and thermal properties of the material are compared by using Finite Element Analysis (FEA). The results were compared with grey cast iron and found that the composite material (Al-12% TiC) is more efficient than the conventional ones.*

Key Words: *Disc Brake, CAD Model, FEA, Tensile Test, Wear Test.*

1. INTRODUCTION

The disc brake is a crucial component in the brake assembly for achieving the safety requirements and deals with the material and design development of disc brake components which are used in a variety of applications including automobiles and heavy machines. The traditional material for automotive disc brake is the grey cast iron. The specific gravity or density of grey cast iron is higher as it consumes much fuel due to high inertia. The disadvantage of grey cast iron material is having poor thermal properties like thermal expansion and heat flux. Fatigue failure of the disc brakes occurs by excessive operating temperature during application of the brake in running condition. In this particular situation, the need for developing the new material for the disc brake application as per those design requirements is required.

To overcome the disadvantage of grey cast iron, metal matrix composites are preferable. Metal matrix composites as advanced engineering materials prove to be tough contenders with potential applications in the areas of aerospace, automotive, defence, electronics, nuclear, general engineering and other advanced structures [1, 2]. Titanium carbide, Aluminium reinforced metal matrix composites are best used as high-speed rotating or reciprocating mass items like pistons, connecting rods, driveshafts, cylinder liners and disc brakes. The vehicle weight reduction to improve performance, lower fuel and oil consumption and reduce emissions is a major objective under constant research by the automotive manufacturers [3].

2. LITERATURE REVIEW

2.1 Aluminium Metal Matrix Composites

Aluminium Metal Matrix Composites (AMMC) increases strength, stiffness and temperature resistance capacity due to its lower density, high wear resistance, low thermal expansion coefficient and good corrosion resistance [4]. The particulate reinforced metal matrix composites possessing isotropic properties are found to be thermally stable and wear-resistant as compared to monolithic materials [5, 6]. Several researchers have proved that the wear resistance of a material depends on its hardness, strength, ductility, toughness, type of reinforcement, volume fraction and particle size [7]. The applied load has the highest impact on the wear rate of the AMCs followed by sliding distance, sliding speed and temperature [8]. The effect of SiC reinforcement on aluminium increases tensile strength, hardness and density of Al/SiC composites while the impact toughness decreased. Also, the yield strength, ultimate strength and ductility of Al/SiC metal matrix composites were in the descending order in Al6061, Al6063 and Al7072 matrix alloys [9]. The strength-to-weight ratio of aluminium SiC composite was about three times more than that of mild steel. Aluminium SiC alloy composite material was lesser in weight than aluminium for the same dimensions. The addition of Al_2O_3 particles increases wear resistance of composites and the composites containing high content of reinforcement would tend to behave differently under wear conditions compared to those with a lower amount of reinforcement [10, 11].

2.2 Titanium Carbide-Reinforced AMC

The controlled stir casting process of fabricated AA 6061/TiC composite helped to achieve the uniform distribution of reinforced particles resulting enhancement of the mechanical characteristics by 7 wt.% of TiC also decreases the wear rate of composite and the coefficient of friction [12]. The analysis of synthesized AA6061/TiCp composite by employing enhanced stir casting technique by varying the volume fractions of TiC significantly improves the specific strength and resistance to wear of the composite material [13]. Heat-treated AA 7075/8%TiC composite had enhanced hardness 200 VHN and tensile strength 600 N/mm^2 than non-heat treated composite [14].

2.3 Application of Composites in Disc Brake

Properties of the composite vary depending on the bonding between matrix and reinforcement, which can be controlled by alloying the material suitable for disc brake Temperature dissipation can be improved by using the ventilated disc. The ventilated disc reduces the temperature, stresses and deformation. The cooling process in the vent disc will decrease the maximum temperature raised [15 - 18]. Finite element analysis techniques are used to predict the temperature distribution and identify the critical temperature of the disc brake. It concludes that cast iron can be used in the disc brake, which will give moderate cooling at low temperature as compared to others. Ceramics has excellent cooling characteristics, but it is costly, can be used in racing cars where high temperature is produced. Analysis of disc Brake in aluminium alloy 6061 metal matrix composite concludes the aluminium composite material is a better replacement for conventional cast-iron discs, and its implementation in vehicles can improve the overall braking efficiency [19, 20].

3. OBJECTIVES AND METHODOLOGY

The objectives of the present work are to fabricate the material Aluminium alloy (AA6082) with Titanium carbide (TiC) at different proportions of (4, 8, and 12%), to compare the properties by varying the chemical composition of the material, to measure the mechanical and tribological properties of composite material, and to analyse the structural and thermal analysis by using Finite Element Analysis (FEA). Fig. 1 represents the methodology of design and analysis of Al/TiC MMC disc brake.

