DESIGN SELECTION OF BRAKE DISC HYBRID ALUMINIUM MATRIX COMPOSITES REINFORCED WITH MICRO AND NANO PARTICULATES

GAN WEI KANG

Report submitted in partial fulfillment of the requirements

for the award of the degree of

Bachelor of Engineering in Manufacturing Engineering

Faculty of Manufacturing Engineering

UNIVERSITY MALAYSIA PAHANG

EXAMINER APPROVAL DOCUMENT

We certify that the thesis entitled " DESIGN SELECTION OF BRAKE DISC HYBRID ALUMINIUM MATRIX COMPOSITES REINFORCED WITH MICRO AND NANO PARTICULATES" is written by GAN WEI KANG. We have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award B. Eng (Hons) of Manufacturing Engineering. We are here with recommend that it be accepted in fulfillment of the requirement for the B. Eng (Hons) of Manufacturing Engineering.

Signature :

Name of panel : En. Kamarul Arifin Bin Mohd Nor

Position : Lecturer

Date : 10 June 2016

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this thesis project is adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering in Manufacturing Engineering.

Signature :

Name of supervisor : Dr. Nanang Fatchurrohman CEng (UK) MIMechE

Position : Senior Lecturer

Date : 10 June 2016

STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotation and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature :

Name : GAN WEI KANG

ID Number : FA12049

Date : 10 June 2016

ACKNOWLEDGEMENTS

First of all, I would like to express my gratitude to my supervisor, Dr. Nanang Fatchurrohman for his advice, guidance, and support in completing my final year project. I am very lucky to have Dr. Nanang Fatchurrohman as my supervisor. He had taught me a lot by the sharing of his experience and knowledge.

Next, I would like to thanks Universiti Malaysia Pahang for giving me the chance to gain knowledge and further my study as a degree student. Without the opportunity, I will not have a chance to experience or do a such final year project. I deeply thank all the FKP lecturers for sharing their knowledge and experience to me, which provided me a fundamental knowledge in completing my project. I would like to thanks my fellow friends who gave me help and support whenever I face problems in any kind of situation.

Last but not least, I would like to deliver my appreciation to my parents who have provide mental support and physical support to me. Without their encouragement and support, I might not be able to focus on and done my final year project before the deadline.

ABSTRACT

In the era of globalization, the use of automotive vehicles becoming more and more general. An brake disc play an important role in the vehicle and it is used to stop or decrease the velocity of the vehicle. The demand of metal matrix composites is greatly increased in fabricating the brake disc since it having a low density and high thermal conductivity. Over-heating will lead to the malfunction of the braking system and affect the safety of vehicle. Low weight of brake disc can decrease the use of fuel of the vehicle thus improve the fuel usage efficiency. This project will proposed suitable material and focus more on selecting best alternative designs for a brake disc. A suitable hybrid Al-MMCs material is identified from the research journal and compared with the conventional material, grey cast iron. Then, the most important parameters and specifications that affecting the design of brake disc are determined from QFD. From the outcomes of QFD, six alternatives design of brake disc are proposed and modeled into CATIA. The model of brake disc are then imported to ANSYS software for structural and thermal analysis. Finally, a decision making tool, AHP is used to chose the best design among the six alternatives design of brake disc.

ABSTRAK

Pada zaman globalisasi, penggunaan kenderaan automotif menjadi lebih dan lebih umum. Cakera brek memainkan peranan yang penting di dalam kenderaan itu dan ia digunakan untuk menghentikan atau mengurangkan halaju kenderaan. Permintaan komposit matriks logam amat meningkat dalam reka cakera brek kerana ia mempunyai ketumpatan yang rendah dan kekonduksian haba yang tinggi. Lebih-pemanasan akan membawa kepada kerosakan sistem brek dan menjejaskan keselamatan kenderaan. Berat badan yang rendah cakera brek boleh mengurangkan penggunaan bahan api kenderaan dengan itu meningkatkan kecekapan penggunaan bahan api. Projek ini akan mencadangkan bahan yang sesuai dan memberi tumpuan lebih kepada memilih reka bentuk alternatif terbaik untuk cakera brek. Gabungan bahan Al-MMCs yang sesuai dikenal pasti dari jurnal penyelidikan dan dibandingkan dengan bahan konvensional, besi tuang kelabu. Kemudian, parameter dan spesifikasi yang paling penting dan mempengaruhi reka bentuk cakera brek ditentukan dari QFD. Dari hasil QFD, enam alternatif reka bentuk cakera brek dicadangkan dan dimodelkan ke dalam CATIA. Model brek cakera kemudiannya diimport ke perisian ANSYS untuk analisis struktur dan terma. Akhir sekali, alat membuat keputusan, AHP digunakan untuk memilih reka bentuk yang terbaik di kalangan reka enam alternatif cakera brek.

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LIST OF SYMBOLS

t_a	Thickness of cast iron brake disc
t_b	Thickness of MMCs brake disc
E_a	Elastic modulus of cast iron brake disc
E_b	Elastic modulus of MMCs brake disc
W_i	Priority
a_{ij}	Numerical equivalent of comparison between i and j
λ_{max}	Maximum or principal eigenvalue of the pair-wise comparison matrix
$R_i W_i$	Importance rating
μ	Coefficient of friction of cast iron
F	Force

LIST OF ABBREVIATIONS

Al	Aluminium
Al_2O_3	Aluminium oxide
AMCs	Aluminium matrix composites
AHP	Analytic hierarchy process
B4C	Boron carbide
Cu	Copper
Cr	Chromium
CA	Customer attributes
CI	Consistency index
CR	Consistency ratio
CATIA	Computer aided three-dimensional interactive application
CMCs	Ceramic matrix composites
Fe	Iron
FEA	Finite Element Analysis
Gr	Graphite
Mn	Manganese
Mg	Magnesium
MMCs	Metal matrix composites
PMCs	Polymer matrix composites

TiB_2	Titanium diboride
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TR	Technical Requirements
TRIZ	Theory of Inventive Problem Solving
QFD	Quality function deployment
SiC	Silicon carbide
VOC	Voice of customer
WC	Tungsten Carbide
Zn	Zinc

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In the era of globalization, the use of automotive vehicles becoming more and more general. The companies are competing with each others to manufacture a better and safer vehicle products. An brake disc play an important role in the vehicle and it is used to stop or decrease the velocity of the vehicle. The demand of metal matrix composites is greatly increased in fabricating the brake disc since it having a low density and high thermal conductivity. By changing the weight fraction of the reinforcement phase, it can enhanced the brake disc in term of mechanical performance (tribology, tensile and compressive properties) and physical properties (thermal expansion, thermal diffusivity and density). This project will focus on hybrid aluminium matrix composites (Maleque et al., 2010; Adebisi et al., 2011).

Many companies offers different designs for their brake disc. Some of the crucial factors need to be included in the design of the brake disc such as safety, reliability, weight, durability, stability, cost and performance. The most important consideration are the thermal performance of brake disc and capability to hold up against high friction and abrasive wear (Maleque et al., 2010).

Comparing candidate design, ranking and choosing the best design is one of the most important stages in design selection process. Sometimes, there is more than one crucial parameters for deciding the best design. A large number of design selection criteria have to be considered. A simplify and systematic tool or method is required in taking a proper design selection decision. The Analytic Hierarchy Process (AHP) is a method that assist in taking the decision of design selection. It can handle the objective as well as subjective factors, and the criteria weights and alternative scores are obtained through the formation of a pair-wise comparison matrix (Zafarani et al., 2014).

Another technique that was chosen in designing the brake disc is finite element analysis. Complicated problems can be solved in a efficient and faster way with finite element analysis and decreasing the need of physical testing for a new design. An ideal design can be accomplished based on preset specification using computational methods (Domond, 2010).

1.2 PROBLEM STATEMENT

There are many things to involved in design a brake. The brake disc must be design properly and it cannot be selected based on the appearance or personal preference. Every design of the brake disc such as size, thickness and diameter must have its purpose and uses. Therefore, proper design and selection process is need to achieve the best brake disc design.

Thermal performance is the one of the properties in affecting the performance of brake disc. Over-heating will lead to the malfunction of the braking system and affect the safety of vehicle. A safe product will increase the confidence and interest of the users to purchase the product and also increase reputation of the manufacturer. There are several design parameters affecting the thermal performance of brake disc, for example thickness is related with stress and temperature distribution. Reducing thickness will increase stress at the critical area. So, an appropriate of thickness of brake disc must be determined for the brake disc (Muthuvel et al., 2015).

Others important properties in brake disc are lubricating effect, wear resistance and weight. Low weight of brake disc can decrease the use of fuel of the vehicle thus improve the fuel usage efficiency. A high wear resistance and lubrication effect is desirable in brake disc so that the surface of the brake disc will not wear and get scratched easily to prolong the lifetime and improve the reliability and safety of the brake disc.

The factors need to involve in designing a brake disc include safety, reliability, durability, stability, and cost. The design of the brake disc and the properties of materials used must be able to fulfill the criteria stated above.

1.3 GOAL AND OBJECTIVES

The goal of this project is to select the best design of a brake disc that made of metal matrix composite. The following are the objectives that have been set to achieve goal:

i. Proposed suitable material for brake disc.
ii. Determine and ranking the important parameters and specifications affecting the brake disc using quality function deployment(QFD).
iii. Modeling of alternatives design of brake disc in CATIA.
iv. Structural and thermal analysis of the alternatives design of brake disc using finite element analysis(FEA).
v. Selecting the best alternatives design by using analytic hierarchy process(AHP).

1.4 SIGNIFICANCES OF RESERACH

The material selection is also an important criteria as the design selection for the brake disc but this research is focus on only the design selection. The significances of this research are:

i. Use hybrid metal matrix composite as the material of brake disc.
ii. Use CATIA to model alternative design of brake disc.
iii. Use FEA to analyze the thermal and structural properties of alternatives design.
iv. Use QFD to determine and rank the important parameters of brake disc.
v. Use AHP to select the best design of brake disc among the alternatives design.

1.5 SCOPE OF RESEARCH

In the selection process of design of brake disc, some of the software and method will be used. The following are the scopes of this project:

i. Identify and propose suitable material and alternative designs of brake disc
ii. Rank the selection parameters with respect to the base of product performance by using the quality function deployment(QFD) method
iii. Test system and performance of brake disc by simulation in a virtual environment by using the ANSYS software.
iv. Ranking and choosing the best design by using the analytic hierarchy process(AHP) software

1.6 BUDGET PLAN

Table 1.1: Budget plan

Item Name	Cost
Brake Disc	**RM127.20**
Other Materials	**Rm122.80**
Total Cost	**RM250.00**

1.7 GANTT CHART

1.7.1 Semester 1

Activity	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14
Meeting SV for understand of the title														
Research about development of brake disc														
Research about design selection and decision making software														
Drafting of chapter 1														
Finding relevant journal														
Drafting of chapter 2														
Drafting of chapter 3														
Milestone 1 submission														
Preparation of presentation														
Presentation Draft FYP1														
Milestone 2 submission														
Milestone 3 submission														

1.7.2 Semester 2

Activity	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14
Meeting SV for the progress														
Installing related software														
Learning to use the software														
Develop a complete QFD														
Analysis of alternatives design in ANSYS														
Selecting the best design using AHP software														
Complete Chapter 4														
Meeting SV for checking														
Complete Chapter 5														
Finalize the complete report														

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In chapter 1, the introduction of this project including problem statement, research scope and goal and objective has been discussed. This chapter will discuss about the relevant literature review survey. The relevant topics are metal matrix composites, brake system, multiple criteria making decision(QFD and AHP), and finite element analysis(FEA).

2.2 BRAKE SYSTEM

A brake system generally consist of brake caliper, brake disc and brake pad. Nowadays, most of the latest vehicle are introduced with the using of brake disc on the front wheels and maybe on the rear wheels as well. The function of the disc brake system is to slow down or stop the vehicle. Thermal energy is converted from kinetic energy of the moving vehicle when there are friction between the brake discs and brake pad.

The vehicle is bring to a halt or slow down when brake pedal is pushed by the driver. This is due to the generation of higher brake fluid pressure and the piston pushes the brake pad toward the brake disc. The brake pad finally will clamp and rub the brake disc to decrease the velocity of the vehicle (Murthy et al., 2012; Thuresson, 2014).

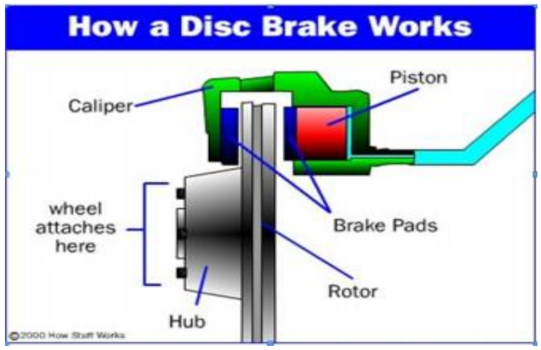


Figure 2.1: Brake disc system

Source: Murthy et al. (2012)

2.2.1 Brake Disc

Brake disc is one of the friction brake in which the braking forces are generated by rubbing between the high friction brake pad rub with the surface of a brake disc. The most important criteria of the brake disc is the ability to dissipate heat, thermal expansion coefficient, thermal conductivity and capacitance as it will affect the performance and safety of the vehicle. There are various shape and design of brake disc.

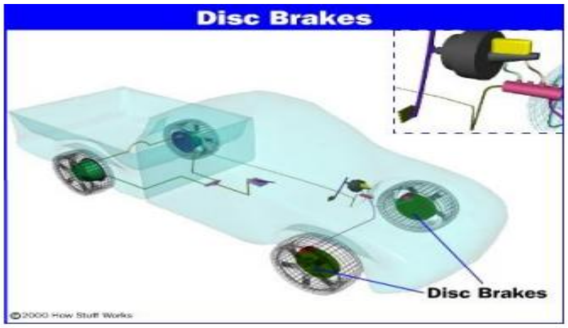


Figure 2.2: Location of brake disc

Souce: Murthy et al. (2012)

Basically, there are two types of brake disc which are solid brake disc and ventilated brake disc. Ventilated brake disc offers a better cooling performance while solid brake disc give the advantages of lower surface temperature rise and lower manufacturing cost. Factors that affecting the brake disc properties are material and design. The focus of this project will be on both design and material of solid brake disc.

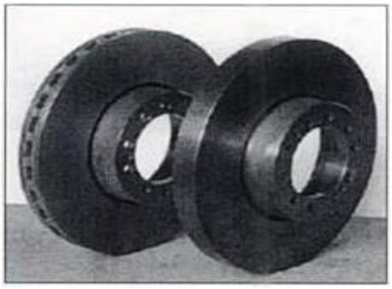


Figure 2.3: Ventilated brake disc(left) and solid brake disc(right)

(Sasikumar 2014) analyze and comparing the coupled thermal-structural of the solid and ventilated brake disc using ANSYS workbench 14.5. Each type of the brake disc that having the same dimension and input parameters are compared in two different materials which are stainless steel and cast iron. The result show that ventilated brake disc has a better thermal performance and undergoes less deformation.

2.2.2 Brake Disc Design Considerations

The rotor is made of two parts which are the hat regions and disc region. The disc region included the inner cheek, vane and outer cheek. Both of the region are assembled together by bolt-nut (Kumar, 2012). There is an correlation between the selected material and the design of the brake disc. The design of the brake disc will affect many parameters of the brake disc such as temperature distribution, tensile strength and deformation. The highest temperature that generated on the surface of brake disc after repetition of braking must can be withstand by the selected material in order to perform well and for ensure safety (Khalid et al,. 2011). There are many kinds of design such as the holes, slot and curved vane on the brake disc.

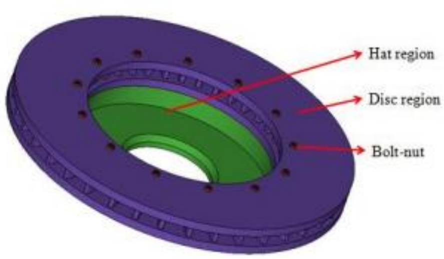


Figure 2.4: Brake disc assembly

Source: Kumar (2012)

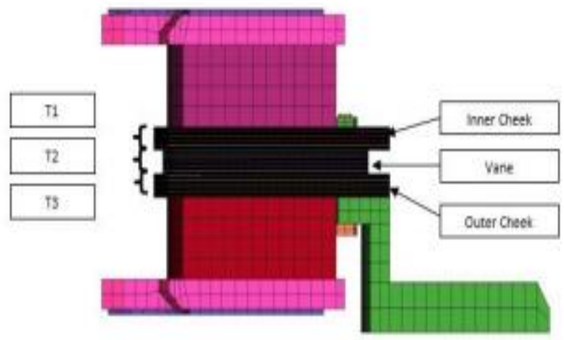


Figure 2.5: Component of disc region

Source: Kumar (2012)

(Kumar, 2012) study about the design and the effect of material on the thermal elastic behavior of the brake disc. The comparison of the design is carried out by changing the thickness of inner cheek, vane and outer cheek. The research conclude that the best design is the brake disc that having of 6mm or 7mm cheek thickness with 20mm disc thickness.

(Chaphale, 2014) investigated the contact stress by varying different load in different design of brake disc system. The study stated that the design consideration of a disc brake system should include diameter of brake disc, type of material of brake disc, speed sensitive, temperature sensitive, pressure sensitive and also surface area. A larger diameter of brake disc has a higher brake power and larger surface area enhance the dissipation of heat

(Nikam et al., 2014) carried out research work by modeling, analyzing and optimizing the brake disc in ANSYS 14.0 workbench software. The design parameters for optimization are thickness and outer diameter of brake disc that will affect the strength and maximum temperature on surface while the analysis criteria are temperature, safety factor and total deformation. The temperature analyzed must be in the allowable range to prevent the effect of brake fading and deformation. The study selected the best design of brake disc that with diameter of 190mm and thickness of 3.9mm.

(Kajabe et al., 2015) research studied about design of brake disc with different dimension and analysis based on different design. The design parameters that included in the analysis are weight, deformation, temperature, tensile strength and Von-misses stress. The best design result from the analysis are the brake disc that with dimension of 170-180mm which has a lower weight, reduced manufacturing cost and permissible stress.

(Gangwar, 2014) study show the design analysis and optimization of brake disc. There are few important aim in designing and optimize the brake disc which are to minimize cost, size and use of material and increase safety of the brake disc. Reducing the thickness of brake disc can cut down cost since it decrease the use of material and lower down the weight but it will increase stress levels.

(Udayakumar & Ponnusamy, 2014) research work compare and analyze different designs of brake disc. There are 4 different designs, solid brake disc, slotted brake disc, curved vane brake disc and S curve vane brake disc. All the four different designs are made of same material. After the analysis, the design of S curved vane show the best result in property of deformation, heat dissipation and heat transfer rate. The design variable that affecting the performance of brake disc are number of vane, radius and thickness of the brake disc.

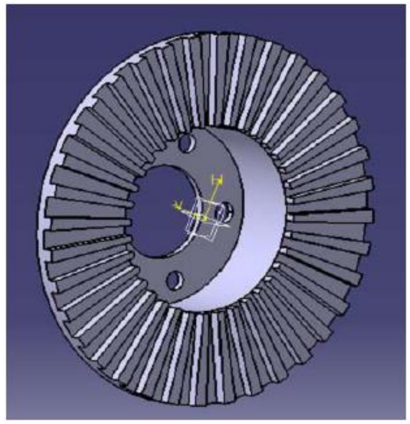


Figure 2.6: Slotted brake disc

Source: Udayakumar & Ponnusamy (2014)

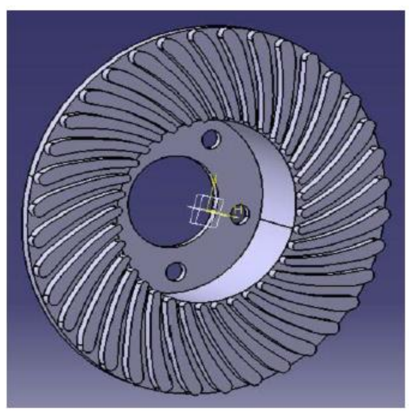


Figure 2.7: Curved vane brake disc

Source: Udayakumar & Ponnusamy (2014)

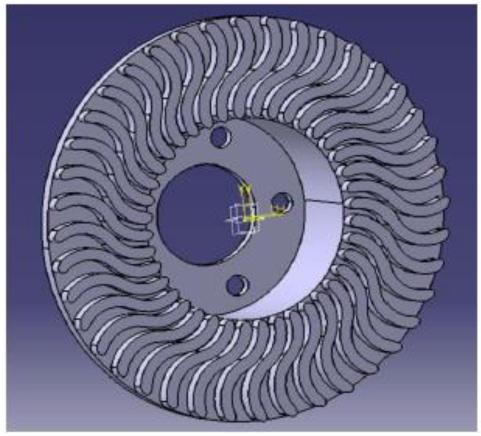


Figure 2.8: S-curved vane brake disc

Source: Udayakumar & Ponnusamy (2014)

(Zaware et al., 2014) research work analyze the modified shape of grey cast iron brake disc and compare it with the original design brake disc. The shape of slot and position of hole is modified. The different designs of brake disc are classified as modified shape 1, modified shape 2, modified shape 3. The modified shape 2 provide the minimum deformation and Von Mises stress compared with the original and other designs.

(Duzgun, 2012) investigated the thermal stress and heat generation of different designs of brake disc. There different designs that being compared are solid brake disc, cross-drilled, cross-slotted and cross-slotted with side groove ventilated brake disc. The result show that ventilation will reduced the heat generation of brake disc but a higher thermal stress developed compared with solid brake disc. The study concluded that the cross-slotted with side groove is the best design since it significantly reduced the heat generation and thermal stresses.

