Value Analysis for Brake Disc Materials – Case of cast iron to composite

by

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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

'IZZUDDIN BIN ISMAIL

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First and foremost, my appreciation goes to God for giving me chance to finish my project.

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ABSTRACT

Most of the automotive disc brakes are manufactured from Grey Cast Iron. Grey Cast Iron is chosen because of low cost and easy to manufacture. Grey Cast Iron also has good properties to withstand the high temperature of brake application. However Grey Cast Iron is heavy. Nowadays, there is also another materials used to manufacture disc brakes which is called composite materials. These materials have many advantages such as very light, can withstand higher temperature and many more other good properties but it is very expensive. In this project the properties of these two materials have been investigated as basis for comparison. In addition, the differences between these two disc brakes materials also been investigated in term of cost and properties and makes comparison which one is better. Weight decision matrix was adopted to compare the properties (weight, reliability, durability, and manufacturing process) and manufacturing cost to manufacture the Grey Cast Iron and composite disc brakes. The result shows that the suitable candidate to replace Grey Cast Iron is Al-MMC composite disc brake. The score for Al-MMC disc brake is 6.8 compared to the Grey Cast Iron disc brake which is 6.88. Thus, the value is almost similar. As Al-MMC is a new material, further research is required to enhance its reliability performance for mass production

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CHAPTER 1 INTRODUCTION

1.1 Background

Brakes are most important safety parts in the vehicles. Generally all of the vehicles have their own safety devices to stop their car. Brakes function to slow and stop the rotation of the wheel. To stop the wheel, braking pads are forced mechanically against the rotor/disc on both surfaces. They are compulsory for all of the modern vehicles and the safe operation of vehicles. In short, brakes transform the kinetic energy of the car into heat energy, thus slowing its speed.

Brakes have been improved ever since their invention. The increases in travelling speeds as well as the growing weights of cars have made these improvements essential. The faster a car goes and the heavier it is, the harder it is to stop. An effective braking system is needed to accomplish this task with challenging term where material need to be lighter than before and performance of the brakes must be improved. Today's cars often use a combination of disc brakes and drum brakes. For normal sedan car, normally disc brakes are located on the front two wheels and drum brakes on the back two wheels. Clearly shows that, together with the steering components and tyres represent the most important accident avoidance systems present on a motor vehicle which must reliably operate under various conditions. However, the effectiveness of braking system depends on the design itself and also the right selection of material.

There are several materials use to manufacture disc brake nowadays. The common usage in a conventional car is the Grey Cast Iron disc brakes. There are also disc brakes manufactured from composite materials and these are only produce for racing cars and luxury cars due to high speed applications and high cost. Due to high cost, they give problems for mass production.

There is method which is called value analysis in order to identify the problems and to begin define the functions that need to be performed. By using this method we can analyse between disc brake rotors made of two different materials for better usage in automotive.

1.2 Problem Statement

This project is concern about the value analysis of the disc brake rotor made from two different materials in manufacturing point of view. Most of the passenger cars today have disc brake rotors that are made of Grey Cast Iron. Grey Cast Iron is chosen for its relatively high thermal conductivity, high thermal diffusivity and low cost. There are also disc brake rotors that made of composite materials. These disc brakes are well-known of its lightweight compare to Grey Cast Iron disc brakes. In this project the author will investigate the properties of these two materials as general knowledge for better understanding of these materials. In addition, the author will also investigate the differences between these two disc brakes in term cost and function and make comparison which one is better.

1.3 Objectives and Scope of Study

To undertake value analysis study of disc brakes materials to replace Grey Cast Iron to other materials

The scopes of the project are:

- To study the normal disc brakes those have different materials (Cast Iron and Composite) in term of manufacturing cost and other criteria such as reliability, durability, weight etc. Composite disc brakes that had been investigated are Carbon/ Carbon composite, Ceramic Matrix Composite and Aluminium Metal Matrix

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Value analysis is a systematic analysis that identifies and selects best value alternatives for designs, materials, processes, and systems. This method is to improve the value of goods or products and services by examination of function. Value, as defined, is the ratio of function to cost. Value can therefore be increased by either improving the function or reducing the cost. It is a primary principle of value analysis that basic functions be preserved and not be reduced as a consequence of pursuing value improvements. Value analysis is a way of thinking about productivity, the proper utilization of manpower and materials and it can yield itself to improved profitability on a large or small scale [1]. From this analysis we can identify relationships that increase or decrease the value. This analysis can be use to compare the effectiveness and manufacturing cost for replacement usage of disc brake in automotive from cast iron to composite material. A literature review was conducted to investigate the research that has been done in many areas related to this work. In addition, manufacturing process of disc brake will be discussed in this chapter.

2.2 Overview

2.2.1 Other study

Vidya Bhusan and Amit Sinha (2000) conducted studies to investigate a case study of cost saving by Indian railway replacing cast iron disc brakes with composite disc brakes. They were conducting two parts of investigation for their research. The first part is investigating about the characteristic of the two types of disc brakes (cast iron and composite). The second part is about the cost involved for manufacturing those two types of disc brakes.

In their first part of study, they are comparing the advantages and the disadvantages of the two types of disc brakes for train. The advantages and disadvantages of each type of disc brake are listed. The advantage of GCI that had been stated is ease of manufacture. GCI requires low technology skill inputs. Also raw materials are easily available one of its major sources being scrap. Also by starting to manufacture GCI blocks in house, IR has been able to relocate some of the idle and surplus manpower. The other advantages of GCI are recyclable and good heat dissipation. The disadvantage of GCI is the poor quality due casting defects such as blowholes, rattails, abrasion etc. The GCI blocks are also heavy. There are 5 times heavier than Composite disc brakes. The other disadvantages are prone to theft due to recycle value, wear rate of GCI is high which result lesser life. GCI blocks have to be replaced after 5000km.

For Composite disc brakes, it is found that the advantages are the quality where composite disc brakes have excellent surface finish. The hardness can be accurately controlled within 180-220 BHN. The brake block also light weight compare to GCI disc brakes. Another advantage is the life of the blocks. It is found that the life is much higher compare to GCI. The life is about 84000km [1].

For the second part, Vidya Bhusan and Amit Sinha conduct a cost analysis. The costs that they had been investigated are [1]

1) Cost of Production
2) Cost of Operation
3) Saving in Manpower
4) Cost of Transportation
5) Administrative Expenses
6) Handling and Storage charges
7) Fitting in Wagons
8) Premature failures (theft)

For cost of production they found that the cost of GCI disc brakes supplied from Railway Workshops is rupees 185 per disc brake. For the composite disc brakes, the procurement cost from their vendor is rupees 498 per disc brake. Although the cost of composite disc brakes are 2.7 times higher but the lifetime for the brakes is 16 times higher compared to the GCI disc brakes. This shows that the operating cost of GCI is cheaper compare to the composite disc brakes. Thus by reducing the operation cost of composite disc brakes it can replace the GCI disc brakes

For cost of operation, they calculate it using the data collected on trial of close circuit BOXN wagon rakes fitted with composite disc brakes. The purpose of this study was to observe

1) Wear pattern and the life of the disc brakes
2) The mechanical strength of the disc brakes
3) Effect of wheel wear and hotspot
4) Brake performance

They were using this data to do a study on the financial implications of this changeover. The detail calculation can be refer to reference [1]

For cost of saving in manpower, the change of disc brakes from GCI to composite disc brakes, there is a decrease in the manpower requirement for maintenance. It is related to the life of the disc brakes. For composite they found that composite disc brakes can be use until 70000 kms while GCI disc brakes needed to be changed every 4500-5000 kms. As the result, it is reducing a lot of money invested in manpower requirements.

For cost of transportation, the composite disc brakes cost are not costly compared to GCI disc brake at the first glance.

For administrative expenses (Overhead), it comprises the ordering and other clerical charges. They found that the cost is equal.

As mention before, the composite disc brakes are lighter in weight compare to GCI disc brakes. This contributed to less time and effort of handling and fitting the composite disc brakes. The calculation is shows in the operation costs [1]

For theft and premature failures the composite disc brakes do not have resale value while the GCI disc brakes have. So the problem for the composite disc brakes to be stolen is zero. This is important because it also contribute to the cost of the product. Furthermore the premature failures of the composite disc brakes are found to be less.

From their research, it is found that composite disc brakes are a good idea. They found that composite disc brakes are not a requirement but rather a necessity. In the present scenario it is found that the cars become more powerful and moving in high speed. So composite disc brakes could be the common usage in conventional car in the future but need to take place in a phased manner with a proper resource and manpower planning. From this research it gives the idea and path to be considered in value analysis for changing the disc brakes from GCI to composite.

