Addis Ababa University

Addis Ababa Institute of Technology

School of Graduate Studies

School of Mechanical and Industrial Engineering

Analytical Selection of Material for Lifan 520 model vehicle Brake Disc

A Thesis Research Paper Submitted for the Partial Fulfillment of Degree of Masters of Science in Mechanical Engineering (Mechanical Design)

By: Hailemariam Getachew Addo

Advisor: Daniel Tilahun (Ph.D.)

Co-advisor: Mr. Natinel Abebaw (PhD Candidate)

Addis Ababa, Ethiopia

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Declaration

This is to certify that the thesis presented by Hailemariam Getachew Addo, titled as "Analytical Selection of Material for Lifan 520 model vehicle Brake Disc" and submitted to the School of Mechanical and Industrial Engineering in the partial fulfillment of the requirements for the award of the degree of masters of science in Mechanical Design Engineering with the regulations of the university, and meet accepted standards with respect to originality and quality.

Hailemariam Getachew Addo	__________________	____________
Name	Signature	Date

This thesis has been submitted for examination with approval as a university advisor.

Daniel Tilahun (Ph.D.)	__________________	____________
Advisor	Signature	Date
Natinel Abebaw (PhD Candidate)	__________________	____________
Co-advisor	Signature	Date

Addis Ababa University

Addis Ababa Institute of Technology

School of Graduates Students

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By

Hailemariam Getachew Addo

Approved by Board of Examiners

Daniel Tilahun (PhD)	______________	______________
Advisor	Signature	Date
Natinel Abebaw (PhD Candidate)	______________	______________
CO-Advisor	Signature	Date
Tollossa Deberie (PhD Candidate)	______________	______________
Internal Advisor	Signature	Date
Tamirat Tesfaye (Dr.-Ing)	______________	______________
External Advisor	Signature	Date
Yilma Tadess(PhD)	______________	______________
Dean of the School	Signature	Date
Ermias Tesfaye (PhD)	______________	______________
Director of Post Graduate	Signature	Date

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Abstract

In automotive engineering sector, the safety aspect is a major consideration in development of a new vehicle. Each single system has been studied and developed in order to meet safety requirements. Widely Disc Type Brake used for this safety requirements and manufactured for first time in 1902 G.C in United Kingdom. In Braking time, the Kinetic energy of a Vehicle changed to heat energy. This high temperature leads to reduce the rotors performance and failures will occur. The existing material of Brake Disc has suitable properties to facilitate this reduction in performance of Brake Disc.

The objective of this research is analytically, Selecting alternative material for Lifan 520 model vehicle Disc Brake Rotor. the weighting of material is done among Cast Iron, Stainless Steel, carbon-ceramic, Aluminum Metal Matrix composite and Titanium alloys. From those Candidate Materials, Digital Logic Methods (DLM) is a method used to Select suitable material for Brake Rotor. Density, wear rate, coefficient of friction, compressive strength, Specific heat and Cost are a property of Candidate materials that considered in selection of suitable material for brake disc by Digital Logic method.

The result of this analysis shows that, Aluminum Metal Matrix composite (AMMC) is the material that higher value of figure of merit (FOM) from all above five Candidate materials. Therefore, this material is best material for Disc Brake than Gray Cast Iron (GCI). Lifan 520 model vehicle is selected for this purpose. Some variables such as: Deceleration of a vehicle, Stopping Distance, mass of Disc, deformation and Von-misses Stress on Brake Disc is calculated in order to see the visible differences between Disc Brake made from new(AMMC) and old(GCI) materials. A 3D Modeling of Disc Brake is done by SOLIDWORK 2018® modeling software and FEA ANSYS 18.2® is used to calculate mass of Disc, deformation and Von-misses Stress.

Result obtained from Numerical and FEA showed that; Disc Brake made from AMMC reduce the mass by 62.4 %, increase Deceleration by 33.16%, Reduce Stopping Distance by 31.7%. Generally, it increases over all performance of Brake Disc by 8.7%. Therefore, based on Shown result, it can be concluding that Aluminum Metal Matrix composite (AMMC) material is the Suitable material for Lifan 520 brake disc.

Key Word: *Disc Brake, Digital Logic methods, FEA, Friction Material*

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Nomenclature

σ_w - *working Stress*

σ_c - *Compressive strength*

F_s - *Factor of Safety*

F_f - *frictional force*

μ- *coefficient of friction*

C_p - *Specific heat*

ρ - *Density of material*

v -*Volume*

V -*Velocity*

m -*mass*

N -number of possible decision

PD-positive decisions

α -*Weighting Factor*

β- *scaled property*

γ -*performance index*

FOM-figure of merit

C_t -*Total cost of the material / unit weight*

$\Delta\gamma$ % -*percentage increase in performance*

Δ *Ct % - percentage increase in cost*

γ_n -*performance indices of new materials*

γ_o- *performance indices of old materials*

C_{tn} - *cost of the new materials*

C_{to} - *cost of the old materials*

2WD-two-wheel Dive

K.E-Kinetic Energy

Q_g - *heat generated*

a - *Deceleration of the vehicle*

S - *distance of vehicle*

$(F_b)_t$ - *tangential Breaking force*

F_c - *clamping force*

ω - angular velocity

g - gravitational acceleration

T_w *-Braking torque on each wheel*

T_d *- Braking torque on each disc*

D -Diameter of Wheel

d -Diameter of disc

R - Radius of Wheel

r -radius of disc

N -revolution

F_b *– Braking force*

a – acceleration of vehicle

R_{rl} *- Rolling resistance* ($R_{rl} = f_{rf}W$)

f_{rf} *- Rolling resistance coefficient*

W – weight of vehicle

R_g *- Grade resistance* ($R_g = W \sin \theta_g$)

R_a *- aerodynamic resistance*

ρ *- density of air* ($\rho = 0.076$ *Ib* $/ft^3 = 1.2$ kg/m^3)

C_D *– aerodynamic drag Coefficient* ($C_D = 0.32$)

A_f *– Frontal area of the vehicle*

d- deceleration

k_{bf} *– fraction of braking load distribution in front wheel*

γ_m *= Mass Factor (inertia of vehicle's rotating parts is taken in to accounts),*

ε_0 *- gear reduction ratio*

List of Abbreviations

IJETT: International Journal of Engineering Trends and Technology

IJRET: International Journal of Research in Engineering and Technology

JMCE: Journal of Mechanical and Civil Engineering

IJMET: International Journal of Mechanical Engineering and Technology

IJIERT: International Journal of Innovations in Engineering Research and Technology

JERS: Journal of Engineering Research and Studies

IJEDR: International Journal of Engineering Development and Research

IJIRSET: International Journal of Innovative Research in Science, Engineering and Technology

IJAUERD: International Journal of Automobile Engineering Research and Development

CHAPTER ONE

INTRODUCTION

Any Machine or Machine components require controlling system to stop, decelerate its speed and to change its directions as much as possible. When a device started initially, it must have accelerated from rest to the operating speed. As a function is completed, the system must frequently have brought to rest. The must here is developing a braking system for the car & its purpose is changing a vehicle's kinetic energy (acceleration) to thermal (Heat) energy using applying friction Force. [10, 12]

1.1. Background

A brake is a controlling device used to bring a moving system to rest and to Control its speed for a certain time under varying Load conditions. Friction-braking systems is the universal adopted method used to retardation of automobiles. Friction brakes operate by converting the vehicles kinetic energy into thermal energy (heat). The heat created in braking is generate by friction between the brake rotor and pad (lining) material. The rate of heat generation in a friction braking system is a function of the vehicles mass, velocity and rate of deceleration. [9, 10]

1.1.1. Types of brakes

The Brake is categorized in to Three (See Figure 1.1- 1.3). Their task is the same but, only the difference is the way/ mechanism of acting external applied Load or actuation Force. The description of those three Brake is to know the most common used Brake in modern car and the case why it is chosen for Brake Separately.

a) **Band brake:** a type of brake, in which the friction material is a flexible band and rolled on external edge of Rotating Drum. In braking time, the band tightened on the drum is exerting a tangential force to control the motion. [10]

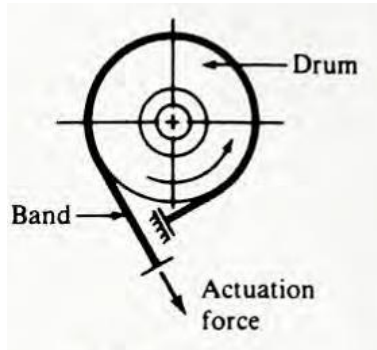


Figure 1.1: Band brake

b) **Block or shoe brake:** Curved & rigid pads (friction material) is forced against the surface of a drum, from either the outside or the inside, exerting a tangential force to stop the load. [10]

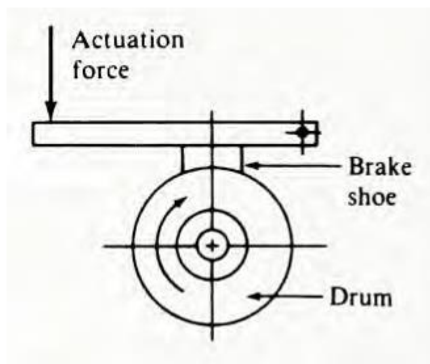


Figure1.2: Short shoe brake

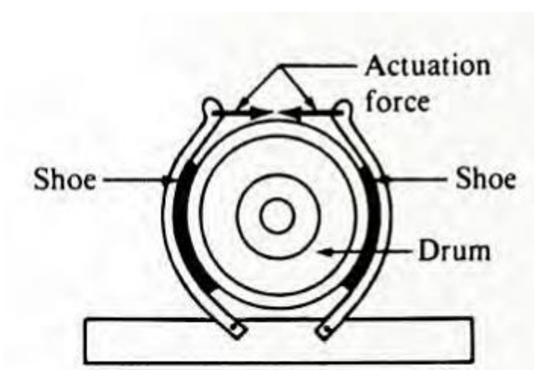


Figure 1.3:Long shoe brake

c) **Caliper disc brake:** A caliper disc brake is the most common type of disc brakes used in modern cars. A disc brake is a wheel brake, which slows down a rotating wheel by the friction caused by pushing brake pads against a brake disc with a set of calipers. Friction pads covering only a small portion of the disc are contained in a fixed assembly called a caliper and forced against the disc by air pressure or hydraulic pressure. [10]

Disc type brakes development and use began in England in the 1890s. The first caliper type automobile disc brake patented by English engineer Frederick William Lanchester in Birmingham UK factory in 1902 and used successfully on Lanchester cars. [3, 11]

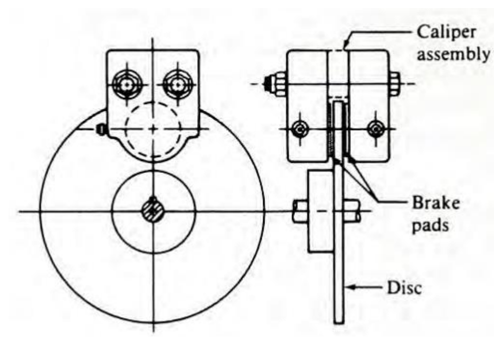


Figure1.4: Caliper disc brake

1.1.2. Disc Brake Materials

Dominantly, Disc brake is manufactured from cast iron due to better metallurgical stability behavior, lower cost and comparatively ease of production and good thermal conductivity, due to the graphite phase but in some cases be made of composites such as reinforced carbon–carbon or ceramic matrix composites. High thermal conductivity due to a greater amount of graphite in the microstructure, allowing lower temperatures in the region under friction, which contributes to an increase in life of the component. [3,12,13]

Recently, automotive industries manufacture high-carbon, high-conductivity gray iron brake rotors & alloyed with Mo, for passenger cars and heavy trucks. These alloys reduce mechanical strength (200 or 150 MPa) of the Rotor. due to this the size of Rotor is bigger and heavier. [13]

Other types of material that have high thermal performance in braking conditions are composite materials of carbon matrix and cast iron with titanium. Composite carbon matrix, used to brake discs for competition cars and aircrafts because they have good heat performance, but its manufacturing cost is high relative to cast iron. Brake disc made of cast iron with titanium is used to increases the mechanical strength of Rotor. However, reduces the friction coefficient, this is a major problem when there a short braking distance. [12]

1.2. Motivation

During Braking, High Heat is produced due to high applied frictional force. frictional force is needed for Braking system, but corresponding un necessary parameter like (high wear, too much Heat….) will take place. this have an impact on overall efficiency of Brake Disc. The materials play a great role in order to reduce side Impact without significant change in brake disc design.

Nowadays there are more than 2000 types of different materials used in commercial brake components. good thermal conductivity, good corrosion strength, low noise, low weight, long durability/ strength, steady friction, low wear rate and good cost/benefit ratio are required parameters for Braking system. There is no Single material to Fulfil required parameters for Braking system among those 2000 types of material. To attain the required properties, a number of material would combine to each other with different Structure and sizes. Therefore, the motivation of this research is the problem that happened in Disc Brake due to Generated Frictional Force between Brake Pad and Disc Brake.

1.3. Problem statement

Since brake rotor is a crucial component from safety point of view. Braking leads to temperature rise in various brake components of the vehicle, that reduces the performance of the brake system. The temperatures in the brake components become too high. This leads to Brake Disc;

- ✓ Excessive wear
- ✓ Highly Stressed
- ✓ Noise
- ✓ Vibration and
- ✓ In extreme cases complete failure.

These is related to material properties which Brake Disc is made in order to Stable the performance of the brake. Current materials used for brake Disc have no efficient properties under varying conditions of load, velocity and temperature. Even if many researchers work on Brake Rotor material based on different point view. There is no Single material for disc brakes that has fully acceptable operation properties in terms stability of the friction coefficient, thermal characteristics, wear intensity and cost. They yet not get one sufficiently enough material which can fulfil the requirements of brake materials.

Therefore, the concern of this paper is on the analytical Selection of better performance rotor disc brake materials which can meet requirements. The most important consideration in the ability of the brake disc material is high friction; less wear and cost for well performance of the braking system. Those are important factors need to consider during the developing phase.

1.4. Objective

1.4.1. General Objectives

Selection of friction material for Brake Disc to increase the performance of Lifan 520 model vehicle Disc Brake Rotor and Analyze Variables analytically (Numerical and FEA) within the same geometry.

1.4.2. Specific Objectives

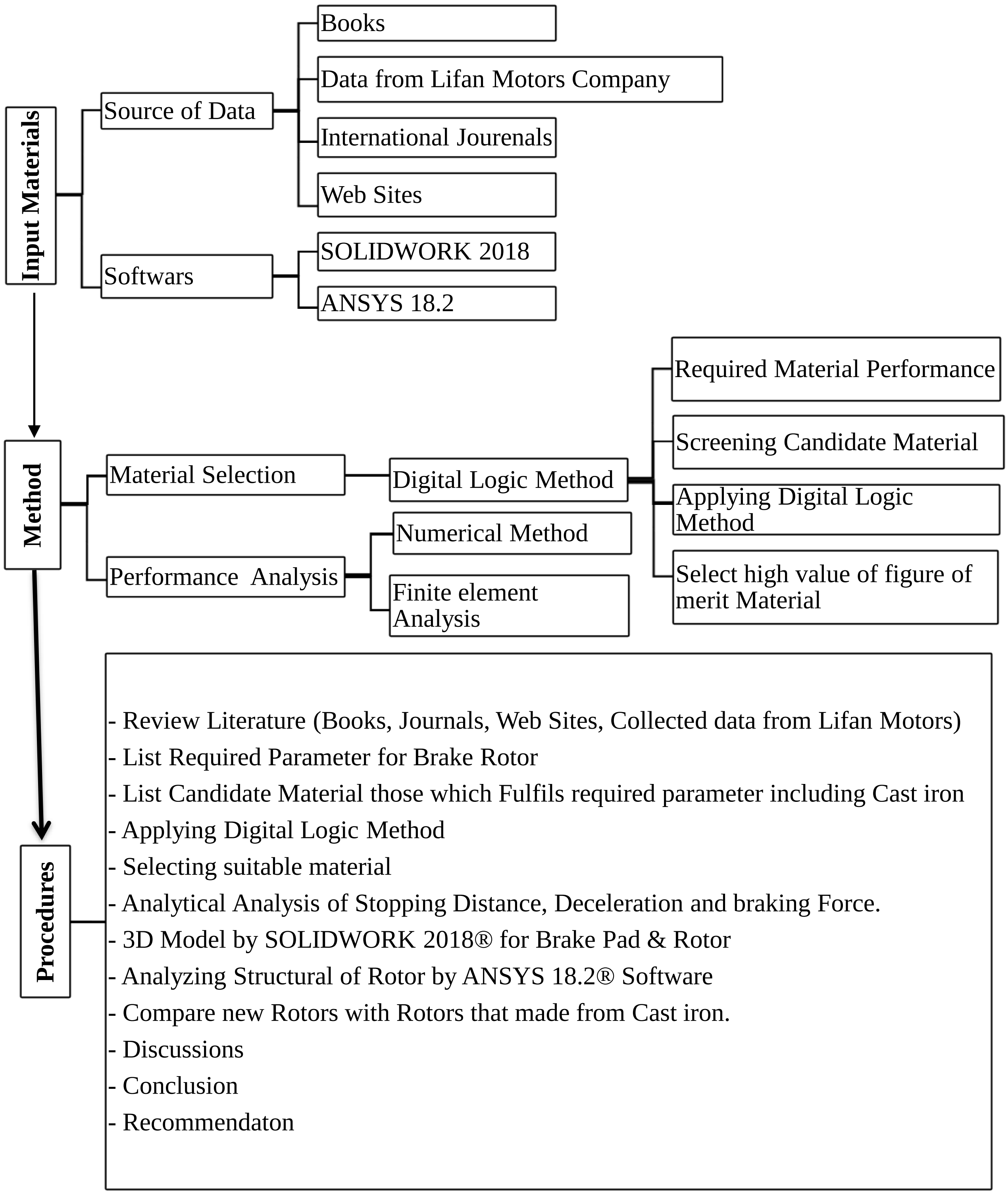
- ✓ Assessment of materials, according to general material performance requirements for disc brake rotor.
- ✓ Analysis numerically; Stop Distance, Maximum Deceleration taken to stop the Vehicle under Maximum Applied Load.
- ✓ FEA of rotor by using ANSYS 18.2® Software.
- ✓ Comparing new Rotor with old Rotor.