Figure 2.9: Four different design of brake disc

Source: Duzgun (2012)

2.2.3 Review Table for Brake Disc

Table 2.1: Literature Review of Brake Disc

Author Name	Titles of Paper	Outcome
Khalid et al., 2011	Performance Investigation of the UTeM Eco-Car Disc Brake System	The highest temperature that generated on the surface of brake disc after repetition of braking must can be withstand by the selected material in order to perform well and for ensure safety.
Chaphale, 2014	A Review on Thermal and Contact Stress Analysis of Disc Braking System	A larger diameter of brake disc has a higher brake power and larger surface area enhance the dissipation of heat.

Nikam et al., 2014	Design and Analysis of Brake Rotor with Parameter Optimization	The temperature generated must be in the allowable range to prevent the effect of brake fading and deformation.
Gangwar, 2014	Design Analysis and Optimization of Disc Brake Assembly of A 4-wheeler Race Car	Reducing the thickness of brake disc can cut down cost since it decrease the use of material and lower down the weight but it will increase stress levels.
Udayakumar & Ramesh, 2014	Computer Aided Design and Analysis of Disc Brake Rotors for Passenger Car	The design variable that affecting the performance of brake disc are number of vane, radius and thickness of the brake disc. Compare and analyze different designs of brake disc that are made of same material. The design of S curved vane show the best result in property of deformation, heat dissipation and heat transfer rate.

2.3 METAL MATRIX COMPOSITES(MMCs)

Before the investigation of MMCs, cast iron are chosen as the material for the brake disc. However, the development of MMCs has replaced the conventional material because of its better properties. Composite materials are comprised of two or more different materials to obtain the outstanding property that are better than their own individual material. Basically, there are three types of composite matrix materials:

1. Ceramic Matrix composites (CMCs)
2. Metal Matrix composites (MMCs)
3. Polymer Matrix composites (PMCs)

But, this project will focus on only hybrid metal matrix composites. Metal matrix composites is composite material composed of at least two different materials. One of the materials must be metal and the other one can be a different metal or different materials such as organic compound or ceramic. It is known as hybrid composite when there are more than two materials. Example of metal matrix composites are aluminum silicon carbide and magnesium silicon carbide.

MMCs are fabricated by combining reinforcing material with the metal matrix. The surface of the reinforcement surface is coated to avoid it from reacting with the matrix. Various combination of useful properties can be obtained from metal matrix composites. These materials have the combination properties of lightweight, high specific strength, stiffness, good corrosion resistance, reduced system maintenance, high thermal conductivity and high wear resistance which are desirable in designing of brake disc (Maleque et al., 2010; Adebisi et al., 2011; Udayakumar & Ramesh, 2014; Zaware et al., 2014).

(Yathish et al., 2013) research compared and analyses the property of both cast iron and aluminium6061-SiC-red mud composite in brake disc. The comparison are carried out in the same parameters. The result show that aluminum silicon carbide composite developed less stress, reduced displacement, more contact status and decreases contact sliding and pressure in the brake disc compared to the cast iron.

2.3.1 Matrix Materials

The material where the reinforcement is inserted into is called matrix. Through the matrix, there is a continuous path to any point in the material. The metal matrix is usually a lightweight metal alloy such as aluminum, magnesium, or titanium and provides support for the reinforcement in structural applications while for the high-temperature applications, the matrix that commonly used are cobalt and cobalt–nickel alloy (Taya & Arsenault, 1989).

A wise choice of selecting matrix materials and also the reinforcement is important as it will affect the property and quality of the composite material. Aluminum alloys is the most popular matrix for use in MMCs because of it lower cost compared to other light metals such as Magnesium and titanium (Anon n.d.; Taya & Arsenault, 1989).

2.3.1.1 Significance of Aluminium Alloy as Matrix Material

(Silva et al., 2013) study the stress corrosion cracking behavior and tensile properties of aluminum alloy. Aluminum alloy is used in aeronautic application because the properties of high ultimate and yield strength while it is in T6 but it has a poor stress corrosion cracking resistance. This study used a new treatment method to produce the aluminum alloy in T7X condition which has a good stress corrosion cracking resistance.

(Rino et al., 2012) research stated that aluminum alloy is a better material that exhibit low density, better wear resistance, good corrosion resistance, excellent mechanical properties and low thermal coefficient of expansion compared with other conventional alloys and metals. This alloy can be fabricate with a low cost and can be used in wide range of applications such as aerospace and automobile.

Table 2.2: Application of Aluminum alloy

Aluminum Alloy	*Common Use*
1050/1200	Food and Chemical Industry
2014	Airframes
5251/5052	Vehicle panelling, structures exposed to marine atmospheres, mine cages.
6063	Architectural extrusions (internal and external) window frames, irrigation pipes.
6061/6082	Stressed structural members, bridge cranes, roof trusses, beer barrels.
7075	Armoured vehicles, military bridges motor cycle and bicycle frames.

Source: Rino et al. (2012)

(Altıntas et al., 2015) research paper reviewed that aluminum alloy provide the properties of low density, high specific strength, high thermal conductivity and corrosion resistance. This alloy was used widely in applications of aerospace and automobile industries for example engine block and cylinder heads.

(Zhang et al., 2015) research work about the microstructure-property characteristic of novel non-weld-thinning friction stir welding process of aluminum alloy. The base metal that used in this paper is 5052 aluminum alloy which has a good corrosion resistance and weldability. This type of alloy is widely used in aerospace and automobiles.

Table 2.3: Chemical composition and mechanical properties of 5052 aluminum alloy

Chemical compositions (wt.%)								Mechanical properties	
Al	Mg	Si	Fe	Cr	Cu	Mn	Zn	Tensile strength	Elongation
Bal.	2.2–2.8	0.25	0.4	0.15–0.35	0.1	0.1	0.1	225 MPa	24%

Source: Zhang et al. (2015)

(Liu et al., 2015) investigated the effect of magnetic field aged on AA219 aluminum alloy. This alloy is of the Al-Cu-Mg series welding aluminum alloy and provide the properties of high toughness, strength and stress corrosion resistance. It was widely used in application of military, aerospace and civilian equipment. The study show that the magnetic field aging treatment enhanced the mechanical and microstructure of aluminum alloy.

(Cardili et al., 2015) research stated that aluminum alloy exhibit the superior properties of lightweight, high specific strength and toughness. This properties lead to the increasing demand of aluminum alloy in the application of plane, construction and automobile. Using a suitable fabrication method of aluminum alloy can enhanced the properties of the alloy.

(Kimura & Nakamoto, 2014) reviewed that aluminum alloy fabricated by selective laser melting exhibit properties of good ductility, strength and corrosion resistance. These properties are very useful in the application of automotive, machinery and aerospace.

(Dhiyaneswaran & Amirthagadeswaran) carried out a comparative study about the brake disc materials. Two material are compared in this study, cast iron and aluminum based MMCs. The comparison of the property such as stress distribution, displacement, and strain energy of both material show that the aluminum based MMCs has a better performance for the brake disc application.

(Adebisi et al., 2011) investigated the distribution of surface temperature in a aluminum matrix composite and cast iron brake disc. After conducted the experiment and finite element analysis, the experiment concluded that the aluminum matrix composite which has a high thermal conductivity and dissipation rate improve the cooling performance and minimize the temperature rise and better temperature distribution.

(Telang et al., 2010) have reviewed that aluminum matrix composite(AMC) provide a better property in term of wear resistance, friction, thermal performance, and lighter weight compared to traditional cast iron. AMC dissipated heat four times faster and it have a two to three times higher thermal conductivity than cast iron. This type of composite is 60% lighter and it does not wear easily compared to cast iron.

2.3.2 Reinforcement Materials

The material that embedded into matrix is called reinforcement. The function of the reinforcement materials is to reinforce and change physical properties of the compound such as thermal performance, density, or coefficient of friction. There are four groups of reinforced MMCs: fiber-reinforced MMCs, particulate-reinforced MMCs, plate-reinforced MMCs and layered MMCs(Anon n.d.; Taya & Arsenault, 1989). The reinforcement material can be in nano size or micro size. More than 2 reinforcement materials with the matrix material is known as hybrid metal matrix composites. A wide range of possible property combination is available based on the choice of matrix and reinforcement materials.

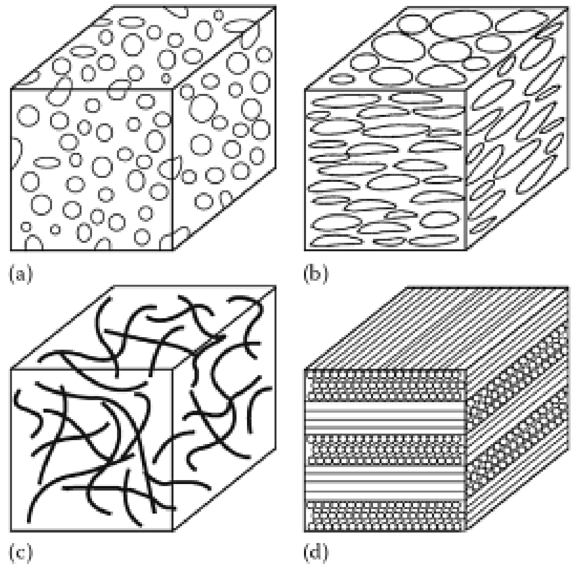


Figure 2.10: Type of reinforcement phase: (a)Particle-reinforced composite materials. (b)Plate-reinforced composite materials. (c)Fiber-reinforced composite materials. (d) Layered reinforced composite materials

Table 2.4: Properties of commonly used particulate reinforcements

TABLE 14.1

Properties of Several Commonly Used Particulate Reinforcements

Particulates	Density/ g cm^{-3}	Thermal-Expansion Coefficient/10^{-1-6} °C	Thermal Conductivity/ W (Cm °C)-one	Hardness/ MPa	Bending Strength/ MPa	Modulus of Elasticity/ GPa
Silicon carbide (SiC)	3.21	4.8	1.8	2700	400–500	427
Boron carbide $(B)_4C$	2.52	5.73	—	2700	300–500	360–460
Titanium carbide (TiC)	4.92	7.40	—	2600	500	—
Alumina (Al_2O_3)	—	9.00	—	—	—	—
Silicon nitride (Si_3N_4)	3.2	2.5–3.2	0.3–0.7	—	900	330
Mullite ($3Al_2O_3$-$2SiO_2$)	3.17	4.2	—	3250	1200	—
Titanium di-boride (TiB_2)	4.5	—	—	—	—	—

Table 2.5: Properties and applications of reinforcement materials

Property	Materials	Application
Wear resistance	SiC-, Al_2O_3-, and/or graphite-reinforced micro and nano MMCs	Bearing surfaces, cylinder liners, pistons, cam shafts, tappets, lifters, rockers, brake components
Light weight, energy absorption	Fly ash cenosphere- and low-density ceramic microballoon-reinforced syntactic foam MMCs	Crumple zones, frame members and reinforcements, pedestrian impact zones, batteries
Self-cleaning	MMCs with hydrophobic reinforcements, biomimetic coatings, and surface finishes	Water pumps, water jackets, exposed metallic components
Self-lubricating	Micro and nano MMCs incorporating graphite, MoS_2, TiB_2, hexagonal BN, or other solid lubricants	Bearing journals, cylinder liners, pistons, cv joints, gear surfaces
High thermal conductivity	Micro and nano MMCs reinforced with high-conductivity carbon, diamond, or cubic boron nitride (cBN) powder	Cylinder liners, water passages, brake components, turbo/supercharger components, catalytic converters, electronics packaging
High strength	Micro and nano MMCs reinforced with SiC or Al_2O_3 particles, CNTs, carbon or Nextel fibers, and in situ ceramics	Connecting rods, brake calipers, brake rotors, brake calipers
Low cost	MMCs containing fly ash or waste sand as fillers	Intake manifolds, accessory brackets, low-load brackets, oil pans, valve covers, alternator covers, water pumps

Source: Dorri Moghadam et al. (2014)

There are two categories of reinforcement material, discontinuous and continuous. Discontinuous MMCs is isotropic and normally fabricated by extrusion, forging, or rolling while continuous is anisotropic which the strength is related with the alignment of the material. Continuous reinforcement uses monofilament wires or fibers. Discontinuous reinforcement uses "whisker", short fibers, or particles. Recent investigation in discontinuous MMCs show that it is more cheaper to fabricate silicon carbide whisker and this lead to the applied of silicon carbide particulate in MMCs. The most common reinforcement materials are alumina and silicon carbide, which most of the recent study are more focused on silicon carbide(Taya & Arsenault, 1989).

2.3.2.1 Micro-reinforced Hybrid MMCs

Micro with micro size reinforcement materials are the most common size that usually use in hybrid metal matrix composite.

(Rajmohan et al., 2015) study about the fabrication of hybrid metal matrix composites, Aluminium+ Titanium oxide +Graphite. Hybrid aluminium matrix composite are used to fabricate brake disc due to its ability to withstand high temperature. Both of the reinforcement materials titanium oxide and graphite is in micro size. Hybrid reinforcement of the solid lubricant particle, graphite enhanced the tribological properties and make the composites more favor in automotive applications. The hybrid metal matrix composites is fabricated by stir casting and the microstructure and mechanical properties is investigated. The result show a uniform distribution of reinforcement material in the aluminium alloy and the ultimate tensile strength and hardness is increased with the addition of reinforced particles.

(Madeva et al., 2013) investigated the mechanical behaviour of aluminium 6061 alloy reinforced with aluminium oxide and graphite hybrid metal matrix composites. Aluminium based graphite particulate MMCs can be used in automotive components. He stated that graphite in form of particulate is well known of its low density and high strength properties while addition aluminium oxide enhanced the mechanical properties of composites. The study show that the hybrid MMCs has a higher tensile strength, hardness and lower ductility compared with AL6061 alloy. The addition weight fraction of aluminium oxide will increase the hardness, tensile strength and decrease the percentage elongation whereas the addition weight fraction of graphite does not vary much the tensile strength but will decrease the hardness and increase the percentage of elongation although it is still has a better properties as compared with the unreinforced Al6061 alloy.

Table 2.6: Hardness measurement with the addition %wt of Al_2O_3 and graphite particulate

Sl. No.	Composition	Mean Micro Hardness No. (VHN)
1	Al6061 alloy	85.24
2	Al6061 alloy+6% of Al_2O_3	104.62
3	Al6061 alloy+6% of Al_2O_3+2% Graphite	98.45
4	Al6061 alloy+6% of Al_2O_3+4% Graphite	94.58
5	Al6061 alloy+6% of Al_2O_3+6% Graphite	93.21

Source: Madeva et al. (2013)

Table 2.7: Tensile test result with the addition %wt of Al_2O_3 and graphite particulate

Sl No	Composition	Yield Stress (MPa)	Ultimate Tensile Strength (MPa)	Percentage Elongation
1	Al6061 alloy	136	146.13	21.23
2	Al6061 alloy+6% of Al_2O_3	147.24	165.97	15.28
3	Al6061 alloy+6% of Al_2O_3+2% Graphite	135.89	159.58	17.15
4	Al6061 alloy+6% of Al_2O_3+4% Graphite	136.32	161.83	18.98
5	Al6061 alloy+6% of Al_2O_3+6% Graphite	151.56	169.78	19.69

Source: Madeva et al. (2013)

(James et al., 2014) research work about the machining and mechanical properties of hybrid alumiunium based MMCs which reinforced with micro size silicon carbide, SiC and titanium diboride, TiB_2. The reinforcements SiC provide the properties of low cost, thermal performance, good machinability and it is chemically compatible with aluminium. Investigation of microstructure, hardness, tensile strength and wear resistance of different weight percentage of reinforcement materials in the composites was carried out. The result shows that the addition of both the reinforcement SiC and TiB_2 increases hardness, but it was different in tensile strength. Addition of TiB_2 reduce the tensile strength of composite by 50-60% while the reinforcement SiC increased 20% strength to the composite. The wear test results show the addition of TiB_2 improved the wear resistance of composite.

Table 2.8: Tensile test results with different wt% of TiB_2

Weight % of reinforcements	Tensile Strength (MPa)
SiC 10% - TiB_2 0%	150.1
SiC 10% - TiB_2 2.5%	54.8
SiC 10% - TiB_2 5%	97.9

Source: James et al. (2014)

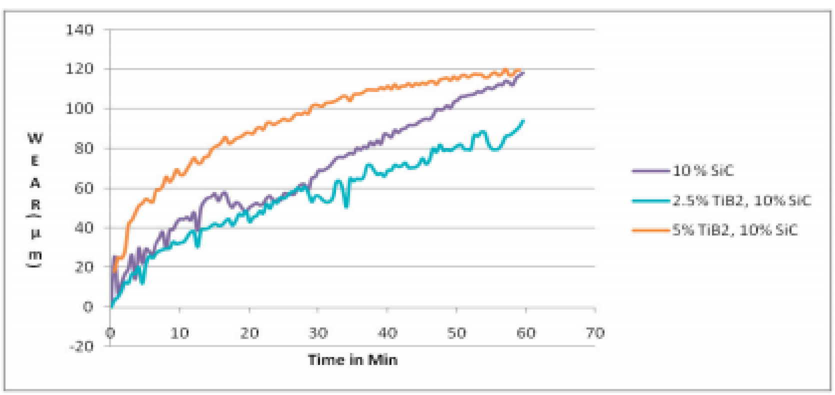


Figure 2.11: Wear test results of addition of TiB_2

Source: James et al. (2014)

(Kumar et al., 2014) investigated the machinability of aluminium based hybrid MMCs which reinforced with silicon carbide and boron carbide. Testing of the mechanical properties of the composite is carried out after it was successfully fabricated by stir casting. The tensile strength and hardness of the composites is improved after the addition of reinforcement.

(Bodunrin et al., 2015) stated that hybrid AMCs is developed for performance optimization with low fabrication cost. Example of reinforcement materials are boron carbide, graphite, tungsten carbide, silicon carbide, alumina, carbon nanotubes and silica. But silicon carbide and alumina are mostly utilized compared to other synthetic reinforcing particulates. The properties of specific stiffness and strength is improved at the cost of decreases ductility and fracture toughness in AMCs that reinforced with SiC or Al_2O_3. The use of two or more synthetic reinforcing particulates is necessary for property optimization. Graphite and Boron carbide are usually used with SiC or Al_2O_3 for performance optimization of AMCs.

(Suresha & Sridhara, 2010) research about the effect of graphite particulates in wear behaviour. Hybrid aluminium matrix composite are becoming more widely used in more applications such as automotive, aircraft and space. Graphite particulates is added as second reinforcement in aluminium matrix composites that reinforced with silicon carbide. Dry sliding wear test is conducted with different of weight percentage of graphite particulate that added into the Al-SiC composites. The result show that the wear resistance of hybrid composites is improved with the adding of 3%, 7.5% and 10% of graphite particulates as compared to the Al-SiC composites.

(Devaraju et al., 2013) study about the properties and microstructure of hybrid AMCs that reinforced with SiC+Al_2O_3 and SiC+Gr. Both microstructure of the hybrid composites are uniform dispersed. The result show that the hardness of the both the hybrid composite is increased compared to aluminium matrix but the Al-SiC/Al_2O_3 hybrid composite has a higher hardness value than the Al-SiC/Gr hybrid composite since Al_2O_3 is a harder material compare to graphite. The wear resistance of Al-SiC/Gr hybrid composite is much better than the hybrid composites Al-SiC/Al_2O_3 since Gr provide the solid lubricant effect compare to aluminium oxide.

2.3.2.2 Nano-Micro Reinforced Hybrid MMCs

Type and relative proportion of reinforcement materials are not only the factors will affect the property of the metal matrix composites but also the size of the reinforcement materials. Hybrid micrometer and nanometer size particulates reinforced in aluminium based composites enhance the mechanical and ductility of the composites. The most popular and common reinforcement materials that are used to reinforced aluminium alloy are SiC, TiC, TaC, WC and B4C(Attar et al., 2015). Change of the size of reinforcement materials from micro to nano scale utilize the properties of the composites(Srivastava et al. 2008).

Nano-particles reinforced MMCs are material that suitable for a large number of applications such as in automotive industries, sport industries and electronic devices. The properties of base material are enhanced by the nano-particles in terms of mechanical strength, wear resistance, and damping properties. Metal alloy such as Al, Mg and Cu are reinforced by nano-ceramic particles such as carbides, nitrides, oxides and carbon nanotubes to fabricate the composites(Casati & Vedani, 2014). The ductility and fracture toughness is improved when nano-particulates are used as reinforcing materials without the significant drop in strength. Ductility and fracture toughness are important for avoiding failures under in-service stress or shock load applications(Bodunrin et al. 2015).

(Lei et al., 2014) study about the thermal properties of hybrid aluminium matrix composites. The nanometer sized reinforcement broaden the application of Al MMCs such as automotive and aerospace. The composites is reinforced with micrometer sized and nanometer sized aluminium oxide particles and a comparison is carried out between different weight percentage of the nanometer sized and micrometer sized reinforcement materials in the composites. The result show that the nanometer sized reinforcement done a better job in utilizing the properties of Al based hybrid composites. The hardness of the composites is higher when a higher weight percentage of nanometer sized reinforcement aluminium oxide is added compared with the same weight percentage of micrometer sized reinforcement aluminium oxide added. The hybrid composites that are added with higher wt% of nanometer sized Al_2O_3 also show a better property of thermal expansion. Fast motion of dislocation is suppressed by the high concentration nanoparticles, thus preventing a fast thermal plastic deformation occurred. Such suppression of dislocation motion by high nanoparticle concentration is consistent with the observed high hardness and wear resistance.