2.2.2 Brake materials

The conventional disc brakes that had been use for many years are Grey Cast Iron. Now there are new brake materials that had been used to manufacture disc brakes which are [6]

1) Particle-reinforced Al (Al-MMC)
2) Carbon Fibre reinforced carbon (C/C)
3) Fibre reinforced ceramics or Ceramic Matrix Composite (CMC)
4) Grey Cast Iron

2.3 Criteria

2.3.1 Weight

Composite disc brake is more lightweight compare to cast iron disc brake. The disc brake weight is about 40 to 50 percent less than a cast-iron disc brake. Thus vehicle weight would be reduced significantly. The weight savings are greater than the numbers might suggest because the disc brake, attached near the extreme end of the suspension, is what engineers call unsprung weight. In cornering, the weight of the rotor adds inertia to the suspension's movement, making it difficult for the spring and the shock absorber to maintain control. Less weight acting on the suspension means the tire is more likely to stay in touch with the road as well as improve ride comfort. [6]

For composite material of carbon fibre reinforced carbon the weight saving is about 60% compare to steel. [15]

For CMC, the use of the high-tech material had revolutionized the brake technology in comparison to the conventional grey cast iron brake disk the carbon-ceramic brake disc weighted round 50% less reducing the un-sprung mass by almost 20 kilograms [6]

For Al-MMC, Skolianos and Kiourtsidis (2002) and Lim *et al.* (1999) have shown that aluminum alloy-based metal matrix composites (MMCs) with ceramic particulate reinforcement exhibited great promise for the substitution of cast iron. Al-MMC having lower density compared to conventionally used gray cast iron is expected to exhibit significant weight reduction

Table 2.1 Average mass or weight of the conventional disc brake (Grey Cast Iron) [6]

Brake disc size	15”	16”	17”
Outside diameter x friction ring thickness	Ø288 x 25	Ø312 x 25	Ø345 x 30
Mass brake disc	7.0	8.1	12.1

Table 2.2 Density of 4 materials

Material	Density x 10^3 (kg/m^3)
Grey Cast Iron	7.1
Carbon reinforced carbon	1.7
Ceramic Matrix Composite	2.3
Al-MMC	2.8

2.3.2 Reliability

The basic problem of thermal layout of vehicle brakes is the decrease of a friction value between brake lining and disc when the temperature rises. From study by [6] with data in table 2.3, this is schematically presented in Figure 2.1. It can be seen clearly that an outstanding decrease of the friction value occurs at brake disc temperature of more than 700°C.

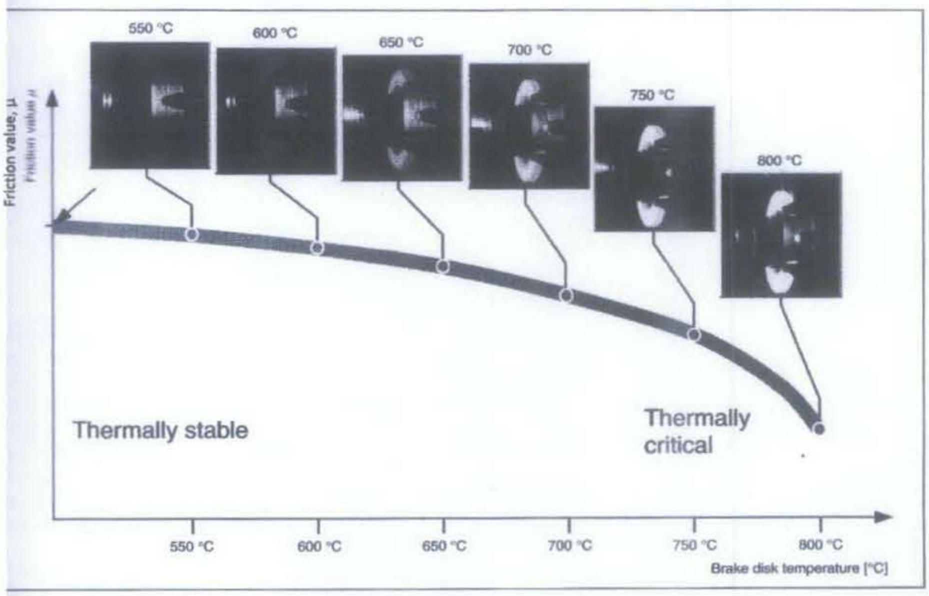


Figure 2.1: Friction value vs Brake disc temperature [6]

The brake disc where all the kinetic energy of the vehicle converted into heat determines the thermal performance of the brake system. This data is for commercial disc brake material which is Grey Cast Iron disc brake.

Table 2.3: GCI properties

Thermal conductivity (w/m K)	50
Thermal expansion (20-300°C)10^{-6} 1/K	18
Thermal capacity (kJ/kgK)	0.65
Layout max working temp (°C)	600
Density (g/cm^3)	7.1
Friction coefficient	0.45

For Carbon reinforced carbon material the capability of structural integrity is at temperature above 1000°C and maximum temperature around 2000 °C. The material has a very high thermal conductivity compare to other composite materials.

Table 2.4: C/C properties [6]

Property	Unit	Carbon-carbon
Compressive strength	Mpa	100-150
Density	g cm-3	1.3-2.5
Tensile strength	Mpa	Up to 900
Thermal expansion	K-1	-2-2x10-6
Thermal conductivity	W m-1 K-1	20-150
Thermal shock resistance	W mm-1	150-170

For Carbon fibre reinforced Ceramics (CMC), it has low thermal expansion of approximately 10^-6 K^-1, and has maximum temperature that can reach to 1400 °C

Table 2.5: CMC properties [13]

Property	Unit	CMC
Density	g cm-3	1.65-1.9
Flexural strength	Mpa	150-230
Thermal conductivity	W m-1 K-1	3.4-4.5
Specific heat capacity	J g-1 K-1	1.2 at 1000degC
Maximum operating temp	Deg C	1400

For Al-MMC, These materials having a higher thermal conductivity as compared to the conventionally used grey cast irons. The heat dissipation capability of the MMC material is much higher than that of a conventional cast iron rotor. By nature, Aluminium is a very good heat conductor, with a thermal conductivity of over four times greater than that of cast iron. One major problem with using an MMC rotor is its maximum operating temperature. As the material contains mostly Aluminium, the MMC rotor has a maximum operating temperature of 450 degrees C Ref [2]. Note that in Figure 2, the maximum temperature the pads were tested to was 430 degrees C.

Table 2.6: Al-MMC properties [2]

Property	Unit	Al-MMC
Density	g cm-3	2.45-3.01
Compressive yield strength	Mpa	109.6-406.5
Tensile ultimate strength	Mpa	76.8-461.6
Compressive ultimate strength	Mpa	202.6
Thermal conductivity	W m-1 K-1	175-190

2.3.3 Durability

For C/C material it has higher friction coefficient compare to cast iron. As they are made of fibrous material, they are soft and silent while braking. But they don't last longer, as there is faster wear and tear in such a material.

For CMC
In comparison with grey cast iron or carbon/carbon, C/C-SiC braking composite exhibits high coefficient of friction (COF), extremely low wear rate, especially strong environmental adaptability.

For Al-MMC, the combination of aluminium alloy and ceramic reinforcement has a favourable combination of high ductility of the aluminium and high strength of the reinforcement. Particulate-reinforced Al alloy based composites have attracted a lot of interest owing to their enhanced wear resistance as compared with the conventional alloys. The addition of small amounts of hard particulate fibre reduces the wear rates markedly. In high temperature applications Al-MMC components resistance against sliding wear and seizure are the principal design criteria. Although these components are often required to operate at temperatures around 100-200C, This Al-MMC can be used in wear limited applications, such as brake disc.

Because of the reinforcement by the SiC particles, the wear behaviour of the Al-MMC proved to be surprisingly lower than the wear rates of existing standard friction ring materials such as grey cast iron and SG iron. The wear rates attained in field tests, over distances of 1.2 x 10^6km, gave an overall predicted wear life of more than 15 years compare to cast iron which the distance takes about 0.5 x 10^6km for only 5 years.

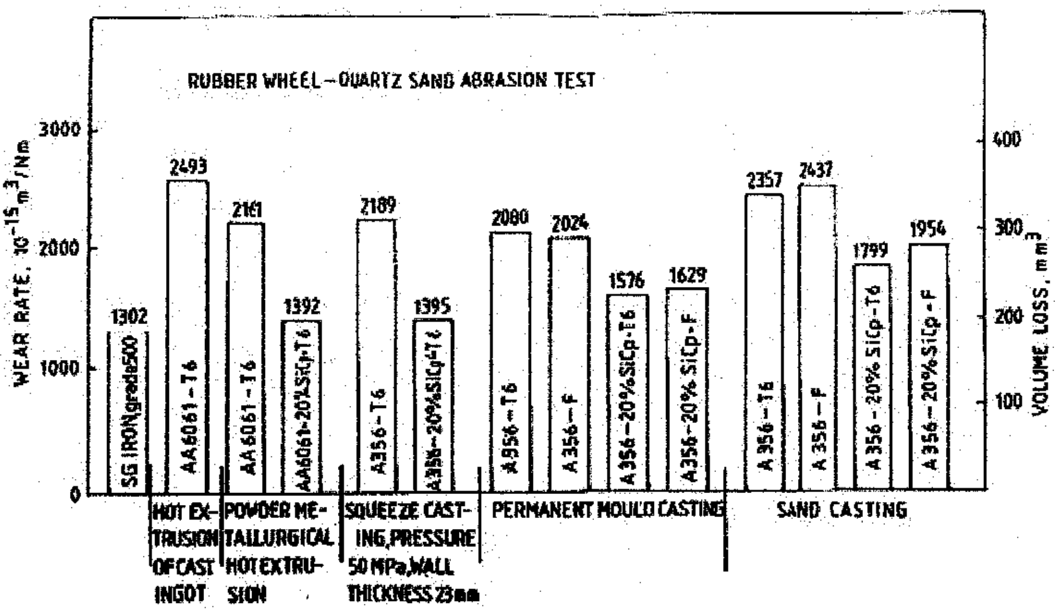


Figure 2.2: Wear Properties of some Al-MMC Compared to the Base Metal [16]

2.3.4 Material cost

i. Material cost for Grey Cast Iron = 1.50USD/kg
ii. Material cost for C/C = 11.00USD/kg
iii. Material cost Aluminium = 5.50USD/kg
iv. Material cost CMC = About same price with carbon fibre or little bit higher

Resource from text book Introduction to Material Science Engineering [21]

2.3.5 Manufacturing process

1) Particle-reinforced Al (Al-MMC) disc brake

The stages of producing Al-MMC are based on the mixture of a different component which are ceramic and Aluminium. Normally the ceramic particles are stirred into the Al melt by special process and cast into bars, which then delivered to the brake disc manufacturer [6]

2) Carbon Fibre reinforced carbon (C/C) disc brake

First stage

The carbon fibre is in spool shape. The next process is to make preform. Preforms are made in several ways. To make the preform by braiding and filament winding, dry fibres are laid over a mandrel. The braided preform is becoming common and widely used for RTM processes. The next process is shaping the composite preform based on suitable fabric architecture for disc brake. Perform are feedstock for the Resin Transfer Molding (RTM) processes, where a reinforcement in the form of a thick two or three dimensional fibre architecture is put in a mold cavity and the resin is injected into the cavity to obtain the composite disc brake shape. [15]

Preform can be any shape, one method is the fibres and binder material are sprayed into a perforated perform screen mold. The mold rotates but the spray gun remains stationary. With gradual application of chopped fibres and binders, a suitable preform thickness builds up. The binder keeps the fibres together and maintains the shape of the preform, in this case the shape of disc brake.

