Study on Mechanical and Tribological Properties of Sintered Metallic Brake Pad with different Graphite, Silicon Carbide, and Copper content

M.Tech. Thesis

By

Vishal Prajapat

DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

JULY 2018

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A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

of

Master of Technology

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"Study on Mechanical and Tribological Properties of Sintered Metallic Brake Pad with different Graphite, Silicon Carbide, and Copper content"** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE of Mechanical Engineering, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from (**May 2017 to June 2018)** under the supervision of **Dr. Jayaprakash Murugesan of Discipline of Metallurgical Engineering & Material Science.**

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

(Vishal Prajapat)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

(Dr. Jayaprakash Murugesan)

Vishal Prajapat has successfully given his M.Tech. Oral Examination held on **06 July 2018**

Signature of Supervisor of M.Tech.thesis Date:	Convener, DPGC Date:
Signature of PSPC Member 1 Date:	Signature of PSPC Member 2 Date:

ACKNOWLEDGEMENTS

I take this opportunity to express my deep sense of respect and gratitude for, **Dr. Jayaprakash Murugesan**, for believing in me to carry out this work under their supervision. His constant encouragement and constructive support have enabled this work to achieve its present form. His innovative perspective towards things and his continuous pursuit for perfection has had a profound effect on me and has transformed me majorly. I feel greatly privileged to be one of his students.

My gratitude is also extended towards my PSPC members **Dr. Indrasen Singh** and **Dr. Eswara Prasad** for their guidance and cooperation.

I would like to express my recondite thanks to my senior Mr. Rajat Kasliwal & Mr. Sheetal for his moral support and the not-so-serious moments shared between us have been highly beneficial during the hardships of this project. Special thanks are extended to my colleagues Abhishek Ahirwar, Milind Choubey, Akhil Verma, Vivek Rana, Arun Ghidode and Prabhat for their help, suggestions whenever I needed and for always giving me company, and to all the M.Tech 2018, Production and Industrial Engineering (PIE) batch.

I am also thankful to Lab staff of Mechanical Engineering MEMS Department Labs and Central Workshop, specially Mr. Anand Petare ASW, IIT Indore, Mr. Mayur and Mr. Suresh Bhagore, for their cooperation in my experiments.

Last, but not least, I would like to dedicate this thesis to my wife, parents, my family and my friends, for their love, patience, and understanding, because without their support, I would have never reached where I am today.

(Vishal Prajapat)

Dedicated

to

My Family

Abstract

Brake friction material is very important part in braking system where they use friction during braking process. The purpose of this research is to determine the optimal friction materials composition of sintered metallic brake pad for wind turbine braking system. The utility of sintered metallic brake pad for wind turbine application is increases rapidly now a day, so the performance of brake pads and their life of operation matters a lot. Hence, the purpose of this research is to improve the wear properties of sintered metallic brake pad by changing their chemical composition. Three different testing which are density and, shore hardness test and wear test and microstructure evaluation were done in order to select which metal is the most suitable for wind turbine application. Three different samples(S-01, S-02, S-03) with different compositions of graphite, silicon carbide (SiC) and copper content were prepared for this study to determine the optimal properties with lower wear rate. Sample S-01 prepared with basic formulation, contained (Fe-70%, SiC-8%, Graphite-12%, $BaSO_4$ -6%, Sn-4%).Sample S-02 prepared with an decreased graphite contained compare to S-01 ,it contained (Fe-70%,SiC-10%, Graphite-10%, $BaSO_4$ -6%, Sn-4%). Sample S-03 further modified with an addition of copper content in the mixture formulation by adjusting the compositions of other additives, S-03 contained (Fe-60%,Cu-10%, SiC-10%, Graphite-10%, $BaSO_4$ -6%, Sn-4%). The selected materials were mixed and compacted into desired mould with 510 MPa of pressure. The compacted samples were sintered at the sintering temperature of 1000^{o}C. These samples were tested for wear test, hardness test & subjected to density measurement and microstructure evaluations. Results shows that sample S-02 have improved wear properties as compare to S-01 due to a decrease in graphite content and an increase in barium sulphate, while sample S-03 gave superior wear properties than S-02, this is due to an increase in copper content which results in faster heat dissipation rate because of its higher thermal conductivity.