Table 2.9: Comparison result of properties of hybrid aluminium based composite reinforced with micrometer sized and nanometer sized Al_2O_3

Materials	Composition (vol.%)			Relative density (%)	Hardness (GPa)
	Al	50 nm Al_2O_3	3 μm Al_2O_3		
AA-1	90	5	5	98.8	1.8
AA-2	85	5	10	98.6	1.9
AA-3	85	10	5	98.7	2.5
AA-4	80	10	10	98.3	2.3

Source: Lei et al. (2014)

(Babu et al., 2007) stated that MMCs that are reinforced with nano particles are widely used in automobiles, aviation and nuclear applications. He research work about the producing and characteristic of aluminium based nano-micro hybrid metal matrix composites by using stir casting method. The A356 aluminium alloy is reinforced with alumina short fiber and graphite nanofiber(GNF). The study show that both the reinforcement materials are well distribute among the aluminium alloy but there are formation of GNF cluster. Nano-indentation is carried out and the result show that the hardness and elastic modulus of the hybrid MMCs is improved but the region of GNF clusters show a decrement.

(Mohapatra, 2013) research about the microstructure, properties and fabrication of hybrid metallic and ceramic reinforced aluminium composites. The reinforced particles are titanium, Ti and aluminium oxide, Al_2O_3 and in the size of micro or nano. There are 5 combinations of composites that produced, Al+Ti, Al+ micro Al_2O_3(Al+MA), Al+ nano Al_2O_3(Al+NA), Al+Ti+micro Al_2O_3(Al+Ti+MA), Al+Ti+nano Al_2O_3(Al+Ti+NA). The microstructure result show that the nano-sized Al_2O_3 particles mix well with the composites and exhibits grain refinement. The study result show that the hybrid composites provide a better properties(hardness, wear resistance, corrosion resistance) compare with composites that reinforced by one material and the nano-sized reinforced hybrid composites show a superior properties to the micro-sized reinforced hybrid composites.

2.3.3 Review Table for MMCs

Table 2.10: Literature Review of MMCs

Author Name	Titles of Paper	Outcome
Taya & Arsenault, 1989	Metal Matrix Composites: Thermomechanical Behaviour	Aluminum alloys is the most popular matrix for use in MMCs because of it lower cost compared to other light metals such as Magnesium and titanium.
Silva et al., 2013	Study of the SCC Behavior of 7075 Aluminium Alloy After One-Step Aging at 163 °	Aluminum alloy is used in aeronautic application because the properties of high ultimate and yield strength.
Rino et al., 2012	An Overview on Development of Aluminium Metal Matrix Composites with Hybrid Reinforcement.	Aluminum alloy is a better material that exhibit low density, better wear resistance, good corrosion resistance, excellent mechanical properties and low thermal coefficient of expansion

		compared with other conventional alloys and metals. This alloy can be fabricate with a low cost and can be used in wide range of applications such as aerospace and automobile.
Suresha & Sridhara, 2010	Effect of Addition of Graphite Particulate on Wear Behavior in Aluminium-Silicon Carbide-Graphite Composite	The wear resistance of hybrid composites is improved with the adding of 3%, 7.5% and 10% of graphite particulates as compared to the Al-SiC composites.
James et al., 2014	Hybrid Aluminium Metal Matrix Composite Reinforced with SiC and TiB_2	The reinforcements SiC provide the properties of low cost, thermal performance, good machinability and it is chemically compatible with aluminium. Addition of TiB_2 reduce the tensile strength of composite by 50-60% but increased the wear resistance of composite.
Bodunrin et al., 2015	Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics	The properties of specific stiffness and strength is improved at the cost of decreases ductility and fracture toughness in AMCs that reinforced with SiC or Al_2O_3. The use of two or more synthetic reinforcing particulates is necessary for property optimization. Graphite and Boron carbide are usually used with SiC or Al_2O_3 for performance optimization of AMCs. The ductility and fracture toughness is

		improved when nano-particulates are used as reinforcing materials without the significant drop in strength.
Lei et al., 2014	Thermal Expansion of Al Matrix Composites Reinforced with Hybrid Micro-/nano-sized Al2O3 Particles	Nanometer sized reinforcement done a better job in utilizing the properties of Al based hybrid composites. The hardness and thermal expansion is higher when a higher weight percentage of nanometer sized reinforcement aluminium oxide is added compared with the same weight percentage of micrometer sized reinforcement added.
Mohapatra, 2013	Processing , Microstructure and Properties of Hybrid Metallic and Ceramic Reinforced Aluminium Composites	The study result show that the hybrid composites provide a better properties(hardness, wear resistance, corrosion resistance) compare with composites that reinforced by one material and the nano-sized reinforced hybrid composites show a superior properties to the micro-sized reinforced hybrid composites.

2.3.4 Potential of Aluminium alloy + Nano-sized SiC + Micro-sized Graphite as Brake Disc Materials

Hybrid MMCs are chosen as the materials for the brake disc since it show a superior properties compared to composites that only reinforced by one materials.

Aluminum alloy was chosen as the matrix materials since it is a better material that exhibit low density, better wear resistance, good corrosion resistance, excellent mechanical properties and low thermal coefficient of expansion compared with other conventional alloys and metals. This alloy can be fabricate with a low cost and can be used in wide range of applications such as aerospace and automobile.

The use of two or more reinforcement materials is necessary for property optimization. Silicon Carbide and graphite was chosen as the reinforcement materials because the properties of silicon carbide and graphite are suited for the application of brake disc. Silicon carbide are mostly utilized compared to other synthetic reinforcing particulates. The reinforcements SiC provide the properties of excellent thermal conductivity, high hardness, high tensile strength, good workability and low cost and it is chemically compatible with aluminium but lower ductility and fracture toughness. Graphite are usually used with SiC for performance optimization of AMCs. Gr provide solid lubricant effect and excellent properties of wear resistance.

One of the reinforcement materials was in nano-sized because the this size of reinforcement materials utilize the properties of the composites. The properties of base material are enhanced by the nano-particles in terms of mechanical strength, wear resistance, and damping properties. The ductility and fracture toughness is improved when nano-particles are used as reinforcing materials without the significant drop in strength and this solve the problems of disadvantages that bring by the silicon carbide. Ductility and fracture toughness are important for avoiding failures under in-service stress or shock load applications.

2.4 MULTIPLE CRITERIA DECISION MAKING IN DESIGN SELECTION

2.4.1 Quality Function Deployment(QFD)

Quality Function Deployment is an approach that translate customer requirements into design quality and technical requirements for each stages of the product development process. QFD sometimes also refer to voice of customer(VOC) (Childs, 2013). The figure 2.12 show the four phases in QFD.

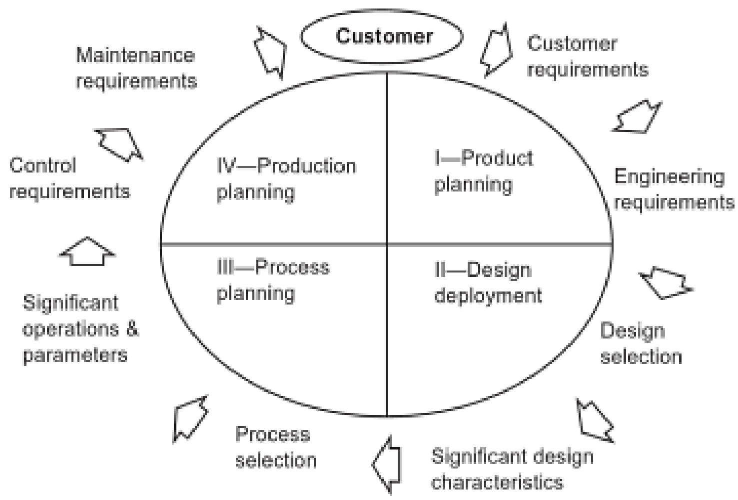


Figure 2.12: QFD phases

Source: Childs (2013)

Table 2.11: Activities included in phases of QFD

QFD phase	Activity
QFD1/Phase I Product planning	Listen to and capture the *voice of the customer*. Interpret the customer's requirements. Translate into engineering requirements. Document in a product design specification using a QFD template.
QFD2/Phase II Design deployment	Develop and select designs. Identify significant design characteristics (the specific assemblies, subassemblies, parts, dimensions, properties, and attributes of the designs considered that directly relate to achievement of customer requirements). Demonstrate that the design fulfills the requirements of the PDS (by applying the appropriate verification plan, appropriate calculations, simulations, tests, etc.).
QFD3/Phase III Process planning	Develop and select manufacturing processes. Identify significant process operations and parameters (the specific operations, e.g. critical assembly steps, and parameters, e.g. feed rates, and material temperatures that directly relate to achievement of significant design characteristics).
QFD4/Phase IV Production planning	Implement the manufacturing processes of phase III in the production environment (i.e. design, build, install, and prove out the required tooling, machinery, fixtures, jigs, and inspection equipment for the selected manufacturing processes). Develop the control requirements (i.e. the factors that should be inspected and monitored, in order to adequately control the significant process operations and parameters). Maintenance requirements (i.e. prepare the maintenance regime for tooling, machinery, etc. to deliver appropriate availability and function).

Source: Childs (2013)

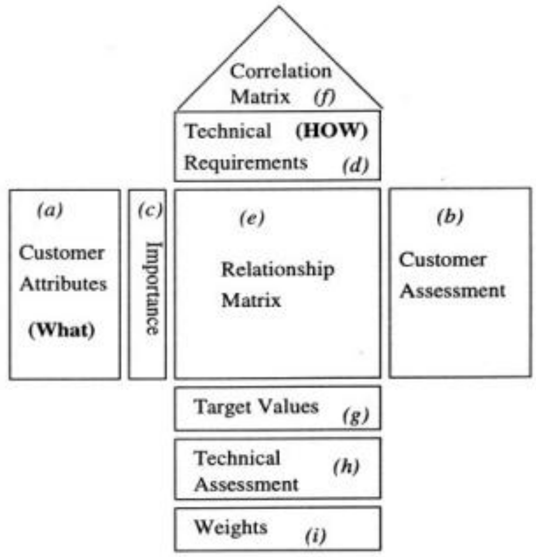


Figure 2.13: House of Quality

Source: Ling (2008)

(Ling, 2008) study about the quality function deployment(QFD) methodology in product development. In this study, a product, clothes horse were analyzed using QFD and a better design is proposed. Voice of customer are gathered by using questionnaire and house of quality is built based on the result and analysis of the questionnaire. From the house of quality, three new design of clothes horse are proposed. Using concept scoring and screening, the best design is selected among the three designs.

(Karimi et al., 2012) research work using the combined QFD-TOPSIS method in the Sum Service company. Sum Service company is an exclusive agent in Iranian Samsung products. This study used QFD to identifies relationship between customer requirements and product design and production. Customer needs and relative importance of individual needs of customer needs is identified and the degree of correlation of customer requirements and technical features is measured using QFD.

(Khangura & Gandhi, 2012) apply the method of QFD in the design of a refrigerator. The most important functions and criteria in the view of customers and technical characteristic is identified using QFD. House of quality are built based on those important parameters. In this study, there are seven important parameters are obtained for the design of refrigerator. A refrigerator design that are able to fulfill the customer requirements will get by improving and utilizing these seven most important parameters.

2.4.1.1 Review Table for QFD

Table 2.12: Literature Review of QFD

Author Name	Titles of Paper	Outcome
Ling, 2008	Product Development Using QFD Methodology	Study about the quality function deployment(QFD) methodology in product development. Clothes horse were analyzed using QFD and a better design is proposed.
Karimi et al., 2012	Applying a hybrid QFD-TOPSIS method to design product in the industry (case study in sum service company)	This study used QFD to identifies relationship between customer requirements and product design and production. Customer needs and relative importance of individual needs of customer needs is identified and the degree of correlation of customer requirements and technical features is

		measured using QFD.
Khangura & Gandhi, 2012	Design and Development of the Refrigerator with Quality Function Deployment Concept	The most important functions and criteria in the view of customers and technical characteristic of refrigerator is identified using QFD. House of quality are built based on those important parameters. A improved refrigerator design can be obtained by improving and utilizing these seven most important parameters.

2.4.2 Finite Element Analysis(FEA)

FEA consists of a computer model of a material or design that is focused and analyzed for specific results. It is used in design of new product and modifying of existing product. Modifying an existing product is to utilized the product or structure for a new service condition(Kumar & Sabarish, 2014). It is mostly used to solve problems in the following areas: structural strength design, thermal analysis, vibration and crash simulations(Gupta et al., 2014).

2.4.2.1 ANSYS

ANSYS is a finite element analysis (FEA) software and generally apply in the design and optimization of a system that are too complicated to be solved by hand. Complicated problems can be solved in a efficient and faster way with finite element analysis by dividing them into smaller pieces called elements. This software executes equations that manage the characteristics of these elements and solves them, by creating a detailed explanation of how the system acts as a whole. The results are presented in graphical or tabulated forms(Parab et al., 2014).

(Parab et al., 2014) research work using ANSYS in assisting the design of brake disc. The purpose of ANSYS software in this paper is for structural and thermal analysis of brake disc that made of three different materials which are cast iron, stainless steel and carbon carbon composite. The ANSYS software results show the comparison of properties of total deformation, equivalent stress and temperature distribution between these three brake disc that made of different materials.

Table 2.13: Comparison of properties shown by using ANSYS

Results	**Cast iron**		**Stainless steel**		**Carbon carbon composite**	
	max	Min	Max	min	max	min
Total deformation(M)	1.8974e-10	0	1.0738e-10	0	2.1513e-10	0
Equivalent stress(Pa)	109.48	1.0818	115.86	1.068	114.93	1.769
Temperature distribution(˚c)	473.23	280	469.54	272.92	470.12	280

Source: Parab et al. (2014)

(Gupta et al., 2014) study the structural analysis of brake disc of BAJA SAE 2013 car by using ANSYS 13.0 software. The brake disc are made of grey cast iron. This study is to analyze the stability and rigidity of brake disc and obtain the best combination of flange width, wall thickness, and material composition in term of properties of total deformation, Von Misses stress and Hoop stress. It is necessary that the maximum value of Von Misses stress induced in the material is less than the strength of the material.

(Balasubramanyam & Prasanthi, 2014) investigated the design and analysis of brake disc for a two wheeler. Thermal analysis and structural analysis of brake disc that made of three different materials are carried out by using ANSYS 10.0 software. Comparison of properties such as deflection, Von Misses stress, total heat flux, normal stress and maximum temperature that obtained from the result of analysis concluded that grey cast iron is the best possible material for the brake disc of two wheeler.

Table 2.14: Comparison results of three different materials obtained from ANSYS

Material	Deflection mm	Normal Stress in x direction MPa	Total heat flux w/mm^2	Max temperature ^{0}c	Von Mises stress MPa
Grey cast iron (material 1)	0.35193	5.9059	0.80704	486.76	50.334
AL-MMC (material 2)	0.35229	64.812	4.3053e^{-002}	29.232	211.98
AL-MMC (material 3)	0.36648	66.345	6.1466e^{-002}	30.307	586.7

Source: Balasubramanyam & Prasanthi (2014)

(Praveena et al., 2014) carried out the research work in modeling and structural analysis of brake disc by using CATIA and ANSYS software. The modeling of brake disc made of four different materials is done by using CATIA and imported to ANSYS for stress and structural analysis. Material properties are compared with the stress values of the four materials obtained from the stress analysis. The result show that aluminium has the lowest stress value and a low stress material is preferred for the application of brake disc.

(Radhakrishnan et al., 2015) study about the design and optimization of ventilated brake disc in heat dissipation. The modeling is done by using SOLIDWORKS and ANSYS is used to carry out the analysis of thermal and structural. There are three different design of holes of brake disc: rectangular, square and hexagon profiles. The best design is selected based on properties of temperature distribution, deformation and Von Misses stress. The result show that square profile of hole of brake disc has the best performance in heat dissipation.

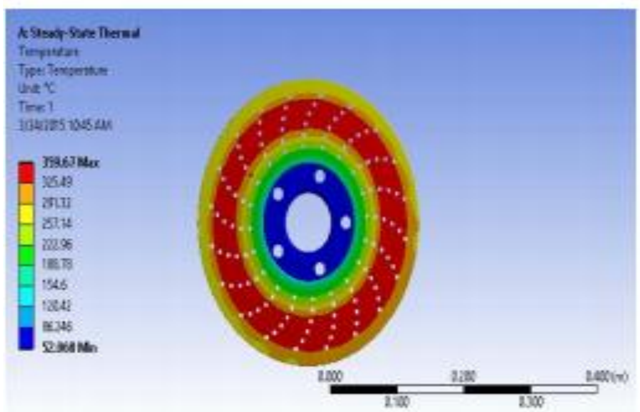


Figure 2.14: Thermal analysis of circular profile

Source: Radhakrishnan et al. (2015)

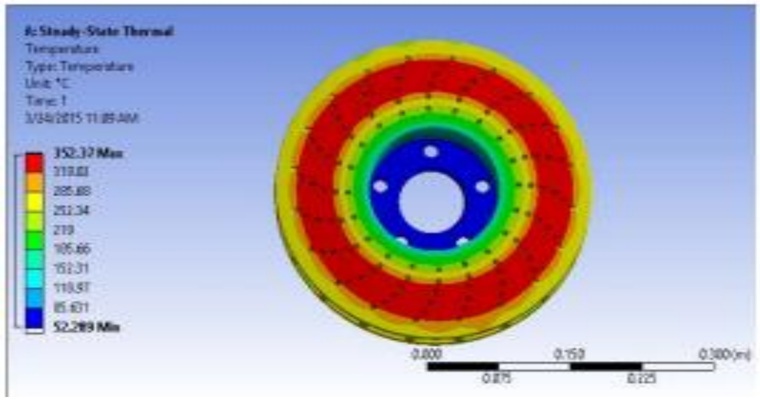


Figure 2.15: Thermal analysis of square profile

Source: Radhakrishnan et al. (2015)

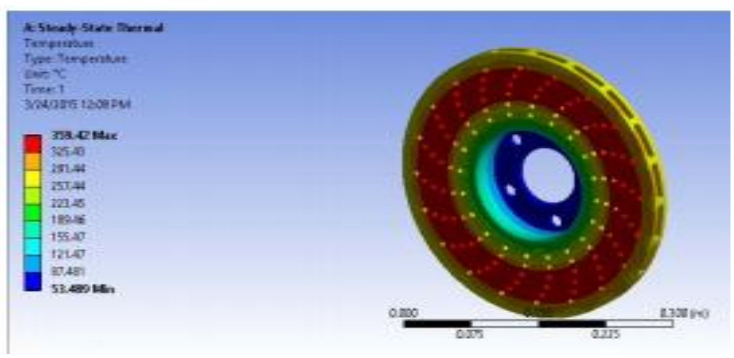


Figure 2.16: Thermal analysis of hexagon profile

Source: Radhakrishnan et al. (2015)

2.4.2.2 Review for FEA

Table 2.15: Literature Review of FEA

Author Name	Titles of Paper	Outcome
Parab et al., 2014	Structural and thermal analysis of brake disc	The ANSYS software results show the comparison of properties of total deformation, equivalent stress and temperature distribution between three brake disc that made of different materials.
Gupta et al., 2014	Thermal Analysis Of Rotor Disc Of Disc Brake Of Baja Sae 2013 Car Through Finite Element Analysis	Analyze the stability and rigidity of brake disc and obtain the best combination of flange width, wall thickness, and material composition in term of properties of total deformation, Von Misses stress and Hoop stress by using ANSYS.
Balasubramanyam & Prasanthi, 2014	Design and Analysis of Disc Brake Rotor for a Two Wheeler	Thermal analysis and structural analysis of brake disc that made of three different materials are carried out by using ANSYS 10.0 software.

2.4.3 Analytic Hierarchy Process

AHP is a commonly used method in an industry that assist in selecting the best multi-criteria alternatives. It used weighted scoring process to assist the decision making by organize priorities. This method has been used mainly in evaluation and selection problems in the area of personal, social categories or engineering. AHP obtain precise ratio scale priorities by using pairwise comparison. The pair-wise comparisons for each level with respect to the goal of the best alternative selection is carried out with a nine-point scale.(Rosli et al., 2013; Azeez et al., 2013).

(Rosli et al., 2013) investigate the strengths of method of Theory of Inventive Problem Solving(TRIZ) and analytical hierarchy process. TRIZ is a method to generate idea of improve a design while AHP is a decision making tool among a few alternatives. In this paper, there are 5 new proposed compartment designs generated by TRIZ and the best design is selected based on the result from Expert Choice software which is an AHP software.