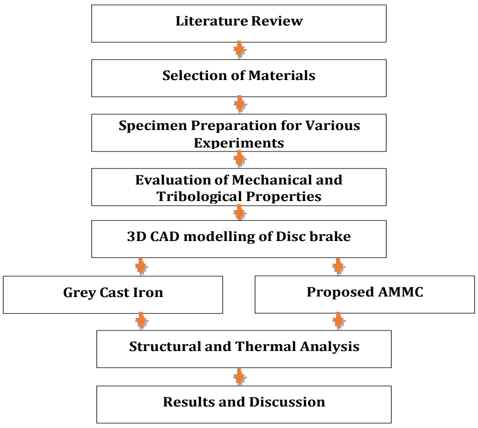


Fig -1: Methodology

4. SYNTHESIS OF THE SPECIMEN

In this culture, Aluminium alloy (Al6082) used as a base alloy. The production of the Metal Matrix Composite (MMC) used in the present study carried out by the liquid metallurgy technique (stir casting method). The composition of Titanium carbide (TiC) and magnesium were used with a motive to accomplish the higher wettability, high hardness, high elastic modulus and precipitation - hardening capability. Table-1 shows the samples of Al/TiC MMC.

Table -1: Material Composition

SAMPLES	COMPOSITION RATIO			
	Aluminium alloy (Al6082)		Titanium carbide (TiC)	
	Volume (%)	Weight (g)	Volume (%)	Weight (g)
1	96	1920	4	80
2	92	1840	8	160
3	88	1760	12	240

Cleaned aluminium ingots were melted above the superheating temperature of about 800^{o}C in graphite crucibles under a layer of flux using an electrical resistance furnace, as shown in Fig. 2. The melt was degassed at 800 °C using solid dry hexachloroethane (C2Cl6) degasser. The preheated titanium carbide particulates were then added to the molten metal and stirred continuously for about 15 minutes at an impeller speed of 600 rpm. Aluminium matrix and titanium carbide particles were weighed using an electronic weighing machine (Accuracy 0.0001 g). During stirring, 1% by weight of magnesium was added to increase the wettability of titanium carbide particles. The melt with reinforced particles were poured by gravity casting into the dried cylindrical permanent metallic moulds of size 14 mm diameter and 120 mm length as shown in Fig. 3. The melt was allowed to solidify in the moulds for about 3 minutes and cooled to room temperature. For comparison, base, alloy samples were also cast under similar processing conditions. Three samples (4, 8, and 12 % by weight) of the cast composite specimen are shown in Fig. 4.

Fig -2: Stir Casting of Al/TiC MMC

Fig -3: Pouring Molten Metal into the Die

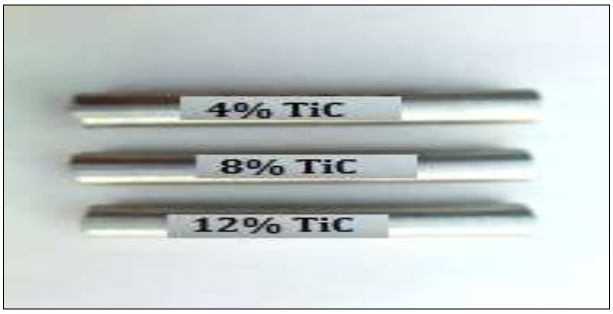


Fig -4: Specimen at various volume fractions

5. TESTING OF SPECIMEN

Specimens are tested for mechanical and tribological properties.

5.1 Hardness Test

Abrasive wear or erosion and thermal deformation are caused by reducing the hardness of the material therefore it is important to identify the sample with greater hardness. The three test samples are subjected to hardness test using a Wilson Wolpert Microhardness Tester. Each sample was tested at four locations with the test specimen being subjected to a load of 0.5 kg for a dwell time of 10 seconds for each location. Fig. 5 represents the specimen sample after hardness test.

Fig -5: Specimen after the Hardness Test

The hardness value of the composites reinforced with micro-sized TiC particles at 4 % volume fraction shows the lowest hardness value (31.3 HV) while composites reinforced with particles at Al-12% TiC shows the highest hardness (58.9HV). The maximum observed increase in hardness of composites compared to Al-4% TiC was 88% as shown in Table-2. The observed increase in hardness was due to hard micro-sized TiC particles acting as a hindrance to the movement of dislocations within the matrix and exhibit greater resistance to indentation. Furthermore, it was evident that an increase in particle size also increased the hardness. Porosity also reduces as the volume fraction of TiC is increased. A galloping increase in hardness is observed between 4% to 12% volume fraction. Since the dispersion of TiC in Al-6082 is prominent and more uniform, and the hardness properties are transferred from TiC to Al matrix.

Table -2: Hardness Test Results

SAMPLES	H.V. @ 0.5 Kg LOAD (avg.)
Al-4% TiC (1,2,3)	31.3
Al-8% TiC (1,2,3)	46.5
Al-12% TiC (1,2,3)	58.9

5.2 Tensile Test

The specimen used for testing was machined according to the ASTM E8 standard. The ultimate breaking load, elongation and ultimate stress were observed to be increased with the increase in the percentage of TiC. The occurrence of cup & cone fracture explains that the tensile strength increases with the increase in TiC percentage. The improvement in tensile strength is since the filler TiC possesses higher strength and lower fineness of dispersion. Fig. 6 shows the specimen after the tensile test.