1.5. Scope and Limitations

The Research Boundary is Assessing a materials based on their property, Analyze Stop Distance, calculate Deceleration, Maximum Braking Force, mass, deformation and Von-misses Stresses of a Rotor. modelling 3D by SOLIDWORK 2018® Software, Finite Element Analysis by ANSYS 18.2 Software and comparison between New & old material based on Analyzed value. Otherwise Experimental prototype is not a part of this paper.

1.6. Methodology

The material selection process performed based on performance shown by materials. Digital logic methods (DLM) is a method used to select materials for knowledge-based selecting and ranking of the materials for a brake disc or rotor because in digital logic method, multiple properties were considered for the optimum selection of the materials. Under this Section, each points about input material, method to used and Procedures that follow to achieve the Objective of the Research is described below in simplified manner.


Input Materials
Source of Data
Books
Data from Lifan Motors Company
International Jourenals
Web Sites
Softwars
SOLIDWORK 2018
ANSYS 18.2
Method
Material Selection
Digital Logic Method
Required Material Performance
Screening Candidate Material
Applying Digital Logic Method
Select high value of figure of merit Material
Performance Analysis
Numerical Method
Finite element Analysis
Procedures
- Review Literature (Books, Journals, Web Sites, Collected data from Lifan Motors)
- List Required Parameter for Brake Rotor
- List Candidate Material those which Fulfils required parameter including Cast iron
- Applying Digital Logic Method
- Selecting suitable material
- Analytical Analysis of Stopping Distance, Deceleration and braking Force.
- 3D Model by SOLIDWORK 2018® for Brake Pad & Rotor
- Analyzing Structural of Rotor by ANSYS 18.2® Software
- Compare new Rotors with Rotors that made from Cast iron.
- Discussions
- Conclusion
- Recommendaton

1.7. Organization of the paper

This thesis organized in to five chapters. In the first chapter introduction, background, statement of the problem, motivation of the research, objectives and methodology of the study will have discussed. The survey of literatures related to the research will investigated in chapter two. The journals, articles and publications that related to this research work is reviewed detail in this chapter.

In the third chapter, materials used, the conditions and the methods of analysis are covered. Assessments of new friction material, Modeling, Numerical and FEA analysis for Brake Rotor will discussed clearly. In chapter four, the FEA results will displayed and performed an appropriate discussion. Lastly, conclusions, recommendations and future work of the research will have stated in the last chapter, chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.1. Brake System

Braking system is the most important part of the vehicle & its function is keeping the safety of the driver, passenger and pedestrian. Today the vehicles use widely caliper type disc brake for this system. A moving vehicle has a certain amount of kinetic energy, and the brakes have to remove this energy from the vehicle in order to stop it. During braking time friction load applied to the disc. Fast and hard braking causes temperature rise in Brake Disc this change of temperature causes large stresses in the material therefor the consequence is thermal shock. [1, 14]

During the braking Time, the heat energy is store in the rotating part (drum brake or disc brake) and release it to the air gradually. The kinetic energy of drum brake or disc brake lost by the applied Frictional force is translated to heat or thermal Energy. if the speed of a vehicle doubles, a minimum of four times much energy is must require to stop the Vehicle because Kinetic energy increases with the square of the velocity mathematically K.E = $\frac{1}{2}mv^2 = E$. This means the braking distance is four times as long. [1]

Braking system in vehicle transmits the force from Driver's foot to break by depressing the Brake pedal. However, the actual brake requires a much greater force than the applied force by Driver Leg, so the vehicle must multiply the force of Driver Leg to stop or reduce the Vehicle's motion. This done in two way's mechanical advantage (pivot or leverage) and hydraulic force multiplication. [1]

In case of mechanical advantage, the pedal will have designed to multiply the applied force from Driver's leg in many /several times before the force reached to the brake pad. In addition, hydraulic system is relatively simple to multiply the given force many times. Therefore, Fluid Force (oil) applied at one point is transmitted to another point using an incompressible fluid. Most brake systems also multiply the force in the process. [1]

Dissipate the heat from Brake to Surrounding for cooling purpose and controlling the motion of vehicle is the theorem of First Law of Thermodynamics known as the law of conservation of energy. This law states that, energy neither created nor destroyed but it can have converted from one form to another. There for, in Braking time kinetic energy will converted to thermal energy. Using friction, the brakes transmit the force to the tires. In addition, the tires transmit that force to the road using friction. [15]

Braking system is an energy converting system that converts vehicle movement into heat. To slow or stop the car, two flat shoes or Pad located on both side of the disk are pushed against the rotor disc by piston due to applied pressure on back side of piston. In this case, the contact between Pad and Brake Disc is take place & causes frictional force at contact area and inhibiting the motion of the vehicle. [1, 17]

Brake operates by converting the vehicles kinetic energy into thermal energy (heat) to slow rotation of the wheel by the friction caused by pushing brake pads against a brake disc with a set of calipers. Due to this friction, Heat created at the interface between a rotor (disc or drum) and stator (pads or shoes). Pad forced against both sides of the disc mechanically, hydraulically, pneumatically or electromagnetically. The friction between the Pad and disk slows and stops the disc as well as control the whole motion of the Vehicles.

During braking, the Disc get too hot and become less effective, a phenomenon known as brake fade. For this reason, surrounding used as temporary thermal storage devices and sufficient cooling of Brake Disc or Rotor is essential to achieve satisfactory performance of the braking system. Therefore, the heat must effectively have dissipated for the successful operation of a braking system. [9, 16]

The methodologies like regenerative braking and friction braking system mostly used in a vehicle. A friction brake generates frictional forces as two or more surfaces rub against each other to reduce movement. Based on the design configurations vehicle friction brake, grouped into two part, drum and disc brakes. The heat transfer rate is low and Time taken for cooling the disc also low if brake disc is in solid body as well as the area of contact between disc and pads are more. In disc brake system, a ventilated disc is widely used in automobile braking system for improved cooling during braking in which the area of contact between disc and pads remains same. [18]

2.2. Disc Brake behavior

The development or investigating of material for automotive vehicles braking systems is depending on a combination of mechanical and thermal properties of the Material. There for practically, it is impossible to select a material and design a component based only on one of these properties. The material used in brake rotors should be able to resist thermal fatigue and should absorb and dissipate, as soon as possible, the heat generated during braking. [13]

development of alternative Material for Braking system gives significant opportunities to improve Brake Rotors performance in terms of strength, wear, Heat energy absorption & dissipation, weight reduction &

space saving and as whole increasing overall service time. There are many journals, thesis papers, books, conference and published Case study in the world related to automotive Disc Brake materials and their analysis. These previous works were trying to address different approaches to design and analyze the automotive Disc Brake by using different materials.

2.3. Related Researches

K.Sowjanya and S.Suresh [1]. A Brake is a device by means of which artificial frictional resistance is applied to moving machine member, in order to stop the motion of a machine. the objective of this study is Structural Analysis of Disc Brake Rotor among three materials, those are Cast Iron, AlMMC1(Aluminum Metal Matrix Composite1) and AlMMC2(Aluminum Metal Matrix Composite2). The model of Disc brake is developed by using Solid modeling software and Structural Analysis is done by using ANSYS Workbench to determine the Deflection, Normal Stress, Von-mises stress.

Comparing the different results obtained from the analysis shows and concluded that Cast Iron is the best possible combination for the present application rather than Aluminum Metal Matrix Composite1 and Aluminum Metal Matrix Composite2.

Suresh Talur et.al [2]. The studies focused on Selection of Material by weighted property (Digital Logic (DL)) method for Savonius Vertical Axis Wind Turbine Rotor blade. They used four materials for this application, these are; Aluminum (7020 Alloy), Mild Steel (grade 55), Stainless Steel (A580) and Polycarbonate sheet. Density, Corrosion rate, Cost, machinability, Yield strength, Tensile strength, Specific modulus and Young's modulus are used as key parameters to select the best material.

Ranking of materials in Weighted factor computed by Digital logic method, among the Aluminum alloy (7020), Mild Steel (55 grade), Stainless Steel and Polycarbonate Sheet, Polycarbonate Sheet shows higher performance value than other material. Generally, by computation the Polycarbonate sheet is optimized material for manufacturing of blade.

Mahmood Hasan Dakhil et.al [3]. This article is focused on optimized Structural Design and Analysis of Disc brake using finite element analysis and evaluating the performance under severe braking conditions. ANSYS Software is used for determining the temperature distribution, variation of stresses and deformation across the disc brake rotor using different braking conditions. And also service life and long term stability is ensured by using mechanical and geometrical data. 10mm & 12mm flange width (Cast iron and stainless steel materials) are used as disc brake. as a result, the maximum stress in cast iron and stainless steel disc brake with 10mm flange width is 3331.746 MPa &259.231MPa respectively. Also with 12mm flange width is 198.159MPa & 185.499MPa for both cast iron and stainless steel disc brake. The factor of safety of cast iron with10mm & 12mm flange width is 1.106 & 1.89 and for stainless steel with 10mm & 12mm flange width is 3.316 & 4.636 respectively. Generally, the researchers are suggesting that a best combustion of material, flange width and well thickness used for disc brake rotor, which yields a low temperature variation across the rotor, less deformation and minimum Von-misses stress possible.

Swapnil Thigale & Chinmay Shah [4]. It is possible to improve fuel consumption only by reducing the weight of the vehicle, when weight of the vehicle reduced by 10%, the fuel consumption of vehicles will reduce by 5-7%. There for, the inertial forces which has to be overcome by engine and the energy required for vehicle to move is reduced/less. The total mass of the vehicle is the combination of many components from that one is Disc Brake so; the reduction in mass of a brake disc is a small percentage of the total mass. The total weight of the vehicle weight has significant impact on performance. Reducing the mass of the rotor alone may seem insignificant; doing so along with mass reductions of all other possible components can be significant.

Main objective of this journal is designing a lightweight brake disc used in two wheelers BAJAJ and compared with existing disc. Topology optimization applied on disc by determining the constraints in the design and appropriate boundary conditions to reduce its weight. This performed by using Altair INSPIRE 9.5 software and the newly optimized disc analyzed in ANSYS16.0. Using this method, a new lightweight brake disc is designed. The results of the design show that the weight of a new brake disc is 26.68% less as compared to the existing brake disc Which is reduced from 5389.79gram to 395.45gram.

Topology optimization performed on disc by determining the constraints in the design and appropriate boundary conditions to reduce its weight. The software INSPIRE 9.5 gives the idea about the initial design with help of which actual design is created. The above result show that the researchers achieve their objective but cross-ponding factors; Maximum Deflection and Max shear stress is increased as well as Factor of safety is less as compared with the pervious Disc. Thus influences the significant role on the performance of Disc Brake especially on overall service Time of Disc.

S. Sarip [5]. From total of the kinetic energy of a passenger car is estimated that, 70% is dissipated through the friction brakes and the other (up to) 30% of the energy could be recuperated (Regain or make up for) e.g. in the form of electrical power (motor/generator (M/G)). weight reduction in automotive industry is a one way of improving product competitiveness and thus achieving commercial success. components made of materials such as iron and steel can be replaced by another lighter material such as polymers and aluminum is a method to reduce the weight.

One area that examined for weight reduction is the brake system, e.g. aluminum and associated composite materials such as metal matrix composites (MMC) for brake rotors have been studied by many a researchers'. This research is focused on analyzing thermal performance of lightweight disc brake models using Finite Element Analysis method. The design requirement, including reducing the thickness, would affect the temperature distribution and increase stress at the critical area. Based on the relationship between rotor weight, thickness and friction criteria have been established for designing. And also the researcher suggests suitable material for Disc Brake in terms of different conditions and concluded that stainless steel is a suitable material than Cast Iron for a lightweight brake disc in terms of mechanical and thermal strength and it is better than Al-MMC(Aluminum Metal Matrix Composites) because of its higher Maximum operating temperature (MOT). A disc made of stainless steel is designed to minimize stresses and distortion.

M.A. Maleque et al [6], The widely used brake rotor material is cast iron, which consumes much fuel due to its high specific gravity. The aim of this paper is to develop the material selection method and select the optimum material for the application of brake disc system emphasizing on the substitution of this cast iron by any other lightweight material. The study has developed weighted property method for selection of optimum material for application of brake disc system, to use light weight material instead of cast iron. Two methods were used for the selection of materials, such as cost per unit property and digital logic methods.

Material performance requirements will analyze and alternative solutions evaluated among cast iron, aluminum alloy, titanium alloy, ceramics and composites. Mechanical properties including compressive strength, friction coefficient, wear resistance, thermal conductivity and specific gravity as well as cost, used as the key parameters in the material selection stages. The analysis led to aluminum metal matrix composite as the most appropriate material for brake disc system.

S.L.N.Reddy et.al[7]. Disc brake is a device used to stop the rotation of a wheel and during Repetitive braking event heat is generated on a Disc. The focus area of this study is analyzing the thermo-mechanical behavior of brake disc during the braking time. Disc brake model is carried out by using solid work and analysis is carried by using ANSYS. Analysis is performed for determining the total heat flux which is caused by using different materials which will reduce thermal loss. The researcher's use Two Material

Aluminum & Structural Steel.

Aluminum is now the second most widely used metal in the world next to Iron due to its properties Like: low density and therefore low weight, high strength, easy machining, excellent corrosion resistance, very easy to recycle and good thermal and electrical conductivity. It's very light, with density = $\frac{1}{3}$ of steel which is 2,700 kg/m^3. The low density of Aluminum accounts for it being lightweight but this does not affect its strength and also Aluminum is an excellent conductor of heat and electricity. Its conductor weighs approximately half as much as a copper conductor having the same conductivity.

The second material is Structural Steel, used as a construction material for making structural steel shape formed with a specific cross section and following certain standards for chemical composition and mechanical properties. Structural steel shapes, sizes, composition, strengths, storage practices, etc., are regulated by standards in most industrialized countries. as a result, the researcher's observed that, when convection heat transfer is applied to Aluminum (Al) & structural steel thermal heat flux is less in structural steel when compared to Aluminum (Al). So it is concluded that structural steel is best when compared to Aluminum (Al).

G. Cueva et.al [8]. optimization of braking systems of automotive vehicle subjected to mechanical and thermal stress is depend on a combination of properties. Practically, it is impossible to select a material based only on one of these properties. These paper is studying wear resistance of three different types of gray cast iron (gray iron grade 250, high-carbon gray iron and titanium alloyed gray iron) used in brake disc rotors and compare obtained result with a compact graphite iron (CGI). (CGI), is interconnector or intermediator of mechanical and thermal properties between those of gray and ductile iron and is an alternative material that has not yet been thoroughly explored/ Examined by the automotive industry due to the limited knowledge of its use in that type of application.

Mechanical and thermal properties of cast iron may be improved through the addition of alloying elements. The wear tests were carried out in a pin-on-disc wear-testing machine. the pin is used as brake pad and manufactured from friction material. The wear was measured by weighing discs and pads before and after the test. The result of the research is, at any applied pressure compact graphite iron (CGI) have greater friction forces, temperatures and mass losses than those three gray irons. However, During CGI tests using lower applied pressures and same friction forces obtained for gray irons, it shows that the wear is greater or at least the same with gray irons.

Marko Reibenschuh et.al [9]. The main objective of this paper is model & analysis the thermal and Stress (centrifugal load) in Train Disc Brakes (from speed of 250 km/h to Standstill). the effect of thermal loads on the temperature field & the effect of centrifugal load in a specific brake disc and models with all the necessary parameters (stresses as a consequence of thermal and centrifugal loads) would be calculated. Different loads are applied to the disc during braking. due to this, braking from 250 km/h to a standstill requires good, reliable brakes.

The paper shows a thermal and stress analysis of a brake disc for railway vehicles using the finite element method (FEM). Performed analysis deals with two cases of braking; the first case considers braking to a standstill (The condition of being stopped or discontinuance); the second case considers braking on a hill (a slope on a road or elevation) and maintaining a constant speed. In both cases the main boundary condition is the heat flux on the braking surfaces and the holding force of the brake calipers. In addition, the centrifugal load1 is considered.

The material used here for the disc brake is graphite cast irons. The new trend of equipping railway vehicles is orientated towards replacing the grey cast iron brake discs by brake discs from composite materials due to its major advantages of Reducing sound barriers and higher resistance to temperatures during braking. Lastly, the result of the paper Concerning on design and material of the disc is The temperatures to which the disc heats up and the stresses are high.

Robert L. Mott, P.E [10]. This book is focused on the concepts, procedures, data, and decision analysis techniques that is necessary to design mechanical system Such as Controlling system, Transmission system, Power system …. etc. Braking system is one of the Controlling system used to control any rotational mechanical motion. from Braking System, Frictional Braking Device is explained in detail in this book. Frictional Brake is a device used to control the motion of the Vehicle by slow its speed or fully stopping.

high coefficient of friction, low wear rate, high heat resistance, high heat dissipation capacity, acceptable mechanical strength, corrosion resistance, good price/benefit ratio are listed as a parameter that considered as much as possible in design of Brake during material selecting phase. types of Brake, some materials used for Braking system, mechanical and thermal behavior of Brake is discussed in detail.

Omar Maluf et.al. [12]. These paper, the researchers are study about material development for automotive disc brakes and mainly focus on Disc Brakes material properties **(**chemical, Physical and Mechanical Properties**)**. They mention the criteria that materials used for braking systems must meet Ideally, these are: good thermal conductivity, good corrosion strength, low noise, low weight, long durability, steady friction, low wear rate and good cost/benefit ratio. Nowadays there are more than 2000 types of different materials used in commercial brake components. There for, combining many materials with different shapes and sizes is recommended to attain the required properties.