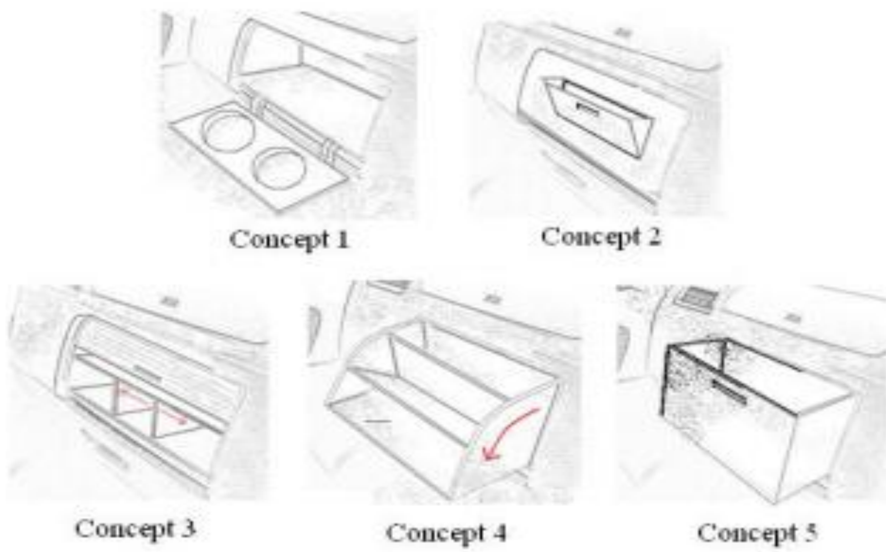


Figure 2.17: Alternatives design of compartment

Source: Rosli et al. (2013)

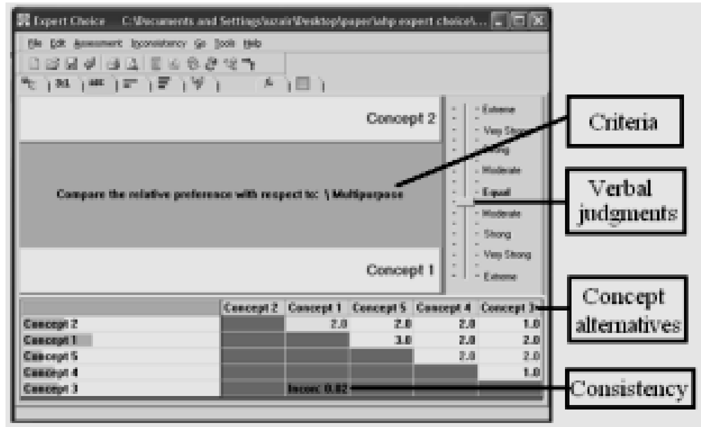


Figure 2.18: Pair-wise comparison with respect to the sub-criteria

Source: Rosli et al. (2013)

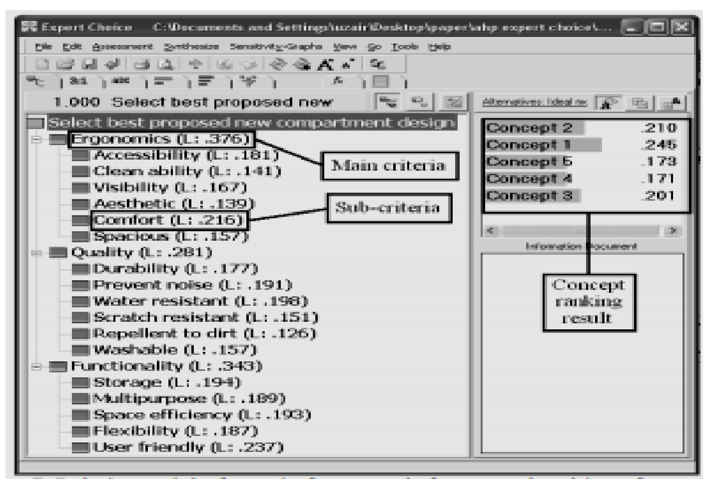


Figure 2.19: Relative weight for main factors, sub-factors and ranking of concept alternatives

Source: Rosli et al. (2013)

(Kalashetty et al., 2012) using AHP to select the best design concept of sprayer among three alternatives. Three different design concept of sprayer are generated and the criteria and sub-criteria are determined. Then a modeling of hierarchy consist the goal, the criteria, sub-criteria and alternatives is done. The priorities are organized among the elements through the series of judgments based on pairwise comparisons of the elements. Synthesize of judgments to give a set of overall priority of the hierarchy. Next, a consistency analysis of the judments is carried out. The best design concept is selected based on the results of the process.

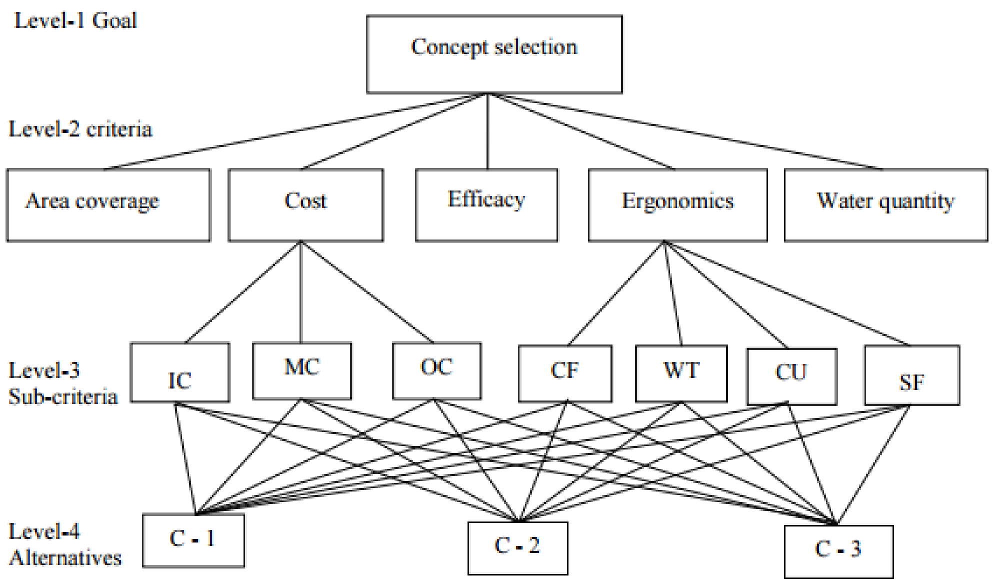


Figure 2.20: AHP hierarchy for design concept selection

Souce: Kalashetty et al. (2012)

(Mansor et al., 2014) research work using analytical hierarchy process select the best design concept of kenaf fiber polymer composites automotive parking brake lever. Five design concept of automotive parking brake lever were generated and modeled into 3-dimensional computer aided design by using CATIA. The best design concept are selected based on the result of process of AHP.

(Hambali et al., 2009) apply the method of AHP in design concept selection of automotive composite bumper beam. There are 8 design concepts of automotive bumper beam as the candidates and the design requirement and factors are determined. The best and the most appropriate design concept are selected based on the results of AHP which provide a clear criteria and priority of the design selection.

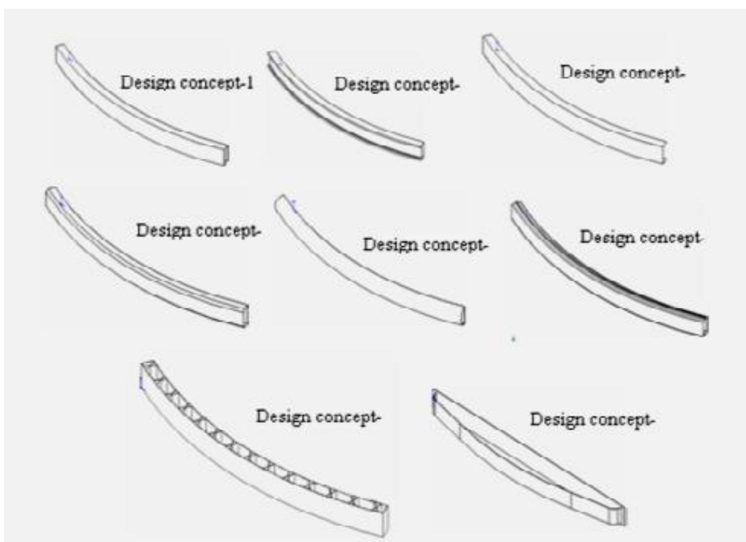


Figure 2.21: Design options of bumper beam

Source: Hambali et al. (2009)

(Laemlaksakul & Bangsarantrip, 2008) investigated the design selection of bamboo chair using AHP method. The software that used is Expert Choice software. There are 3 design of bamboo chair proposed and a decision hierarchy is built. Weight criteria analysis is done by using the software and the best design is selected based on the results of the software.

Figure 2.22: Three design concept of bamboo chair

Source: Laemlaksakul & Bangsarantrip (2008)

Table 2.16: Results of weight for main criteria analysis

Design No.	Function 0.248	Material 0.024	Construction 0.417	Ergonomics 0.129	Process 0.030	Economy 0.055	Aesthetic 0.096	Total
1	0.203	0.014	0.290	0.053	0.020	0.007	0.013	0.600
2	0.023	0.002	0.031	0.037	0.008	0.005	0.074	0.180
3	0.023	0.009	0.096	0.039	0.002	0.042	0.008	0.219

Source: Laemlaksakul & Bangsarantrip (2008)

Table 2.17: Results of ergonomics weight for sub-criteria analysis

Design No.	Lumbar Support	Backrest Angle	Seat Height	Width/Depth	Armrest	Seat Angle	Total
	0.011	0.016	0.047	0.023	0.023	0.011	
1	0.003	0.007	0.016	0.017	0.008	0.004	0.053
2	0.001	0.007	0.016	0.002	0.008	0.004	0.037
3	0.008	0.002	0.016	0.003	0.008	0.004	0.039

Source: Laemlaksakul & Bangsarantrip (2008)

2.4.3.1 Review Table for AHP

Table 2.18: Literature Review of AHP

Author Name	Titles of Paper	Outcome
Rosli et al., 2013	Integrating TRIZ and AHP: A MPV"s Utility Compartment Improvement Design Concepts	In this paper, there are 5 new proposed compartment designs generated by TRIZ and the best design is selected based on the result from Expert Choice software which is an AHP software.
Kalashetty et al., 2012	Selection of Design Concept : A case study	Use AHP to chose the best design concept of sprayer among three alternatives.
Hambali et al., 2009	Application of AHP in the design concept selection of automotive	Apply the method of AHP in 8 design concept selection of automotive composite bumper beam. The best and the

	composite bumper beam during the conceptual design stage.	most appropriate design concept are selected based on the results of AHP.

CHAPTER 3

METHODOLOGY

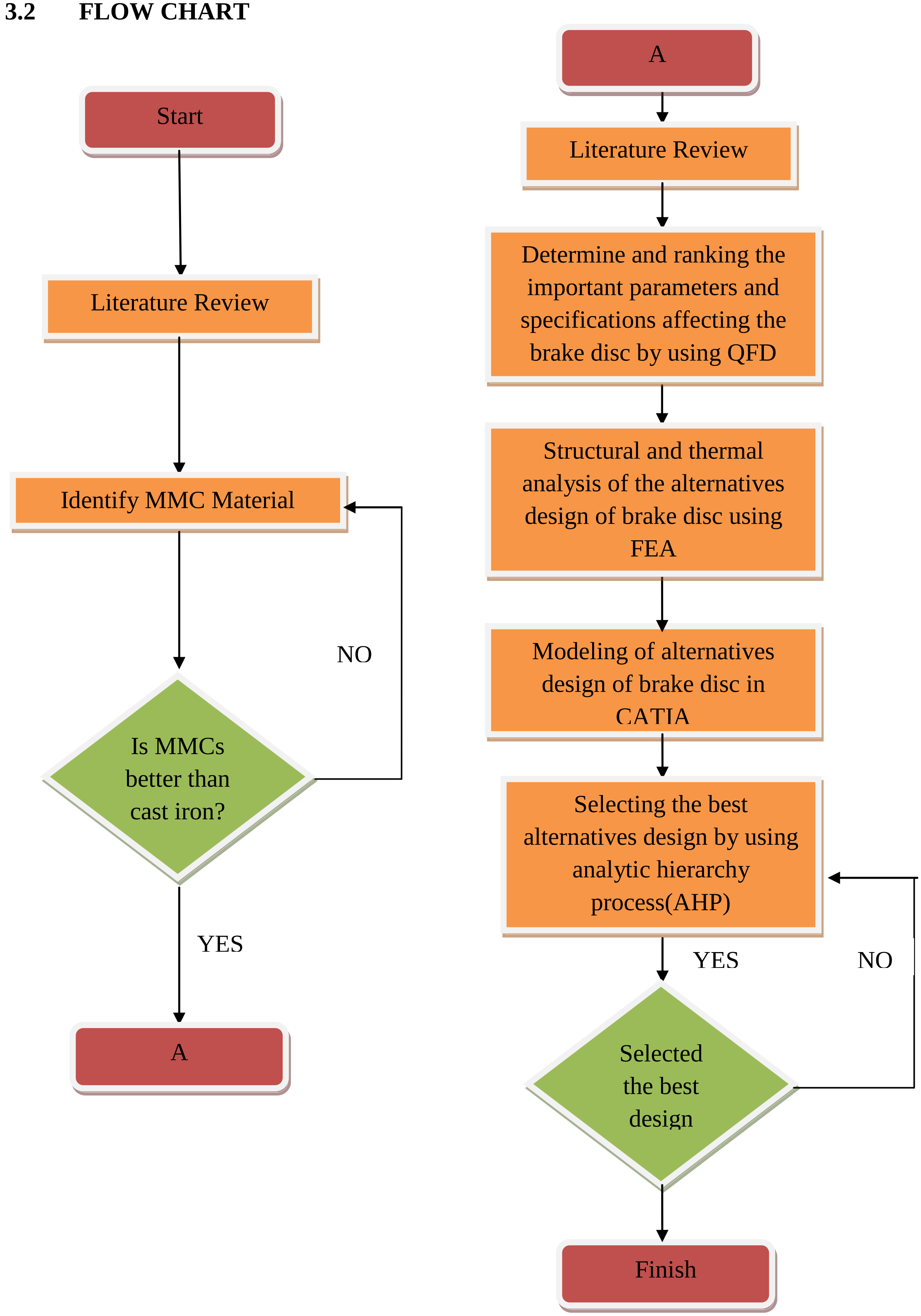
3.1 INTRODUCTION

In this chapter, we will discuss on how to complete the project by modeling the design of brake disc, analysis of the alternatives design and decision making. This chapter will give an rough idea on how the process of design selection is carried out and every process in this project will be clearly defined.

To complete this project, suitable methodology should be selected to assist and monitor the processes during the project to ensure the goal and objectives are achieved. The suitable material that identified from the literature review of MMCs materials is Al+SiC+Gr. There are few methods used in this project which are three-dimensional computer aided design(3D CAD), quality function deployment(QFD), finite element analysis(FEA) and analytic hierarchy process(AHP).

First of all, the most important parameters and specifications that affecting the design of the brake disc are determined from QFD that. Then, six alternatives design of brake disc are proposed and modeled into CATIA. The model of brake disc are then imported to ANSYS software for structural and thermal analysis. Finally, a decision making tool, AHP is used to chose the best design among the six alternatives design of brake disc.

3.2 FLOW CHART



3.3 METHODOLOGY

3.3.1 Quality Function Deployment

Quality Function Deployment is an approach that translate customer requirements into design quality and technical requirements for each stages of the product development process. QFD sometimes also refer to voice of customer(VOC). In this project, QFD are used to determine and rank the important parameters of brake disc. There are six basic elements of QFD, which are :

1. Identify the customer needs(HOQ what).
2. Fulfill the customer needs.
3. Establish relationship among the requirements and how to achieved them(HOQ how).
4. Target values of requirements.
5. Met the relationship between the requirements.
6. Quantification and ranking of the importance of the requirements.

Figure 3.1 show the four phases of QFD.

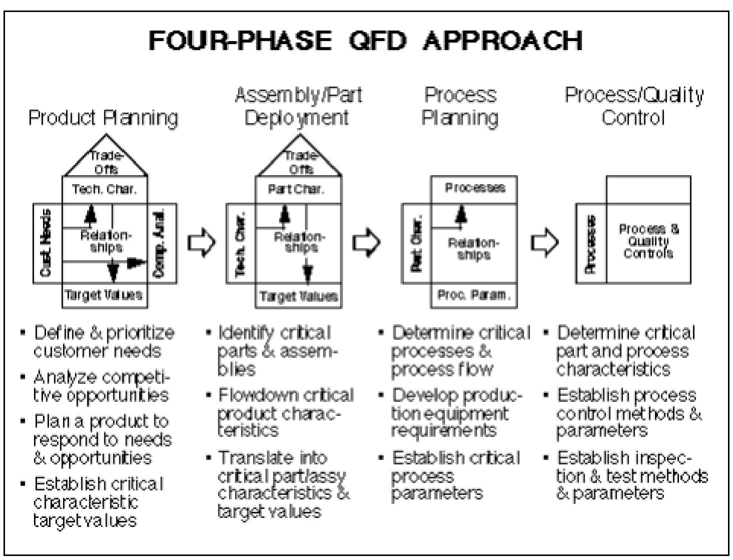


Figure 3.1: Phases of QFD

3.3.1.1 House of Quality

This project will only do the first phase product planning which is also known as house of quality. House of Quality is a matrices of an iterative process. The purpose of is to reflect customers' desires, taste or requirements. It provides a framework in which all participants can communicate their thought about a product. It is used to identify the relationships between customer requirements based on different viewpoint.

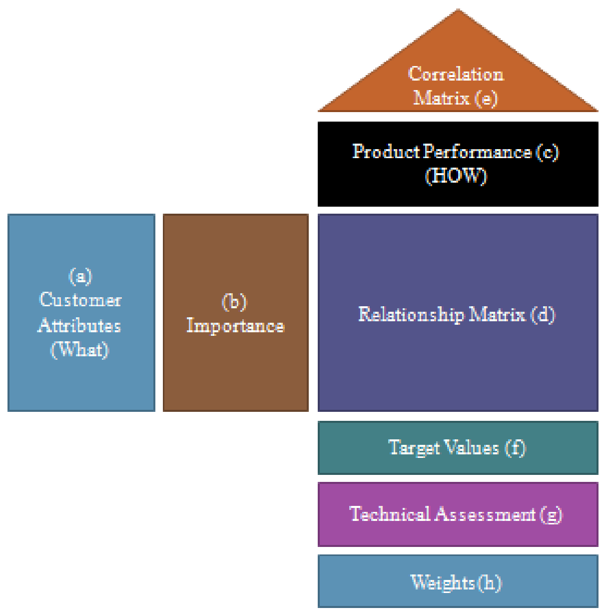


Figure 3.2: House of Quality

Step 1(HOQ what): Identify the customer requirements or customer attributes(CA). Customer attributes are the desired customer needs in a product or service and this is the "what", area (a) of the HoQ. The priorities or importance of these CA are indicated in the area (b). These priorities are determined based on user's direct experience and knowledge with about the product.

Step 2(HoQ how): Measureable technical requirements(TR) are indicated as the “how” of the HoQ. These technical requirements are identified by the user and presented on the area (c) on the matrix diagram.

Step 3: Establish the relationship matrix in area (d). The user determine the relationship and impacts between the CAs and TRs. The symbols used to represent relationships are not standardized, it can be strong or weak, positive or negative.

Step 4: Establish correlation matrix in area(e) which the relationships between the physical and technical requirements are shown on an array that also known as “the roof matrix”.

Step 5: Identify and ranking the technical assessment or difficulty and present on area(g). The target value for the technical requirements(f) are determined by the consideration of the link between the CAs, TRs, and customer assessments.

Step 6: The weights of the TRs in area (h) located at the base of the quality matrix. It is the main outcome of the HOQ, and are calculated by equation (3.1):

$$\text{Weight}(TR)_i = V(TR)_{i1} \times \text{Imp}(CA_1) + V(TR)_{i2} \times \text{Imp}(CA_2) + \ldots + V(TR)_{in} \times \text{Imp}(CA_n) \quad (3.1)$$

where $V(TR)_{in}$ is the correlation value of TR_i with CA_n, and $\text{Imp}(CA_n)$ represents the priority of CA_n .

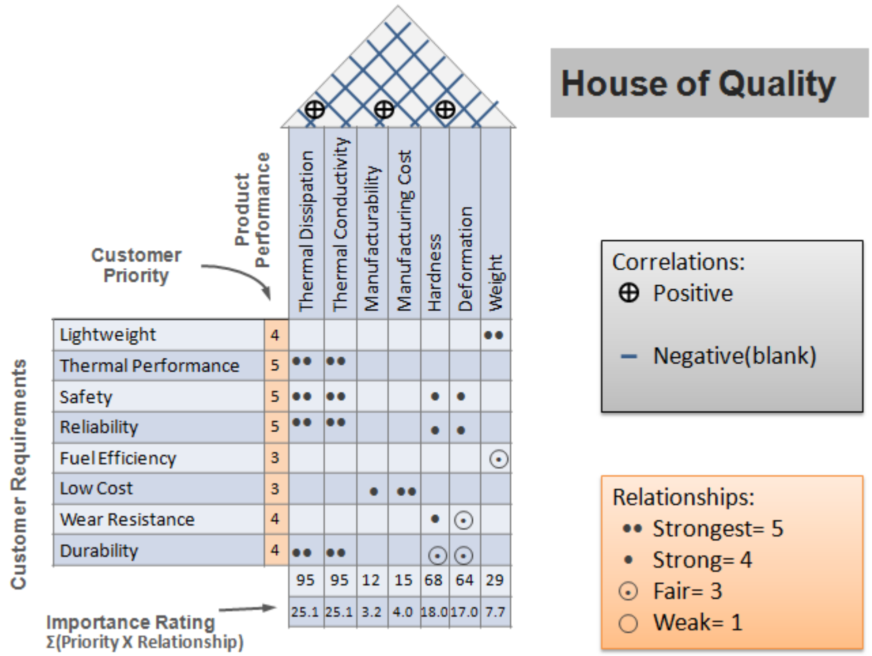


Figure 3.3: House of Quality of Brake Disc

3.3.2 Modeling Software

CATIA(Computer Aided Three-Dimensional Interactive Application) V5 is a three dimensional computer aided design software that used as the modeling tool in this project.

3.3.2.1 CATIA V5

The CATIA V5 is a 3D parametric solid modeler with the abilities of modeled part and assembly. Pieces of model part can be draw in separately and then combined into a complex assemblies. Part is designed by sketching its components shapes and defining their dimension and inter relationships. The shape and dimension of the model part can be modified easily when a wrong dimension is found on the drawing. A parts that include mixture of curved and angular features can be drawn. Six alternatives design of brake disc are designed in this software based on the output obtained from QFD.

3.3.2.2 Modeling Process

The modeling process of CATIA is as follow:

1. Determined the dimension and characteristic
2. Model the base feature
3. Establish the remaining features
4. Analyze and revised the part
5. Modify the part if necessary

3.3.2.3 Designs of Brake Disc

There are six alternatives design of brake disc are proposed including the original design of cast iron brake disc. The alternatives design are model by modifying the original brake disc design. The figure 3.4 show the original brake disc design.