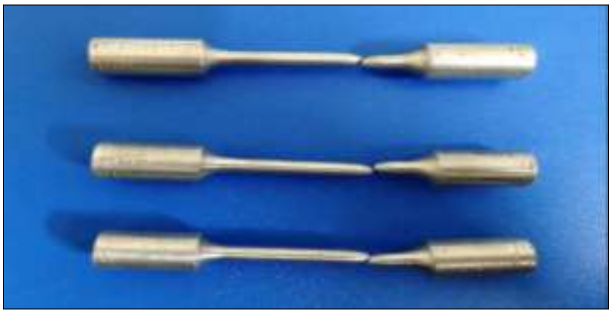


Fig -6: Specimen after the Tensile Test

Table -3: Tensile Test Results

PROPERTIES	Al6082-4%TiC	Al6082-8%TiC	Al6082-12%TiC
Tensile Strength (MPa)	177.42	184.10	189.43
Ultimate Break Load (kN)	18.10	19.54	20.24
Yield Strength (MPa)	139.24	143.65	148.45
Strain (%)	6.7	5.1	4.4

Table-3 shows the results of tensile test of the specimens. With the increase in the percentage of TiC volume fraction, the tensile strength also increases. The lowest tensile strength value (177.42 MPa) was observed in Al-4% TiC, while the highest tensile strength of (189 MPa) was observed in Al-12% TiC. Thus, an increase in tensile strength by about 6.8% was observed in composites compared to the Al-4% TiC. This can be attributed to the fact that the addition of micro-sized titanium carbide leads to an increase in hardness and tensile strength. The increase in tensile strength with an increase in micro-sized titanium carbide particle content may be a result of closer packing of reinforcement within the flexible aluminium matrix.

The yield strength also increased with the increase in the volume fraction of the composite. The lowest yield strength value (139.24 MPa) was observed in Al-4% TiC, while the highest yield strength of (148.45 MPa) was observed in Al-12% TiC. Thus, the composite with Al-12% TiC yields more than the Al-4% TiC. This is due to the increased TiC grain refinement and strong multi-directional stress at the Al-TiC interface.

5.3 Impact Test

The Al/TiC composite samples are subjected to the Charpy impact test. The Al/TiC composite is obtained in the form of a 16 mm diameter rod, three samples of the Al/TiC composite are milled to the length of 55 mm and a cross-section of 10x10 mm, having a V-notch with an angle of 45° and a depth of 2mm. Fig. 8 represents the specimen after the impact test.

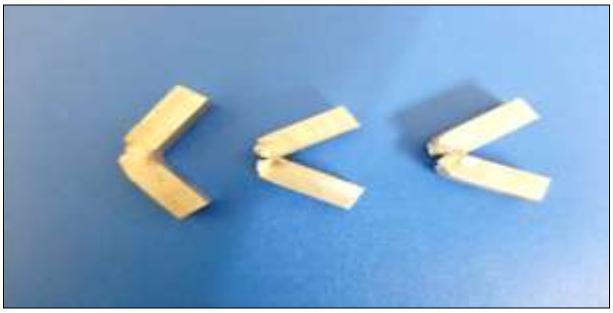


Fig -7: Specimen after the Impact Test

Table -4: Impact Test Results

SAMPLES	IMPACT STRENGTH (J)
Al-4% TiC	8.27
Al-8% TiC	8.29
Al-12% TiC	7.87

Impact strength of composite specimens reinforced with micro-sized titanium carbide particles of different weight percentages (4, 8 and 12%) particle sizes are presented in Table-4. The impact strength of composites increased with an increase in the volume fraction of micro-sized titanium carbide up to Al-8% TiC. The highest Impact strength value (8.29 J) was observed in Al-8% TiC, while the lowest impact strength of (7.87 J) was observed in Al-12% TiC.

The impact strength of Al-8% TiC composite particle increased due to particle strengthening and grain refinement. After that, the impact strength begins to reduce because the particles are dispersed heterogeneously and increased porosity. Due to the agglomeration of void spaces, brittle characteristics are induced. This kind of microstructural homogeneity can create a local strain gradient and reduce the tensile strength with an increase in reinforcement particle content. Due to the increase in ductility, the impact load acting on the composite material will not be transferred evenly between the reinforcement and the matrix members. The interface between the phases will be too futile to withstand the impact load. The difference in the elastic modulus of the phases (reinforcement and matrix) will differ, which leads to a reduction in impact strength.

5.4 Dry Sliding Wear Test

During the experiment, the specimen remains fixed and the disc rotates. Wear test was carried out at sliding velocities of 2 m/sec, 3 m/sec, and 4 m/sec against normal loads of 20 N, 50 N, and 70 N. In this work, the wear rate was calculated over a time period of 10 minutes. The specimen under test is continuously cleaned with woollen cloth to avoid the entrapment of wear debris and also to achieve uniform experimental procedure. After each test, the disc was cleaned using the Acetone solution. A sample record of the measured height loss and frictional force as a function of time for different volume fractions is shown in Fig. 9. Each test was repeated thrice, and the average values obtained were taken as wear rate and coefficient of friction for the composite material.