The geometry, the dimension and the chemical composition of brakes affect the thermal and Mechanical Properties of Disc Brake. due to the better metallurgical stability behavior, lower cost and comparatively ease of production, cast iron is often more used but, theoretically several materials would be able to attend the requirements for a good performance. For instance, the Listed materials are composite materials of carbon matrix, cast iron with titanium and Aluminum alloys containing silicon carbide are used to produce disc brakes.

composite materials of carbon matrix have excellent heat performance than Cast iron, but the manufacturing cost is high. cast iron with titanium increases the strength, but reduces the friction coefficient. This is a major problem when there is little braking distance and the Last Aluminum alloys containing silicon carbide also used because they have low density. These give us lower weight than cast iron but these alloys do not dissipate the heat as well as gray cast iron.as a researcher's point of view All alloy elements tend to increase mechanical strength and the most efficient are vanadium, molybdenum and chrome.

M. A. Maleque & Sarker Dyuti [13]. Generally, this paper is focused on developing the material selection method and select the optimum material for the application of bicycle frame. cost per unit property and digital logic methods are Two methods used in selection of materials, such as cost per unit property and digital logic methods. To select the optimum material by cost per unit property is consider only strength of materials. But, in case of digital logic method, multiple properties of materials are considered. such as, tensile strength, yield strength, young's modulus, toughness and density. The Ashby's material selection chart was used for the initial screening of the candidate materials. The screened candidate material from Ashby's chart is AISI 1020 steel, Ti-alloy, carbon fiber reinforced polymer (CFRP), Kevlar fiber reinforced polymer (KFRP) and glass fiber reinforced polymer (GFRP). The research is concluded that KFRP has a least/ Lower cost material other material in case of cost per unit property. And also, it shows the highest figure of merit value than the other material in digital logic method. Therefore, based on this Value the researcher's Select KFRP as a suitable material for the bicycle frame.

Stanly Wilson Louis et.al [14]. this research is focused on thermal performance on disc brake. Thermal performance is studied using the model done by CATIA and (ANSYS) Software. Cast iron, Stainless steel, AL7075, AL –MMC are materials used for the analysis and Selection criteria were focused on price, thickness and lightweight. among those material the research concluded that AL-MMC is a suitable material for a brake disc in terms of mechanical and thermal strength. AL-MMC has three times the tensile strength of cast iron therefor for disc thicknesses less than 8 mm AL-MMC is suitable. and also for disc thicknesses of 8 mm or greater, cast iron is better material due to its high thermal conductivity and low Young's modulus, which limit the amount of disc damage caused by the heat flux generated by friction.

Prof A. D. Dhale et.al [15]. The aim of the project is analyzing of structural and thermal characteristics of Disc Brake.3D Modeling is done using CATIA and FEA is done using ANSYS Software. Structural analysis is done on the disc brake to validate the strength of the disc brake and thermal analysis is done to analyze the thermal properties.

Structural and Thermal study on the disc brakes is using three materials Stainless Steel and Cast iron & carbon - carbon composite. Comparison between those material can be focus on deformation, stresses and temperature to check which material is best form the three materials. The paper concludes that, that the stainless steel can provide better brake performance than others from deformation point of view whereas cast iron provides better performance from stress point of view.

Mr. P. N. Gunjal et.al [18]. studied about selection of the disc brake material using pin on disc apparatus. The aim of the researchers is developing the competitive material selection and select optimum material for the application of brake disc system for better working. They concerned more on the tribological behavior of four candidate materials. Those candidates are: - Gray Cast Iron, Structural steel, Aluminum and High speed steel (HSS).

They Test those four materials on wear machine to suggest better new material compared to conventional existing material by checking major tribological parameters such as: low wear rate, low frictional force, low coefficient of friction, low cost, better mechanical properties. for these four materials and try to suggest better new material compared to conventional existing material.

They conclude from observations and graphs Gray Cast Iron is low wear rate, no fluctuation on wear rate, low cost, better mechanical properties than other materials. But Structural steel and High Speed Steel Have Higher frictional force as well as coefficient of friction. Concerned on tribological point of view, they conclude that Gray Cast Iron is best suitable coating material for disc brake applications.

Rehman A et.al [19]. In this review, special attention is given to aluminum composites materials as alternate materials for automobile brake application due to its light weight, strength, abrasion resistant and less corroded behavior. Composite materials (combination of material with in a microscopic scale) provide such unique combination of properties. various combinations of useful properties, usually not attainable by alloys, can be obtained through composite materials by suitable tailoring/ adjusting the matrix and reinforcement (dispersoids/second phase particles).

The reinforcement of hard ceramic particles like silicon carbide, alumina, silica, zircon in aluminum alloys has been found to improve the wear resistance as well as high temperature strength properties. Generally, The Aluminum Matrix Composites (AMCs) is coefficient of friction 25- 30% times of cast iron, thermal conductivity be two or three times of cast iron, Thermal Diffusivity which is the rate of heat dissipation compared to that of storage is four times of cast iron and disc could be 60 % lighter than an equivalent cast iron component.

Rahul Raosaheb Pind & Prof. Swami M. C [20]. The study is investigating alternative material for brake rotor by using computer aided design (CAD) software which are Catia v5 & ANSYS 16. The objective is to design and analyze the thermal and structural stress distribution of brake rotor at the real time condition during braking process and reducing stress concentration & weight of the brake rotor.

General material performance requirement, Initial screening of candidate material, preparing geometric model, performing Finite element analysis, Comparing FEA results, optimum material selection, creating prototype or sample and Validating results is consequent Flow chart of material selection method. Initial Screening of Candidate Materials Are Cast Iron, Titanium Alloys, Aluminum-Metal Matrix Composite (AMC) and Carbon Fiber.

thermal behavior of brake disc for all above screened materials is done by the computer software ANSYS 16 and the result obtained from above study is that the carbon Fiber is the optimum material for the brake disc as it can withstand to both dynamic load as well as thermal load coming on brake disc also it lighter in weight.

Muthanna K. P et.al [21]. The aim of this study is to analyze the performance of disc brake for different materials (Cast iron & Aluminium6061-SiC-red mud composite) under same working conditions and parameters. And the material impact on displacement, stress, contact pressure, contact sliding distance of disc and pad assembly is carried out using ANSYS software.

The pressure applied at the inner surface of the brake pad used for the finite element analysis is 2.5 Mpa and angular speed of 100rps and 150rps are considered for analysis. the result they(Researcher's) get from this study is stress developed in the disc brake is comparatively less, displacement is reducing, Contact sliding, contact pressure decreases in New material (Al6061-3% SiC-9% red mud) than Old material (cast iron)

Harshal Nikam et.al [22]. During Braking time, high frictional forces lead to develop higher heat energy in Brake Rotor. the rotor deforms Due to combined effect of mechanical forces and temperature rise. pre-manufacturing analysis of rotor is needed to avoid this problem. this paper is focused on analyses of mechanical forces acting on rotor and heat generated due to friction between caliper pads & rotor surface and optimization of its dimensions for strength with reduction in weight.

As a result, diameter and thickness of the Rotor varies strength and temperature on rotor surface significantly. So from various possible combinations of rotor diameters and thickness,190mm and 3.9 mm is selected respectively.

Anudeep.B and Naga Sunil.B[23]. Braking is a process which converts the kinetic energy of the vehicle into mechanical energy which must be dissipated in the form of heat. This paper study detail about Aluminum metal matrix composite (AMMC) and zirconia-based ceramic coating (Mgzr03) materials for aircraft Disc Brake Rotor. the 3D model of aircraft disc brake rotor was created by using CATIAV5R20 and structural and thermal analysis is carried out by ANSYS 14.5. The analysis is also done mathematically, then compare this result with ANSYS results for both Disc Rotor which made from Aluminum metal matrix composite (AMMC) and zirconia-based ceramic coating (Mgzr03) materials.

Finally, finite element Results and theoretical analysis is almost the same so they can say that finite element analysis (FEA) is a good tool to consume time. And from the Results Shown by analysis, they suggest that Mechanical and thermal properties of aluminum alloy may be improved through the addition of ceramic coatings on the surface which in contact with the brake pad.

Dr. P.A. Makasare et.al [24]. Any Engineer gives priority for safety measure in His Design. because of safety is the first important thing that He must focus on anything's that related to human being. brake is one of the major device which contributes in safety system in case of automobiles. This project researchers, analysis Tangential Force & Torque on Disc Brake of motorcycle/ BAJAJ and Optimization of Disc Rotor by using ANSYS Software.

By using the same material (Cast Iron), they studied the relationship between Tangential Force, Torque and stop distance of motorcycle only by varying Rotor Dimension. The result shows that When dimension of disc brake was changed, brake torque is changed but tangential force and the motorcycle's stop distance are similar. brake torque is increase with in increasing in Dimension of Rotor.

Prof. Mit Patel et.al [25]. Durability/existence, safety and affordability (is not too expensive) vehicles part or product is important for optimization of technical aspects in automobile and to satisfy the users need. The brakes are very important part of a vehicle used to reducing or stopping functions the vehicle's motion as requirements. Analyzing thermo-mechanical behavior of the brake disc during the braking time is The aim of this study. This thermo-mechanical analysis including Kinetic Energy of Vehicle, stopping distance of vehicle, braking force**,** Angular velocity of rotor and Heat Flux.

CHAPTER THREE

MATERIALS, CONDITIONS AND METHODS

3.1. Materials

As we have seen from different literatures (previous chapter), Traditional material for automotive brake rotor is the cast iron. Cast Iron is commonly used Due to good cast-ability (in foundry), corrosion resistance, machinability, relatively low cost than the other materials. Lifan Vehicles whose model 520 is one of the vehicle uses Ventilated Disc Brake which made from cast iron. The aim of this paper is numerically Selecting the competitive material for the application of brake disc system emphasizing/ regarding on the substitution of this cast iron by any other efficient material for model 520 Lifan Executive Vehicles.

3.1.1. General Disc Brake material performance requirements

In many Literatures (previous chapter) the characteristics of material used for the brake system should have Listed. Material used for brake systems should have stable(resistance) and reliable(trust) frictional and wear properties under varying conditions of load, velocity, temperature, environmental factors and high durability (Existing for a long time). The following characteristics are a factors to be considered in selecting a brake disc material. So the material should have: -

- ✓ High coefficient of friction which remain constant over the entire surface with change in temperature.
- ✓ Low wear rate.
- ✓ High heat resistance.
- ✓ High heat dissipation capacity.
- ✓ Low coefficient of thermal expansion.
- ✓ Adequate(acceptable) mechanical strength.
- ✓ Corrosion resistance.
- ✓ Good price/benefit ratio.

Those are important factors need to be considered during the design phase. In this paper more weight is given to mechanical properties of the materials.

3.1.2. Initial screening of candidate material

Practically, it is impossible to select/obtain one material that is acceptable for Braking applications by fulfilling fully the above Listed requirements. The selected material has good performance in some of considered factors listed above and less efficient than the other next competitive materials in some of rest factors/ requirements.

In different literatures there are many materials used for Braking system based on their different vehicle structure and performance. From all Literatures (pervious chapter) eleven materials that suggested by researchers are Selected for this study and initial screening of candidate material is done. Initial screening of candidate material is based on low, equal and grater but closest cost to Cast iron, availability/abundancy mechanical and thermal properties of the materials including coefficient of friction, wear resistance, compressive strength, thermal conductivity and specific gravity as well as cost. These properties are some main key parameters in this material selection phase.

Current cost of material is gathered form trade company website. Five material is screened among eleven materials as Brake material based on above Listed parameters. The table 3.1 shows result of cost of each candidate material and used in material selecting phase [26-28]. Therefore, Material performance requirements were analyzed and alternative solutions were evaluated among Cast Iron, Stainless Steel, carbon-ceramic, Aluminum Metal Matrix composite and Titanium alloys.

Table 3.1: current cost of candidate material.

Material	C_t(US $/ kg)
Cast Iron (GCI)	1.35
Aluminum Metal Matrix composite (AMC)	2.2
Titanium alloys (Ti-6Al-4V)	43.55
Stainless Steel	1.705
Carbon- ceramic	2.3

The Following section will describe the potential candidate materials those can be used for brake rotor application.

Cast Iron: The material less than 2% dissolved carbon within its matrix, we call it Steel but when between 2%-4.5% carbon content it is Metallic iron kwon as gray cast iron because of its characteristic color. Gray cast iron is an attractive material used in Braking applications due to its some properties such as good cast-ability (in foundry), corrosion resistance, machinability, low cost, resist cracking and high vibration damping capacity.

The main reason why it used widely for Braking system is its Advantages of low cost, thermal stability and ease of manufacturability. GCI (Gray Cast Iron) have Compressive Strength :1293MPa, coefficient of friction (μ): 0.41, wear rate: 2.36 x10^{-6} mm^3/N/m, Specific heat (Cp) :0.46 KJ/Kg. K and specific gravity: 7.2Mg/m^3 [6,20].

Cast iron usually refers to grey cast iron. more than 95% is Iron and the left 5% is alloy elements those are 2.1-4% carbon and 1-3% appreciable amounts of silicon. The graphite is present in the form of flakes. There for, grey cast iron is represented with chemical formula Fe-C-Si alloys and have Young's modulus (E) = 125 GPa, Poisson's ratio (v) =0.25, Thermal co-efficient of expansion (K_{XX})= 9.9 *10^{-6}/°c, Thermal conductivity (K)= 54.0 W /m k, Ambient temperature (ta) =25 °c, Density 7100kg/ m^3 [3,24,25].

Metallic(Cast) iron is categorized in to ductile iron, compact graphite iron (CGI) and gray iron. ductile cast iron is a metallic iron with minimum carbon content which is near to 2%. While, compact graphite iron (CGI) is interconnector, resulting in intermediate mechanical and thermal properties between those of gray and ductile irons. It is used for rail road brake rotors in Europe and it has Extremely sharp thermal and mechanical stresses (excellent combination between high Wear resistance and good heat-transfer capacity) than gray and ductile irons. due to the limited knowledge of its use in that type of application, the automotive industry is not use as an alternative material. gray Cast is the third metallic (Cast) iron. It is the ending portion of Iron which have more carbon (near to 4%) in its content [8].

Stainless Steel: There are three main groups of stainless steels those are, austenitic (American Iron and Steel Institute, AISI 200 and 300 series**),** ferritic (AISI 400 series, designated as 405. 409, 430, 446, and so on.), and martensitic (AISI 400 series, including 403, 410, 414, 416. 420, 431, and 440 types). From the above three categories of Stainless Steel Martensitic stainless steel (SS410 grade) is considered for Brake rotor due to their good corrosion resistance, high strength and hardness [10,22].

Stainless steel contains principally iron and a minimum of 10.5% chromium. The reason why Stainless steel is used for braking system is, good corrosion and heat resistance. The mechanical properties of Stainless is Young's modulus = 200 Gpa, Poisson's ratio = 0.3, Thermal co-efficient of expansion (KXX)= 6 *10^{-6}/°c, Thermal conductivity (K)= 40 W /m k, Specific heat (cp) = 460 J / Kg K, Ambient temperature (ta) =25 °c, Density 7800kg/ m^3 [3, 20].

Stainless steel has a chromium content of at least 10%. Most have 12% to 18% of chromium contented. Due to this alloy it characterizes high level of corrosion resistance. They are magnetic, can be heat-treated, and have higher strength than the austenitic.

They develop very high strengths with heat treatments at relatively low temperatures, from 900°F to 1150°F (480°C-620°C). the part needs high-strength like, turbine engine parts**,** pump parts and Vehicle part is Typically, applicable area of Stainless steel [10].

stainless steel has a higher tensile strength but lower thermal conductivity than Cast Iron. It can be concluded that stainless steel is a suitable material for a lightweight brake disc in terms of mechanical and thermal strength, provided that the tribological characteristics are suitable such as Density, ρ (kg/ m^3) = 7800, Thermal Expansion, (K^{-1}) = 11.0×10^{-6} and Min. Tensile Strength (MPa) = 910 [5].

Carbon ceramics: carbon-ceramic material used for Disc brake is a material made from the ceramic composite. Both the carbon-ceramic brake disk body and the friction layers applied to each side consist of carbon fiber-reinforced silicon carbide. In comparison to the conventional (grey cast iron) brake disk the carbon-ceramic brake disc has 50% less weight than gray cast iron. also, high thermal stableness, no hot judder, high abrasion resistance and thus longer life time and the advantage of avoiding almost completely brake dust.

The mechanical properties of the Carbon-Ceramic Brake Disks material are given below. Density, ρ (g/ cm^3) = 2.45, Tensile Strength (MPa) = 40, modulus of elasticity = 30GPa, maximum operating Temperature (brake disc) = 900°c, Thermal conductivity (K)= 40 W /m k, Specific heat (cp) = 800 J / Kg K.

Aluminum Metal Matrix composite (AMMC): Aluminum alloy based on metal matrix composites (MMCs) have lower density and higher thermal conductivity as compared to the conventionally used gray cast irons and 50-60% of less weight than gray cast irons in brake systems [20]. During repeated braking causes, it loses its coefficient of friction gradually and significantly increase its wear rate. To prevent this problem additional of abrasive particles is needed. This particle is Silicon Carbide (Sic)/ Carborundum (compound of silicon and carbon) which provide high strength to the resultant material. Ores or powdery of silicon carbide can be bonded together by sintering (coherent/ Sticking together mass by heating without melting) to form very hard ceramics that are widely used in applications requiring high endurance, such as brakes and clutches [23].

The Properties of Aluminum Metal Matrix composite is Density(kg/m^3) = 2670, Specific heat (J/kg K) = 910, Thermal conductivity(W/mk) = 250, Elastic modulus (GPa) = 71, Bulk modulus (Pa) = 6.96E+10, Shear modulus (Pa) = 2.66E+10, Poisson ratio = 0.33, Co efficient of thermal expansion(10^{-6}/K) = 0.22, Compressive Strength (MPa) = 761, Young's modulus (GPa) = 113, Friction coefficient(μ) = 0.44, Wear rate($x10^{-6}mm^3/N/m$) = 2.91and Specific gravity (Mg/m^3) = 2.8[6, 20,23].

widely investigated matrix for use in MMCs is Aluminum and its alloys. Al-alloy as a matrix material has be low cost relative to other light structural metals such as Mg, Ti, etc. wear is the most Vital in the application of brakes. by adding ceramic particles such as Sic and Al_2O_3 to the matrix alloy the wear resistance of Aluminum alloys can be increased [19].