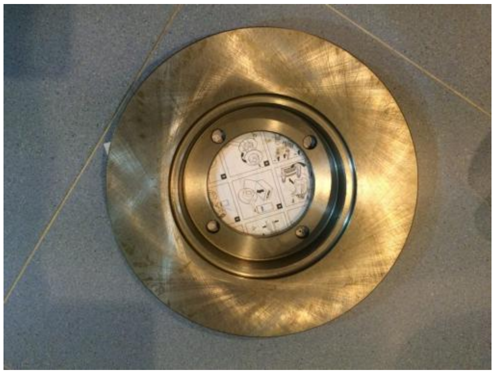


Figure 3.4: Original brake disc

There are six alternatives design of brake disc are proposed including the original design of cast iron brake disc. The alternatives design are model by modifying the original brake disc design. Holes, slots and vanes are added to the design for the purpose of improve thermal performance. Holes are added to improve the heat dissipation while slots and vanes are added to create a path for better air circulation to increase the heat transfer rate (Udayakumar & Ponnusamy, 2014; Duzgun, 2012). Although the material and the manufacturing cost is higher in complex design, but it can be compensated by the high fuel usage efficiency, high performance and a longer lifetime. The thickness of brake disc that are made of MMCs are calculated by using the equation (3.2):

$$t_b = \left[\frac{E_a {t_a}^3}{E_b}\right]^{\frac{1}{3}} \tag{3.2}$$

where, t_a is the thickness of cast iron brake disc and t_b is the thickness of MMCs brake disc, E_a and E_b are the modulus of elasticity of cast iron brake disc and MMCs brake disc respectively. The diameter of the six design are remains the same for MMCs brake disc.

The elastic modulus, density, poisson's ratio, ultimate tensile strength thermal conductivity and thermal expansion coefficient are calculated by equation (3.3) based on the rule of mixture (Debnath et al., 2012; Prasad et al., 2014; Krishna et al., 2016):

$$x_{hybrid} = x_1 v_1 + x_2 v_2 + x_3 v_3 \tag{3.3}$$

where x_{hybrid} is the elastic modulus, density, poisson's ratio, hardness, ultimate tensile strength, thermal conductivity and thermal expansion coefficient of hybrid composites; x_1, x_2, x_3 are the elastic modulus, density, poisson's ratio, hardness, ultimate tensile strength, thermal conductivity and thermal expansion coefficient of aluminium alloy, SiC and graphite respectively; v_1, v_2, v_3 are the volume fraction of aluminium alloy, SiC and graphite respectively.

Table 3.1: Property of individual material that composed to become the hybrid MMCs

Property	Al Alloy(87%)	SiC(10%)	Gr(3%)	AlSiCGr
Elastic Modulus(GPa)	69.9	400	20	101.4
Density(g/cm^3)	2.70	3.10	2.49	2.73
Poisson's Ratio	0.33	0.14	0.23	0.31
Hardness(MPa)	340	26250	326	2931
Ultimate Tensile Strength(MPa)	310	336	76	306
Thermal Conductivity(W/mK)	167	120	114	161
Thermal Expansion C(/K)	2.34^10^{-6}	4.0x10^{-6}	5.2x10^{-6}	2.6^10^{-6}

Example Calculation

Elastic Modulus = (0.87 x 68.9) GPa + (0.1 x 400) GPa + (0.03 x 15) GPa

= 101.4 GPa

Density = (0.87 x 2.70) g/cm^3 + (0.10 x 3.10) g/cm^3 + (0.03 x 2.49) g/cm^3

= 2.73 g/cm^3

Table 3.2: Properties of Cast Iron and Aluminium Alloy

Property	AlSiCGr	Cast Iron	Units
Elastic Modulus	101.4	100	GPa
Density	2730	7200	kg/m^3
Poisson's Ratio	0.31	0.27	
Hardness	2931	2040	MPa
Ultimate Tensile Strength	306	250	MPa
Thermal conductivity	161	54	W/m.K
Thermal Expansion Coefficient	2.6^10^{-6}	1.2^10^{-5}	/K

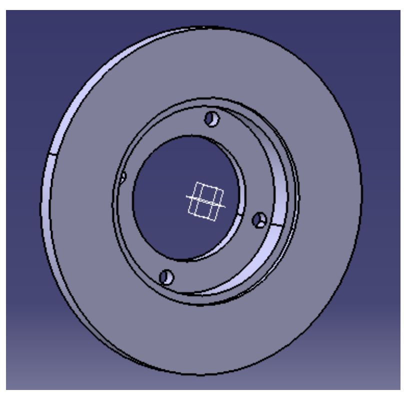


Figure 3.5: Alternative design 1

Alternative design 1 is the original design of the current brake disc and it is made of cast iron. Other alternatives design are modified from the current design and made from AlSiCGr.

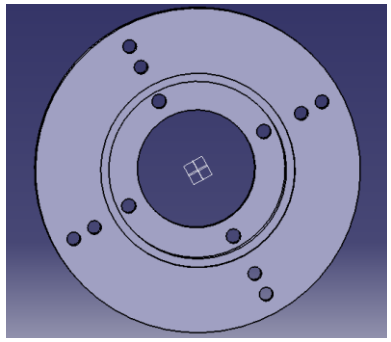


Figure 3.6: Alternative design 2

8 holes are added to the surface of brake disc in alternative design 2. The holes added are expected to improve thermal performance and heat dissipation of the brake disc.

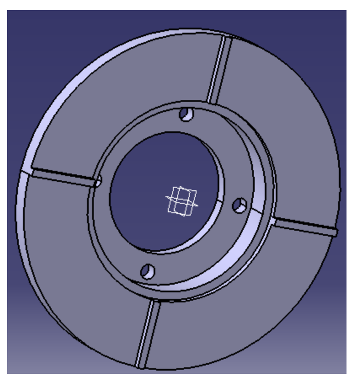


Figure 3.7: Alternative design 3

In alternative design 3, 4 slots are added on the surface of the brake disc. These slots are expected to improve the heat performance by creating a path for better air circulation to increase the heat transfer rate.

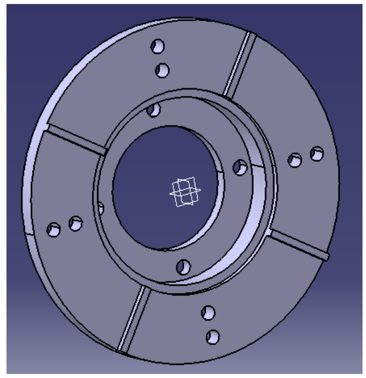


Figure 3.8: Alternative design 4

In alternative design 4, slots and holes are added to the brake disc. This design has the advantages of combination of both the holes and slots.

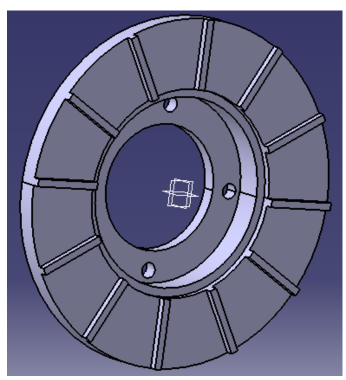


Figure 3.9: Alternative design 5

The number of slots are tripled which is 12 compared to alternative design 3. This design are expected to dissipate heat more efficient and faster since there are more air path created for the air circulation on the surface of brake disc.

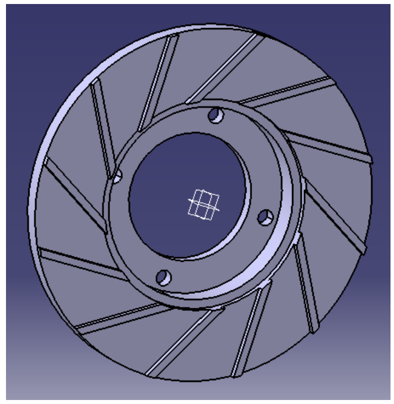


Figure 3.10: Alternative design 6

For this design, the number of slots are remain the same as alternative design 5 but angle are added to this slot. The angle of a slot is related with airflow. The slot should have the smallest angle possible with respect to the direction of airflow to enhance the airflow and centrifugal forces moving air in and out of the slot (Callahan et al., 2004; Carley, 2006). This 30° angled slot will increase the area of air contact with the brake disc and allowing more heat transfer from the brake disc to the surrounding.

3.3.3 Finite Element Analysis

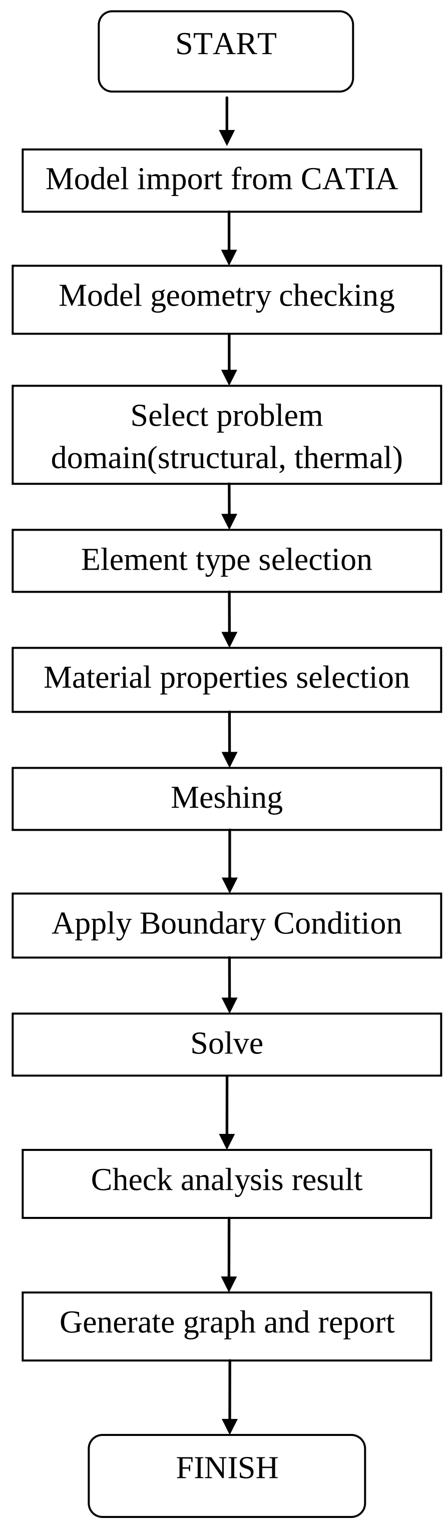
FEA included a computer model of a material or design that is focused and analyzed for specific results. It is apply in the design of a new product or modifying of existing product. It is mostly used to solve problems in the following areas: structural strength design, thermal analysis, vibration and crash simulations. In this project, ANSYS software is used to implement the finite element analysis.

3.3.3.1 ANSYS

After the modeling in CATIA, the model is save in IGES file format and imported into ANSYS. ANSYS is a finite element analysis software and generally apply in the design and optimization of a system that are too complicated to be solved by hand. Complicated problems can be solved in a efficient and faster way with finite element analysis by dividing them into smaller pieces called elements. This software executes equations that manage the characteristics of these elements and solves them, by creating a detailed explanation of how the system acts as a whole. The results are presented in graphical or tabulated forms. It involved interaction of three stages of activity:

- Preprocessing - Involves the preparation of finite element data such as nodal coordinates, element connectivity, boundary conditions, loading and material information.
- Solution - In this phase, matrices that describe the behavior of each element are generated and assembled. Unknown values of primary field variables such as displacement, temperature and additional derived variables such as reaction forces and stresses heat flow can be computed by back substitution of the primary field variables.
- Postprocessing - Review and presentation of the results. Typically, the deformed configuration, mode shapes, temperature & stress distribution are computed & displayed at this stage.

3.3.3.2 Flow Chart of ANSYS



3.3.4 Analytic Hierarchy Process

AHP is a commonly used method in an industry that assist in selecting the best multi-criteria alternatives. It used weighted scoring process to assist the decision making by organize priorities. This method has been used mainly in evaluation and selection problems in the area of personal, social categories or engineering. AHP obtain precise ratio scale priorities by using pair-wise comparison. The pair-wise comparisons for each level with respect to the goal of the best alternative selection is carried out with a nine-point scale.

3.3.4.1 Steps of AHP

Step 1: Develop a hierarchy framework.

All the factors are classified into groups of level. There are 3 levels in the hierarchy. The order of the level are from top to bottom which are from first level goal, criteria level, sub-criteria level to alternatives level. Level 1 stands for the goal of the decision. Level 2 consisting of criteria and sub-criteria. Level 3 stands for alternative.

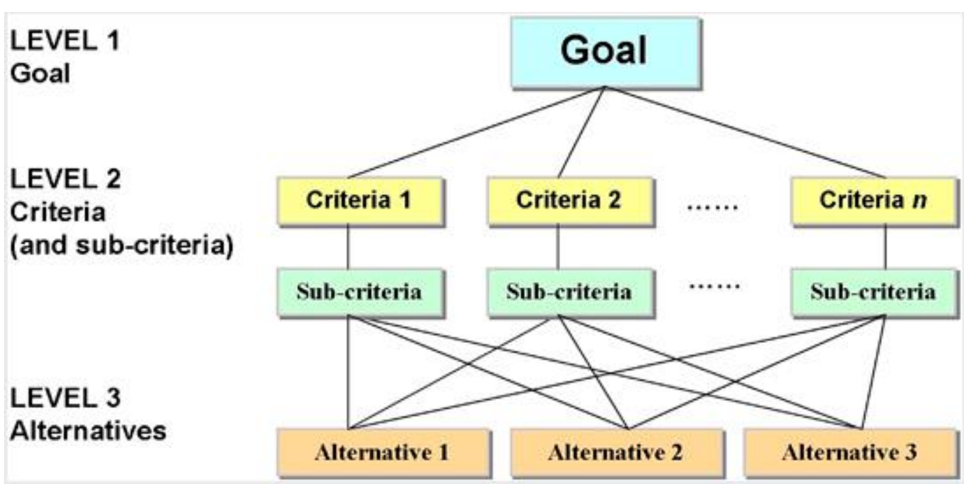


Figure 3.11: Hierarchy process of decision making

Step 2: Construction of pair-wise comparison matrices

The pair-wise comparison matrix presents the relative importance of the factors in the current level with respect to factors in higher level. The number of elements represent the number of matrices at each level while the order of the matrix at each level are depend on the number of elements at the level that it links to. The comparison of each elements made by using the Saaty's relative importance 1-9 point scale and the judgments are done based on the decision makers experience and knowledge. Reciprocals are automatically assigned to each pair-wise comparison.

Table 3.3: Scale for pair-wise comparison

Relative intensity	Definition	Explanation
1	Equal value	Two requirements are of equal value
3	Slightly more value	Experience slightly favours one requirement over another
5	Essential or strong value	Experience strongly favours one requirement over another
7	Very strong value	A requirement is strongly favoured and its dominance is demonstrated in practice
9	Extreme value	The evidence favouring one over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between two adjacent judgments	When compromise is needed
Reciprocals	Reciprocals for inverse comparison	

Step 3: Synthesizing the pair-wise comparison

This step involves assessment of the vectors of priorities and overall priority . The calculation of priorities of the elements start at the lower levels of the hierarchy and next get the overall priority vector. To calculate the vectors of priorities, the average of normalized column (ANC) method is used. This is a process of averaging over the normalized columns. The priorities can be calculated by using the equation (3.4):

$$W_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_i^n a_{ij}}, i,j = 1,2,\dots n \qquad (3.4)$$

a_{ij} = Numerical equivalent of comparison between i and j

n = number of criteria

Step 4: Evaluation of consistency.

Since the comparisons are made through personal or subjective judgments, some degree of inconsistency may be occurred. To guarantee the judgments are consistent, a consistency verification is carried out. The consistency ratio (CR) is used to estimate the consistency of the judgments among the pair-wise comparisons. It is defined as

$$CR = \frac{CI}{CR} \tag{3.5}$$

where CI is the consistency index which is defined as $CI = \frac{\lambda_{max} - n}{n-1}$, where $\boldsymbol{\lambda}_{max}$ represents the maximum or principal eigenvalue of the pair-wise comparison matrix and n represents size of the matrix. The closer λ_{max} is to n the more consistent is the judgment matrix. If the CR is less than 0.1, the judgment matrix is consistent and acceptable. However If CR is greater than 0.1, the judgment matrix is inconsistent. A revised and improvement of the judgments should be carried out to obtain a consistent matrix.

Step 5: Overall priority ranking

A calculation of the overall priority vector to chose the best design concept is carried out when the consistency evaluation is done. The best design concept is selected based on the highest value of priority of the results.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This chapter will present and discuss the results and discussion of the project. The results included the outcomes of House of Quality, simulation of thermal and structural analysis of 6 alternatives design of brake disc in ANSYS and Analytic Hierarchy Process. The flows of the discussion is in the order of House of Quality, ANSYS and Analytic Hierarchy Process.

4.2 HOUSE OF QUALITY

In order to design a brake disc by using HoQ, we need to gather and collect data about the brake disc. The first step of HoQ is collect date or information customer requirements which are also known as VOC. Then, we need to find out the related product performance that are correlated with the customer requirements and grouped them into the HoQ. In this project, the data is collected through the analysis from research journal.

After analyzing and collected sufficient information, the important criteria of brake disc in the view of customer and performance will be listed out and put into HoQ. Next, a ranking of the customer requirements carried out based on their priorities and preference. A scale 1-5 is used to rank the customer requirements. Meanwhile, the correlation between the product performance will be done at the roof matrix. A positive and negative sign are used to show this relationship.

After that, the customer requirements is correlated with product performance and a calculation of importance rating is performed by using the following formula:

$\sum_{i=1}^{n} R_i W_i$ = importance rating

where R = Customer requirements and

W = Product performance.

The highest value of importance rating is the most important criteria that must be focused on in designing a brake disc in order to meet the customer satisfaction.

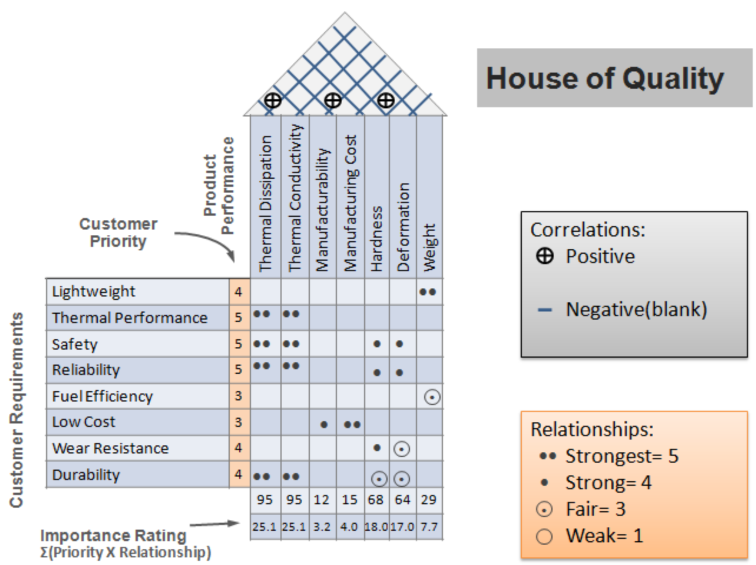


Figure 4.1: Outcome of House of Quality

The outcome of the HoQ show that the most important criteria for the brake disc from the view of customers are thermal performance, safety and reliability which has the same customer priority ranking of 5. Thermal performance is related with the safety and reliability of a brake disc since over-heating of the brake disc will lead to the malfunction of the braking system and affect the safety of vehicle. Moreover, a customer surely will not consider to purchase a product that will put their life in risk. A reliable and safe brake disc are the most important requirements to attract customers.

On the other hand, The most important criteria for brake disc in the view from product performance are the thermal dissipation, thermal conductivity which has the highest score of 21.3 and followed by hardness and deformation. All this four criteria are directly affected the thermal performance, reliability and safety of the brake disc. This four properties are very important for a brake disc since it will prolong the lifetime of brake disc, assure the functionality and safety of the vehicle and users.

By improving the most important criteria stated above, we will get a design of brake disc that are able to satisfy and meet the requirements of customers.

4.3 ANSYS

In this project, ANSYS are used to carry out the thermal analysis and structural analysis of 6 alternatives design of brake disc. Thermal analysis is related to the thermal performance and heat dissipation while the structural analysis is to investigate the deformation of the brake disc under the force applied.

4.3.1 Thermal Analysis

The objective of thermal analysis of brake disc is to evaluate the thermal performance of different designs of brake disc under the condition applied. We can get the maximum temperature which can dissipated by the brake disc due to the condition applied. First, a comparison is carried out between the two original design of brake disc that are made of two different materials, cast iron and AlSiCGr. Then, thermal analysis is performed on the remaining five alternatives design that are made of hybrid Al-MMC, AlSiCGr.

4.3.1.1 Assumptions

1. Brake are applied on the front two wheels.
2. The mass of vehicle is 1300kg and speed is 150km/h.
3. The initial temperature of brake disc is 150 ℃.
4. 60% of weight of the car is located at front part of the vehicle.
5. There are no forced convection but only ambient air cooling involved in the analysis.
6. The thermal conductivity of the material is uniform throughout.
7. The specific heat of material is constant.
8. Kinetic energy is converted to heat energy during the application of brake.
9. The deceleration of vehicle is uniform.
10. Steady state thermal analysis.

4.3.1.2 Calculations and Results

Firstly, the original design that made of two different materials is compared and then continue with the other 5 alternative designs that are made of hybrid Al-MMC. The conditions is remained the same with all the analysis performed.