Second stage

The composites are then machined to near net shape. The disc grows slightly during high temperature treatment following the infiltration process and final machining. This final high temperature treatment is generally required to achieve the desired frictional performance characteristics [18]. A longer CVD infiltration cycle is then performed to provide the final density to the composite.

The method of manufacturing a carbon-carbon composite brake disc includes the following steps.

i. A textile-based preform is provided, roughly in the shape of an annular brake disc. The preform typically has a volume about 50% greater than the volume of the carbon-carbon composite brake disc to be manufactured.
ii. The preform is subjected to CVD processing for from about 3 to about 7 days, in order to densify it to a density of not more than approximately 1.0 g/cc.
iii. This low-density preform is machined to a shape having a volume which is no more than about 10% greater than the volume of the carbon-carbon composite brake disc to be manufactured.
iv. The preform is subjected to another cycle of CVD processing, for from about 10 to about 15 days, to further densify the preform. The resulting densified preform is machined to a shape having a volume no more than about 5% greater than the volume of the carbon-carbon composite brake disc to be manufactured.
v. The preform is subjected to a last cycle of CVD processing, of up to about 12 days, in order to further densify the preform to more than 1.7 g/cc. The resulting fully densified preform is subjected to final machining to provide the desired carbon-carbon composite brake disc product.

<u>Machining</u>

For machining it is like the usual machining process to make grey cast iron brake where there are face milling operation, drilling and boring operations.

3) Fibre reinforced ceramics or Ceramic Matrix Composite (CMC) disc brake

For manufacturing method, DaimlerChrysler has been developed a patented manufacturing process which focuses on the following procedure [6]

First stage

The process starts by mixing of carbon fibers and phenolic resin. The fibers are carefully chosen for length and thickness (diameter). The resin is in solid granular form.

Second stage

The next stage is hot pressing to form required structure. The ingredients are mixed together and then loaded into a steel mold. The mold halves are closed, pressure and heat are applied. When the molding dies are opened and the cores are extracted, a near-net-shape brake rotor emerges. The amount of excess material is minimized because removing it with subsequent operations is difficult due to the extreme hardness of a finished CCM rotor. While what emerges looks like a finished part, it's not yet ready for use.

Carbonisation of the structure to porous C/C at 900…1100° C and Siliconisation at 1500…1650° C. The serious business begins when the molded rotors are placed with other like parts in an oven with the ability to maintain an oxygen-free environment at high temperature. In addition to numerous rotors, a quantity of solid silicon is placed in the oven. Nitrogen is pumped in to displace the air and the temperature dial is set for 1000-degrees Celsius (1850-degrees Fahrenheit)[7]. That temperature is maintained for many hours during which the silicon becomes a liquid and pyrolysis (essentially burning in the absence of oxygen) occurs. The silicon gradually migrates into the pores of the parent material by capillary action and the original carbon and phenolic materials are transformed into silicon carbide, a hard and highly heat resistant ceramic substance.

After the oven cools to room temperature at a controlled rate, the rotors are removed and machining operations begun. The inner and outer diameters, mounting locations, and braking faces must be finished with high accuracy to assure excellent braking performance with minimal noise and vibration. Grinding operations with diamond tools achieve the desired dimensions.

A coating is applied to all surfaces of the CCM brake rotor to provide oxidation protection.

Next is the assembling process. The centre section is attached to the CCM rotor with stainless-steel screw, nut, and anti-rattle hardware. Some axial and radial movement (float) between the metal hat and CCM rotor must be provided because the two components have drastically different temperature-expansion rates. Anti-rattle springs allow this movement while preventing noise and vibration.

4) Grey Cast Iron disc brake

First Stage

Casting is a process by which a fluid melt is pour into a mold, allowed to cool in the shape of the form, and then ejected to make a fabricated part or casing. Four main elements are required in the process of casting: pattern, mold, cores, and the part. The pattern, the original template from which the mold is prepared, creates a corresponding cavity in the casting material. Cores are used to produce tunnels or holes in the finished mold, and the part is the final output of the process.

Second stage

Machining and surface finish

Facing is a process of making a flat surface as the result of a tool's being fed across the end of the rotating workpiece. Facing may be done either from the outside inward or from the center outward.

2.3.5.1 Manufacturing cost equation

Manufacturing cost begin to determined the embodiment design, as design details get firmed up

A detail estimate of manufacturing cost is as following steps

1) The detailed analysis of the product and the preparation of list of the components are been made, with an accurate count of the number of parts required
2) A manufacturing process plan is draw for each component
3) The material costs for each component is determined
4) The manufacturing time (cycle time) for each manufacturing operation listed in step 2 is determined
5) The labor and overhead (burden) rates is applied to each operation.
6) The manufacturing cost is the sum of steps 3 and 5

The manufacturing cost per unit C_u is given by

$$C_u = C_M + C_L + OH \quad (2.1)$$

C_M = material cost per unit

C_L = labor cost per unit

OH = overhead

Where,

$$C_M = (\eta V_n k_v + OH_M) + (B + OH_b) \ldots\ldots\ldots..(2.2)$$

η = allowance factor

V_n = net volume of the part such that $V_g = \eta V_n. k_v$, where V_g gross volume

OH_M = material overhead to account for procurement, inspection, storage, interest on this inventory, and material handling cost

B = purchase cost of the component

OH_b = overhead on B

$$C_L = C_{dl} + C_{su} + OH_L \ldots\ldots\ldots\ldots\ldots..(2.3)$$

$C_{dl} = k_L t_u$ is the direct labor cost

C_{su} = cost of machine setup

OH_L = overhead of direct labor

2.3.6 Manufacturing cost

The manufacturing cost that involve in manufacturing are as followed

1) Labor cost
   - Direct labor (Ld), which changes the product's condition, status, shape, packaging, appearance, or function
   - Overhead (OHL), which provide supporting supervision. Clerical and administrative personnel, labor relations, maintenance, safety, janitorial and security activities without direct product contact. [18]

2) Overhead
   - Indirect operating expenses
   - Procedures for establishing and using standard factory overhead rates are similar to the methods of dealing with the estimated direct and indirect factory overhead and its application to jobs and products. An overhead budget for the rate calculation provides a budget allowance for a specific, predetermined level of activity, while a flexible budget provides allowance for various levels of activity.[19]

Table 2.7: An example of the effect of volume on overhead cost per unit [19]

Production volume (units)	80,000	90,000	100,000	110,000
Factory overhead:				
Variable	$112,000	$126,000	$140,000	$154,000
Fixed	60,000	60,000	60,000	60,000
Total	$172,000	$186,000	$200,000	$214,000
Factory overhead per unit:				
Variable	$1.40	$1.400	$1.40	$1.400
Fixed	0.75	0.667	0.6	0.545
Total unit overhead cost	$2.15	$2.067	$2.00	$1.945

3) Material

  - Purchase cost of component (Direct material), are those which become part of the product and include the scrap which is generated by chips and errors in the fabrication
  - Can best defined as those materials which support the manufacturing operation but are not actually used in the manufacturing process [18]

4) Equipment cost

  - Each piece of manufacturing equipment and machinery, and each piece of materials handling and storage equipment. [18]