Titanium alloys: Like other material, this material is also widely used as a high performance automotive material. titanium has higher strength level (800-1080 MPa). Density is simply the weight of a material for a given volume such as grams per cubic centimeter. The density of titanium showed (4.43 g/cm^3). The density of a material certainly is an important factor in materials evaluation [13]. the other physical and thermal properties are mentioned in different literatures (chapter two) and other websites.

3.1.3. Material selection using digital logic (DL) method

Common and analytical methods used in materials selection are: Cost versus property, Benefit-Cost Analysis and Weighted Property Indices (digital logic method). In cost per unit property and Benefit-Cost Analysis, only one property is considered whereas in digital logic method, multiple properties were considered for the optimum selection of the materials. The digital logic (DL) method is suitable method for the material selection with ranking. in this method evaluations are arranged such that, two properties are considered at a time. Every possible combination of properties is compared. table is constructed to determine the relative importance of each property.

3.1.3.1. Relevant Properties of Materials in Material Selection

The properties of the material in Material Selection for Disc Brake is a series issue because the comparison between them is based on their physical, chemical and thermal properties. therefore, the properties that consider in this paper is listed below.

a) **Compressive Strength**

Compressive strength is the ability of a material to resist compacting/squeezing force or pressures acting on a Disc Brake by Brake Pad. Strength is necessary parameter in Braking System in order to reduce wear rate of the materials. Ultimate Compressive strength(σ_c) is directly proportional to the Factor of Safety (F_s) ($F_s = \frac{\sigma c}{\sigma w}$, where σ_w is the working Stress due to applied compressive load). from above mathematical expression we understand that, the material which have high Compressive strength is a high Factor of Safety (F_s) and has ability to resist the applied load.

b) Coefficient of Friction

Coefficient of friction is one of important factors that considered in material selection section. the aim here is developing more frictional force to control the movement of vehicle's. coefficient of friction directly proportional to the frictional force ($F_f = \mu F_N$), Friction is not a material property; it is a system response. Its value is taken from the different Literatures which records the coefficient of frictions between Brake Pad and Disc by Test apparatus. Therefore, the material which have high coefficient of frictions are required for Disc Brake in order to generate more frictional force.

c) Wear Rate

Wear is the surface damage or the removal of the material from the two contact solid surface due to sliding, rolling or impact motion. as frictional force wear is not material properties, it is a system response. wear rate is the Volume of material loss from one Surface per unit sliding distance. the material ability to resist wear is calculated by Archard's formula, $W = k_A * A * P$ (where W is Wear, k_A is Archard wear constant of material, A is area of contact surface and P is applied pressure). therefor the material which have lower wear rate is best material for Braking system.

d) Specific Heat

In Braking processes, a lot of heat is generated due to friction between Disc Pad and Brake Disc. C_p is the Specific heat capacity at constant pressure and it specify the amount of heat required to raise temperature 1kg material by 1^oc (K).it measured by Calorimetry (J/Kg. K). if the specific heat of the Brake Disc material is low, the Brake Disc will heat up rapidly/ quickly, lea ding to lower Brake Disc life. and also. if the specific heat of the Brake Disc material is high, the Brake Disc will heat up Slowly. This leading to increase the resistance of thermal energy of the Materials and as whole increase Life Time of the Disc.

e) Density

Density is a material property and is the relationship between the mass(m) of the material and how much space it takes up (Volume, v). mathematically , $\rho = \frac{m}{v}$, (where ρ is Density of material). the mass of the material is depending on Density because, Volume(v) of Disc Brake is the same for all material. the material whose Density is low value is required for these paper in order to make Brake Disc Light.

3.1.3.2. Number of positive decisions for brake disc material selection

Density, wear rate, coefficient of friction, compressive strength, Specific heat are a factors considered in selection of optimal material for brake disc. The number of possible decision depends upon the number of properties. here number of properties is five (n = 5). The number of possible decision is calculated by using the formula,

$$N = \frac{n(n-1)}{2} \quad \text{......(1)}$$

$$N = \frac{5(5-1)}{2} = 10$$

In comparing two properties, the more important properties are given the number 1 and the less important is given as 0. The properties and decision numbers are listed in table below.

Table 3.2: Evaluation of Positive decisions for brake disc

Material Properties	**Decision Numbers**										**Positive decisions**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
Compressive Strength	0	0	0	1	0	0	0	0	0	0	1
Coefficient of Friction	1	0	0	0	1	0	1	0	0	0	3
Wear Rate	0	1	0	0	0	0	0	1	1	0	3
Specific Heat	0	0	1	0	0	1	0	0	0	0	2
Density	0	0	0	0	0	0	0	0	0	1	1
Total Numbers Decision(N)											10

3.1.3.3. Weighting Factor (α) Analysis

The weighting factor is obtained from the positive decision table in which each of the properties are compared with one another. A relative-emphasis coefficient or weighting factor - for each properties is obtained by dividing the number of positive decisions(PD) for each property into the total number of possible decisions (N). Mathematically given by

$$\alpha = \frac{PD}{N} \quad \text{......(2)}$$

Table 3.3: Evaluation of weighting factor for brake disc

Material Properties	**Positive decisions**	**Weighting Factor ($\alpha = \frac{PD}{N}$)**
Compressive Strength	1	$\frac{1}{10} = 0.1$
Coefficient of Friction	3	$\frac{3}{10} = 0.3$
Wear Rate	3	$\frac{3}{10} = 0.3$
Specific Heat	2	$\frac{2}{10} = 0.2$
Density	1	$\frac{1}{10} = 0.1$
Total(N)	10	1.0

3.1.3.4. Evaluation of Scaled Property Value

In order to complete the DL method, the step next to weighting factor is scale the properties of the materials based on their respective weighting factor in order to obtain the performance indices. The scaled property value is calculated for beneficial (where higher value is required) and non-beneficial (where lower value is required) attributes. For this evaluation of scaled property, materials with higher compressive strength, coefficient of friction and Specific heat are beneficial and highest value is rated as 100. and the rest wear rate and Density are non-beneficial for brake disc, therefore, their lowest value is considered as 100.

scaled values are calculated using equation

1. for beneficial; scaled property = $\frac{\text{Numerical value of property}}{\text{Maximum value in the list}}$x100……………………………..(3)
2. for non-beneficial; scaled property = $\frac{\text{Minimum value in the list}}{\text{Numerical value of property}}$ x100…………………………(4)

The Table below is the Properties of candidate materials for brake disc used to know Maximum & Minimum value in the list. [3,5, 6,8,13]

Table 3.4: Properties of candidate materials for brake disc

Materials	**Number of properties**				
	1	**2**	**3**	**4**	**5**
	Compressive strength(MPa)	**Coefficient of friction (µ)**	**Wear rate ($x10^{-6}$ mm^3/N/m)**	**Specific heat, Cp (KJ/Kg. K)**	**Density, ρ (kg/ m^3)**
Cast Iron (GCI)	1293	0.41	2.36	0.46	7100
Aluminum Metal Matrix composite (AMC)	761	0.44	2.91	0.92	2670
Titanium alloys (Ti-6Al-4V)	1070	0.34	246.3	0.58	443
Stainless Steel	910	0.22	2.24	0.46	7800
Carbon- ceramic	500	0.36	2.48	0.8	2450

The Maximum (higher)value of compressive strength, coefficient of friction and Specific heat are 1293 MPa, 0.44 & 0.92 Cp (KJ/Kg. K) respectively. So the used equation here is eq (3). and the minimum(Lower) value of wear rate and Density are 2.24 and 443 respectively. the used equation here is eq (4). there for the scaled property is evaluated in table below.

Table 3.5: Scaled property of candidate materials for brake disc

Materials	**Scaled property(β)**				
	1	**2**	**3**	**4**	**5**
Cast Iron (GCI)	$\frac{1293}{1293}x100 = 100$	$\frac{0.41}{0.44}x100 = 93$	$\frac{2.24}{2.36}x100 = 95$	$\frac{0.46}{0.92}x100 = 50$	$\frac{443}{7100}x100 = 6$
Aluminum Metal Matrix composite (AMC)	$\frac{761}{1293}x100 = 59$	$\frac{0.44}{0.44}x100 = 100$	$\frac{2.24}{2.91}x100 = 77$	$\frac{0.92}{0.92}x100 = 100$	$\frac{443}{2670}x100 = 17$
Titanium Alloys (Ti-6Al-4V)	$\frac{1071}{1293}x100 = 83$	$\frac{0.34}{0.44}x100 = 77$	$\frac{2.24}{246.3}x100 = 0.9$	$\frac{0.58}{0.92}x100 = 63$	$\frac{443}{443}x100 = 100$
Stainless Steel	$\frac{910}{1293}x100 = 70$	$\frac{0.22}{0.44}x100 = 50$	$\frac{2.24}{2.24}x100 = 100$	$\frac{0.46}{0.92}x100 = 50$	$\frac{443}{7800}x100 = 6$
Carbon- Ceramic	$\frac{500}{1293}x100 = 39$	$\frac{0.36}{0.44}x100 = 82$	$\frac{2.24}{2.48}x100 = 90$	$\frac{0.8}{0.92}x100 = 87$	$\frac{443}{2450}x100 = 18$

3.1.3.5. Performance index

performance index (γ) is used in ranking of the material based on their values. The performance index is analyzed by summing up the values of weighting factor and the scaled property values for all relevant properties. Thus the formula for calculating performance indices is

$\gamma = \sum_{i}^{n} \alpha i \beta i$ ……………………………………………………………………………………………(5)

Table 3.6: performance index(γ) of candidate materials for brake disc

Materials	**Weighting Factor (α) x Scaled property(β)**					**Performance index(γ)**
	1	**2**	**3**	**4**	**5**	
Cast Iron (GCI)	10	27.9	28.5	10	0.6	77
Aluminum Metal Matrix composite (AMC)	5.9	30	23.1	20	1.7	83.7
Titanium Alloys(Ti-6Al-4V)	8.3	23.1	0.27	12.6	10	54.3
Stainless Steel	7	15	30	10	0.6	62.6
Carbon- Ceramic	3.9	24.6	27	17.4	1.8	74.7

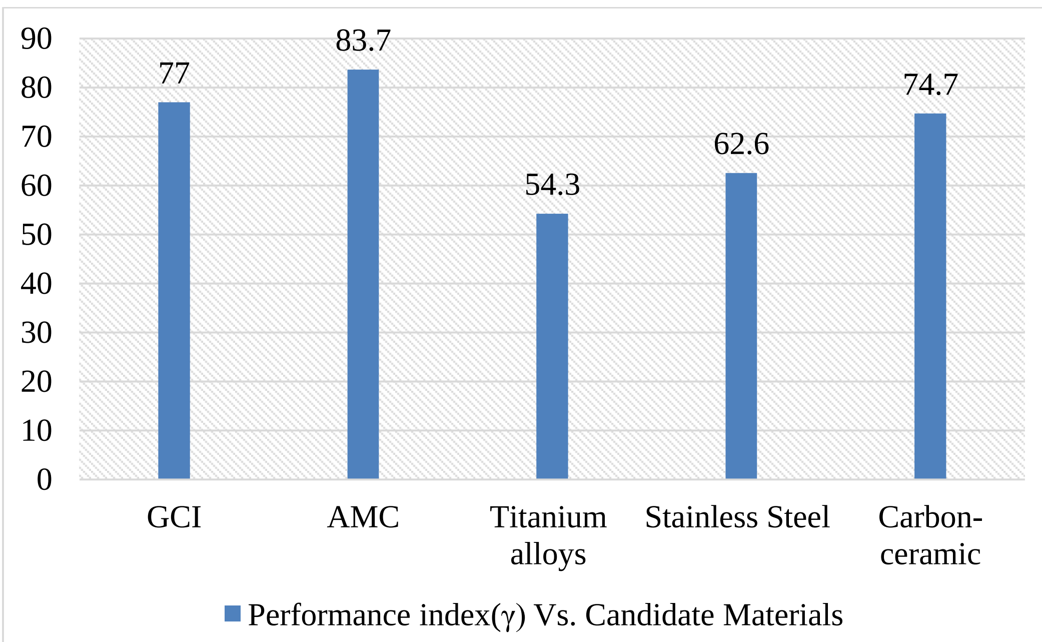


Figure 3.1:performance index(γ) of candidate materials

3.1.3.6. Figure of merit (FOM)

The performance index indicates that the technical ability of the material without considering the cost. It is important to consider the cost of material before making any final design or ranking. Therefore, by introducing the density of the material and the market price, the figure of merit (FOM) is calculated by the equation [6]

$$FOM = \frac{\gamma}{C_t\rho} \quad (6)$$

where: γ is performance index,

C_t is Total cost of the material / unit weight,

ρ is density of the material

Table 3.7: figure of merit of candidate materials for brake disc

Material	**C_t(US $/ kg)**	**ρ (kg/ m^3)**	**γ**	**FOM = $\frac{\gamma}{C_t\rho}$**
Cast Iron (GCI)	1.35	7100	77	$\frac{77}{1.35*7100}$ = 0.008033
Aluminum Metal Matrix composite (AMC)	2.2	2670	83.7	$\frac{83.7}{2.2*2670}$= 0.01425
Titanium Alloys(Ti-6Al-4V)	43.55	443	54.3	$\frac{54.3}{43.55*443}$= 0.002814
Stainless Steel	1.705	7800	62.6	$\frac{62.6}{1.705*7800}$ = 0.004707
Carbon- Ceramic	2.3	2450	74.7	$\frac{74.7}{1.2*2450}$ = 0.0132

3.1.3.7. Ranking

different mechanical, physical, and chemical properties with widely different Cost and numerical values are combined. The property with higher numerical value will have more influence than Lower Value by its weighting factor. The ranking of the material based on the figure of merit (FOM) calculated from the performance indices (γ), Total cost of the material / unit weight(C_t) and density of the material (ρ) values. The material having highest figure of merit value is ranked as 1, the material having second highest value is ranked as 2, The next one is ranked as 3 and so on.

Table 3.8: Ranking of candidate materials for brake disc

Material	C_t(US $/ kg)	γ	FOM	Ranking
Cast Iron (GCI)	1.35	77	0.00803	3
Aluminum Metal Matrix composite (AMC)	2.2	83.7	0.01425	1
Titanium Alloys(Ti-6Al-4V)	43.55	54.3	0.00281	5
Stainless Steel	1.705	62.6	0.00470	4
Carbon- Ceramic	2.3	74.7	0.0132	2

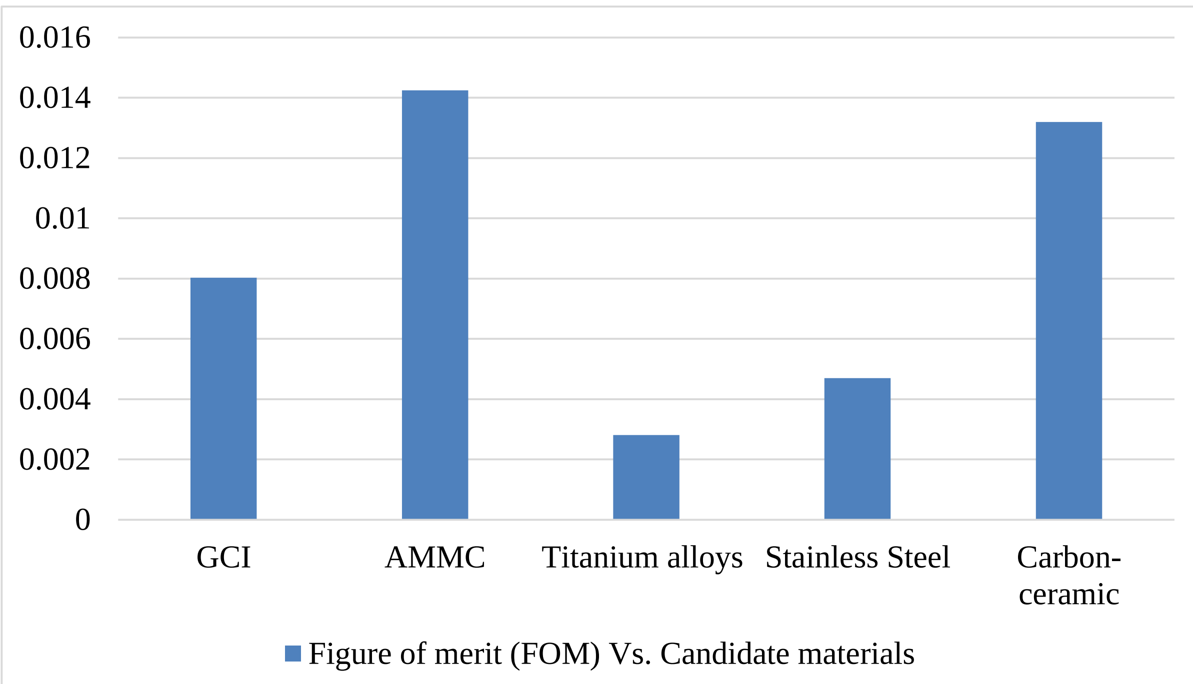


Figure 3.2: Figure of merit (FOM) for candidate materials

The material that have higher value of figure of merit (FOM) from all above five candidate materials is Aluminum Metal Matrix composite (AMMC) which is 20% SiC reinforced Al-Cu alloy. There for, this material is best material for Disc Brake than Gray Cast Iron (GCI).