Alternative Design 1(Cast Iron)

Coefficient of friction of cast iron, $\mu = 0.2$

Mass of vehicle, M = 1300kg

Area of surface of brake disc = 0.0276 m^2

Speed of vehicle = 150 km/h = 41.67 m/s

Force applied on the brake disc = μMg

= (0.2)(1300)(9.81)

= 2550.6N

Deceleration, a = Force/mass

= 2500.6/1300

= 1.962m/s^2

Time for stopping vehicle = velocity/deceleration

= 41.67/1.962 = 21.24s

Assumed K.E convert to H.E

K.E = $0.5mV^2$

$= 0.5(1300)(41.67m/s)^2 = 1128.652kJ$

Power = K.E/time

$= 1128.652KJ/21.24$

$= 53.138kW$

Assumed 60% of mass located at front and 2 wheels

$= (0.6)(0.5)53.138kW = 15.941kW$

Heat Flux = Power/time/Area

$= 27193W/m^2$

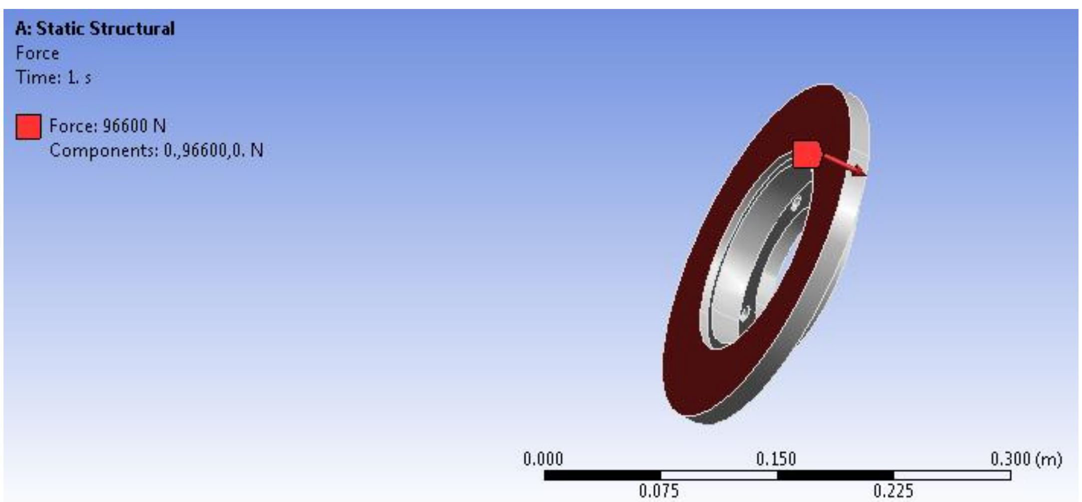


Figure 4.2: Location and direction of force applied on the brake disc

The force is applied as shown in figure 4.1 because there is where the clamping force exerted by the brake pad when brake pedal is pushed by driver. The location and direction of force applied are the same for all the alternative designs of brake disc.

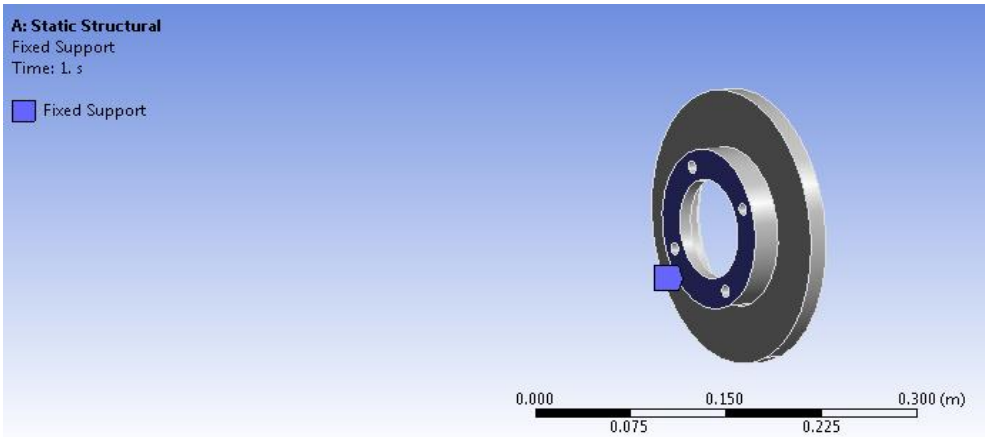


Figure 4.3: Location of fixed support applied on the brake disc

The fixed support is applied as shown in figure 4.2 as this is where the bolt nuts tighten and secured the brake disc. The location of fixed support is the same for all the alternative design of brake disc.

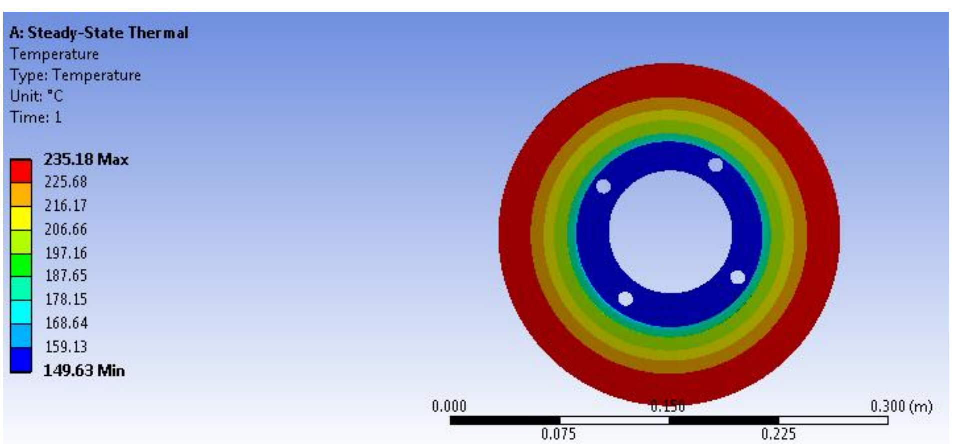


Figure 4.4: Thermal analysis of original design cast iron brake disc

Alternative Design 1(AlSiCGr)

Coefficient of friction, $\mu = 0.35$

$A=0.0276m^2$

Heat Flux = 83241 W/m^2

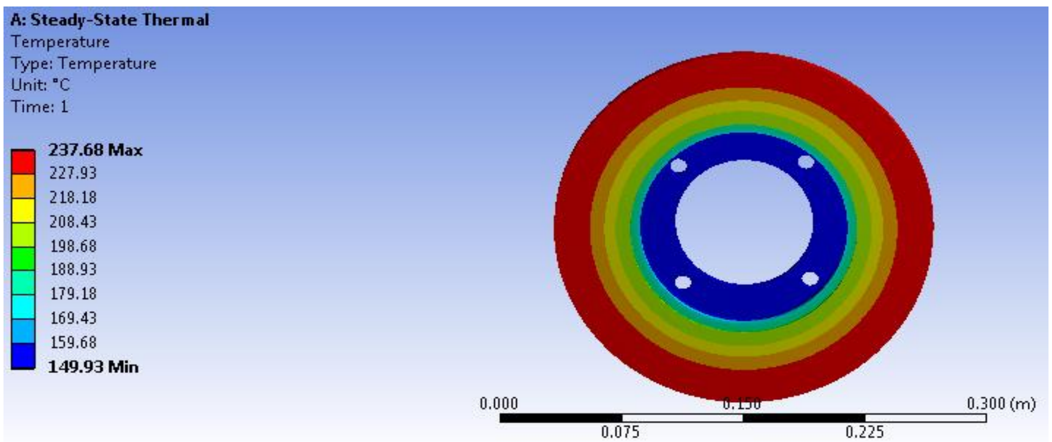


Figure 4.5: Thermal analysis of original design AlSiCGr brake disc

Alternative Design 2

$A=0.027m^2$

Heat Flux = 85091 W/m^2

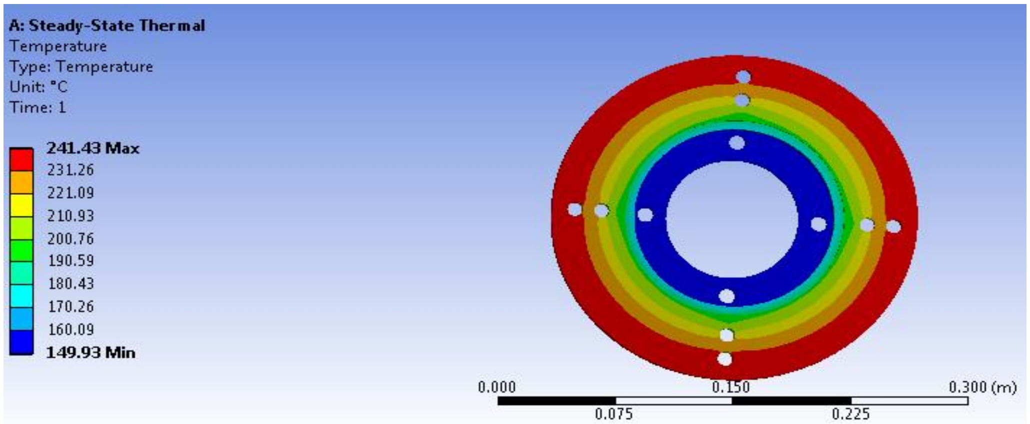


Figure 4.6: Thermal Analysis of Alternative Design 2

<u>Alternative Design 3</u>

Area = $0.0268m^2$

H.F = 85726 W/m^2

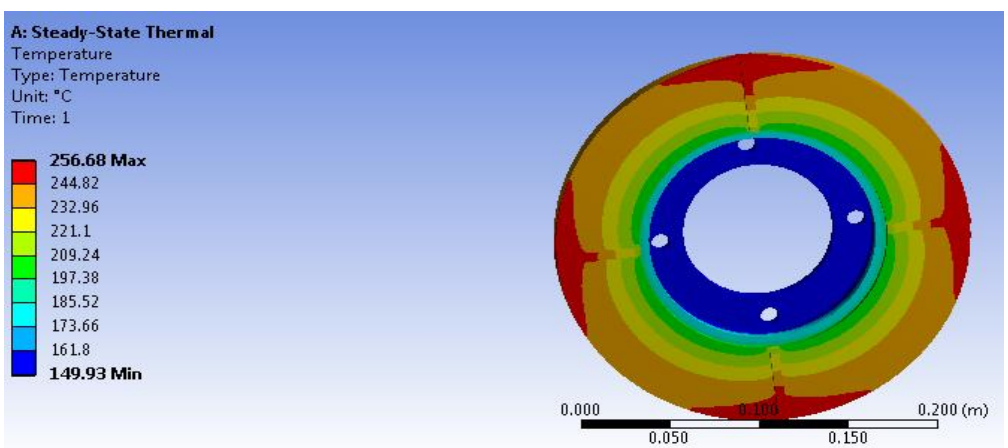


Figure 4.7: Thermal analysis of alternative design 3

Alternative Design 4

Area = 0.026m^2

H.F = 88363 W/m^2

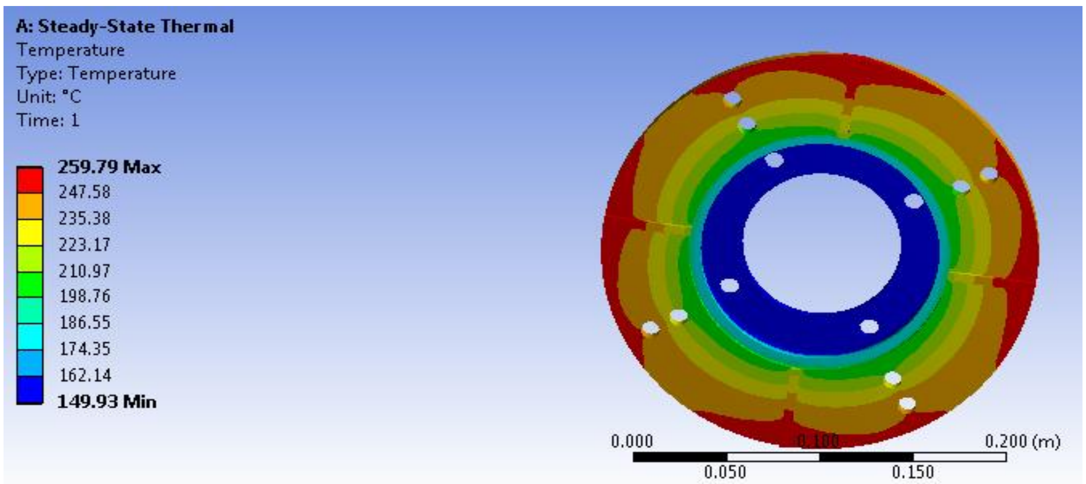


Figure 4.8: Thermal analysis of alternative design 4

Alternative Design 5

Area = 0.0252m^2

H.F = 91169 W/m^2

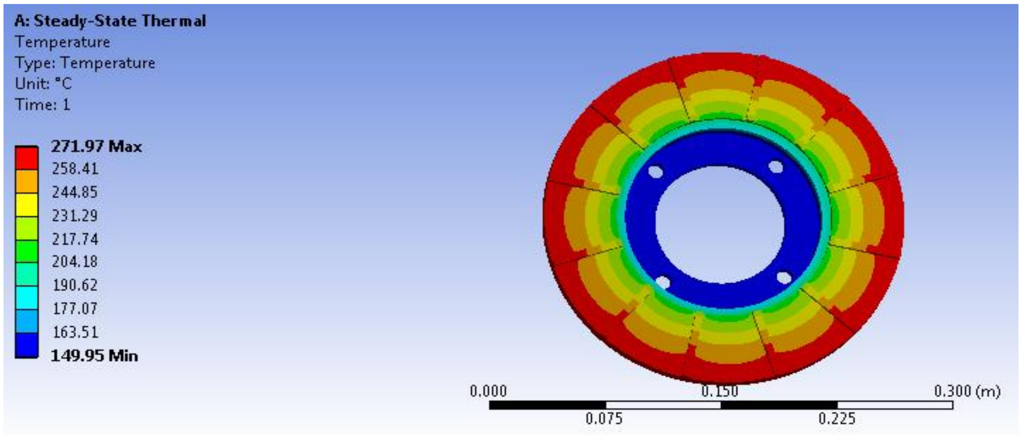


Figure 4.9: Thermal analysis of alternative design 5

Alternative Design 6

Area = 0.024m^2

H.F = 95727 W/m^2

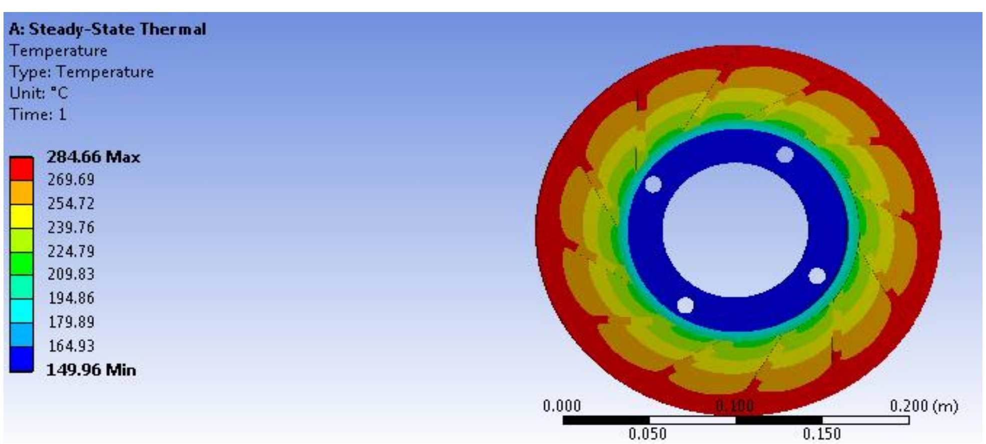


Figure 4.10: Thermal analysis of alternative design 6

4.3.2 Structural Analysis

The objective of structural analysis of brake disc is to evaluate the deformation of different designs of brake disc under the condition applied. We can get the maximum and minimum deformation of the brake disc under the condition applied. First, a comparison is carried out between the two original design of brake disc that are made of two different materials, cast iron and AlSiCGr. Then, structural analysis is performed on the remaining five alternatives design that are made of hybrid Al-MMC, AlSiCGr.

4.3.2.1 Assumptions

The calculation of all the alternative designs are used the same formula. Assume brake pipeline pressure variation is approximately

1. Low level braking = 1-2MPa
2. Medium level braking = 2-4MPa
3. Panic braking = 4-7MPa

The pressure used in the calculation is 7MPa which is the highest pressure that can exert on the two brake disc to evaluate the highest and maximum deformation that will occurred on the brake disc. The fixed support is applied on the bolt of the brake disc contact surface.

4.3.2.2 Calculations and Results

<u>Alternative Design 1(Cast Iron)</u>

Area = 0.0276 m^2

Force on one brake disc = Pressure x Area

= (7MPa x 0.0276)/2

= 96.6kN

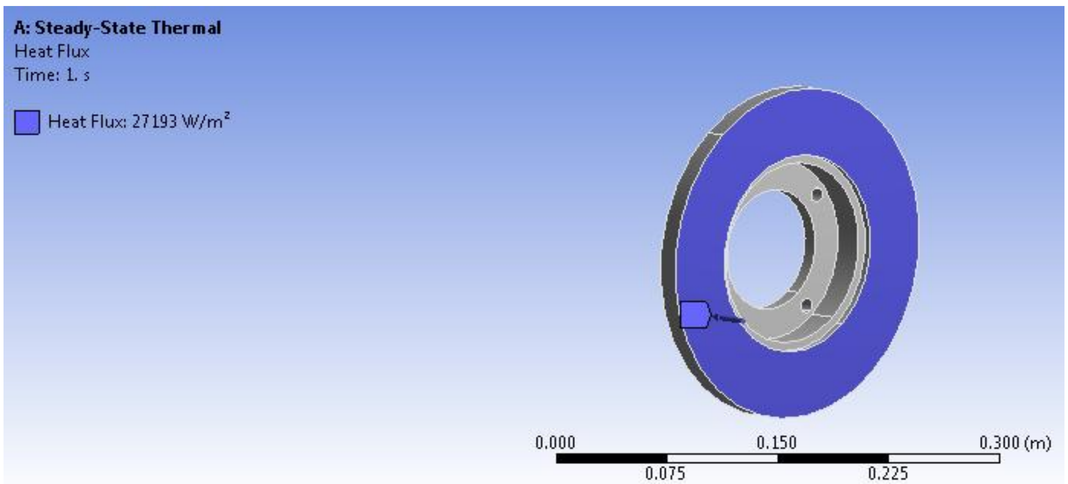


Figure 4.11: Location of heat flux applied on the brake disc

The surface of the brake disc in figure 4.10 is where the rubbing of brake bad and brake disc occurred. The friction generated from the rubbing will producing heat energy on the surface of the brake disc. The location of heat flux applied is all the same for all the alternative designs of brake disc.