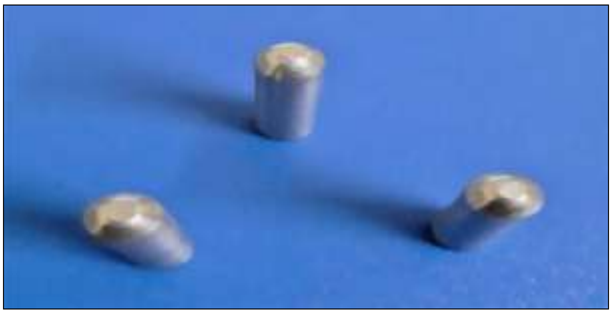
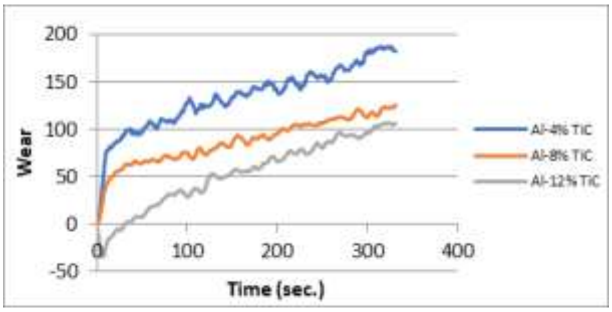
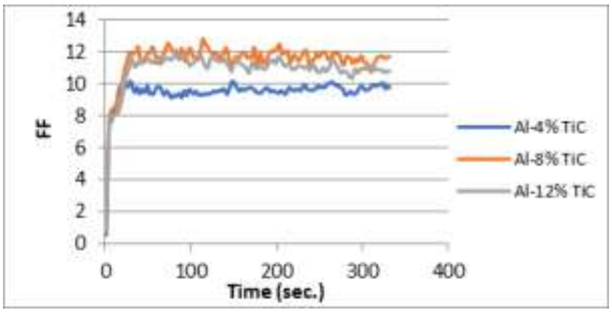


Fig -8: Specimen after the Wear Test

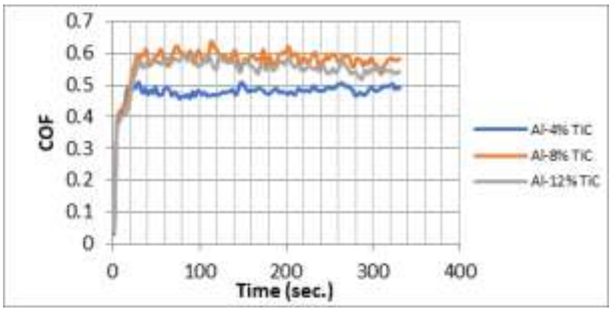
A critical evaluation of the graphical plots shows that Al-12% TiC has less wear rate as compared to the Al-4% TiC. This implies that the strength of the material is high in Al-8% TiC and Al-12% TiC due to the presence of TiC particulates. The friction rate for each TiC composites undergoes peak saturation at a period of 40 min. and the results revealed that wear rate is relatively low for Al-12% TiC and Al-4% TiC have shown higher wear rate due to the absence / irregular grain boundary. Fig. 9 (a-c) shows the graphical representation of Al / TiC composites wear rate (µm) with respect to the time period. Fig. 10 (a-c) represents the SEM images of Al / TiC composites on the course of wear test.



(a) Wear Rate Vs. Time

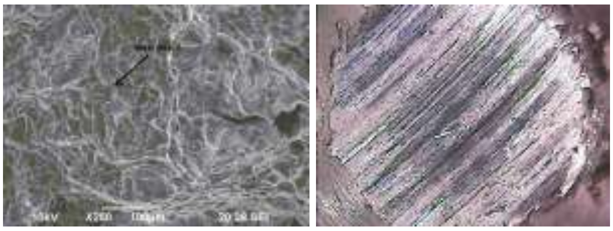


(b) Frictional Factor Vs. Time

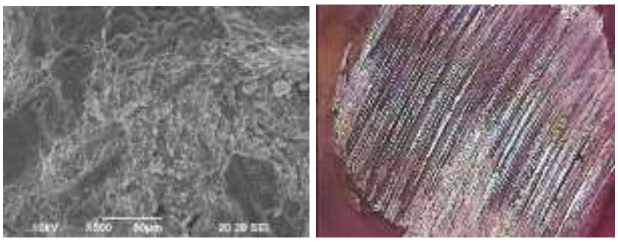


(c) Coefficient of Friction Vs. Time

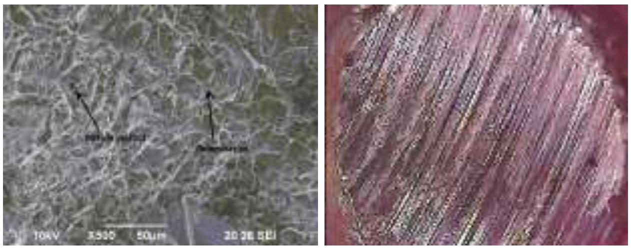
Fig -9: (a-c) Graphical representation of Al / TiC composites wear rate (µm) with respect to the time.



(a) 25-40µm - Al-4% TiC



(b) 25-40µm - Al-8% TiC



(c) 25-40µm - Al-12% TiC

Fig -10: (a-c) SEM image of Al / TiC composites on the course of wear test.

5.5 Density Test

Density is the physical property that characterizes the nature of the composite material. It is observed that the density of the base matrix material is lesser than that of the composite material. Also, the density of the composites increases with an increase in the weight fraction of the composite. The increase in density of composites can be attributed to a higher density of reinforcement particles. This is because higher density particles have more tendencies to settle down in molten metal than a low-density particle.