The candidate with the highest performance index(γ) is Selected when the Cost is not Considerable.so in this thesis paper Cost is Considerable factor due to this, higher value of figure of merit (FOM) candidates must perform at a higher level than the currently used material (Gray Cast Iron). to know The percentage increase in performance (Δγ %) and the corresponding percentage increase in cost (Δ Ct %) for both the

New and old material is calculated by

$$\Delta\gamma\ \% = \frac{\gamma n - \gamma o}{\gamma o} * 100 \quad \text{......(7)}$$

$$\Delta C_t\ \% = \frac{Ctn - Cto}{Cto} * 100 \quad \text{......(8)}$$

Where: - γ_n and γ_o = performance indices of the new and old materials

C_{tn} and C_{to} = cost of the new and old materials

Table 3.9: percentage increase in performance (Δγ %) and corresponding percentage increase in cost (Δ Ct %) for both the candidate materials

Material	**γ**	**C_t(US $/ kg)**	**$\Delta\gamma\ \% = \frac{\gamma n - \gamma o}{\gamma o} * 100$**	**$\Delta C_t\ \% = \frac{Ctn - Cto}{Cto} * 100$**
GCI	77	1.35		
AMMC	83.7	2.2		

3.2. Modeling of Disc Brake Rotor

3.2.1. Geometrical modeling

Geometrical modeling is the representation of conceptual/ imaginary object by real object without losing information/data. there is different Software which is used to do this modeling. in this Thiess paper, Geometrical modeling is 3D Modeling of Automotive Disc Brake done by SOLIDWORK ,2018 modeling software. This is done by taking the actual data from a selected type of vehicle. The Lifan 520 model vehicle is selected for this purpose. the availability of this Vehicle in Ethiopian Commercial Market is the reason why it is selected due to easily taking of necessary data. the data that is collected from Lifan motor's is Listed in Table 3.10 below.

Table 3.10: Collected data of Lifan 520 model from Lifan Moters

No	Descriptions	Value
1	Mass of the vehicle – m [kg]	1560
2	Disc brake type (solid / Ventilated)	Ventilated
3	Disc Brake Material	Cast Ion
4	Pad material	Asbestos
5	Types of car (4WD/2WD)	2WD
6	Max. speed of car(km/h)	220
7	Inner Diameter of Disc(mm)	142
8	Outer Diameter of Disc(mm)	226
9	Thickness of Disc(mm)	18
10	Number of wheel(n)	4
11	Diameter of Wheel(mm)	550
12	LxWxH(mm) of vehicle	4100x1722x1540

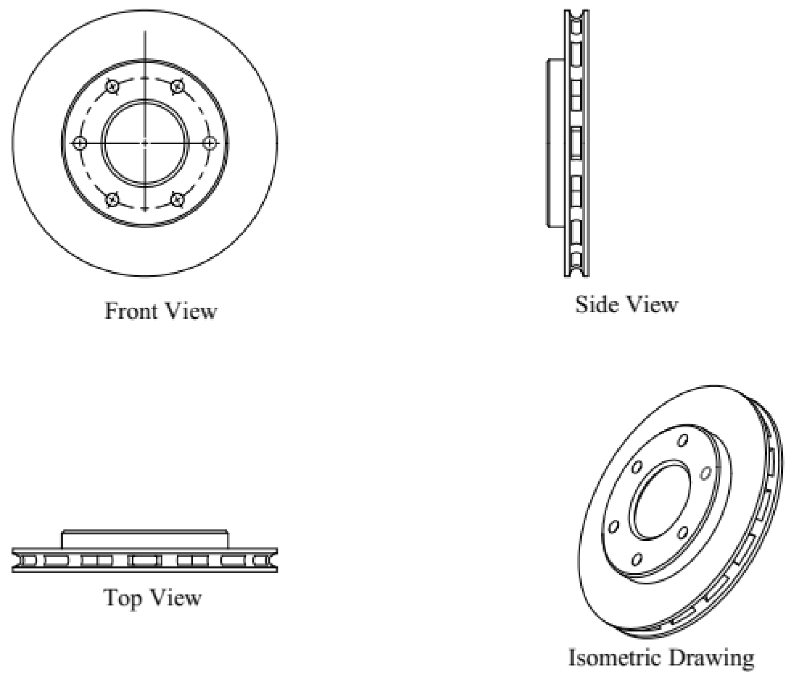


Figure 3.3: 2D & 3D drawing of Disc Brake Rotor

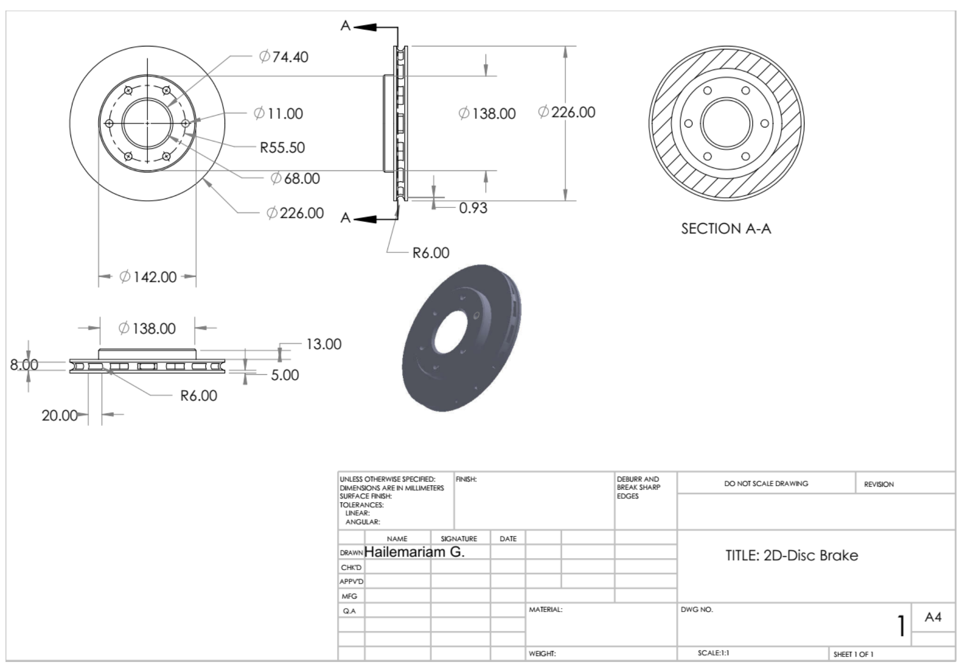


Figure 3.4: Drawing of Disc Brake Rotor with dimension

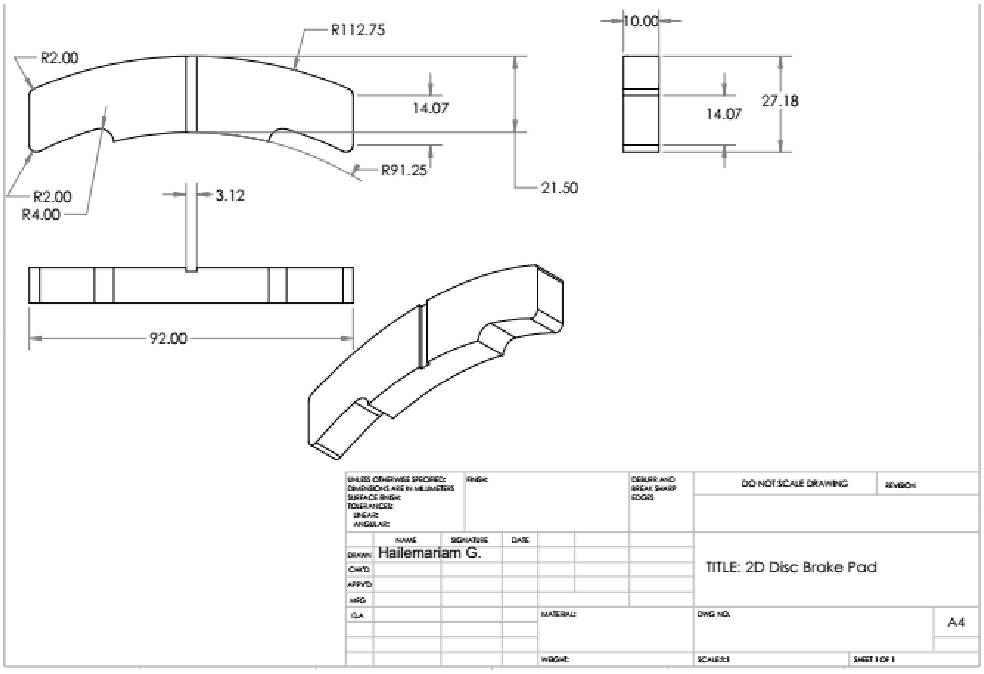


Figure 3.5: Drawing of Disc Brake Pad with dimension

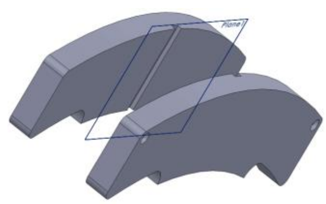


Figure 3.6: 3D drawing of Disc Brake Pad

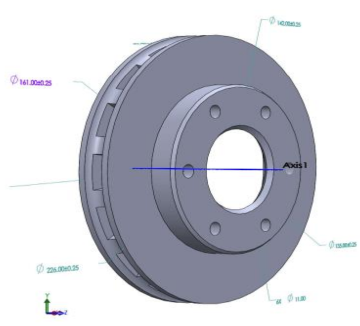


Figure 3.7: 3D drawing of Disc Brake Rotor

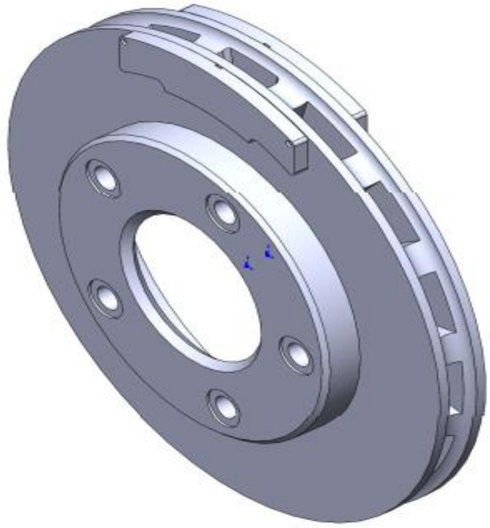


Figure 3.8: Assembly drawing of Disc Brake

3.2.2. Mathematical modeling

This section is focused on two materials those are Aluminum Metal Matrix composite (AMC) and Gray Cast Iron (GCI) in order to Compare their Numerical Value to each other. under this section normal Force, deceleration and angular velocity (ω) are calculated for both adopted and New Materials.

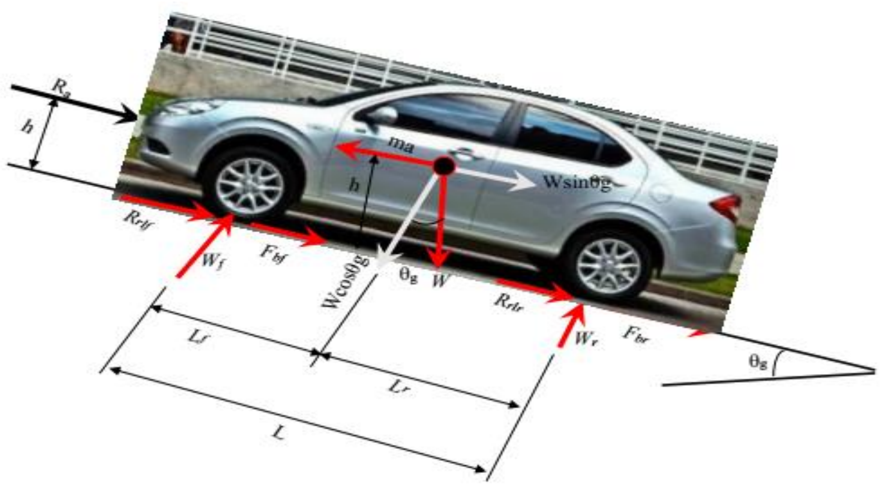


Figure 3.9: Car model for analysis

a) Normal Force (w_f)

During braking, there is a load transfer from the rear axle to the front axle. By considering the equilibrium of the moments about the rear tire-ground contact points, the normal loads on the front and rear axles, Wf can be expressed as [31]

$F + \sum R = ma$ …………………………………………………………………………………… eq (9)

$ma = F_{bf} + F_{br} + Ra + R_{rl} + R_g$ ……… $F_{bf} + F_{br} = F_b$

$ma = F_b + Ra + R_{rl} + R_g$

Sum moments about the rear tire contact point:

$\sum M_{rear} = 0$ …………………………………………………………………………………… …. eq (10)

$-R_a*h - W\sin\theta*h + W\cos\theta*L_r + ma*h - W_f*L = 0$, $\cos\theta = 1$ for small angles

$-R_a*h - W\sin\theta*h + W*L_r + ma*h - W_f*L = 0$

$W_f*L = W*L_r - W\sin\theta*h - R_a*h + ma*h$….(But… $W\sin\theta = R_g$)

$W_f*L = W*L_r - R_g*h - R_a*h + ma*h$

$Wf = \frac{W*Lr + h\,(ma - Ra - Rg)}{L}$ But $ma = F_b + R_a + R_{rl} + R_g$ Therefore, $F_b + R_{rl} = ma - R_a - R_g$

$Wf = \frac{W*Lr + h\,(Fb + Rrl)}{L}$, $R_{rl} = f_{rl}W$ ………………………………………………………… eq (11)

The brake force and rolling resistance helps to decelerate the vehicle, therefor

$F_b + R_{rl} = m(-a)$, $-a = d$ and $m = w/g$

$F_b + R_{rl} = (w/g)\,d$ …………………………………………………………………………… eq (12)

Substituting in eq (11), $Wf = \frac{W*Lr + h\,((w/g)\,d)}{L}$

$$Wf = \frac{W}{L}(Lr + \frac{h\,d}{g})$$

b) Deceleration

from eq (12),

F_b = (w/g) d - R_{rl} = (w/g) d - f_{rl}W = w (d/g- f_{rl}) …………………………………………………… eq (13)

F_{bf} = k_{bf} F_b = k_{bf} w (d/g- f_{rl}) …………………………………………………………...................... eq (14)

$(F_{bf})_{max} = \mu W_f = \mu \frac{W}{L}(Lr + \frac{h\,d}{g})$………………………………...……………...…………………… eq (15)

Equating eq (14) and eq (15)

$\mu \frac{W}{L}\left(Lr + \frac{h\,d}{g}\right)$ = k_{bf} w (d/g- f_{rl}) ………………………………………………………………… eq (16)

$$\mu \frac{W}{L} Lr + \mu \frac{W}{L}\left(\frac{h\,d}{g}\right) = k_{bf} * w\,(d/g) - k_{bf} * f_{rl} W$$

by re arranging, and get

$(\frac{d}{g})max = \frac{\frac{\mu}{L}Lr + kbf * frl}{kbf - \mu\frac{h}{L}}$ Deceleration to lock front wheel ……………………….………. eq (17)

Assume braking force distribution is the same in front and rear wheel (50%, 50%) so $k_{bf} = k_{br} = 0.5$

<u>For Gray Cast Iron:</u> -

$$(\frac{d}{g})max = \frac{\frac{\mu}{L}Lr + kbf * frl}{kbf - \mu\frac{h}{L}} \text{ , } = 0.01(1 + \frac{61.11}{147}) = 0.01415$$

$$(\frac{d}{g})max = \frac{\frac{0.41*2.05}{4.1} + 0.5 * 0.01415}{0.5 - 0.41 * \frac{0.77}{4.1}} = \frac{0.205 + 0.007075}{0.5 - 0.077} = \frac{0.21915}{0.423} = 0.518$$

deceleration, d = 0.518g = 0.518 x 9.81 = 5.08 m/s^2

For Aluminum Metal Matrix composite: -

$$(\frac{d}{g})max = \frac{\frac{\mu}{L}Lr + kbf * frl}{kbf - \mu \frac{h}{L}}$$

$$(\frac{d}{g})max = \frac{\frac{0.44*2.05}{4.1} + 0.5 * 0.01415}{0.5 - 0.44* \frac{0.77}{4.1}} = \frac{0.22 + 0.007075}{0.5 - 0.207} = \frac{0.227075}{0.292} = 0.777$$

Deceleration, d = 0.777g = 0.777 x 9.81 = 7.6m/s^2

c) Braking distance

Stopping distance is another parameter used for evaluating the overall braking performance of a vehicle. To analysis the stopping distance, the basic principles in dynamics are used. The interrelationships among stopping distance, braking force, vehicle mass, and vehicle speed, may be expressed as follows.

$$F + \sum R = \gamma_m * ma \quad \text{eq (18)}$$

$$F_b + R_a + Rrl + R_g = \gamma_m * ma, \ldots m = \frac{w}{g}$$

$$a = \frac{F_b + Ra + Rrl + Rg}{\gamma m * \frac{w}{g}} \quad \text{eq (19)}$$

$$Vdv = ads \quad \text{eq (20)}$$

$$ds = \frac{Vdv}{a} = \frac{V}{\frac{F_b + Ra + Rrl + Rg}{\gamma m * \frac{w}{g}}} dv \text{ , integrate both sides}$$

$$\int_0^s ds = \int_{v1}^{v2} \frac{V}{\frac{F_b + Ra + Rrl + Rg}{\gamma m * \frac{w}{g}}} dv = \gamma_m * \frac{w}{g} \int_{v1}^{v2} \frac{V}{F_b + Ra + Rrl + Rg} dv \text{ , } Ra = \frac{\rho}{2} C_D A_f V^2$$

$$S = \gamma_m * \frac{w}{g} \int_{v1}^{v2} \frac{V}{F_b + \frac{\rho}{2} C_D A_f V^2 + frlW + wsin\theta} dv = \gamma_m * \frac{w}{2g} \int_{v1}^{v2} \frac{V}{F_b + \rho C_D A_f V^2 + frlW + wsin\theta} dv$$

$$= \gamma_m * \frac{w}{g \rho C_D A_f} \ln\left(\frac{F + f_{rL}W + wsin\theta + \frac{\rho}{2} C_D A_f v_1^2}{F_b + f_{rL}W + wsin\theta + \frac{\rho}{2} C_D A_f v_2^2}\right), V_2 = 0$$

$$= \gamma_m * \frac{w}{g\rho C_D A_f} \ln\left(1 + \frac{\frac{\rho}{2} C_D A_f v_1^2}{F_b + f_{rL} W + w\sin\theta}\right),\ \sin\theta = 0 \text{ for small angle}$$

for minimum braking distance $F_b = \mu w$, and W = mg there for

$$S_b = \gamma_m * \frac{m}{\rho C_D A_f} \ln\left(1 + \frac{\frac{\rho}{2} C_D A_f v_1^2}{W(\mu + f_{rL})}\right),\ \gamma_m = 1.04 + 0.0025\varepsilon_0^2$$