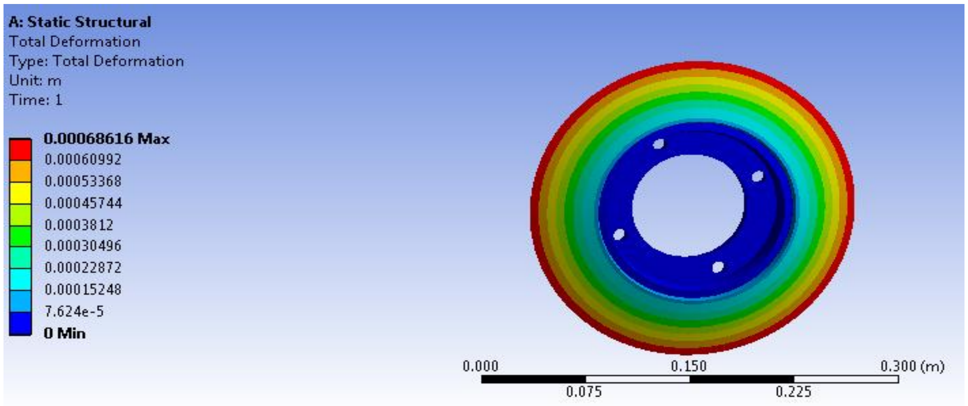


Figure 4.12: Structural analysis of original design cast iron brake disc

Alternative Design 1(AlSiCGr)

Area = 0.0276 m^2

Force on one brake disc = 96.6kN

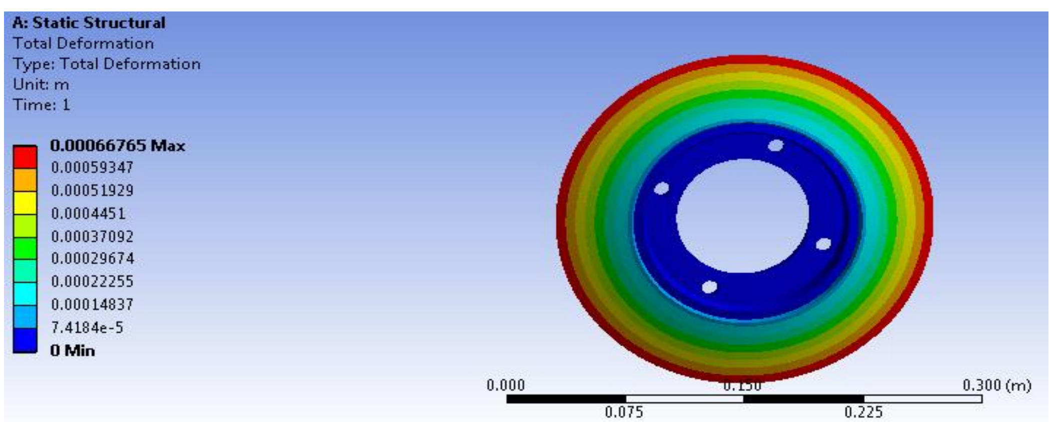


Figure 4.13: Structural analysis of original design AlSiCGr brake disc

Alternative Design 2

Area = $0.027m^2$

F = (7MPa x 0.027)/2

= 94500

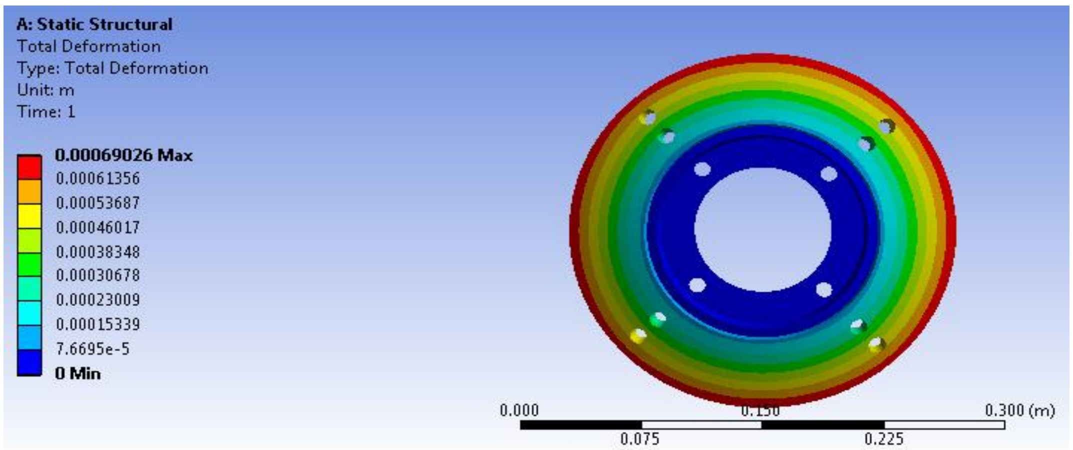


Figure 4.14: Structural analysis of alternative design 2

Alternative Design 3

Area = $0.0268m^2$

F = 93800N

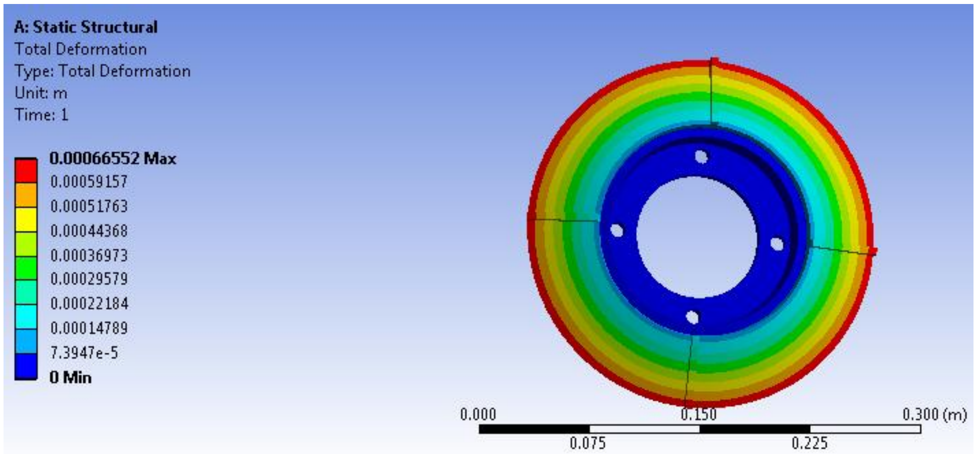


Figure 4.15: Structural analysis of alternative design 3

<u>Alternative Design 4</u>

Area = 0.026m^2

F = 91000N

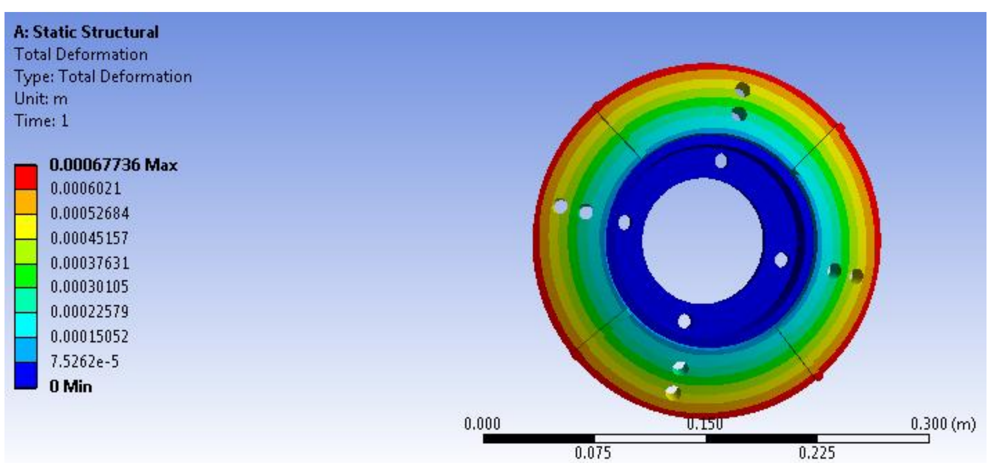


Figure 4.16: Structural analysis of alternative design 4

Alternative Design 5

Area = $0.0252m^2$

F = 88200N

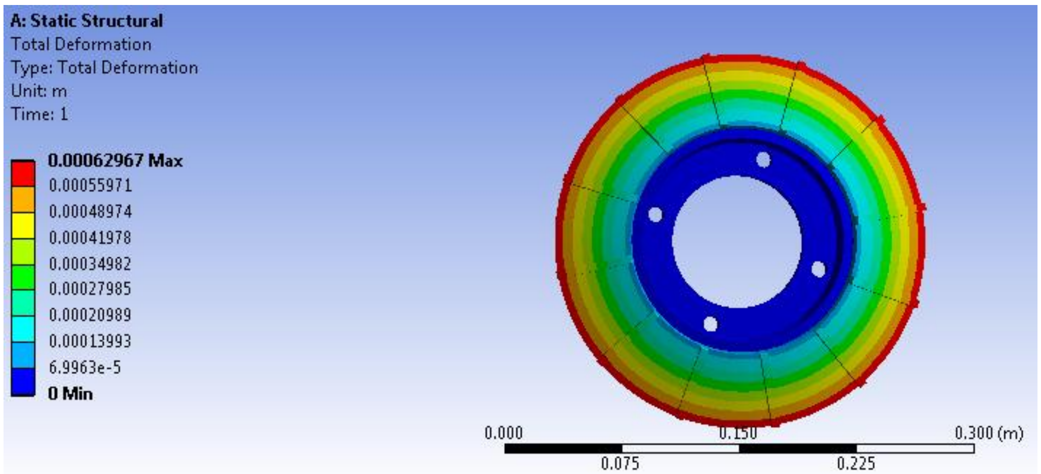


Figure 4.17: Structural analysis of alternative design 5

Alternative Design 6

Area = $0.024m^2$

F = 84000

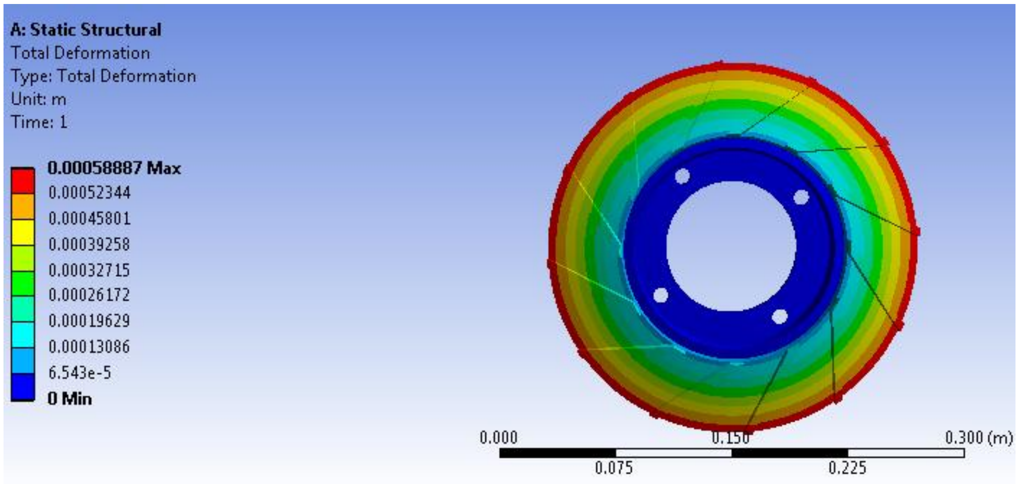


Figure 4.18: Structural analysis of alternative design 6

4.3.3 Summary Results of ANSYS

Table 4.1: Analysis Result from ANSYS

Alternative Design	Thermal Dissipation(℃)	Deformation (mm)	Mass (kg)
	Max.	Max.	
1(cast iron)	235.18	0.6862	3.7231
1(AlSiCGr)	237.68	0.6677	1.4117
2	241.43	0.6903	1.3817
3	256.68	0.6655	1.4185
4	259.79	0.6774	1.3946
5	271.97	0.6297	1.4441
6	284.66	0.5889	1.4569

For thermal analysis, higher maximum temperature mean the brake disc is able to dissipate heat faster. Higher heat dissipation prevent the overheating of the brake disc that could cause the malfunction of the brake system. The analysis showed that higher temperature is at the outer part of the surface of the brake disc and heat is transfer in a circular direction from middle to outside. A comparison has done between the same alternative design 1 with different material which is cast iron and AlSiCGr. The result show that the hybrid Al MMC able to dissipate heat faster compare to cast iron which the hybrid Al-MMC is able to dissipate maximum temperature of 237.68 ℃ that is higher than maximum temperature 235.18 ℃ dissipated by cast iron. This is due to the higher thermal conductivity of hybrid Al-MMC material. From the thermal analysis, it also show that design of adding holes and slots improve the thermal performance of the brake disc. Besides that, alternative design 3(4 slots added) dissipate heat faster than alternative design 2(8 hole added) which mean the design of adding slot is better than adding hole on the surface area of brake disc. Slots create a path for better air circulation fasten the heat transfer rate. The combination of slots and holes further improve the heat dissipation which is shown by alternative design 4 that dissipate maximum temperature of 271.94 ℃. The alternative design 6(angled slots) has the best performance is dissipating heat that able to dissipate maximum temperature of 284.66 ℃.

For structural analysis, higher deformation value mean the brake disc is deformed more under the force applied and this is undesirable for a design of brake disc. A comparison has also done between the same alternative design 1 with different material which is cast iron and AlSiCGr. The result show that the hybrid Al MMC deform less compare to cast iron. This is due to the higher tensile strength, hardness and elastic modulus of hybrid Al-MMC. Hybrid Al-MMC brake disc deform 0.6677mm whereas cast iron brake disc deform 0.6862mm. From the result of structural analysis, it also showed that adding of holes make will make the deformation of brake disc increases which are undesirable while adding slots will decrease the deformation. This can be observed from the comparison result between alternative design 2(8 holes added) which deform 0.6903mm and alternative design 3(4 slots added) which deform 0.6655mm. Adding more and modified the angle of slots will further improve the deformation of brake disc which is shown in the alternative design 6 that deform 0.589mm.

The mass of hybrid Al-MMC are 63% lower compared to cast iron. Although the manufacturability and the cost of hybrid Al-MMC is higher but it can be compensated by the better thermal performance, lower deformation and lower mass which can improve the reliability, safety, fuel consumption efficiency and durability.

4.3.4 Comparing Different Angles of Slot for Alternative Design 6

The thermal analysis show that the design of brake disc with angle slot is better compared with straight slots and holes. The best angle for the brake disc is determined for the best thermal performance. Different angles of slot have been modeled into CATIA and compared in thermal analysis of ANSYS.

Table 4.2: Results of thermal analysis for different angles of slot in alternative design 6

Angle of Slot	Thermal Dissipation(℃)
15 °	293.48
30 °	284.66
45 °	281.97
60 °	279.76

The maximum temperature for the thermal dissipation is decreases when the angle increases. The best angle of slot for the brake disc is 15 °for obtaining the optimum thermal performance.

4.4 ANALYTIC HIERARCHY PROCESS

This is the final step in this project. AHP is used to select the best design of brake disc among the six alternative design. It selecting the best multi-criteria alternatives by using weighted scoring and organize priorities. The software that used to carry out the AHP is SuperDecisions software.

4.4.1 Summary Table of Properties and ANSYS Results

Table 4.3: Properties and ANSYS results of Al-MMC material and cast iron in different alternative designs

Alternative Design	Thermal Dissipation(℃)	Thermal Conductivity (W/m.K)	Deformation (mm)	Mass (kg)	Hardness (MPa)
	Max.		Max.		
1(AlSiCGr)	237.68	161	0.6677	1.4117	2931
2	241.43	161	0.6903	1.3817	2931
3	256.68	161	0.6655	1.4185	2931
4	259.79	161	0.6774	1.3946	2931
5	271.97	161	0.6297	1.4441	2931
6	284.66	161	0.5889	1.4569	2931
7(Cast Iron)	235.18	54	0.6862	3.7231	2040

All the thermal dissipation, deformation and weight value are get from the result of ANSYS structural analysis and thermal analysis whereas the hardness value are get from the research journal. From this table we can compare and found out that which design is better in thermal performance, deformation, mass or hardness and this enable the pair-wise comparison carry out easier and increase the consistency and accuracy of the ranking process. The alternative design 1 has the same design with alternative design 7 but it is made of different material, Al hybrid MMC and cast iron. Alternative design 1-6 is made of different design with Al hybrid MMC.

4.4.2 Results and Discussions

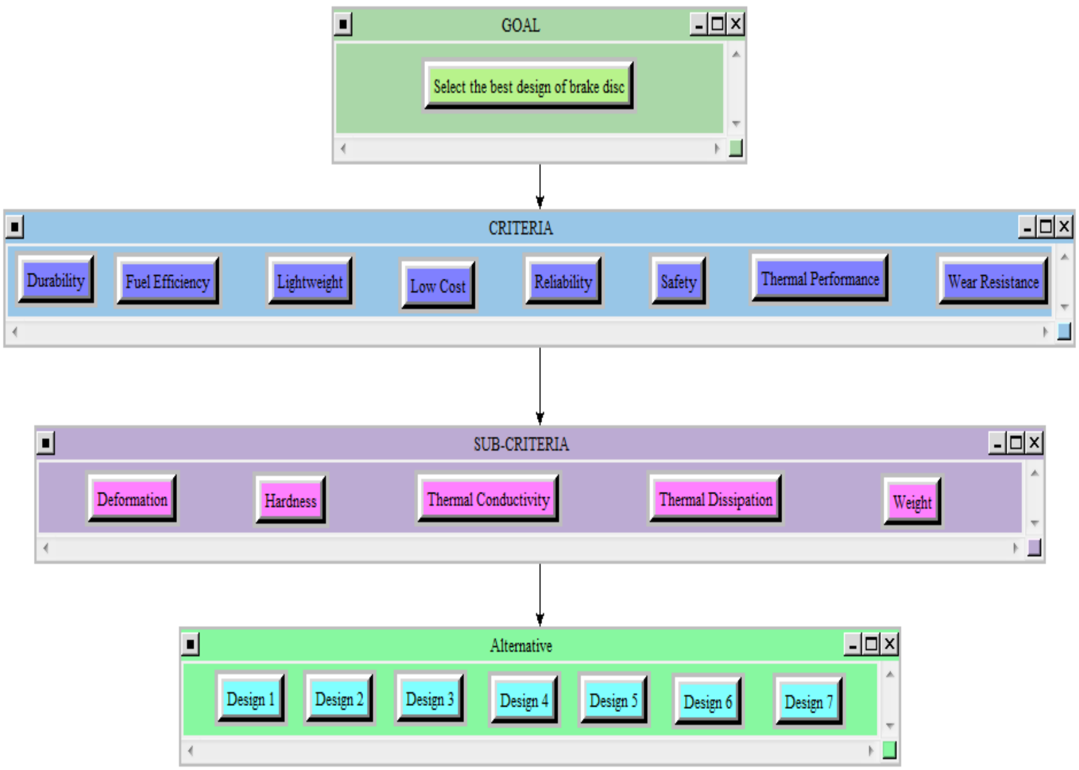


Figure 4.19: AHP hierarchy for selecting the best design of brake disc

The AHP hierarchy consist of 4 level which are goal, criteria, sub-criteria and alternative design. The goal is to select the best design of brake disc among 7 alternative designs. Based on house of quality, the criteria that affecting the design of brake disc are durability, fuel efficiency, lightweight, low cost, reliability, safety, thermal performance and wear resistance while the sub-criteria are deformation, hardness, thermal conductivity, thermal dissipation and weight. The alternative design 1 has the same design with alternative design 7 but it is made of different material, Al hybrid MMC and cast iron. Alternative design 1-6 is made of different design with Al hybrid MMC.

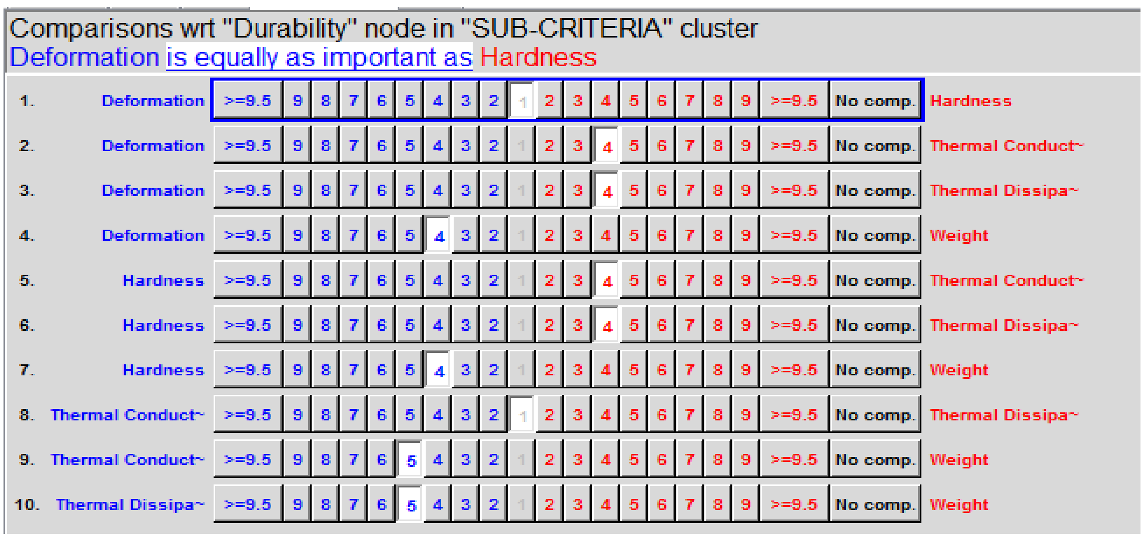


Figure 4.20: Sample of questionnaire that carry out the pair-wise comparison

Figure 4.20 show the sample questionnaire that rank the relative importance of each sub-criteria. The pair-wise comparison of criteria and relative advantages of each alternative design is also carried out by using this kind of questionnaire. All the inconsistency ratio of pair-wise comparison should be less than 0.1 in order the make the judgments acceptable, if it is more than 0.1, a revision on the comparison should be carried out.

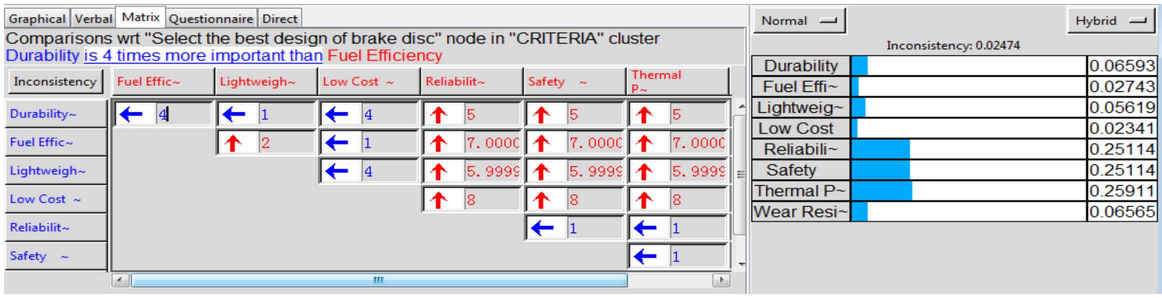


Figure 4.21: Pair-wise comparison and relative priority of main criteria with respect to the goal

From figure 4.21, we can found out that thermal performance is the most important criteria that affecting the design of brake disc which has the highest relative priority of 0.25911 and followed by reliability, safety and durability. The inconsistency ratio is 0.02474.

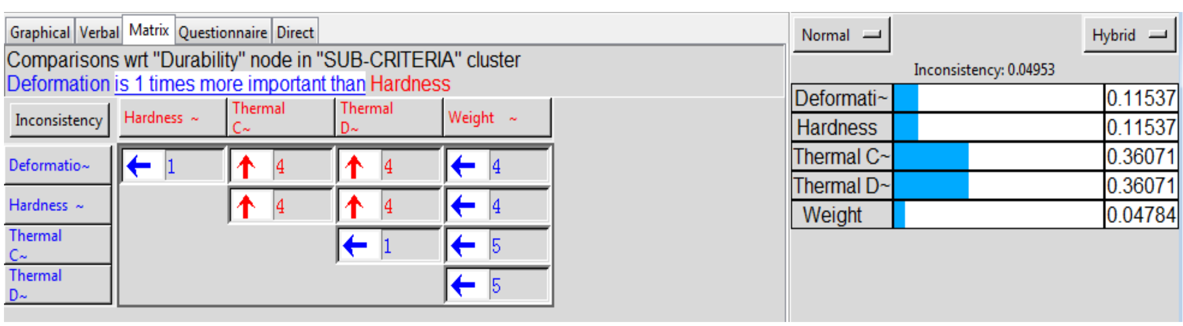


Figure 4.22: Pair-wise comparison and relative priority of sub-criteria

Figure 4.22 show the sub-criteria brake disc. The highest relative priority for sub-criteria are thermal conduction and thermal dissipation which has the same weight of 0.36071 and followed by deformation, hardness and weight. The inconsistency ration is 0.04953.