When the matrix is reinforced with Al-12% TiC, the molecules in the composites are closely packed and thus avoiding the accumulation of voids leads to the higher density (about 2976.4 kg/m^3) which is a whisker above 6% when compared to the density of an Al-4% TiC. Table-5 shows the variation of the density of Al 6082 with a weight fraction of micro-sized titanium carbide composite.

Table -5: Density Results

SAMPLES	DENSITY (Kg/m^3)
Al-4% TiC	2798.8
Al-8% TiC	2887.6
Al-12% TiC	2976.4

5.6 RESULTS OF MATERIAL PROPERTIES

The highlighted values in Table-6 and 7 represents the best results.

Table -6: Comparison of material properties

Samples	Tensile Strength (MPa)	Hardness (HV)	Impact Strength (J)	Wear Rate (μm)	Density (Kg/m^3)
Al-4% TiC	177.42	31.3	8.27	183	2798.8
Al-8% TiC	184.10	46.5	8.29	132	2887.6
Al-12% TiC	189.43	58.9	7.87	106	2976.4

Al-12% TiC has maximum mechanical and wear properties than the other two samples. So, as per the material requirement conditions, Al-12% TiC has been selected for finite element analysis with grey cast iron.

Table -7: Material Selection as per their Properties

MATERIAL PROPERTIES	SAMPLE PRIORITY RANK
Tensile strength (MPa)	Al-12% TiC
Hardness (HV)	Al-12% TiC
Impact strength (J)	Al-8% TiC
Wear rate (μm)	Al-12% TiC
Density (Kg/m^3)	Al-12% TiC

6. DESIGN AND ANALYSIS OF DISC BRAKE

The disc brake under-performs mainly due to reasons such as induced stress being greater than allowable stress, deformation is more than the permissible limit and high-temperature rise in the disc brake. It is imperative to determine and ascertain that the performance parameters are within the safe limits when the disc brake is made of the proposed material, namely, Al6082-12% TiC composite. Disc brake was made conventionally from grey cast iron. The prediction of structural and thermal analysis of titanium carbide composite disc brake and its comparative analysis with the grey cast iron disc are the objectives of the present study.

6.1 CAD Model of Disc Brake

The Disc brake is modelled in SOLIDWORKS 2019 as shown in Fig. 11, which is one of the most effective modelling packages. IGES (Initial Graphics Exchange Specification) is the ANSI standard that defines a natural format for the exchange of information between CAD/CAM systems with an IGES translator. Fig. 12 represents the drawing details of the disc brake.

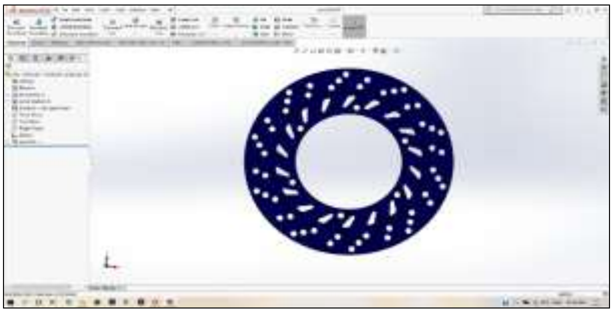


Fig -11: CAD model of disc brake

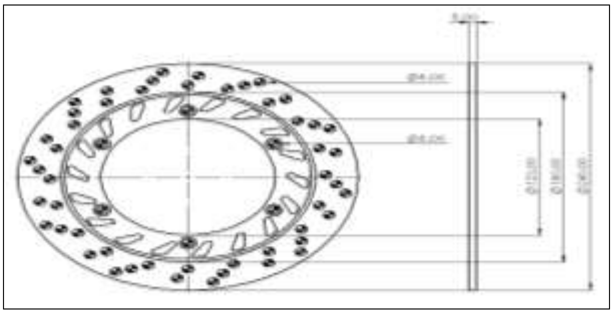


Fig -12: Drawing details of the disc brake

6.2 Disc Brake Performance Calculations

Table-8 shows the design data collected from **Honda CB Unicorn 150**.

Table -8: Design Data

ITEMS	VALUES
Disc Outer Diameter	240 mm
Disc inner Diameter	123 mm
Disc thickness	5 mm
Brake pad area (standard)	2800 mm^2
Initial velocity, v	110 km/hr. = 28 m/s
The mass of the vehicle + driver	145+75= 220 kg
Size of the front tyre	2.75-18
The radius of the front tyre, r1	500 mm
Coefficient of friction between the brake pads and disc, μ	0.4
Acceleration due to gravity, g	9.81 m/s^2
Maximum pressure	1MPa (106 Pa)

Rotational Speed (ω),
$\omega = v/r_1$
$= 28/0.5$
$\omega = 56$ rad/s

Resistive force of friction (F),
$F = \mu \times m \times g$
$= 0.4 \times 220 \times 9.81$
$F = 863.28$ N

Deceleration of the Vehicle (a),
$a = F/m$
$= 863.28/220$
$a = 3.924\ m/s^2$

Stopping Distance
$= v^2/2a$
$=28^2/2(3.924)$
Stopping Distance = 99.9 m

Time taken to stop the vehicle (t),
$t = v/a$
$=28/3.924$
$t = 7.14$ sec

In this case, it is assumed that entire Kinetic energy is converted into heat energy,