CHAPTER 3 METHODOLOGY

3.1 Methodology flowchart

The flow of the activity for the project is shown in Figure 3.1

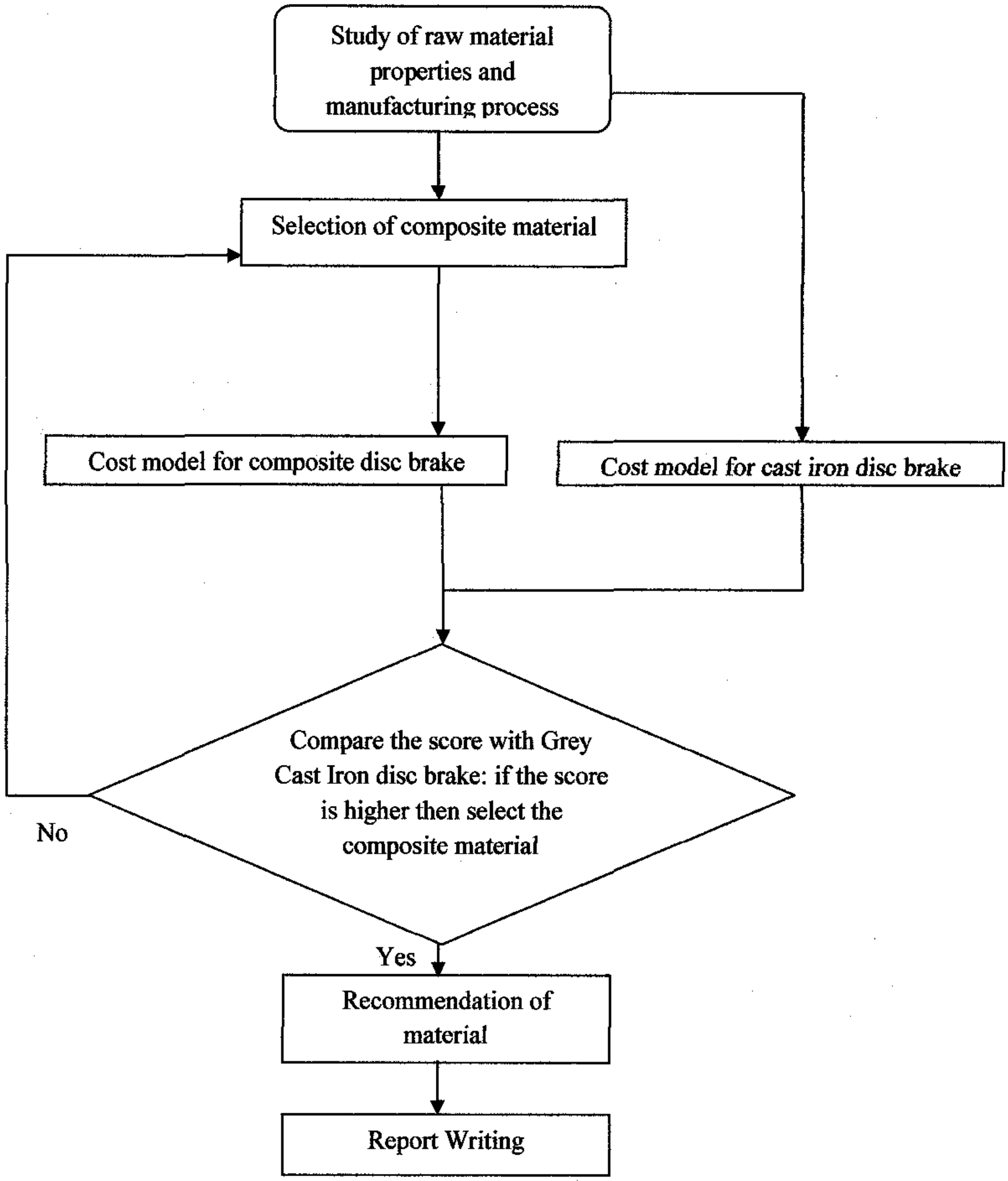


Figure 3.1: Methodology flowchart

3.2 Methodology Preliminary Study

Study of raw material properties and manufacturing process

The crucial criteria that need to be considered to chose the composite disc brake is the manufacturing process. Each of the processes is determined from raw material until become a product which is disc brake. The manufacturing process is found from book and journal. After gathering the information, the process plan is developed. The detail process plan is shown in result part for each of material of the disc brake.

Selection of composite material

To select the composite material, some criteria need to be chosen to evaluate the properties of the disc brake. The criteria that had been chosen are weight, reliability, durability, manufacturing process, material cost and lastly the manufacturing cost.

Table 3.1: Template weight decision matrix

Number (n)	Design criterion (F_n)	Weight factor (W_n)	Units	Material (M_i)		
				Magnitude	Score (S_n)	Rating (R_n)
1	F_1	W_1	$/unit	0	S_1	0
2	F_2	W_2	$/kg	0	S_2	0
3	F_3	W_3	Kg	0	S_3	0
4	F_4	W_4	0	0	S_4	0
5	F_5	W_5	Experience	Satisfactory	S_5	0
	Score (TS)					**0**

For each material (M_i) for Design criterion (F_n)

$R_n = W_n \times S_n$.........(3.1) $n = 1,2,3,4,5.....$

$TS = \sum W_n S_n$...........(3.2)

$= W_1S_1 + W_2S_2 + W_3S_3 + W_4S_4 + \ldots W_nS_n$

$= \sum R_n$

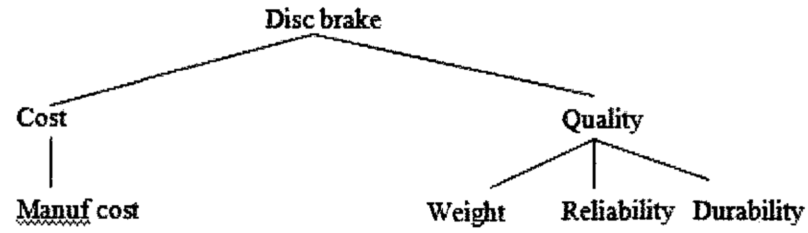
Where, R_n = Rating at n

W_n = Weight factor at n

S_n = Score at n

TS = Total score

Weight factor (W_n) is determine using Objective tree method



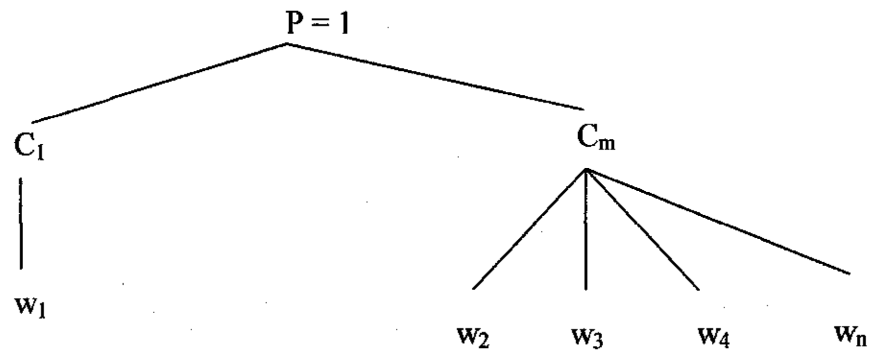


Figure 3.2: Objective tree for disc brake

From this we develop mathematical model as below

For Project (P)

$\sum C_m = 1$ (maximum value) …….(3.3) $m = 1,2,3,4,5,\ldots$

$C_1 + C_2 + C_3 + C_4 + C_m = 1$

For criteria (C_m)

$\sum w_{nm} = 1$ (max value)………(3.4) $n = 1,2,3,4,5..$ (value of n corresponding with the function number F_n)

$w_1 + w_2 + w_3 + w_4 + w_{nm} = 1$

$\sum w_{nm}$ is weight n of criteria m (C_m)

To get the weight of a factor on lower level, multiply the weight as go up of the chain.

$W_n = w_{nm} \times C_m \times P$………(3.5)

Where, W_n = Weight factor at n

w_{nm} = Weight for criteria m

C_m = criteria at m

P = Project

For weight the density of each material need to be found from Grey Cast Iron, Al-MMC, Carbon reinforced Carbon and Ceramic Matrix Composite

After the density of each material found, the GCI density is use as the datum. The average weight of normal brake is about 7kg. After that the author use formula below to calculate the volume of GCI disc brake

$$\rho = m/V \ldots\ldots\ldots (3.6)$$

The volume get from GCI is use to calculate the weight reduction of composite material.

Second criteria that need to be considered are the reliability of the disc brake. Reliability need to be considered because the brake disc is deal with heat and friction. It also involves the security of the vehicle and the people. So it needs to have very good reliability disc brake. The information of each of disc brake material is gathered. The information that relate with reliability are thermal conductivity, thermal expansion, thermal capacity, maximum working temperature, the strength of the material and many more. So this entire characteristic is compared to select which one of the composite materials is more reliable. The characteristic is shown in literature review part. The result is shown in the result part.

Third criteria that had been considered are durability of the disc brake. The durability is related to the friction and the lifetime of the disc brake. The information is gathered from journal and internet and the composite disc brake is compared which one have high durability. The datum use for comparison is the GCI disc brake. The rank is shown in the result part

Cost model for GCI and composite disc brake

Develop a cost model to determine which costs needed for the manufacturing of the disc brake. After that the breakdown cost is applied to all of the process involves to manufacture GCI and composite disc brake. The cost involves such as material cost, labor, overhead, equipment and any other cost related. Then the data of each process is collected and the total cost of production is calculated using EXCEL. The method to determine the material and manufacturing cost is using equation as shown

Material cost = Volume x Density x Unit Cost ......(3.7)

Manufacturing cost = (Direct labor cost per kg x Quantity per day x Mass of raw material use) + Overhead cost + Equipment depreciation cost + Material cost ....(3.8)

Comparison between GCI and composite disc brakes

In the Weighted Decision Matrix table there are design criterion (Weight, reliability, durability, manufacturing cost), weight factor, units, magnitude, score and rating for each material of disc brake.

The score (S_n) is given based on the literature review using evaluation scheme for design objective table. The rating of each disc brake from GCI until Al-MMC is calculated and the Total Score (TS) is received.

Table 3.2: Evaluation scheme [17]

Evaluation scheme for design objectives

11-point scale	Description	5-point scale	Description
0	Totally useless solution	0	Inadequate
1	Very inadequate solution		
2	Weak solution	1	Weak
3	Poor solution		
4	Tolerable solution	2	Satisfactory
5	Satisfactory solution		
6	Good solution with a few drawbacks		
7	Good solution	3	Good
8	Very good solution		
9	Excellent (exceeds the requirement)	4	Excellent
10	Ideal solution		

Recommendation of material

The comparison is made between GCI and composite disc brake. If the Total Score (TS) of composite disc brake is better than GCI then the composite material will be recommended. If not the process is repeat again to the selection of composite material stage until achieved the best selection of composite materials.