For Gray Cast Iron: -

$$S_b = \gamma_m * \frac{m}{\rho C_D A_f} ln\left(1 + \frac{\frac{\rho}{2} C_D A_f v_1^2}{W(\mu + f_{rL})}\right)$$

$A_f = 1.6 + 5.6 \times 10^{-4}(m - 765) = 1.6 + 0.00056(1560 - 765) = 2.04 m^2$

$$S_b = 1.04 * \frac{1560}{1.2*0.32*2.04} ln\left(1 + \frac{\frac{1.2}{2}*0.32*2.04*61.1^2}{1560*9.81(0.41 + 0.01415)}\right),\ C_D = 0.32,\ \rho = 1.2\ kg/m^3$$

$= 207.107 * \ln(1.022858)$

$= 207.107 * 0.02058$

$= 4.14$ m

For Aluminum Metal Matrix composite: -

$$S_b = \gamma_m * \frac{m}{\rho C_D A_f} ln\left(1 + \frac{\frac{\rho}{2} C_D A_f v_1^2}{W(\mu + f_{rL})}\right)$$

$$S_b = 1.04 * \frac{1560}{1.2*0.32*2.04} \ln\left(1 + \frac{\frac{1.2}{2}*0.32*2.04*61.1^2}{1560*9.81(0.44 + 0.01415)}\right)$$

$= 207.107 * \ln\left(1 + \frac{1483.7269824}{69501.2994}\right)$

$= 207.107 * \ln(1.0136)$

$= 207.107 * 0.01350$

$= 2.8$ m

d) Braking Force

For Gray Cast Iron: -

From eq (15)

$(F_{bf})_{max} = \mu W_f = \mu \frac{W}{L}(Lr + h\frac{d}{g}) = 0.41 * \frac{1560*9.81}{4.2}(2.1 + 0.77 * 5.08)$

$= 0.41 * \frac{1560*9.81}{4.2}(2.1 + 0.77 * 5.08)$

= 0.41*21904.5528

= 8.98KN

For Aluminum Metal Matrix composite: -

$(F_{bf})_{max} = \mu W_f = \mu \frac{W}{L}(Lr + h\frac{d}{g}) = 0.44 * \frac{1560*9.81}{4.2}(2.1 + 0.77 * 5.36)$

$= 0.44 * \frac{1560*9.81}{4.2}(2.1 + 0.77 * 5.36)$

= 0.44*22690.1376

= 9.98 KN

e) Angular velocity of rotor

Maximum speed of vehicle is 220 km/hour or 61.11 m/s

Velocity, $V = (\pi \times D \times N)$ ……. where, D is Diameter of Wheel……………………………………………. (20)

$N = \frac{V}{\pi \times D} = \frac{61.11 \text{ m/s}}{\pi \times 0.55\text{m}}$

N = 35.36 rps (revolution per second)

Angular velocity, $\omega = 2\pi N$

$= 2 \times \pi \times 35.36 = 222.2$ rad/s

3.3. Finite Element Method and Analysis

In this paper, structural analysis is performed on a simple Finite Element (FE) model of a real disc brake assembly to obtain the mass of the Disc, Total deformation of the Disc and the Von Mises stress in disc interface by utilizing the ANSYS 18.2 FE software. Sensitivity study on rotation of the disc, load pattern and coefficient of friction is also performed.

Von-Mises stress(σ_{vm}) is an equivalent or effective stress at which yielding (σ_y) is predicted to occur in ductile materials. according to von Mises's failure criterion, the material under multi-axial loading will yield when the von Mises stress is equal to or greater than the critical value for the material. [32]

Numerically: $\sigma_{vm} \geq \sigma_y$

$$\sigma_{vm} = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)}{2}} \; , \sigma_z = \tau_{yz}^2 = \tau_{zx}^2 = 0$$

$$\sigma_{vm} = \sqrt{(\sigma_x)^2 + (\sigma_y)^2 - \sigma_x\sigma_y + 3\tau_{xy}^2} \quad \text{……………………………………………(21)}$$

where: $\sigma_x = \sigma_1 , \sigma_y = \sigma_2 , \sigma_z = \sigma_3$

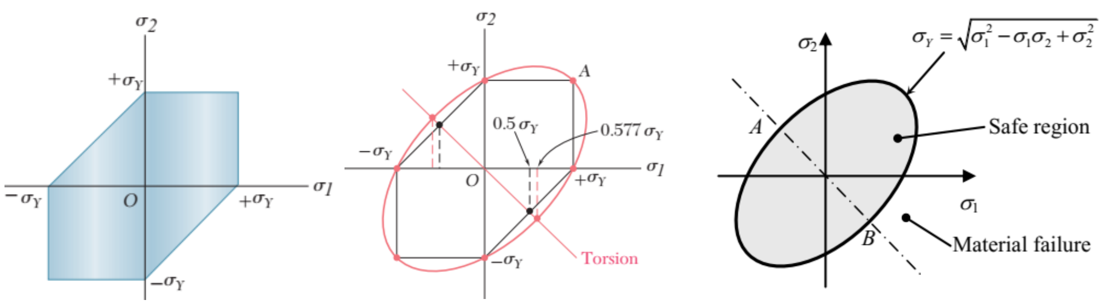


Figure 3.10: Failure envelope of the distortion energy theory

Total deformation of the Disc of homogeneous, isotropic materials can be described relatively simply by using the Young's and Shear module. The Cartesian strains resulting from a state of plane stress ($\sigma z = 0$) are: -

$$\varepsilon_x = \frac{1}{E}(\sigma_x - v\sigma_y)$$

$$\varepsilon_y = \frac{1}{E}(\sigma_y - v\sigma_x)$$

$$\gamma_{xy} = \frac{1}{G}\tau_{xy} \quad \text{……………………………………………(22)}$$

Using matrix notation, these relations can be written as: -

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E} & \frac{-v}{E} & 0 \\ \frac{-v}{E} & \frac{1}{E} & 0 \\ 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \quad \text{...(23)}$$

In the above relations there are three elastic constants: The Young's modulus (E), Poisson's ratio (ν), and the shear modulus (G). relationship between each of this constant can be obtained from the relation below:

$$v = \frac{E}{2G} - 1 \quad \text{...(24)}$$

3.3.1. Finite Element analysis

Finite Element Analysis FEA is the mathematically modeling of products and numerically solving of very complex structural, fluid, and multiphasic problems with in short period of time. due to the complexity of the material properties, the boundary conditions and the structure itself, analytical solutions are not suitable for many engineering problems. The problem includes design of shafts, trusses, bridges, aero plane structures, buildings, heating and ventilation, fluid Flow, electric and magnetic fields, and so on. FEA is the practical application of the finite element method (FEM), which is used to represent a body or a structure by an assemblage of subdivisions (Discretization) called finite elements. [3,7]

A finite element (FE) model have predefined points, which form the shape of the element and Loads can be applied, called nodes. nodes are the fundamental governing entities of the element and it is founded a place where the element connects to other elements, boundary conditions are assigned and forces are applied. A node possesses degrees of freedom. Degrees of freedom are the independent translational and rotational motions that can exist at a node. This mesh(Discretization) is programmed to contain the material and structural properties which define how the structure will react to certain loading conditions. Before meshing of the body it is necessary to add the material properties, external loads, and apply the boundary conditions. In order to start of the problem, only parameters of the calculation regime should be added to the input file. [3,7,15]

3.3.2. Methods of Finite Element Analysis

The procedure for static thermal analysis consists of three main steps

1. **Building the model/Pre-processor: -** is the stage of defining the problem which will be analyzed by FEM. The importing CAD file, element type and material properties are defined under this section.
2. **Solution/Analysis: -** The preprocessor is used as input to the finite element code itself, which constructs and solves a system of linear or nonlinear algebraic equations [K][U] =[F], where K, U and F are coefficient Matrix, displacements and externally applied forces at the nodal points respectively. meshing and assigning constraints are sated under this section.
3. **Obtaining and Reviewing the results/Post-processing: -** further processing and viewing of the results such as; Temperature distribution**,** Deformation**,** Weight and Stress. [3,7,15]

Structural analysis: - There are seven types of structural analysis available in ANSYS. One can perform the following types of structural analyses.

1. Static analysis.
2. Modal analysis.
3. Harmonic analysis.
4. Transient analysis.
5. Spectrum analysis.
6. Buckling analysis.
7. Explicit dynamic analysis.

Static analysis: - A static analysis calculates the effects of steady loading condition on a structure by ignoring time varying loads. A static analysis can, however include steady inertia loads such as gravity and rotational velocity, and time varying loads that can be approximated as static equivalent loads commonly defined in many building codes.

Static Finite Element Analysis procedure using ANSYS Workbench software for Disc Brake is shown with chart below.

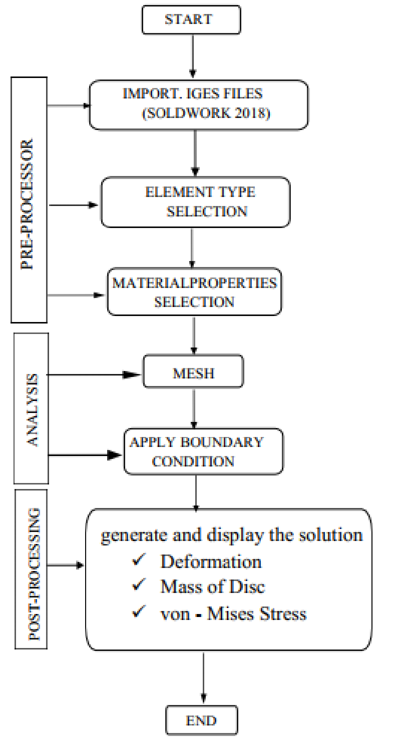


Figure 3.11: FEA procedure chart

Importing the model geometry

The geometric modeling of Disc Brake is done by SOLDWORK 2018 software. This 3D model should be imported to ANSYS18.2 Workbench in IGES format which is compatible with the ANSYS software package for the finite element analysis.

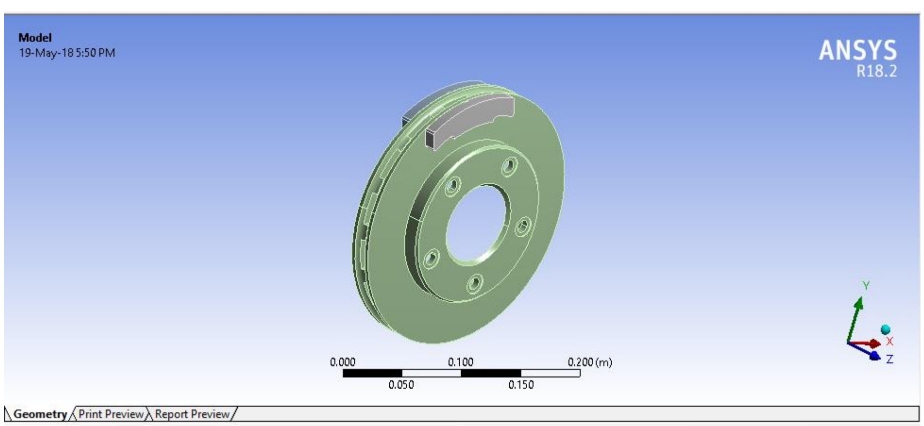


Figure 3.12: Imported model of Disc Brake

Element type selection

The material type and its properties such as density, compressive strength, Young's modulus shear modulus, coefficient of thermal expansion and Poisson's ratio are specified under engineering data. The material applied for this purpose is Gray Cast Iron(GCI) and Aluminum Metal Matrices composite (AMMC) materials. The engineering data helps to input the material properties of both Gray Cast Iron(GCI) and Aluminum Metal Matrices composite (AMMC) material. The material property of the both Gray Cast Iron(GCI) and Aluminum Metal Matrices composite (AMMC) material are stated in the table below. [3,6, 20,23,24,25]

Table 3.11: Material properties of GCI and AMMC used for FEA.

No	Properties	GCI	AMMC	Asbestos
1	Thermal Conductivity*k* [W/m ºC]	54	250	5
2	Density [kg/m^3]	7100	2670	2000
3	Specific Heat*Cp* [J/Kg ◦k]	460	910	1000
4	Poisson's ratio *v*	0.28	0.33	0.25
5	Thermal expansion *α* [1/k]	8.1*10^{-6}	0.22*10^{-6}	10
6	Elastic modulus *E* [GPa]	125	113	1000
7	Compress strength (Mpa)	1293	761	

Table 3.12:Workbench GCI mechanical property specification(Engineering data)

Outline of Schematic A2: Engineering Data

	A	B
1	Contents of Engineering Data	
3	Gray Cast Iron	
4	Asbestos	
5	Aluminum Metal Matrix composite	

Properties of Outline Row 3: Gray Cast Iron

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	7100	kg m^-3		
4	Isotropic Elasticity				
5	Derive from	Young's Mod...			
6	Young's Modulus	125	MPa		
7	Poisson's Ratio	0.28			
8	Bulk Modulus	9.4697E+07	Pa		
9	Shear Modulus	4.8828E+07	Pa		
10	Specific Heat, C_p	460	J kg^-1 K^-1		

Details of "Geom\Brake Disc"

Definition	
Suppressed	No
Stiffness Behavior	Flexible
Coordinate System	Default Coordinate System
Reference Temperature	By Environment
Behavior	None
Material	
Assignment	Gray Cast Iron
Nonlinear Effects	Yes
Thermal Strain Effects	Yes
Bounding Box	
Properties	

Figure 3.13**:** Assignment of the GCI material to the model on ANSYS workbench.

Table 3.13:Workbench AMMC mechanical property specification

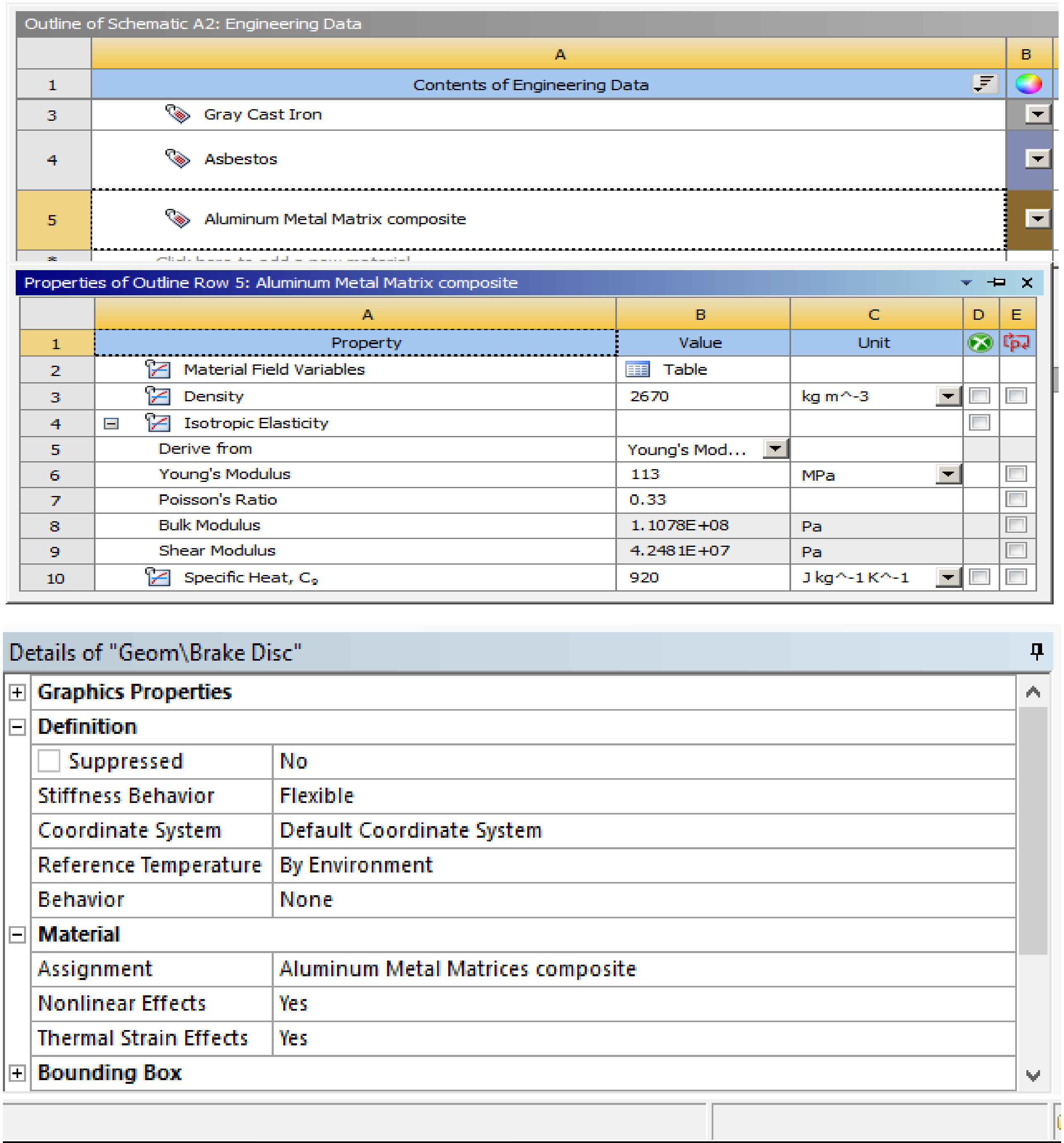


Figure 3.14**:** Assignment of the AMMC material to the model on ANSYS workbench.

Meshing the object

In the finite element analysis, the basic concept is to analyze the structure which is an assembly of discrete pieces called elements which are connected together at a finite number of points called nodes. A network between these elements is known as meshing. meshing is the mechanism of dividing the complex geometry model into small elements to solve easily with accuracy. in a finite element analysis more time is spent on generating elements and nodal data. Pre-processor allows the user to generate nodes and elements automatically at the same time allowing control over size and number of elements through meshing of the geometry.