Kinetic energy (K.E),
$K.E = mv^2/2$
$=220(28^2)/2$
K.E = 86240 J

Power (P),
$P = K.E/t$
$=86240/7.14$
P = 12078.43 W

Since only about 35% of the mass of the vehicle will act to the front and hence the power will be reduced to
$P = (12078.43x0.35) /2$
P = 2113.73 W

Heat flux produced in the disc brake (H_f)
$H_f = P/t/A$
Where A is the rubbing surface area of the disc brake are 0.0028 m^2 respectively.
Heat flux, $H_f = 2113.73/7.14/0.0028$
$H_f = 105728.57\ W/m^2$

6.3 Finite Element Analysis of Disc Brake

The finite element model of disc brake constructed for the dimensions as the inner diameter, outer diameter and thicknesses of the disc is 123 mm, 240 mm and 5 mm for grey cast iron and Al-TiC respectively to both cases. Fig. 13. represents the CAD model imported to ANSYS Workbench 2019 software.

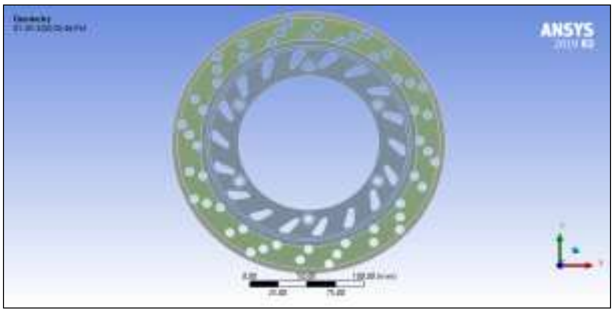


Fig -13: Disc brake CAD model in Ansys

The material properties are represented in Table-9.

Table -9: Material Properties

MATERIAL PROPERTIES	GREY CAST IRON	Al 6082-12% TiC
Density (Kg/m³)	7200	2976
Young's modulus (GPa)	110	120
Poisson's ratio	0.28	0.29
Thermal conductivity (W/mK)	46	188
Specific heat (J/Kg-k)	380	473

A finite element mesh model of the disc brake generated is shown in Fig. 14. The elements used for the mesh of the model are tetrahedral three-dimensional elements. The number of nodes is 72276 and elements is 28847.

Fig -14: Mesh of the disc brake

For analysis, the initial and final boundary condition is introduced in the static structural module of ANSYS Workbench as represented in Table-10.

Table -10: Loading and Boundary Conditions

Structural Analysis	
Initial temperature of the disc	22°C
Pressure applied on both surfaces	1 MPa
Rotational speed of the disc	56 rad/s
Thermal Analysis	
Initial temperature of the disc	22°C
Heat flux	105728.57 W/m²

Structural analysis is performed to know the Total deformation, Equivalent elastic strain, Equivalent stress, Shear stress developed on a disc brake for different materials. Thermal analysis is also performed to know the temperature distribution and toat heat flux developed on a disc brake.

The loading and boundary conditions for structural and thermal analysis are represented in Fig. 15 and 16 respectively.

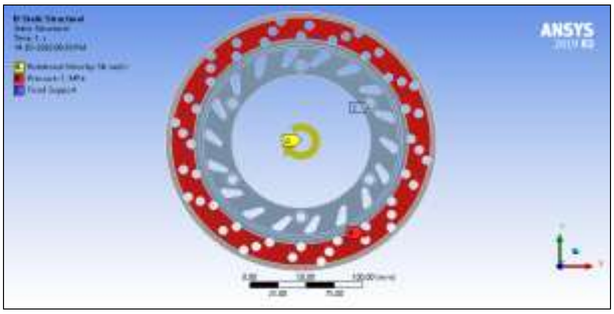


Fig -15: Loading and boundary condition for structural analysis

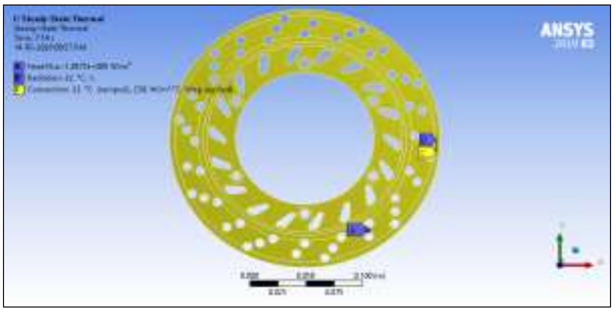
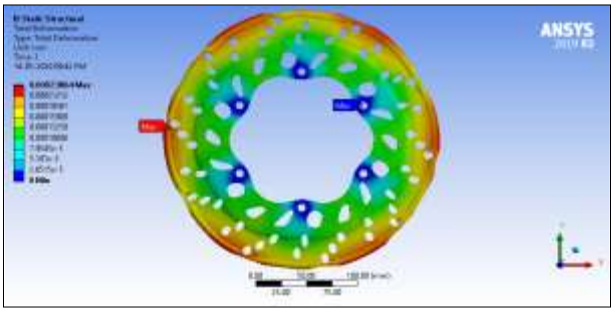
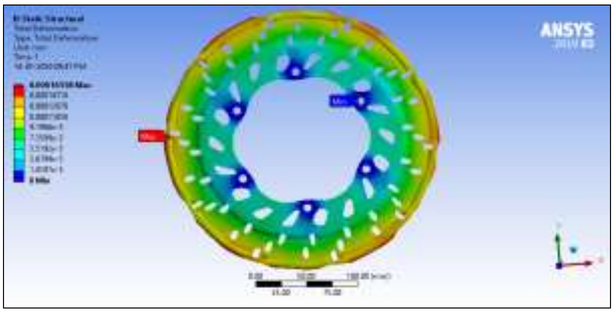