CHAPTER 4 RESULTS & DISCUSSION

4.1 Results

4.1.1 Material cost

i. Material cost for Grey Cast Iron = 1.50USD/kg
ii. Material cost for C/C = 11.00USD/kg
iii. Material cost Aluminium = 5.50USD/kg
iv. Material cost CMC = About same price with carbon fibre or little bit higher

For material cost, the best cost is always the GCI, followed by Al-MMC, CMC and C/C

4.1.2 Weight comparison

Using Grey Cast Iron as a datum, the volume of 7kg disc brake according to their density are

$\rho = m/V$

$V = \rho / m$

$= 0.000992 m^2$

So the volume is used to calculate the weight reduction of composite based on their density

For C/C

$m = \rho V = (1.7 \times 10^3)(0.000992) = 1.7$ kg

Thus, the % of weight reduction are $(7-1.7)/7 \times 100 = 76\%$

For CMC

$m = \rho V = (2.3 \times 10^3)(0.000992) = 2.3$ kg

Thus, the % of weight reduction are (7-2.3)/7 x 100 = 67%

For Al-MMC

m = ρ V = (2.8 x 10^3)(0.000992) = 2.8 kg

Thus, the % of weight reduction are (7-2.8)/7 x 100 = 60%

So the rank of the best weight are C/C > CMC > Al-MMC

4.1.3 Reliability

Reliability is measured by the maximum operating temperature of four different materials. The maximum operating temperature of GCI is set as a datum which is 600°C. For C/C the maximum operating temperature is above 1000 to 2000 °C, for CMC is 1400°C and Al-MMC is below GCI which is 430 °C

So calculation to determine the reliability as below

Due to C/C disc brake has the higher maximum operating temperature, so author take the materials as datum to calculate reliability

C/C, 2000/2000 = 1

CMC, 1400/2000 = 0.7

GCI, 700/2000 = 0.35

Al-MMC, 450/2000 = 0.23

4.1.4 Durability

For durability it is measured by the wear rate of the 3 composite material compare to GCI. From the literature review the best wear resistance is CMC followed by Al-MMC and the last one is C/C.

4.1.5 The process flow in manufacturing of Disc Brake.
For Grey Cast Iron

Figure 4.1: Manufacturing process flow for Grey Cast Iron

For composite
Particle-reinforced Al (Al-MMC)

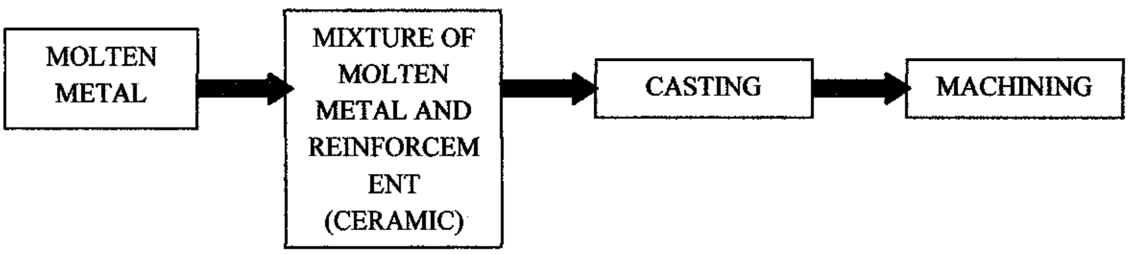


Figure 4.2: Manufacturing process flow for Al-MMC

Carbon Fibre reinforced carbon (C/C)

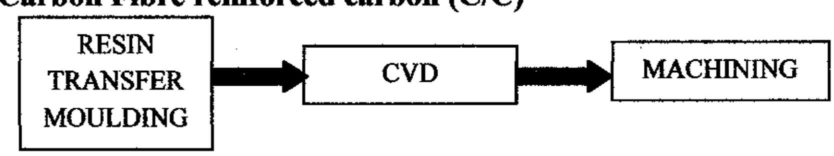


Figure 4.3: Manufacturing process flow for C/C

Fibre reinforced ceramics or Ceramic Matrix Composite (CMC)

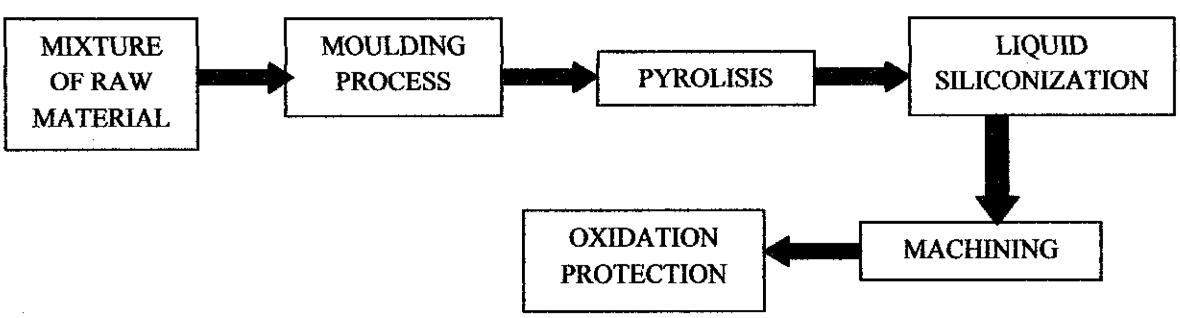


Figure 4.4: Manufacturing process flow for CMC

4.1.6 Manufacturing cost

For manufacturing cost, the cost is segregated into four types which are Labor, Overhead, Equipment Depreciation and also including the Material cost. The lists of the cost for GCI and composite disc brake are as following table. There are estimation manufacturing costs for each material. The estimation was done by referring to the cost of each process to manufacture GCI and composite disc brakes in the internet [22] and from reference [14]

Table 4.1: Estimation Manufacturing cost for Grey Cast Iron disc brake

Cast iron

1) Process - Molten metal	Cost ($)	Cost for 1kg	Quantity per day	Quantity per year	Weight (kg)	Total cost
a) Labor						
i) Direct labor	$6.60	$0.0066	1,000	350,000	7.00	$16,170.00
b) Equipment Depreciation (1yr)	$10,000.00					$10,000.00
					TOTAL	$26,170.00
2) Process - Casting						
a) Labor						
i) Direct labor	$25.69	$0.0257		350,000	7.00	$62,940.50
b) Equipment Depreciation (1yr)	$32,000.00					$32,000.00
					TOTAL	$94,940.50
3) Process - Machining/Finishing						
a) Labor						
i) Direct labor	$20.00	$0.0200		350,000	7.00	$49,000.00
b) Equipment Depreciation (1yr)	$2,000.00					$2,000.00
					TOTAL	$51,000.00
4) Materials	$15.68	$0.0157	1,000	350,000	7.00	$38,416.00
5) Overhead	$0.23	$0.0002	1,000	350,000	7.00	$563.50
				TOTAL PRODUCTION COST		$160,090.00

Table 4.2: Estimation Manufacturing cost for Al-MMC disc brake

Particle reinforced Al (Al-MMC)

1) Process - Molten metal	Cost ($)	Cost for 1kg	Quantity per day	Quantity per year	Weight (kg)	Total cost
a) Labor						
i) Direct labor	$75.00	$0.0300	1,000	350,000	2.80	$29,400.00
e) Equipment Depreciation (1yr)	$8,000.00					$8,000.00
					TOTAL	$37,400.00
2) Process - Mixture and reinforced						
a) Labor						
i) Direct labor	$6.05	$0.0061		350,000	2.80	$5,929.00
e) Equipment Depreciation (1yr)	$2,000.00					$2,000.00
					TOTAL	$7,929.00
3) Process - Casting						
a) Labor						
i) Direct labor	$25.69	$0.0257		350,000	2.80	$25,176.20
e) Equipment Depreciation (1yr)	$32,000.00					$32,000.00
					TOTAL	$57,176.20
4) Process - Machining/Finishing						
a) Labor						
i) Direct labor	$35.00	$0.0350		350,000	2.80	$34,300.00
e) Equipment Depreciation (1yr)	$2,000.00					$2,000.00
					TOTAL	$36,300.00
5) Materials	$5.50	$0.0055	1,000	350,000	2.80	$5,390.00
6) Overhead	$0.23	$0.0002	1,000	350,000	2.80	$225.40
				TOTAL PRODUCTION COST		$144,420.60

Table 4.3: Estimation Manufacturing cost for C/C disc brake

Carbon fibre reinforced carbon (C/C)

1) Process - Resin Transfer Molding	Cost ($)	Cost for 1kg	Quantity per day	Quantity per year	Weight (kg)	Total cost
a) Labor						
i) Direct labor	$1.44	$0.0014	1,000	350,000	1.70	$856.80
b) Equipment Depreciation (1yr)	$120,000.00					$120,000.00
					TOTAL	$120,856.80
2) Process - CVD						
a) Labor						
i) Direct labor	$1.44	$1.4400	1,000	350,000	1.70	$856,800.00
b) Equipment Depreciation (1yr)	$120,000.00					$120,000.00
					TOTAL	$976,800.00
3) Process - Machining/Finishing						
a) Labor						
i) Direct labor	$35.00	$0.0350		350,000	1.70	$20,825.00
b) Equipment Depreciation (1yr)	$2,000.00					$2,000.00
					TOTAL	$22,825.00
4) Materials		$11.0000	1,000	350,000	1.70	$18,700.00
5) Overhead	$0.16	$0.0002	1,000	350,000	1.70	$95.20
				TOTAL PRODUCTION COST		$1,139,277.00