The meshing process can be performed only after the specification of element type (Pre-processing). ANSYS offers several convenient options to assist in meshing. These include Automatic Meshing, Smart Sizing, and Mapped Meshing. One of the best features of ANSYS is automatic mesh generation. With automatic meshing, the user can still provide specific preferences for mesh density and shape. If no preferences are specified by the user, ANSYS uses the default preferences. [3,15,17]

In this specific research work, Meshing is done by using this automatic meshing generation method and the refinement is done, specifically in the disc-pad contact zone because in this zone, the temperature varies significantly, in this strongly deformed due to high stress concentrations zone.

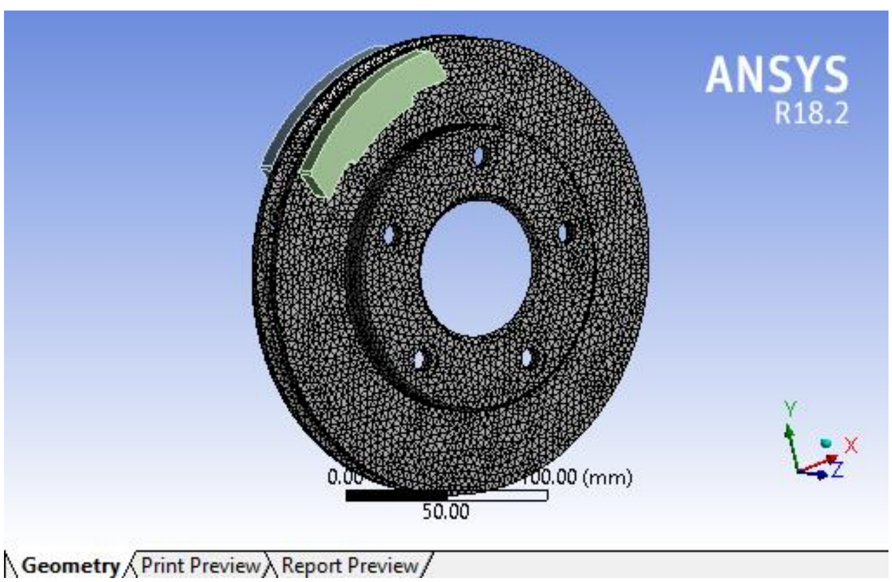


Figure 3.15: Meshing of the model on ANSYS Workbench

The general mesh statistical data of both GCI & AMMC after meshing of the imported models is shown figure below.

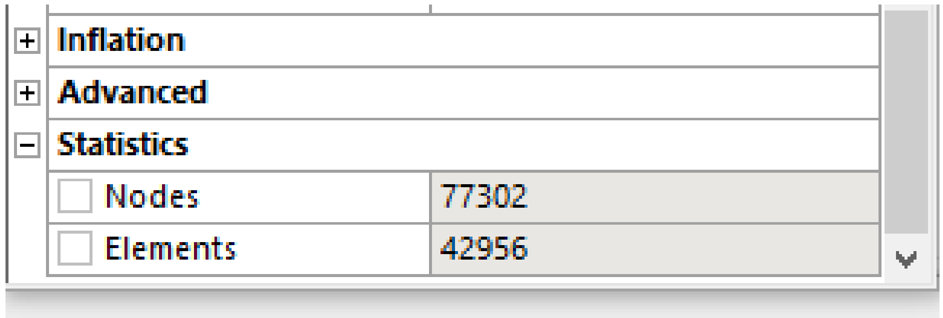


Figure 3.16:mesh statistical data of both GCI & AMMC material

Applying boundary conditions

The next step of finite element analysis involves applying appropriate boundary conditions and the proper loading mechanism. There are two ways to apply the boundary conditions and loading to the model in ANSYS; either apply the conditions to the solid model (key point, lines and areas), or the conditions can be directly imposed on the nodes and elements. In this research work, the first approach is preferable; because if it is decided to change the meshing, there will not need to reapply the boundary conditions and the loads to the new finite element model.

Deformation and Stress analysis of rotor; - Rotor is subjected to stresses due clamping force by caliper and wheel torque. This leads to deformation of rotor. To avoid this, rotor should be tested for its structural strength. This analysis is done in ANSYS Workbench for solving. Select ‘Static Structural’ analysis system in workbench interface. This analysis consists of following step by step procedures.

Loading Conditions: - There are three types of mechanical stresses subjected by the disc brake. The first one is the traction force created by the centrifugal effect due to the rotation of the disc brake when the wheel is rotating which is represented by angular velocity (ω = 222.22rad/sec) and no braking force is applied to the disc.

During braking operation, there are another two additional forces experienced by the disc brake:

***Firstly**,* compression force is created as the result of the force exerted by the brake pad pressing perpendicular onto the surface of the disc to slow it down. this exerted Force /Clamping force is applied on both side of Brake Rotor by brake pad and calculated by: -

F_z = 8980/2 = 4490N, for GCI and

F_z = 9890/2 = 4945N, for AMMC

***Secondly**,* the braking action due to the rubbing of the brake pad against the surface of the disc brake is translated into frictional or traction force on the disc surface which acts in the opposite direction of the disc rotation. this frictional force generated between Brake Rotor and Brake pad can be calculated by: - $F_f = \mu * F_z$, Same magnitude of frictional force is applied on other side of rotor too. Frictional force is calculated as:

F_f = 0.41* 4490 = 1840.9N, for GCI

F_f = 0.44* 4490 = 2175.8N, for AMMC

Constraints: - A commercial FE software, namely ANSYS 18.2 is fully utilized to simulate structural deformation, mass of the Disc and the Von Mises stress. Boundary conditions are imposed on the models as shown in Figure below with necessary Boundary conditions. The disc is rigidly constrained at the bolt holes in all directions except in its rotational direction. Fixed support is applied at the bolt rotor contact surface. This makes holes for rotor bolts fix irrespective of forces acting on the rotor. Meanwhile, the pad is fixed in all degrees of freedom except in the normal direction to allow the pads move to contact with the disc surface. Using vehicle data as given under Loading Conditions and Equations (21)- (24), structural Total deformation and the Von Mises stress, respectively.

Generate solutions: - After selecting required solutions, generate for solving to obtain the results. The solution is generated based on the above input parameters. The total deformation and the equivalent (Von-Mises) stress are the basic variables to be solved by this analysis (see figure 3.17 & 3.18).

Finally, the solution of each dependent parameter can be displayed individually. Once the solution is generated, each dependent parameter is solved and ready to be seen and interpreted. This will be clearly discussed in the next chapter.

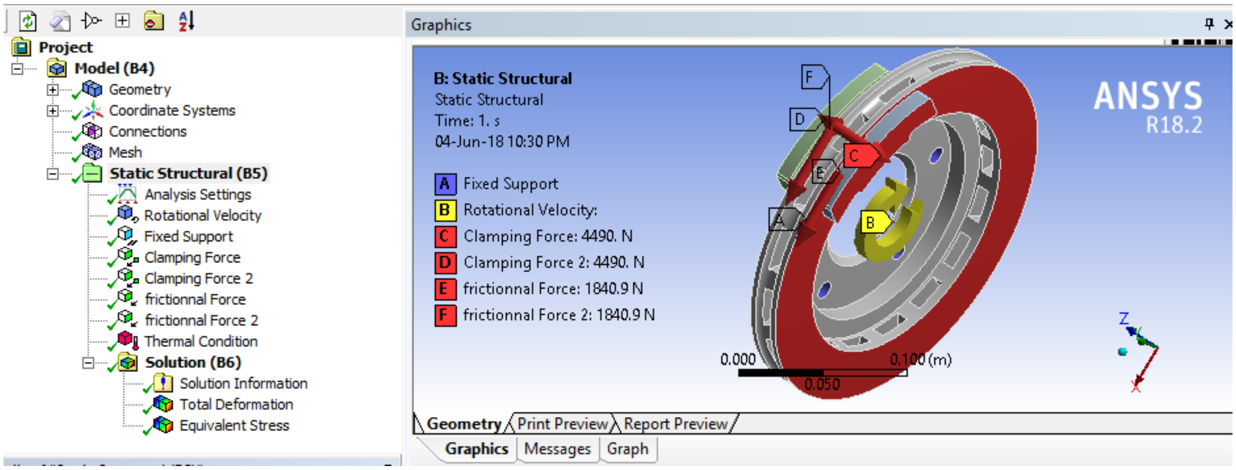


Figure 3.17: Generating the solution for GCI

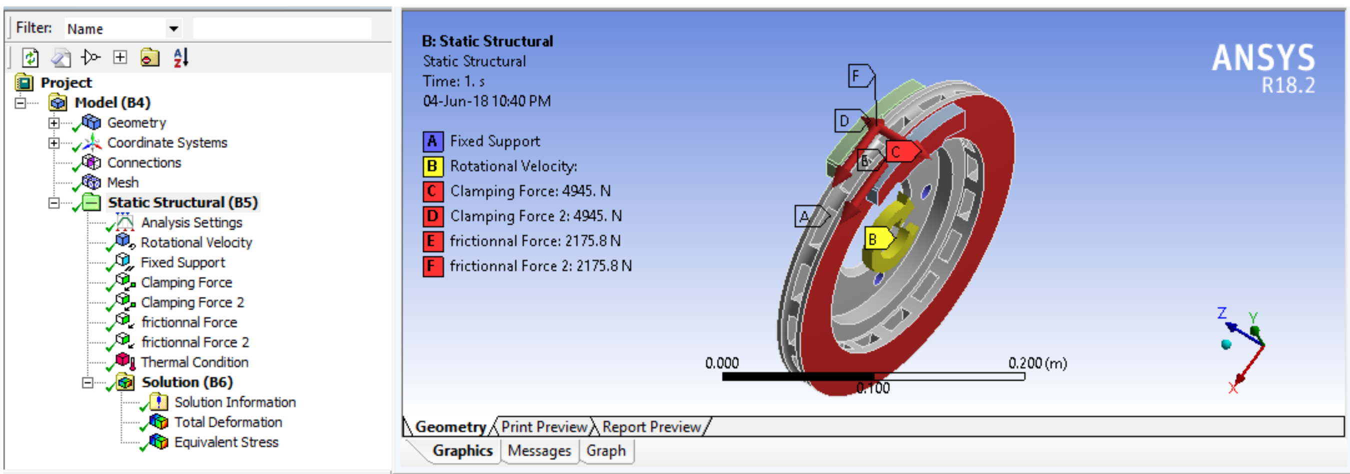


Figure 3.18: Generating the solution for AMMC

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter describes results obtained from Numerical and FEA (Static structural analysis) of the Disc Brake during the present study. After completion of the structural Static analysis in ANSYS Workbench, results were reviewed. Basically, the two significant types of results were recorded from this analysis of the imported model. The results are presented for all categories namely: mass, equivalent stress (von Mises stress) and total displacement. The most important step of finite element analysis procedure is the physically realistic interpretation of the results by the analysis.

4.1. Analysis

The model and analysis is performed using finite element method with the software ANSYS Workbench 18.2 that consist of Static Structural. This is for the purpose of getting the maximum and minimum equivalent stress and deformation on the structural model. The Static Structural analysis determines characteristics of the stress and deformation of the Disc Brake caused by the applied loading systems and boundary conditions. The following typical Static Structural analysis system of ANSYS Workbench 18.2 could be performed one by one to complete the analysis and get an appropriate solutions of the problem.

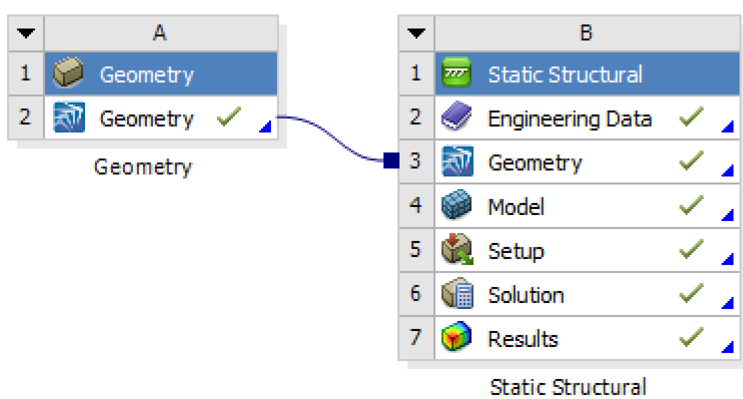


Figure 4.1: ANSYS Workbench Static structural analysis system

4.2. Results

Total deformation

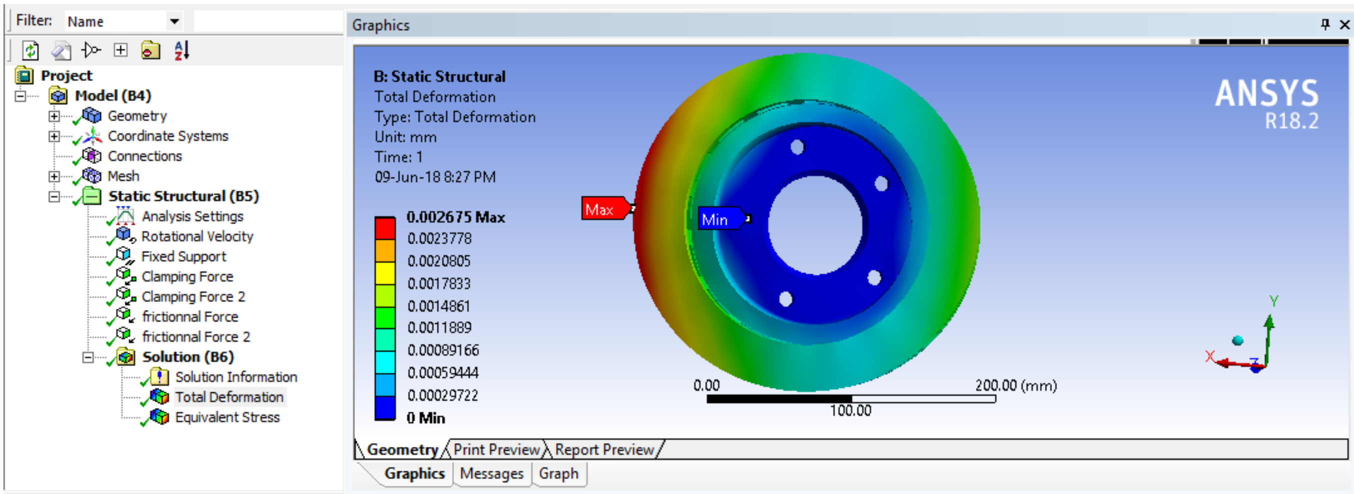


Figure 4.2: deformation of Disc Brake (GCI)

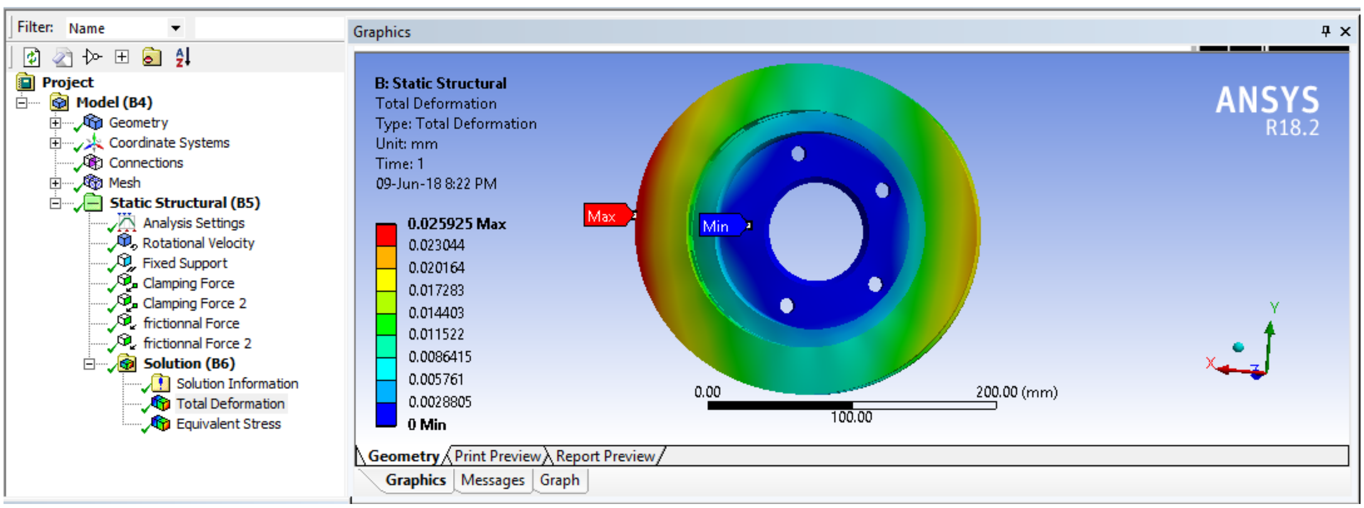


Figure 4.3: deformation of Disc Brake (AMMC)

Von-Mises stress

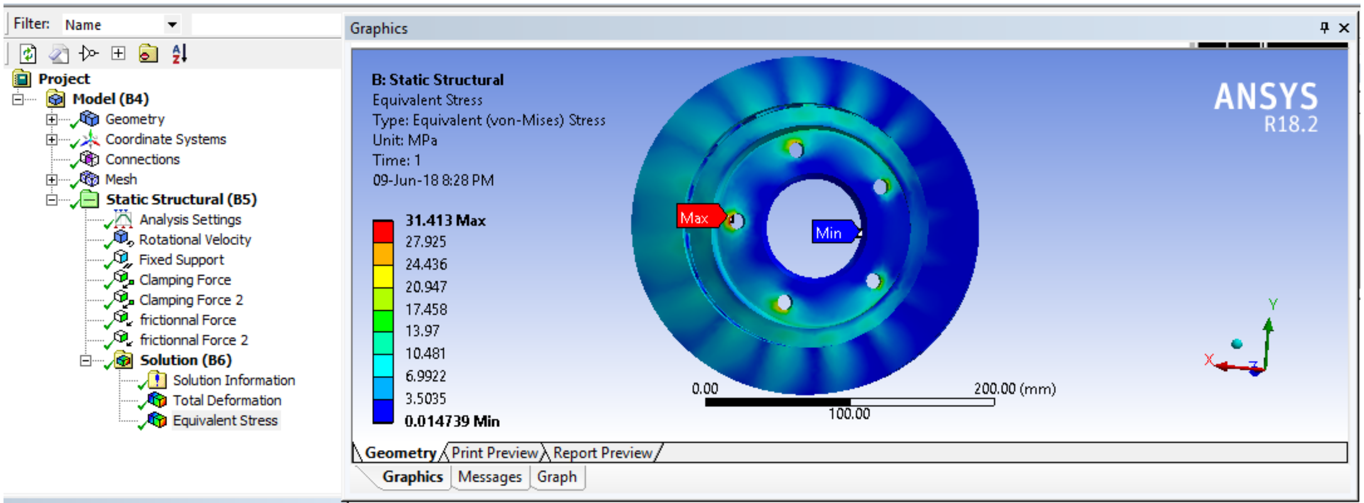


Figure 4.4: von - Mises stress of Disc Brake (GCI)