Fig -16: Loading and boundary condition for thermal analysis

Fig. 17 (a-b) Represents the total deformation of disc brake for grey cast iron and Al-12% TiC.



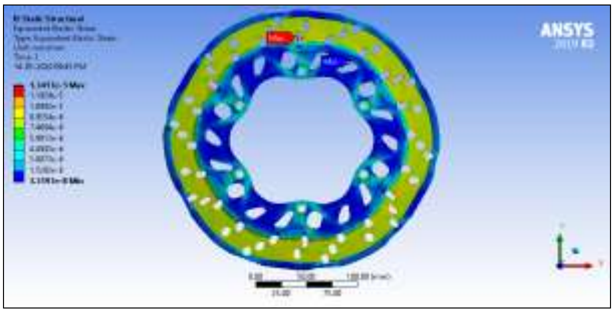
(a) Grey Cast Iron



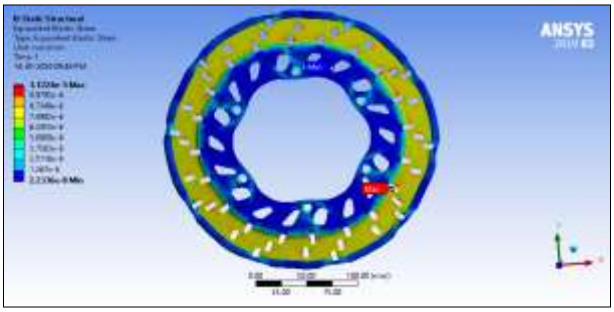
(b) Al-12% TiC

Fig -17: Total Deformation

Fig. 18 (a-b) Represents the equivalent elastic strain of disc brake for grey cast iron and Al-12% TiC.



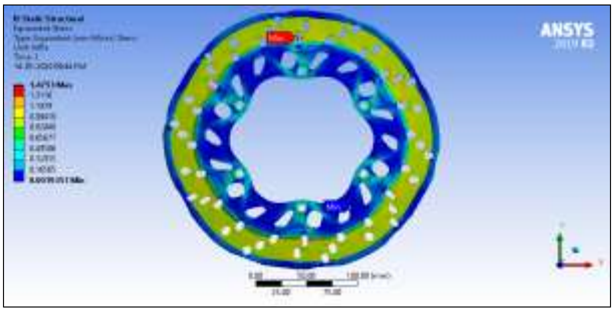
(a) Grey Cast Iron



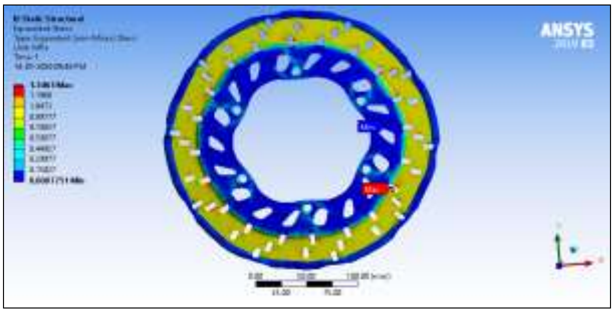
(b) Al-12% TiC

Fig -18: Equivalent elastic strain

Fig. 19 (a-b) Represents the equivalent stress of disc brake for grey cast iron and Al-12% TiC.



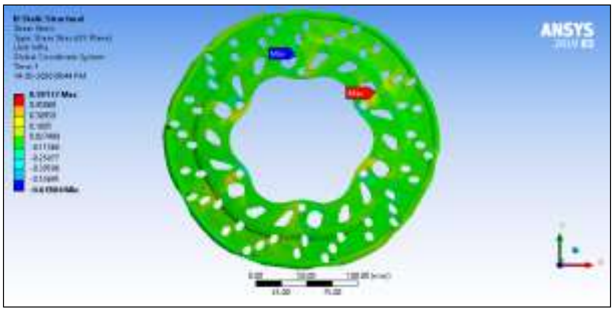
(a) Grey Cast Iron



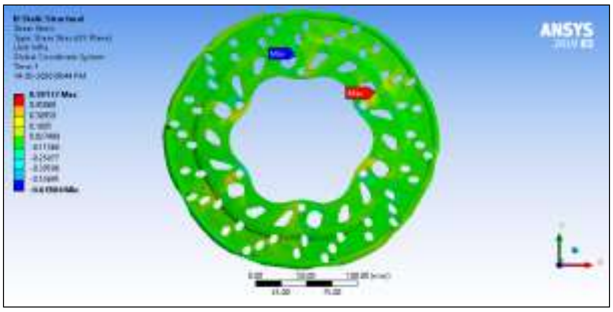
(b) Al-12% TiC

Fig -19: Equivalent Stress

Fig. 20 (a-b) Represents the shear stress of disc brake for grey cast iron and Al-12% TiC.