Table 4.4: Estimation Manufacturing cost for CMC disc brake

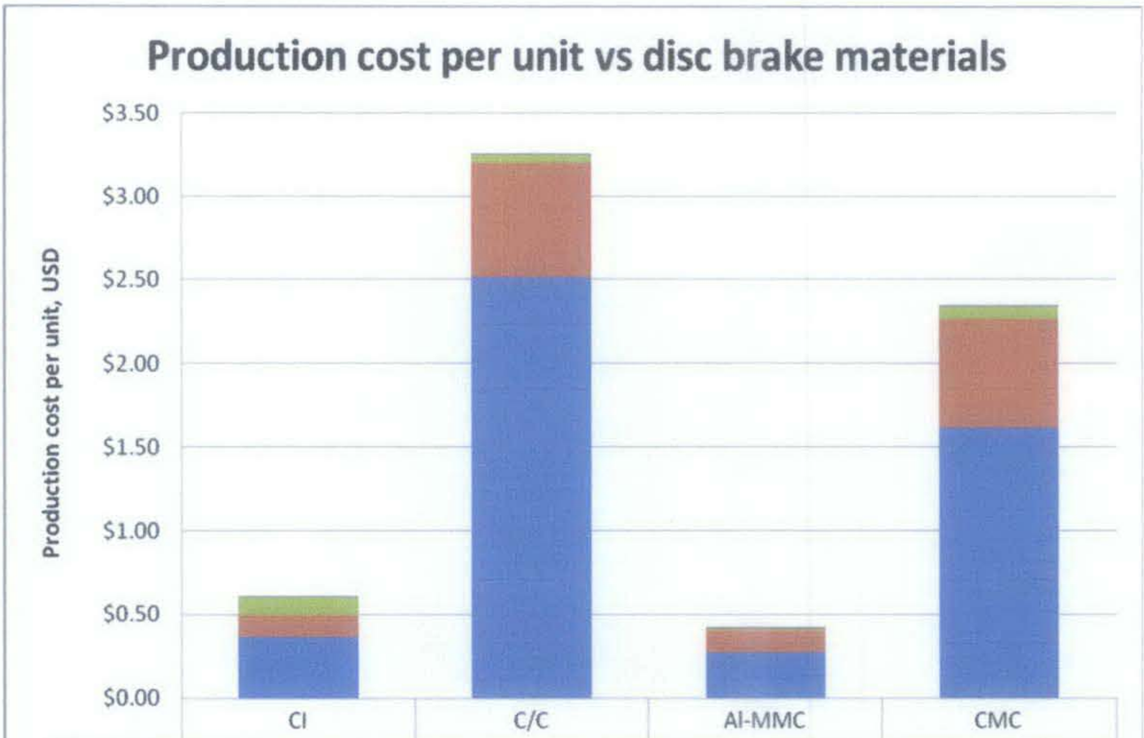
Fibre reinforced ceramics or Ceramic Matrix Composite (CMC)

1) Process - Mixture of elements	Cost ($)	Cost for 1kg	Quantity per day	Quantity per year	Weight (kg)	Total cost
a) Labor						
i) Direct labor	$6.05	$0.0061		350,000	2.30	$4,870.25
e) Equipment Depreciation (1yr)	$2,000.00					$2,000.00
					TOTAL	$6,870.25
2) Process - Moulding						
a) Labor						
i) Direct labor	$25.69	$0.0257		350,000	2.30	$20,680.45
e) Equipment Depreciation (1yr)	$32,000.00					$32,000.00
					TOTAL	$52,680.45
3) Process - Pyrolisis						
a) Labor						
i) Direct labor	$0.67	$0.0007	1,000	350,000	2.30	$539,350.00
e) Equipment Depreciation (1yr)	$180,000.00					$180,000.00
					TOTAL	$719,350.00
4) Process - Liquid siliconizaton						
a) Labor						
i) Direct labor	$0.67	$0.0007	1,000	350,000	2.30	$539.35
e) Equipment Depreciation (1yr)	$200.00					$200.00
					TOTAL	$739.35
5) Process - Machining/Finishing						
a) Labor						
i) Direct labor	$35.00			350,000	2.30	$0.00
e) Equipment Depreciation (1yr)	$2,000.00					$2,000.00
					TOTAL	$2,000.00
6) Process - Oxidation						
a) Labor						
i) Direct labor	$0.67	$0.0007	1,000	350,000	2.30	$539.35
e) Equipment Depreciation (1yr)	$10,000.00					$10,000.00
					TOTAL	$10,539.35
c) Materials		$11.0000	1,000	350,000	2.30	$25,300.00
b) Overhead	$0.16	$0.0002	1,000	350,000	2.30	$128.80
				TOTAL PRODUCTION COST		$817,608.20

From the list of the costs stated above, the cost is divided into four categories which are labor, equipment depreciation, material and overhead cost for each materials of disc brake as shows in the table below:

Table 4.5: Estimation Manufacturing cost for disc brake per unit

	CI	C/C	Al-MMC	CMC
Labor	$0.37	$2.51	$0.27	$1.62
Equipment depreciation	$0.13	$0.69	$0.13	$0.65
Materials	$0.11	$0.05	$0.02	$0.07
Overhead	$0.0016	$0.0003	$0.0006	$0.0004
Total Cost per unit	**$0.60**	**$3.26**	**$0.41**	**$2.34**



	CI	C/C	Al-MMC	CMC
Overhead	$0.0016	$0.0003	$0.0006	$0.0004
Materials	$0.11	$0.05	$0.02	$0.07
Eqmt dep.	$0.13	$0.69	$0.13	$0.65
Labor	$0.37	$2.51	$0.27	$1.62

Figure 4.5: Graph Production cost per unit vs disc brake materials

The Annual Production cost for each material of disc brake is transfer to a graph format as above. From this graph, we can estimate and compare the cost of labor, materials, overhead, and equipment depreciation for four types of disc brakes.

1) Overhead cost

From the estimation, the higher overhead cost is GCI disc brake. This is due to high quantity of production of GCI disc brakes. So the cost of owning and operating the required building for material inventories, facilities usage and equipments is higher.

For C/C and CMC, the overhead cost is almost similar. The quantity of production for these materials is low. This contribute to the lower cost for inventories, facilities usage, equipments etc.

For Al-MMC, it shows the second highest of overhead cost due to the quantity of production is average between C/C & CMC and GCI disc brake.

2) Material cost

This is a major contribution to the production cost. From the graph, the author found that even the composite materials is costly per kg but due to the mass usage is low, the annual materials cost for composite disc brake is low compare to GCI. So this could be the advantage of composite materials compare to GCI if the production quantity is the same. But we know that the demand for composite disc brake is low for now due to other reason that will be discuss for another two types of production cost.

3) Equipment Depreciation cost

From the graph, it is found that the equipments depreciation cost for GCI and Al-MMC is similar. The equipments use is almost the same such as CNC machine and casting machine. Because of the easy way to handle the materials, the manufacturing processes are suitable for standard equipment.

For C/C and CMC, it is found that the Equipment Depreciation cost is very high. The new technology equipments need to be used to handle these materials to make sure that the equipments can handle the characteristic of those composite materials. The cost comparison of the equipment between GCI, Al-MMC and C/C with CMC is about five times greater

4) Labor cost

For labor cost, the highest is C/C disc brake due to the complicated process involve in making the disc brake, the difficulty of the operator to handle the equipment and the process, the time taken to produce the disc brake and etc. It is also a similar case for CMC disc brakes manufacturing which is the second highest labor cost.

For Al-MMC the labor cost is lower than GCI and this is very good finding. But there is also another criteria need to be consider also.

So from all of this costs, to make sure the composite disc brake can be commercialize in automotive market, the cost of labor and equipment cost need to be reduced. This two costs is very close related because the operator is handling the equipment. If the equipment cost can be reduced in the future, thus it also can reduce the labor costs.

From the graph, the very low annual production cost is Al-MMC and it is lower than GCI disc brake. So this could be the new composite material that can be use to produce commercialize disc brake after GCI