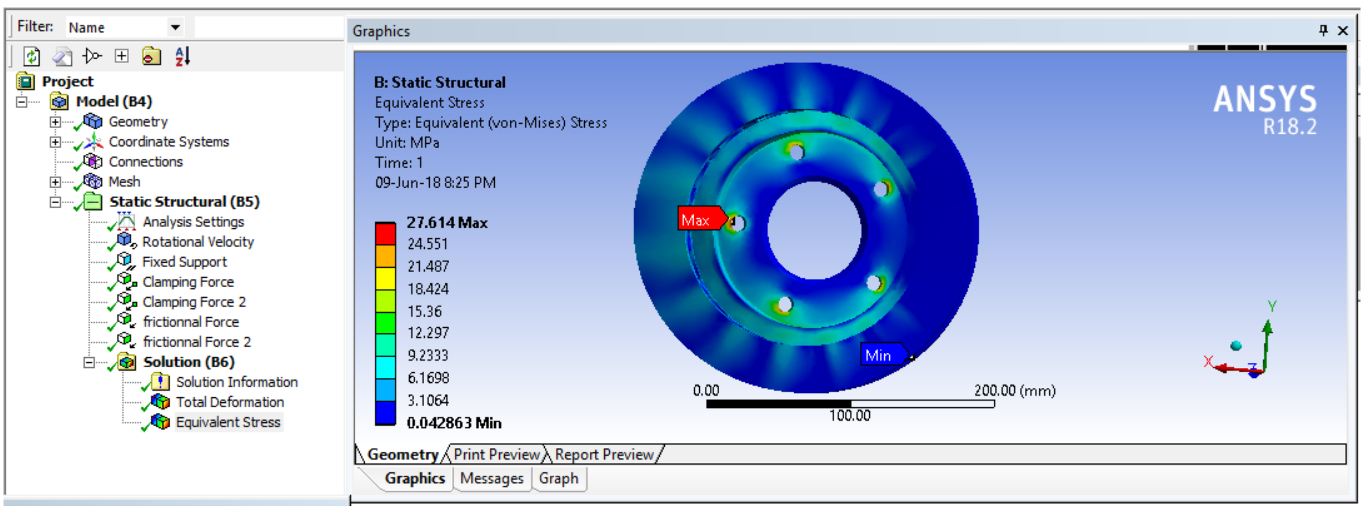


Figure 4.5: von - Mises stress of Disc Brake (AMMC)

4.3. Discussions

Comparing the results obtained by Numerically and FEA of the Disc Brake which made from AMMC with the Brake Disc made from GCI materials is important to see the improved achievement. the Numerical and Finite element analysis result is generally summarized in table 4.1

Table 4.1: Summery of Numerical and FEA results of the Disc Brake for GCI & AMMC materials

Description	**Unit**	**GCI**	**AMMC**
Deceleration, d	m/s^2	5.08	7.6
Stopping Distance, S	m	4.14	2.8
Braking Force, F_b	kN	8.98	9.98
Mass of Disc	kg	2.7494	1.0339
Deformation(Max.)	mm	0.26×10^{-2}	2.59×10^{-2}
von - Mises stress	MPa	31.413	27.614

4.3.1. Numerical Analysis discussions

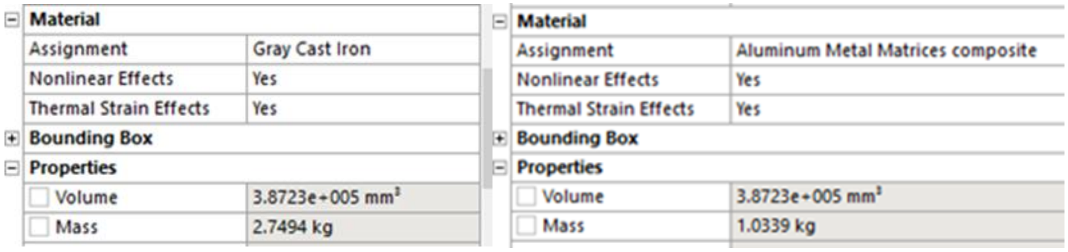
Deceleration of the Vehicle, Braking Force and Stopping Distance if the Vehicle Analyzed Numerically. As a result, the Deceleration of Disc Brake made from AMMC is greater (7.6 m/s^2) than Disc Brake made from GCI (5.08m/s^2). the Braking Force is considering only the Front wheel of Lifan 520 Vehicle. due to greater Coefficient of friction of the material property, 10.2% Higher Frictional Force/ Braking Force(9.98kN) is generated in AMMC Disc Brake than GCI. Lastly it is obviously knowing that, Higher Braking Force reduces Stopping Distance of Vehicle much more. due to this Stopping Distance of Lifan 520 is reduced from 4.14m to 2.8m.

4.3.2. Finite Element Analysis discussions

In this research the comparison between the results of the FEA of these materials is carried out by making the same geometrical modelling, same rotational velocity and same method of FEM analysis but different material properties, frictional & clamp force due to coefficient of friction.

Mass of Disc

The Figure 6 show that the Volume of both material (Gray Cast and Aluminum Metal Matrices Composite) are the same due to similar geometry of Disc Brake. the mass of the Disc is depending on Density of material. Therefore, mass of AMMC Disc is reduced by 62.4 % than that GCI Disc. The smaller mass of the AMMC Disc Brake helps to make the vehicle lightweight, so that the efficiency and fuel consumption of the vehicle is improved by reducing its dead weight.



Material	
Assignment	Gray Cast Iron
Nonlinear Effects	Yes
Thermal Strain Effects	Yes
Bounding Box	
Properties	
Volume	3.8723e+005 mm³
Mass	2.7494 kg

Material	
Assignment	Aluminum Metal Matrices composite
Nonlinear Effects	Yes
Thermal Strain Effects	Yes
Bounding Box	
Properties	
Volume	3.8723e+005 mm³
Mass	1.0339 kg

Figure 4.6: mass of Disc Brake for GCI and AMMC

Maximum deformation of the Disc Brake

GCI have higher Young's (125 Mpa) and Shear module (48.828Mpa) than AMMC (113 and 42.481Mpa) respectively (see Table 3.12 & 3.13). therefore, it is expected that, GCI is Less Deformed compared to AMMC due to its Greater Young's module and Compressive Strength. This Figure 4.7 shows that; the maximum deformation of the Disc Brake which made from AMMC has the higher (0.025925mm) value than GCI (0.002675mm). Disc Brake made from GCI lower by about 89.7% than the Disc Brake made from AMMC. This values show that GCI material has greater rigidity than AMMC material.

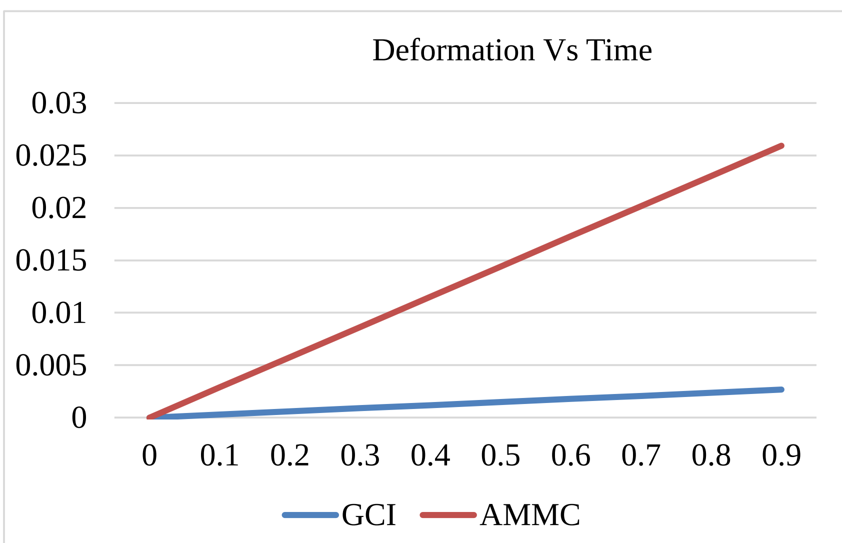


Figure 4.7: deformation of Disc Brake which made from GCI and AMMC

Von-Mises stress distribution

Equivalent (Von Mises) stress, which arises from distortion energy failure theory, is widely used by designers to check whether their design will withstand a given load condition. Using the ANSYS Workbench 18.2 software, along with the given boundary conditions and applied loads, the values for equivalent (von-Mises) stress is calculated.

Figure 4.8 shows distributions of the equivalent Von Mises stress for both GCI and AMMC over braking period and it is shown that the highest stress occurs at the bolt holes at the time t = 1s. This is due to the disc having experience in torsion and shear modes. This high stress concentration can cause a rupture/ sudden noisy break/ to the bolt holes.

The results of this analysis shows that, the equivalent (Von-Mises) stress developed in the disc brake is comparatively less in the material AMMC which is 27.614Mpa compared to the GCI material which is 31.413Mpa. This implies that AMMC material is less stressed and thus, has a better performance.

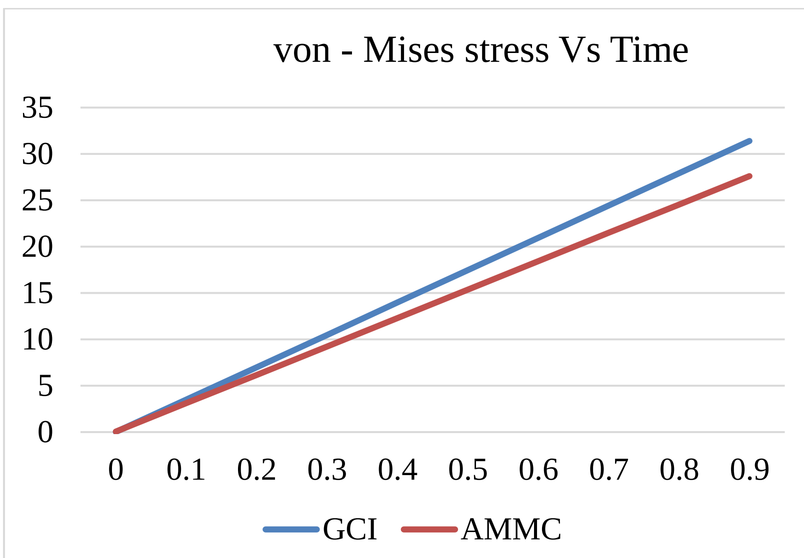


Figure 4.8: Von-Mises stress concentration of Disc Brake which made from GCI and AMMC

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The material selection for automotive brake disc are done using digital logic method which is the best method than Cost versus property and Benefit versus Cost Analysis method to identified an optimum material among the candidate materials for brake disc. During this Selection, coefficient of friction and density were considered twice for determining the performance index because as higher friction coefficient and lower density are advantageous from the technical and economical point of view for this type of application. This consideration could have its effects on the final selection.

In order to achieve the goal of this study, different tasks were performed (Numerically & FEA) and the following conclusions are drawn.

The properties of Aluminum Metal Matrix composite materials are attractive for the developing of lightweight. The result obtained from this study shows that Aluminum Metal Matrix composite (AMMC) material has much Lighter than Gray Cast Iron (GCI).it reduces the mass of Brake Disc by 62.4 %. So, it can be concluded that AMMC is a suitable material for a lightweight brake disc in terms of mechanical and thermal strength. Due to higher coefficient of friction of AMMC Disc Brake Reduce Stopping distance by 31.7%. this is very important for short Braking Distance (according to accident point of View).

Generally, Among Titanium Alloys, Stainless Steel, Carbon-ceramic, Aluminum Metal Matrix composite (AMMC) and Gray Cast Iron (GCI) candidate materials, the digital logic method showed the highest figure of merit (FOM) for Aluminum Metal Matrix composite (AMMC) material which is 0.01425 than GCI (0.00803). this show that, AMMC Material improves overall performance by 8.7% and cross ponding cost is also increasing by 62.96 %.

Lastly, it can be concluding that Aluminum Metal Matrix composite (AMMC) material is the best material for Brake Disc in order to increases the performance of Lifan 520 vehicle Brake Disc.

5.2. Recommendation

The following research areas are recommended for future studies:

- ✓ Repeat the analysis by searching/Selecting other form of material to increase Braking performance than AMMC and GCI.
- ✓ Dynamic/ Vibration Analysis of the AMMC Disc Brake (Failure Analysis due to Vibration).
- ✓ Thermal analysis of the AMMC Disc Brake (Temperature distribution, Heat dissipating mechanism and capacity).

References

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

2) Suresh Talur et.al "Selection of Material by weighted property method for Savonius Vertical Axis Wind Turbine Rotor blade" International Research Journal of Engineering and Technology (IRJET), Volume: 02 Issue: 01- Apr-2015.

3) Mahmood Hasan Dakhil et.al "Structural Design and Analysis of Disc Brake in Automobiles". Https://Www.Researchgate.Net/Publication/274373222 Article · January 2014.

4) Swapnil Thigale1, Chinmay Shah2 "Weight Reduction in Brake Disc Using Topology Optimization" International Journal of Research in Engineering and Technology Oct-2016.

5) S. Sarip "Design Development of Lightweight Disc Brake for Regenerative Braking – Finite Element Analysis" International Journal of Applied Physics and Mathematics, Vol. 3, No. 1, January 2013.

6) M.A. Maleque et.al "Material Selection Method in Design of Automotive Brake Disc" Proceedings of the World Congress on Engineering 2010 Vol III June 30 - July 2, 2010, London, U.K.

7) S.L.N.Reddy et.al "Steady State Thermal Analysis of Rotor Disc Break" Journal of Mechanical and Civil Engineering (Iosr-Jmce) (Mar. - Apr. 2016.

8) G. Cueva et.al. Wear resistance of cast irons used in brake disc rotors. ARTICL IN PRESS, São Paulo, SP, Brazil, Wear 255 (2003), 1256-1260.

9) Marko Reibenschuh et.al. Modelling and Analysis of Thermal and Stress Loads in Train Disc Brakes – Braking from 250 km/h to Standstill, Journal of Mechanical Engineering, University of Maribor,2009 Slovenia.

10) Robert L. Mott, P.E. Machine Elements in Mechanical Design, Fourth Edition, University of Dayton.

11) International Business Machines (IBM), the Case for Smarter Transportation, IBM Corporation, United States of America, September 2010.

12) Omar Maluf et.al. Development of materials for automotive disc brakes, University of São Paulo, São Carlos, SP, Brazil.

13) M. A. Maleque & Sarker Dyuti. Materials selection of a bicycle frame using cost per unit property and digital logic methods, International Journal of Mechanical and Materials Engineering, January 2010.

14) Stanly Wilson Louis et.al. Numerical Analysis of a Rotor Disc for Optimization of the Disc Materials,

Journal of Mechanical Engineering and Automation 2015.

15) Prof A. D. Dhale et.al. "Structural and Thermal Analysis of Brake Disc" 2014 IJEDR | Volume 2
16) www.yamaco-yamashin.com
17) http://www.saylor.org/courses/me203/
18) Mr. P. N. Gunjal et.al. Selection of the disc brake material using pin on disc apparatus, international journal of innovations in engineering research and technology [ijiert], volume 2, issue 11, nov. -2015.
19) Rehman A et.al. Alternate materials in automobile brake disc applications with emphasis on al composites- a technical review, Journal of Engineering Research and Studies JERS/Vol. I/Issue I/July-Sept. 2010/35-46.
20) Rahul Raosaheb Pind & Prof. Swami M. C. Analysis and Computational Investigation of Brake Disc for Composite Materials, © 2016 IJEDR (International Journal of Engineering Development and Research) | Volume 4, Issue 4 | ISSN: 2321-9939.
21) Muthanna K.P et.al. Performance analysis and material optimization of disc brake using MMC, International Journal of Innovative Research in Science, Engineering and Technology, Vol. 2, Issue 8, August 2013.
22) HARSHAL NIKAM et.al. Design and analysis of brake rotor with parameter optimization, International Journal of Automobile Engineering Research and Development (IJAuERD), Vol. 4, Issue 4, Aug 2014, 21-30.
23) Anudeep.B and 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.
24) Dr. P.A. Makasare et.al. Design and Optimization of Disc Brake Rotor (For Two Wheeler), International Engineering Research Journal Page No 288-300.
25) Prof. Mit Patel et.al. Design of Disc Brake's Rotor, IJEDR | Volume 4, Issue 4.
26) http://www.sanghvienterprise.com/stainless-steel-products/ss-plate.
27) http://www.jinyushunda.en.alibaba.com, Beijing jinyu shunda Technology Co.Ltd, china Mainland trading Company.
28) http://www.asminternational.org
29) Shaoxing Lingfeng Machinery Factory, china(Mainland) Manufacturer Company.
30) Sadiq Sius LAWAL et.al. Development and production of brake pad from sawdust composite.

Leonardo Journal of Sciences, Federal University of Technology in Niger State, Nigeria, 30, January-June 2017

31) J.Y. Wong. Theory of Ground Vehicle, third edition,2001

32) Ferdinand P. Beer et.al. Mechanics of Materials. Seventh Edition, 2015