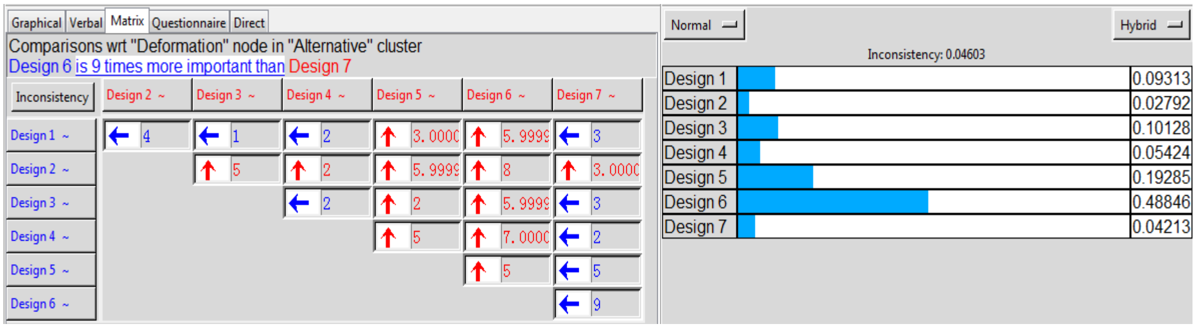


Figure 4.23: Pair-wise comparison and relative priority of deformation in the seven alternative design of brake disc

Figure 4.23 show the relative priority of deformation in the seven alternative designs. Alternative design 6 has the highest relative priority of 0.48846 in deformation which mean this design can resist itself from undergoing deformation the most compare with other alternative designs. The inconsistency ratio is 0.04603.

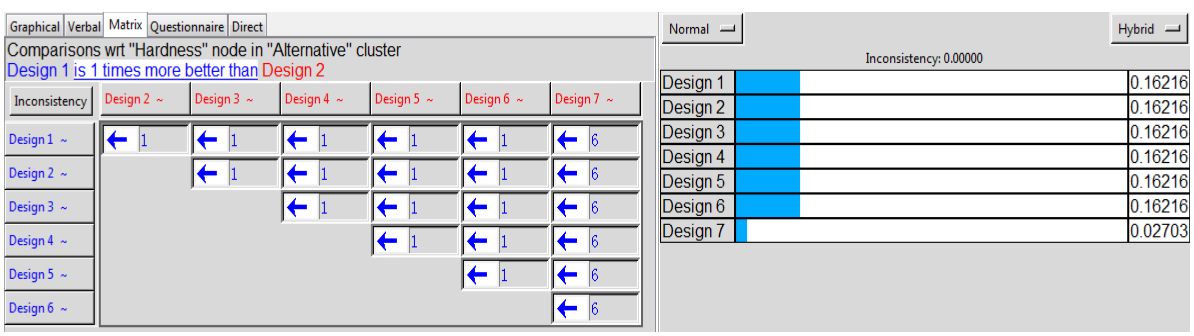


Figure 4.24: Pair-wise comparison and relative priority of hardness in the seven alternative designs of brake disc

From figure 4.24, it show that alternative design 1-6 has the same relative priority of 0.16216 in hardness since they are made of same material, hybrid Al-MMCs while alternative design 7 is made of grey cast iron. Hybrid Al-MMCs has a higher hardness value compare with gray cast iron. The inconsistency ratio is 0.

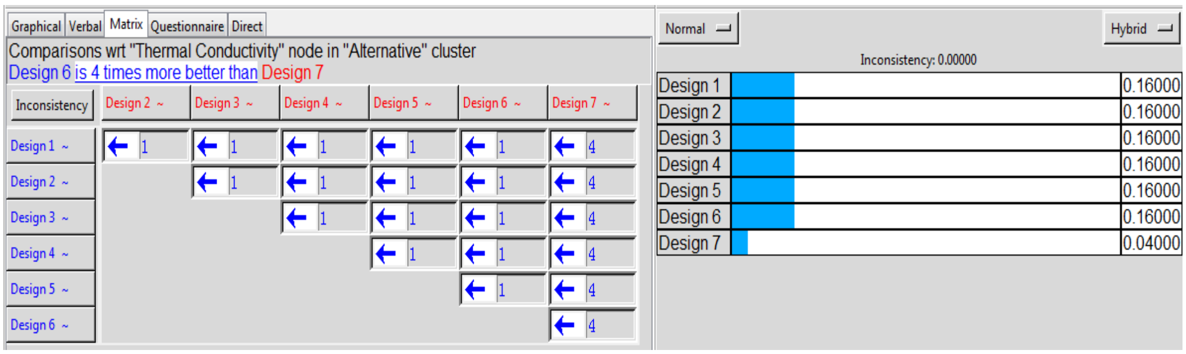


Figure 4.25: Pair-wise comparison and relative priority of thermal conductivity in the seven alternative designs of brake disc

The pair-wise comparison in figure 4.25 show that alternative design 1-6 has the same relative priority of 0.16 in thermal conductivity since they are made of same material, hybrid Al-MMCs while alternative design 7 is made of grey cast iron. Hybrid Al-MMCs has a better property of thermal conductivity compare with gray cast iron. The inconsistency ratio is 0.

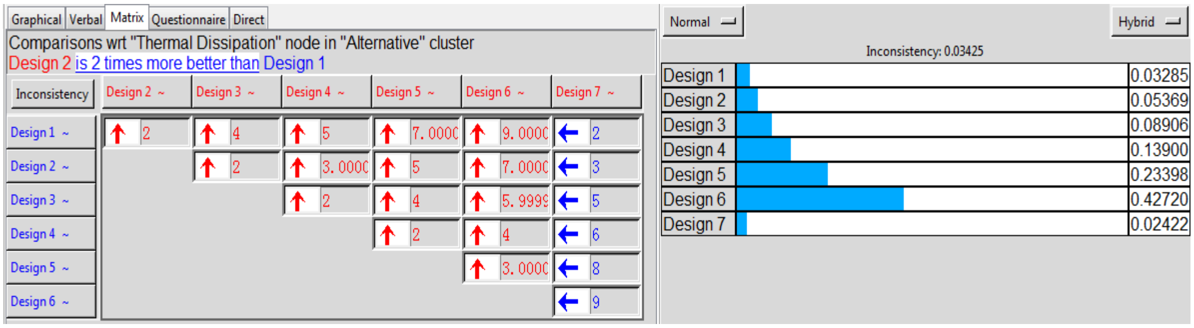


Figure 4.26: Pair-wise comparison and relative priority of thermal dissipation in the seven alternative designs of brake disc

From figure 4.26, the pair-wise comparison show that alternative design 6 has the highest relative priority of 0.42720 in thermal dissipation which mean this design can dissipate heat fastest compare with other alternative designs. The inconsistency ratio is 0.03425.

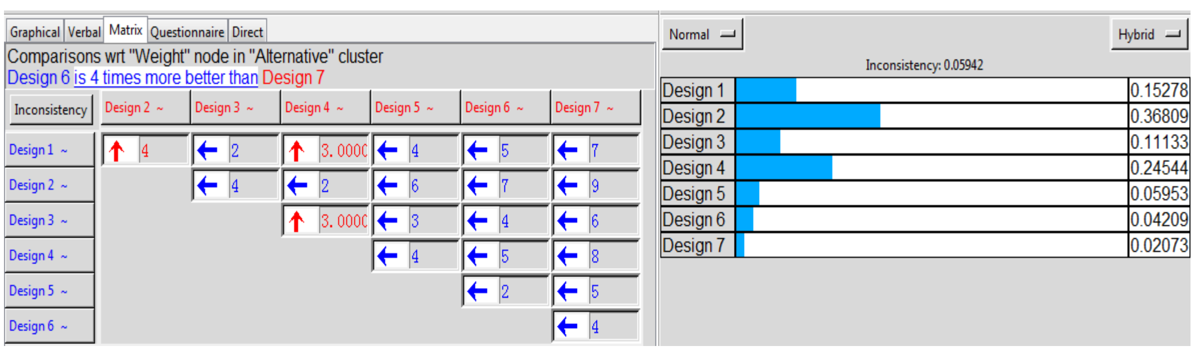


Figure 4.27: Pair-wise comparison and relative priority of weight in the seven alternative designs of brake disc

The pair-wise comparison in figure 4.27 show that alternative design 2 has the highest relative priority of 0.36809 in weight which mean this design is the lightest compare with other alternative designs. The inconsistency ratio is 0.05942.

Here are the overall synthesized priorities for the alternatives. You synthesized from the network Super Decisions Main Window: AHP brake disc.sdmod

Name	Graphic	Ideals	Normals	Raw
Design 1		0.392556	0.107653	0.035600
Design 2		0.468738	0.128545	0.042509
Design 3		0.457143	0.125366	0.041457
Design 4		0.552158	0.151422	0.050074
Design 5		0.661326	0.181360	0.059974
Design 6		1.000000	0.274237	0.090688
Design 7		0.114559	0.031416	0.010389

Figure 4.28: Relative priority in selecting the best design of brake disc among the seven alternative designs with respect the main criteria and sub-criteria

Graphic	Alternatives	Total	Normal	Ideal	Ranking
	Design 1	0.0356	0.1077	0.3926	6
	Design 2	0.0425	0.1285	0.4687	4
	Design 3	0.0415	0.1254	0.4571	5
	Design 4	0.0501	0.1514	0.5522	3
	Design 5	0.0600	0.1814	0.6613	2
	Design 6	0.0907	0.2742	1.0000	1
	Design 7	0.0104	0.0314	0.1146	7

Figure 4.29: Total relative priority and ranking of the seven alternative designs of brake disc

Figure 4.29 show the final result of AHP. The results of SuperDecision software select alternative design 6 as the best design of brake disc after putting the criteria and sub-criteria into the consideration.

4.4.3 Sensitivity Analysis

The sensitivity analysis is carried out to verify the accuracy of the results of AHP. This is done by changing the weight or relative priority of criteria and observe the changes on the final result. The priority setting on the criteria will affect the final selection of best design. Even a small changes in the priority value will contribute to the final result.

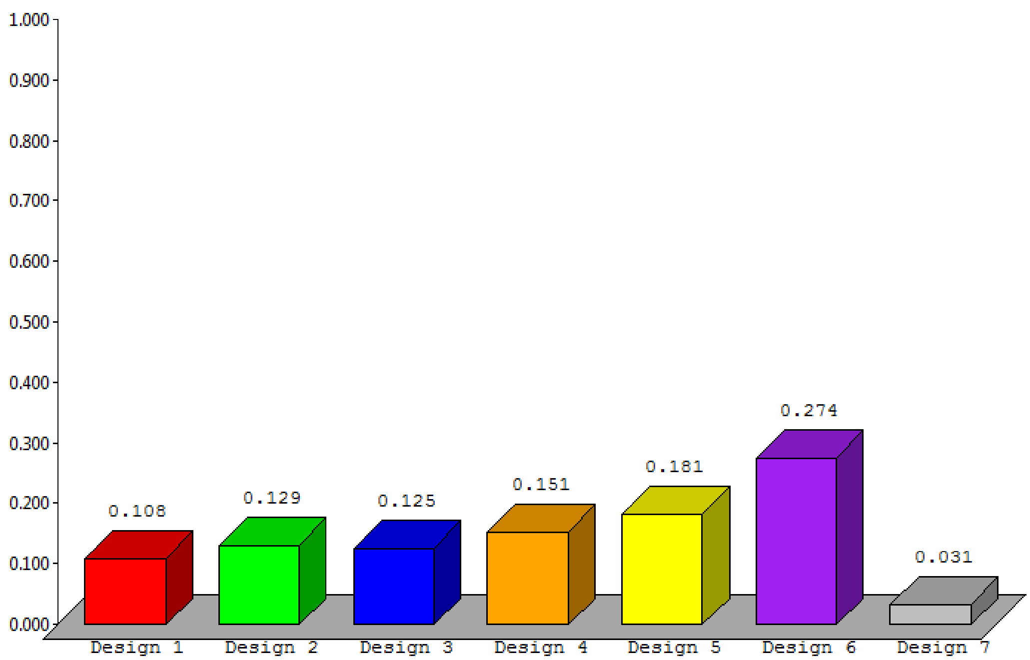
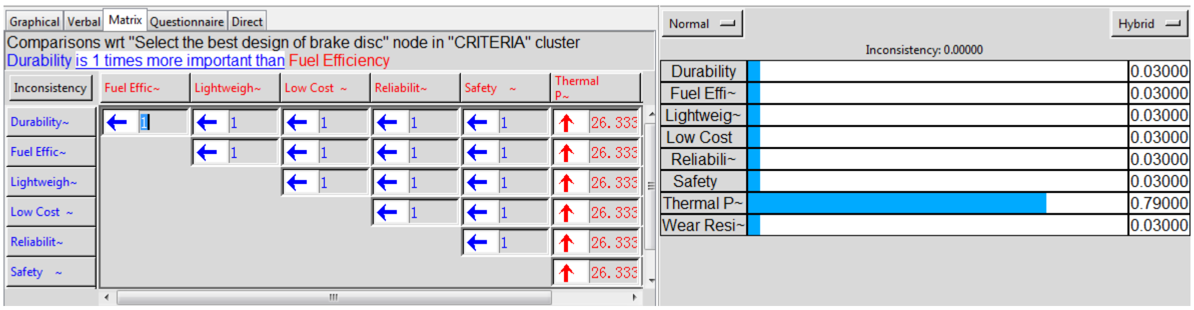


Figure 4.30: Sensitivity graph of 7 alternative designs

Firstly, we make one of the criteria, thermal performance become the most important by changing the ranking on the questionnaire and increasing the relative priority to 0.79. Then we observe how does it affect the final selection of best design of brake disc.



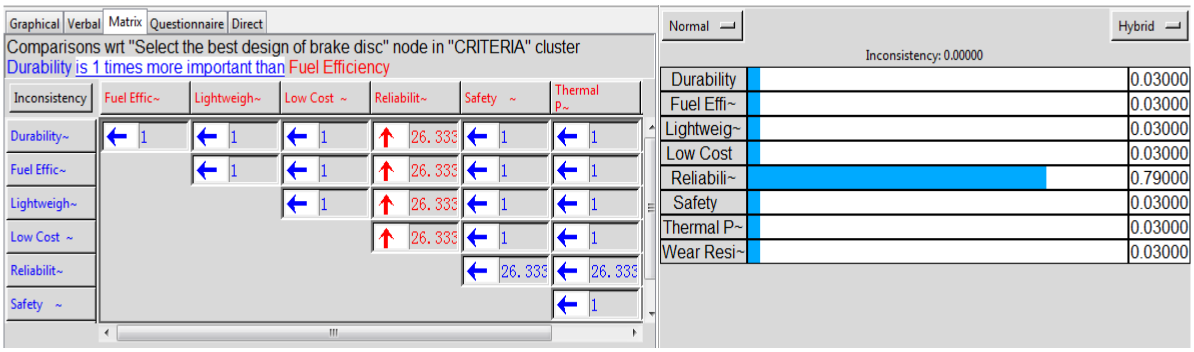
(a) New assigned weight

Graphic	Alternatives	Total	Normal	Ideal	Ranking
	Design 1	0.0335	0.1015	0.3637	6
	Design 2	0.0404	0.1226	0.4390	5
	Design 3	0.0410	0.1241	0.4446	4
	Design 4	0.0507	0.1535	0.5498	3
	Design 5	0.0619	0.1875	0.6715	2
	Design 6	0.0921	0.2792	1.0000	1
	Design 7	0.0104	0.0315	0.1128	7

(b) Final result of AHP

Figure 4.31: Sensitivity analysis of thermal performance

By changing the relative importance of thermal performance to the most important criteria, only a small changes to the final result of ranking 4 and 5. This is because the thermal performance is still the most important criteria among the other criteria in the pair-wise comparison and now the final selection best design ranking is chose based on only the thermal performance. The sub-criteria that under the criteria thermal performance are thermal dissipation and thermal conduction. The first, second and third best alternative designs still remained the same as they have a better property of thermal dissipation and thermal conduction.



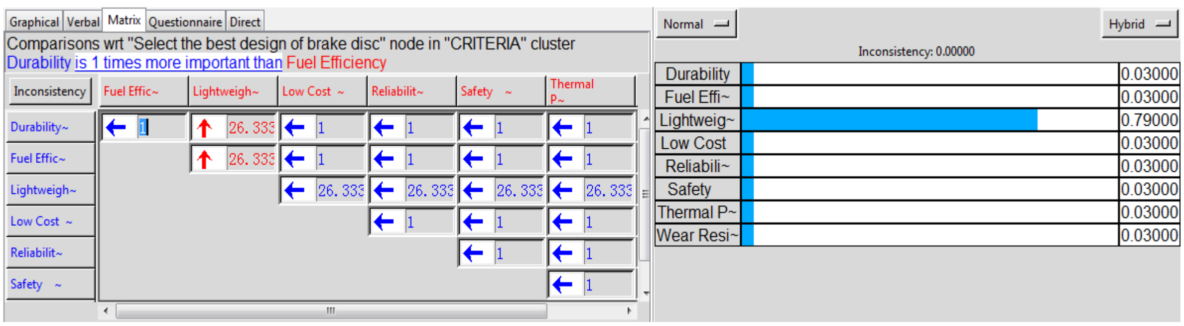
(a) New assigned weight.

Graphic	Alternatives	Total	Normal	Ideal	Ranking
	Design 1	0.0358	0.1086	0.3962	6
	Design 2	0.0412	0.1249	0.4555	5
	Design 3	0.0420	0.1272	0.4638	4
	Design 4	0.0496	0.1503	0.5484	3
	Design 5	0.0605	0.1835	0.6692	2
	Design 6	0.0904	0.2741	1.0000	1
	Design 7	0.0104	0.0314	0.1147	7

(b) Final result of AHP.

Figure 4.32: Sensitivity analysis of reliability

Then, we make the other criteria, reliability become the most important criteria by changing the ranking on the questionnaire and increasing the relative priority to 0.79. Then we observe how does it affect the final selection of best design of brake disc. We can observe that the changes is just like the previous sensitivity analysis. There are only a small changes to the final result of ranking 4 and 5. Reliability became the most important criteria and the sub-criteria that affecting the reliability are thermal conduction, thermal dissipation, deformation and hardness. The ranking of final decision of brake disc is now based on the relative advantages of the alternative designs in the sub-criteria. The first, second and third best alternative designs still remained the same as they have a better property of thermal dissipation, thermal conduction, hardness and resist deformation.



(a) New assigned weight.

Graphic	Alternatives	Total	Normal	Ideal	Ranking
	Design 1	0.0481	0.1457	0.4452	3
	Design 2	0.1080	0.3273	1.0000	1
	Design 3	0.0375	0.1138	0.3477	4
	Design 4	0.0755	0.2287	0.6988	2
	Design 5	0.0263	0.0798	0.2438	6
	Design 6	0.0271	0.0822	0.2510	5
	Design 7	0.0075	0.0226	0.0690	7

(b) Final result of AHP

Figure 4.33: Sensitivity analysis of lightweight

Lastly, we make the other criteria, lightweight become the most important criteria and increasing the relative priority to 0.79. We can observe that there are changes on all the ranking except rank 7. The sub-criteria under the criteria of lightweight are weight. The ranking of final decision of best brake disc is now based on the weight of the alternative designs. Alternative design 2 became the best design of brake disc since it has the lowest weight or highest relative priority in weight in the pair-wise comparison and followed by alternative design 4 and alternative design 1.

From the sensitivity analysis, we can noticed that the alternative design 7 is always rank last in the best design selection of brake disc. This is because alternative design 7 is made of grey cast iron and it exhibit a lower property of hardness, thermal performance and higher weight.

As a conclusion, we can concluded that the final selection or ranking of best design is sensitive to the changes of relative priority or weight of the criteria and sub-criteria in the pair-wise comparison. An accurate distribution of relative importance and priority is very important for the AHP software to get the accurate result.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

A suitable material, Al hybrid MMC is proposed which meet the objective 1 of the project. Al hybrid MMC is a material better compared with grey cast iron in fabricate a brake disc since it is excellent in dissipate heat, high wear resistance, high thermal conductivity, high hardness and lightweight. The objective 2 is achieved through the result from QFD, the most important criteria to be consider in the design of brake disc are thermal performance, reliability and safety. The sub-criteria of criteria thermal performance are thermal dissipation and thermal conduction while for reliability and safety are deformation, hardness, thermal dissipation and thermal conduction.

Objective 3 is achieved by modelling the six alternative designs into CATIA software after considerate the important criteria of brake disc that found out from QFD. Next, the alternative designs are imported into ANSYS software for thermal analysis and structural analysis. FEA simulation results show that alternative design 6 posses higher thermal performance and lower deformation compare with the others. This meet the objective 4. Lastly, the pair-wise comparison is done with the outcome of QFD and FEA. Objective 5 is achieved by the selection of best alternative design 6 from the AHP results.

5.2 RECOMMENDATIONS

For future study, the following recommendations can be done:

1. Fabrication of the hybrid MMCs, AlSiCGr in order to get the actual material properties instead of getting it from calculations.

2. The real product of design of brake disc with the material AlSiCGr should be fabricated. With the fabrication of the brake disc, some experiment testing such as hardness testing and thermal testing can be carried out on the different designs of brake disc. The results of the experiment testing obtained can be used to compared with the results of simulation testing in the virtual environment of ANSYS.

3. The criteria in selecting the best brake disc design should include manufacturing cost and manufacturability after knowing the cost of fabricating of the material and brake disc.

4. The analytic hierarchy process (AHP) method can be enhanced by applied it along with theory of inventive problem solving (TRIZ) method. This can help to reduce the cost and increase the efficiency of designing the brake disc.

5. Ventilated brake disc should be included in selecting the best brake disc design instead of solid brake disc only.

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