4.2 Evaluating using Weighted Decision Matrix

4.2.1 Determine the weight factor for each criterion

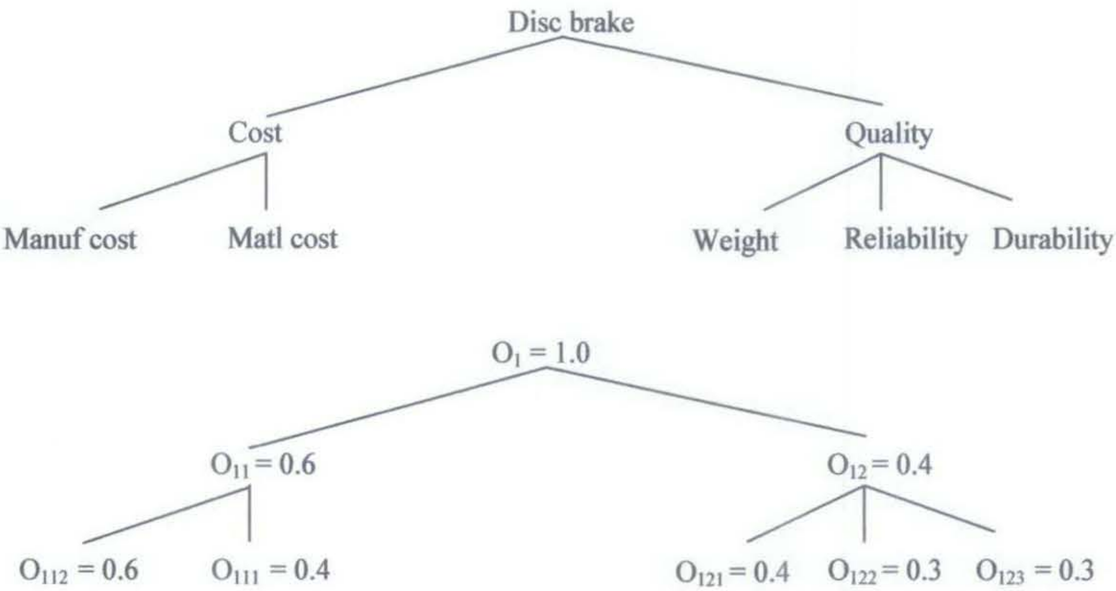


Figure 4.6: Objective tree for disc brake

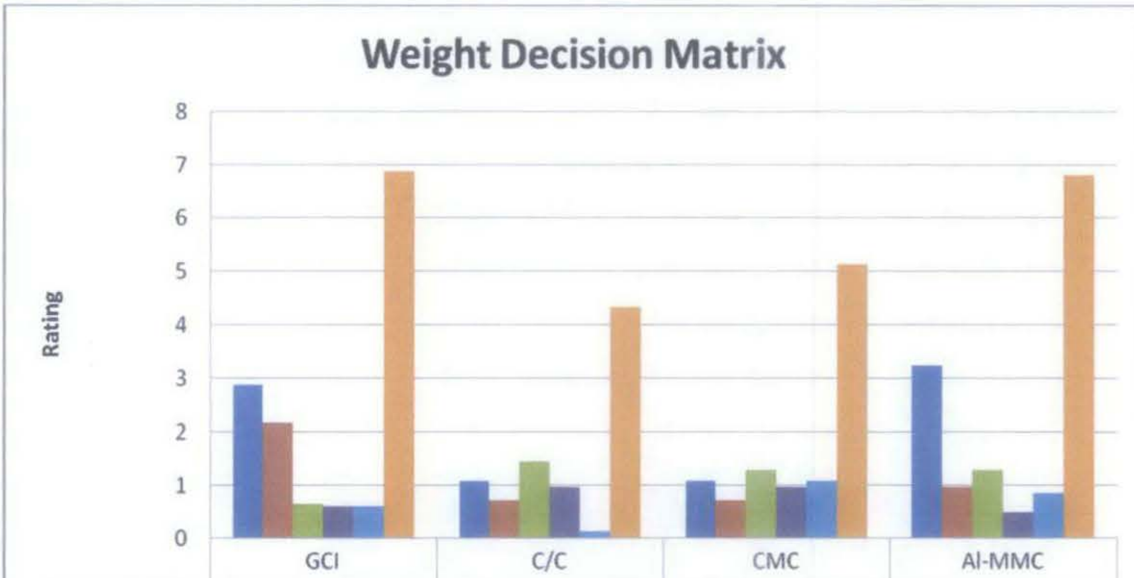
To get the weight of a factor on lower level, multiply the weight as go up of the chain.
For weight of $O_{111} = 0.4 \times 0.6 \times 1.0 = 0.24$
For weight of $O_{112} = 0.6 \times 0.6 \times 1.0 = 0.36$
For weight of $O_{121} = 0.4 \times 0.4 \times 1.0 = 0.16$
For weight of $O_{122} = 0.3 \times 0.4 \times 1.0 = 0.12$
For weight of $O_{123} = 0.3 \times 0.4 \times 1.0 = 0.12$

4.2.2 Weight Decision Matrix for disc brake

Table 4.6: Weight Decision Matrix

Design	Weight		GCI			C/C			CMC			Al- MMC		
criterion	factor	Units	Magnitude	Score	Rating	Magnitude	Score	Rating	Magnitude	Score	Rating	Magnitude	Score	Rating
Manuf cost	0.36	$/unit	0.6	8	2.88	3.26	3	1.08	0.41	3	1.08	2.34	9	3.24
Material cost	0.24	$/kg	1.5	9	2.16	11	3	0.72	11	3	0.72	5.5	4	0.96
Weight	0.16	Kg	7	4	0.64	1.7	9	1.44	2.3	8	1.28	2.8	8	1.28
Reliability	0.12	N/A	0.35	5	0.6	1	8	0.96	0.7	8	0.96	0.23	4	0.48
Durability	0.12	Experience	Satisfactory	5	0.6	Poor	1	0.12	Excellent	9	1.08	High	7	0.84
Score					6.88			4.32			5.12			6.8

The score was assigned from the finding in literature review. The characteristic such as weight, reliability and durability is scored by evaluate the capabilities and properties of each of material. The cost is also found from the literature review and calculate using cost model equation.



	GCI	C/C	CMC	Al-MMC
Manuf cost	2.88	1.08	1.08	3.24
Material cost	2.16	0.72	0.72	0.96
Weight	0.64	1.44	1.28	1.28
Reliability	0.6	0.96	0.96	0.48
Durability	0.6	0.12	1.08	0.84
Score	6.88	4.32	5.12	6.8

Figure 4.7: Graph for weight decision matrix

From the graph, the following are noted

- The best manufacturing cost is Al-MMC disc brake followed by GCI, CMC and the last one is C/C disc brake
- The best material cost is GCI, followed by Al-MMC, CMC and C/C
- The best weight would be the C/C disc brake, followed by CMC, Al-MMC and lastly GCI
- The best reliability would be C/C and CMC, followed by GCI and lastly Al-MMC

- The best durability CMC, then Al-MMC, GCI and the least durability is C/C
- From this rating, the highest score is GCI, the second one is Al-MMC followed by CMC and lastly C/C

CHAPTER 5 CONCLUSION & RECOMMENDATION

5.1 Conclusion

From this thesis the manufacturing cost of each material which is Grey Cast Iron, Aluminium Metal Matrix (Al-MMC), Carbon reinforced Carbon (C/C) and Ceramic reinforced Composite (CMC) has been investigated.

The manufacturing costs of GCI and composite disc brake were segregated into several costs such as Labor, Overhead, Material and Equipment Depreciation cost. The costs that had been considered are according to process plan in the literature review. These costs are studied to eliminate any unnecessary process in making disc brake in order to reduce the cost. The result shows that Al-MMC is the best choice. This is due to the lower cost for material and labor. The material is easily available and easy to manufacture.

For the properties of these four materials, it is found that the lightest weight is C/C disc brakes due to its low density. This material also has the best reliability compared to three other materials. It is due to the maximum temperature operation which can withstand until 2000°C.

For the best durability, CMC and Al-MMC is the best because their low wear rate compare to GCI and C/C disc brakes. When the wear rate is low, the life of the disc brake is longer and it can be use for longer distance travel by a vehicle

After all the information was collected, the Weighted Decision Matrix was adopted to compare each of the properties and cost for every materials. From this method it is found that the best choice is still the GCI followed by Al-MMC, CMC and lastly C/C disc brakes.

For Al-MMC, it shows that this material has better performance compared to commercial Grey Cast Iron. But for Al-MMC, there is one disadvantage that had been discovered where the maximum temperature to operate is below the commercial GCI.

For CMC, it has greater performance but the manufacturing process is complicated, even higher cost and time consuming. Even now there are already produce this type of disc brake but it is not suitable for mass production yet.

For C/C it is the lowest rating for replacement of disc brake. This is not suitable for mass production. This type of disc brake although has the best performance but there is disadvantage in the performance which is easy to wear. This also shows that it is not suitable for common car users that always use their car. It is only suitable for function use such as racing.

5.2 Recommendation

For Al-MMC and CMC, these two materials are the best materials to replace the Grey Cast Iron disc brake.

But there are disadvantages that need to be considered. The disadvantage of Al-MMC is the lowest operating temperature compare to GCI. The disadvantage of CMC disc brakes are the expensive cost of equipment use to produce it. Due to that matter the labor cost also increase for certain process.

So for the future, the technology needs to minimize the equipment cost thus the labor cost will also reduce. When the cost reduce it will be possible for composite disc brake to be in mass production for conventional cars. In addition the material cost for composite also need to be reduce with the modernizing technology because it also contribute huge effect to the manufacturing cost.