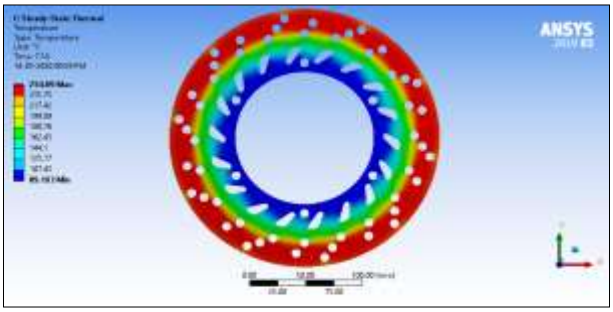
(a) Grey Cast Iron



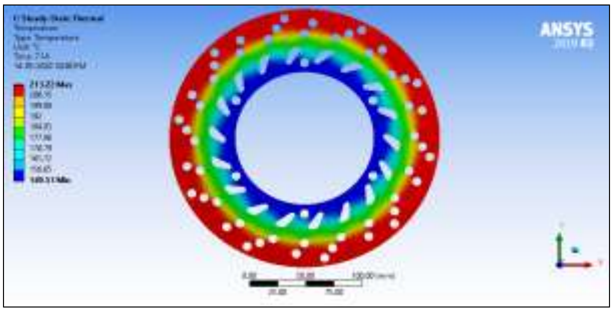
(b) Al-12% TiC

Fig -20: Shear Stress

Fig. 21 (a-b) Represents the temperature distribution of disc brake for grey cast iron and Al-12% TiC.



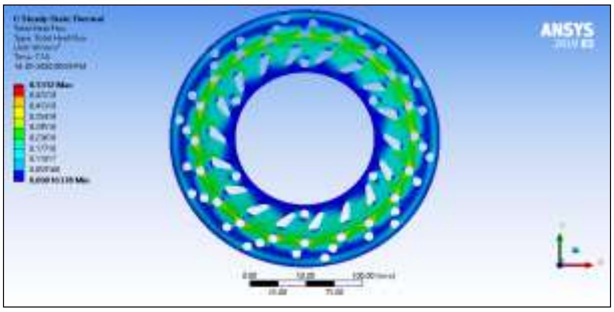
(a) Grey Cast Iron



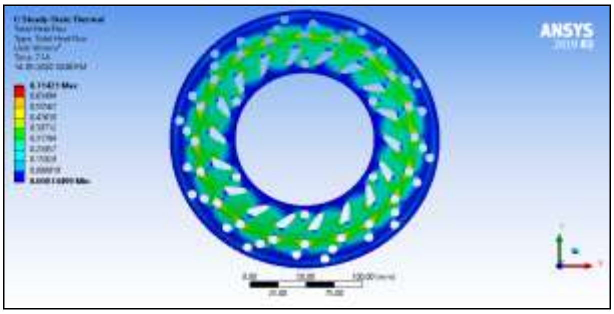
(b) Al-12% TiC

Fig -21: Temperature Distribution

Fig. 22 (a-b) Represents the total heat flux of disc brake for grey cast iron and Al-12% TiC.



(a) Grey Cast Iron



(b) Al-12% TiC

Fig -22: Total Heat Flux

6.4 RESULTS OF FINITE ELEMENT ANALYSIS

The modelling and analysis of the conventional grey cast iron and Al-TiC composite material model disc brakes with the same loading and boundary conditions. The results are tabulated in Table-11.

Table -11: Results from Analysis

PARAMETERS	GREY CAST IRON	Al 6082-12% TiC
Total Deformation (mm)	0.000239	0.000166
Equivalent Elastic Strain (mm/mm)	1.3417E-5	1.1224E-5
Equivalent Stress (Mpa)	1.4753	1.3463
Shear Stress (Mpa)	0.5918	0.3136
Temperature (^oC)	254	213.22
Total Heat Flux (W/mm^2)	0.5312	0.7142
Weight (Kg)	1.015	0.419

In this project, a comparative study has been made between grey cast iron and Al-12% TiC for structural and thermal analysis. Among these two materials, the best value is obtained by Al-12% TiC. Which has total deformation (0.000166 mm), equivalent stress (1.3463 MPa), shear stress (0.3136 MPa) and temperature (213.22 ^oC). Based on the values obtained from the analysis Al-12% TiC is the best material to enhance the performance of the disc brake.

7. CONCLUSIONS

The fabrication of MMC was made with three different proportions Al6082(96%)/TiC(4%), Al6082(92%)/TiC(8%) and Al6082(88%)/TiC(12%) by stir casting process. By using three different compositions of AMMC, Al-12% TiC was selected based on the betterment of results.

The temperature of the Al-12% TiC composite material is reduced by16% compared to grey cast iron.

Maximum heat flux of 0.7142 W/mm^2 is observed in Al-12% TiC composite, which results in high heat dissipation.

The weight of the Al-12% TiC composite material is 0.419 Kg, which is 58% less than grey cast iron material.

From the above results, it is found that Al-12% TiC composite material is better than grey cast iron material.

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