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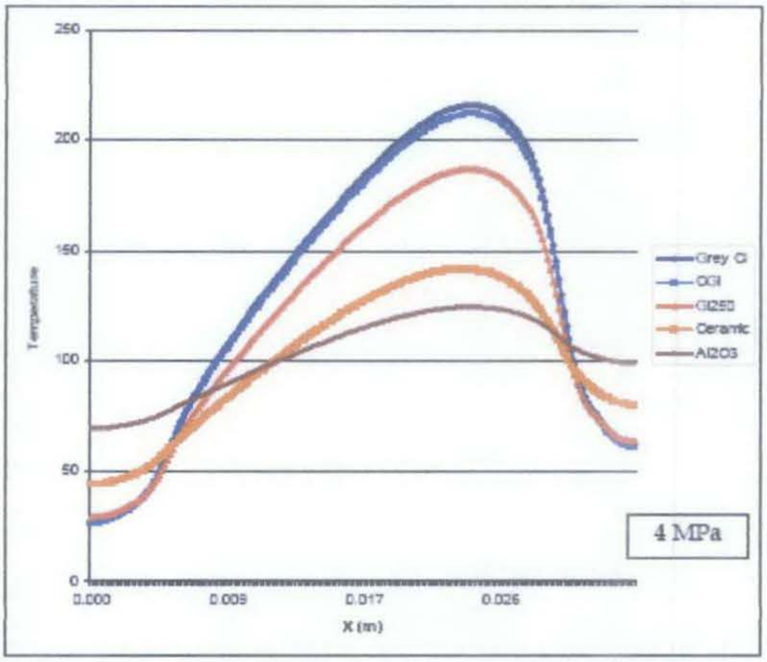
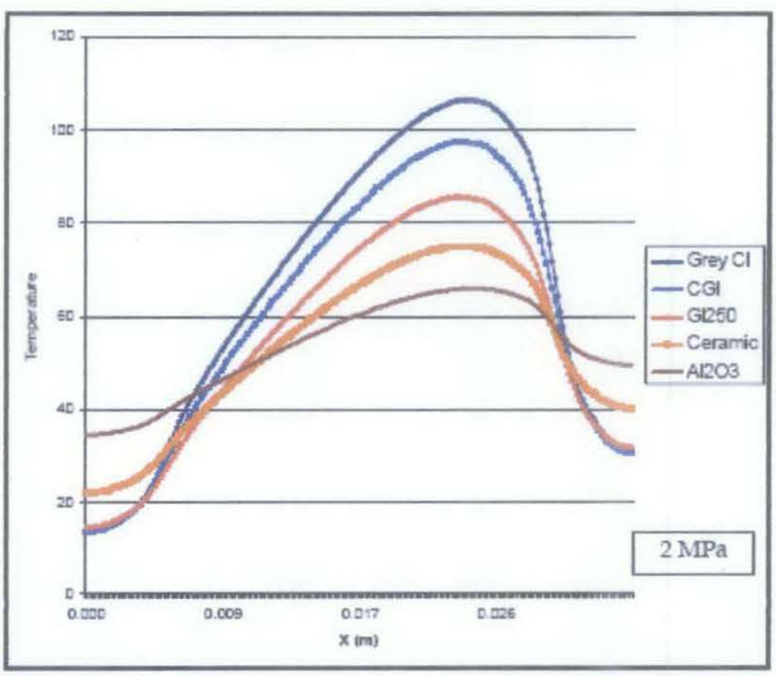
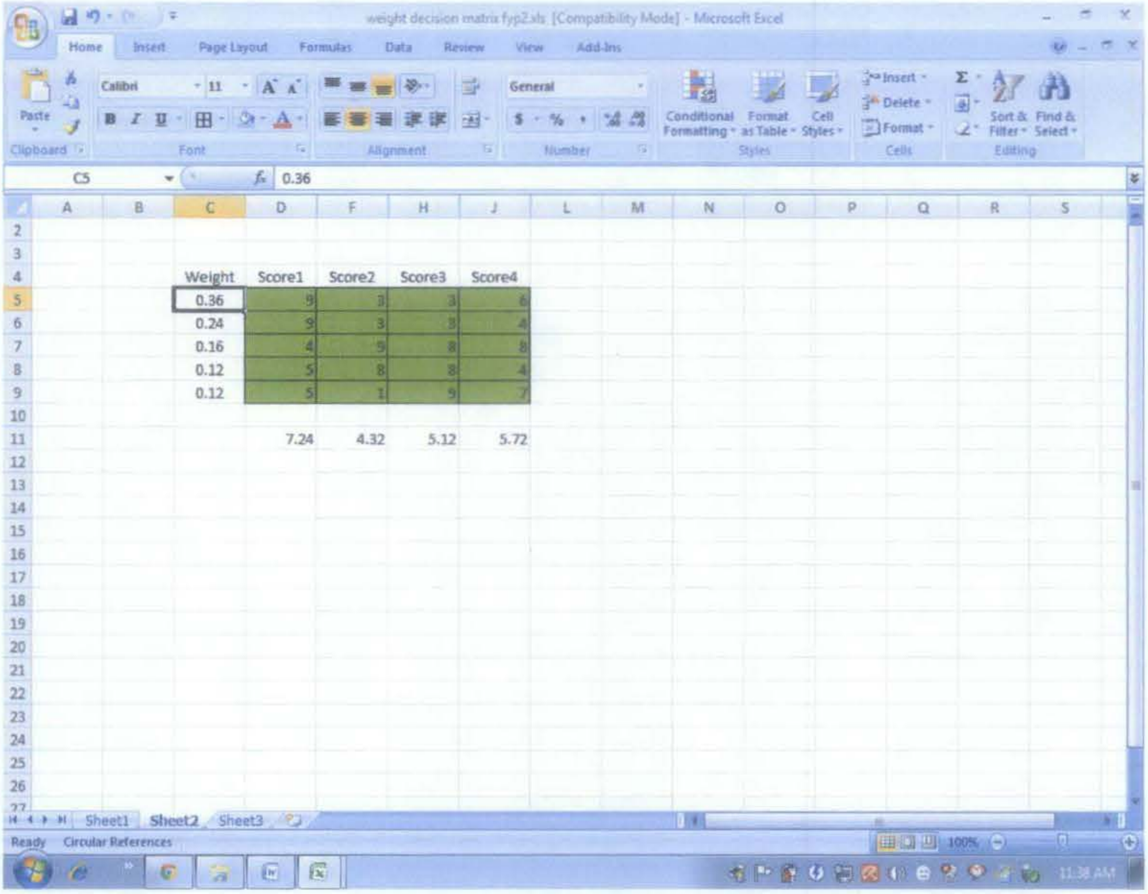


a)

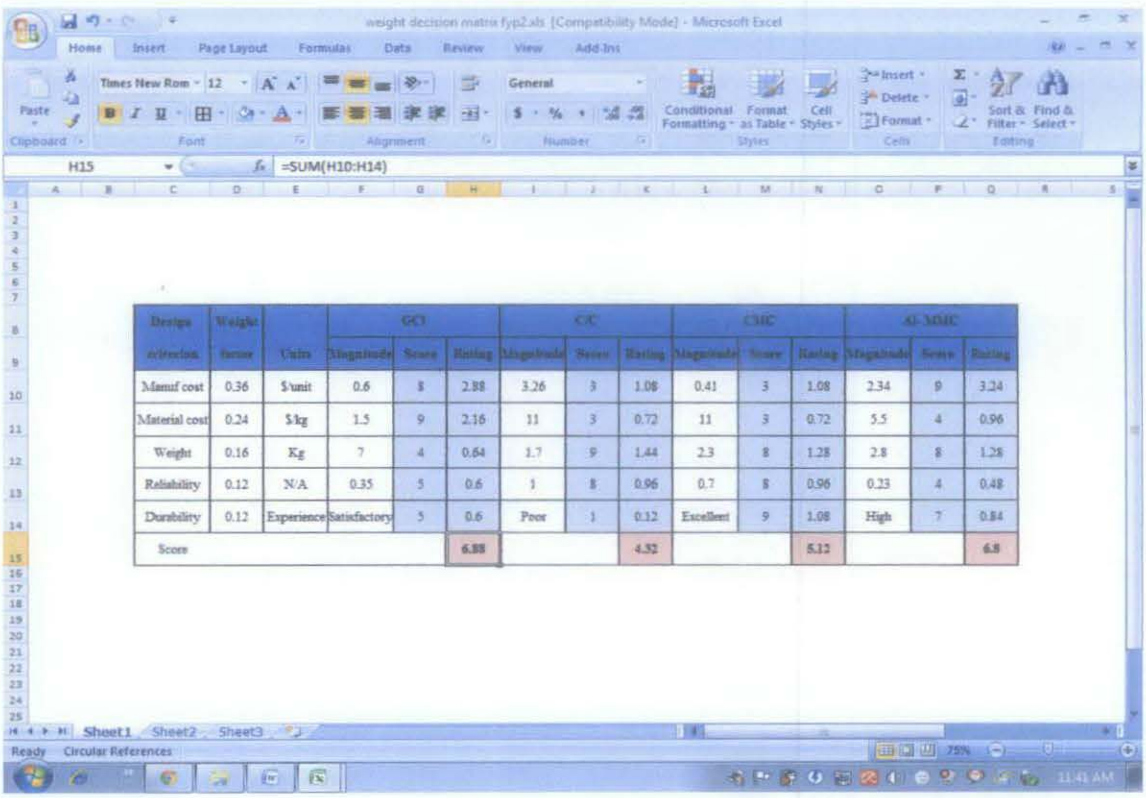


b)

Figure 11. Comparison between the temperature distribution produced in Grey CI, CGI,GI250, Ceramic, and Al2O3 disk brakes at a pressure of a) 4MPa b) 2MPa



	Weight	Score1	Score2	Score3	Score4
5	0.36	9	3	3	6
6	0.24	9	3	3	4
7	0.16	4	9	8	8
8	0.12	5	8	8	4
9	0.12	5	1	9	7
11		7.24	4.32	5.12	5.72



Design criterion	Weight factor	Units	GCI			C/C			CMC			Al-MMC		
			Magnitude	Score	Rating	Magnitude	Score	Rating	Magnitude	Score	Rating	Magnitude	Score	Rating
Manuf cost	0.36	$/unit	0.6	8	2.88	3.26	3	1.08	0.41	3	1.08	2.34	9	3.24
Material cost	0.24	$/kg	1.5	9	2.16	11	3	0.72	11	3	0.72	5.5	4	0.96
Weight	0.16	Kg	7	4	0.64	1.7	9	1.44	2.3	8	1.28	2.8	8	1.28
Reliability	0.12	N/A	0.35	5	0.6	1	8	0.96	0.7	8	0.96	0.23	4	0.48
Durability	0.12	Experience	Satisfactory	5	0.6	Poor	1	0.12	Excellent	9	1.08	High	7	0.84
Score					6.88			4.32			5.12			6.8