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NOMENCLATURE

SMBP	Sintered Metallic Brake Pad
FGM	Functionally Graded Material
PM	Powder Metallurgy
COF	Coefficient of Friction
FF	Frictional Force
SD	Sliding Distance
HRB	Rockwell Hardness Value on B Scale
S-01	Sintered Metallic Brake Pad Sample with basic formulation
S-02	Sintered Metallic Brake Pad Sample with a decrease Graphite content
S-03	Sintered Metallic Brake Pad Sample with an addition of Copper
Fe	Iron
Cu	Copper
SiC	Silicon Carbide
$BaSO_4$	Barium Sulphate
Sn	Tin
$C_{36}H_{70}O_4Zn$	Zinc Stearate
^0C	Degree Celsius
g/cm^3	Gram per centimeter cube
h	Hours
µm	Micrometer
Φ	Diameter
mm	Micrometer
MPa	Mega Pascal
kN	Kilo Newton
atm	Atmospheric
T_m	Melting Temperature
T_s	Sintering Temperature
K	Kelvin

min	Minute
mmHg	Millimeters of Mercury
W/m-K	Watt per meter Kelvin
g/MN-m	Gram per mega Newton meter
g/MJ	Gram per mega joule
Kgf	Kilogram force
Hz	Hertz
gm	Gram
cm	Centimeter
m	Meter
ρ	Density
m_1	Weight of material in air
m_2	Weight of material in Water

Chapter 1 INTRODUCTION

1.1Introduction

1.1.1 Sintered Metallic Brake Pad (SMBP)

Sintered metallic brake pads (shown in fig 1) are metal matrix-ceramic composites, made by fusing metallic particles under heat and pressure (powder metallurgy) to create a compound, which reflects in higher resistance to heat and good resistance to wear. Bronze is generally used as the base metal because it presents a good thermal conductivity and it also helps maintain the friction coefficient in high temperatures. Iron, silica and graphite are other materials that compose a sintered brake pad. Iron helps increase wear resistance and friction, while silica, being an abrasive, helps the increasing of the friction coefficient.

Figure 1: Sintered metallic brake pad [1]

1.1.2 Applications of Sintered Metallic Brake Pad

Sintered metallic friction materials are more popularly used where energy to be evolved during engagements is high. The most common applications are as follow:

- Wind turbine braking system.
- Aircraft braking system.
- Automobile braking system

1.1.3 Composition of SMBP

The sintered friction material consists of a metal matrix (basically either Fe-based or Cu-based), non-metallic constituents such as carbides and ceramics (like SiC), and solid lubricants (like graphite). The metallic constituents give strength and whereas the nonmetallic, ceramics are responsible for rise in coefficient of friction (COF) and better braking performance [2].

1.2 Problem Defined

According to current research, it is still hard to explain the relation among the materials that compose a brake pad and the friction behavior and improvements in the composition of these materials are usually tested by trial and error. Metal-to-metal contacts friction and wear have been studied extensively and plenty of information can be found in tribology literature. The sliding characteristics of metal pairs are understood in terms of "compatibility" of the two metals based on an adhesion mechanism of pure metals at the friction interface. The friction coefficient obtained from pure metal-to-metal contact, however, often differs from the ones made of a composite containing metals sliding against a metallic counter surface; and this discrepancy is due to influences of other ingredients in the composite.

Iron based sintered friction materials are best suited for brake applications where temperature during braking may even go up to 1100^o C while the copper based sintered friction materials with stand only up to 600^o C. Further, the iron based sintered friction materials are less costly as compared to the later one [3]. Therefore, iron based friction materials are used in heavy duty brake applications such as in commercial/fighter aircrafts.

So it still becomes a problem to find out the excellent composition & optimum operating parameters of formation of SMBP , such that it give superior service during its whole operating life cycle.

Hence, the purpose of this research to study the effects on properties of brake pad by changing the composition of graphite, SiC and copper content in the chemical composition.

1.3 Objective

To study the effects on mechanical and tribological properties of sintered metallic brake pad by changing the composition of graphite, SiC and copper content in the chemical composition. The analysis was done by

1) Decrease in graphite and increase in silicon carbide content.
    - The graphite content was decreased from 12 % for sample S-01 to 10% for sample S-02, while the content of silicon carbide was increased from 8% for sample S-01 to 10% for sample S-02.
2) An addition of copper content.
    - Copper was add into the mixture formulation about 10% in sample S-03, and these compensated by iron content decreased from 70% to 60%.

1.4 Research Methodology

Figure 2, presents the research methodology used in the present work to meet the identified research objectives.

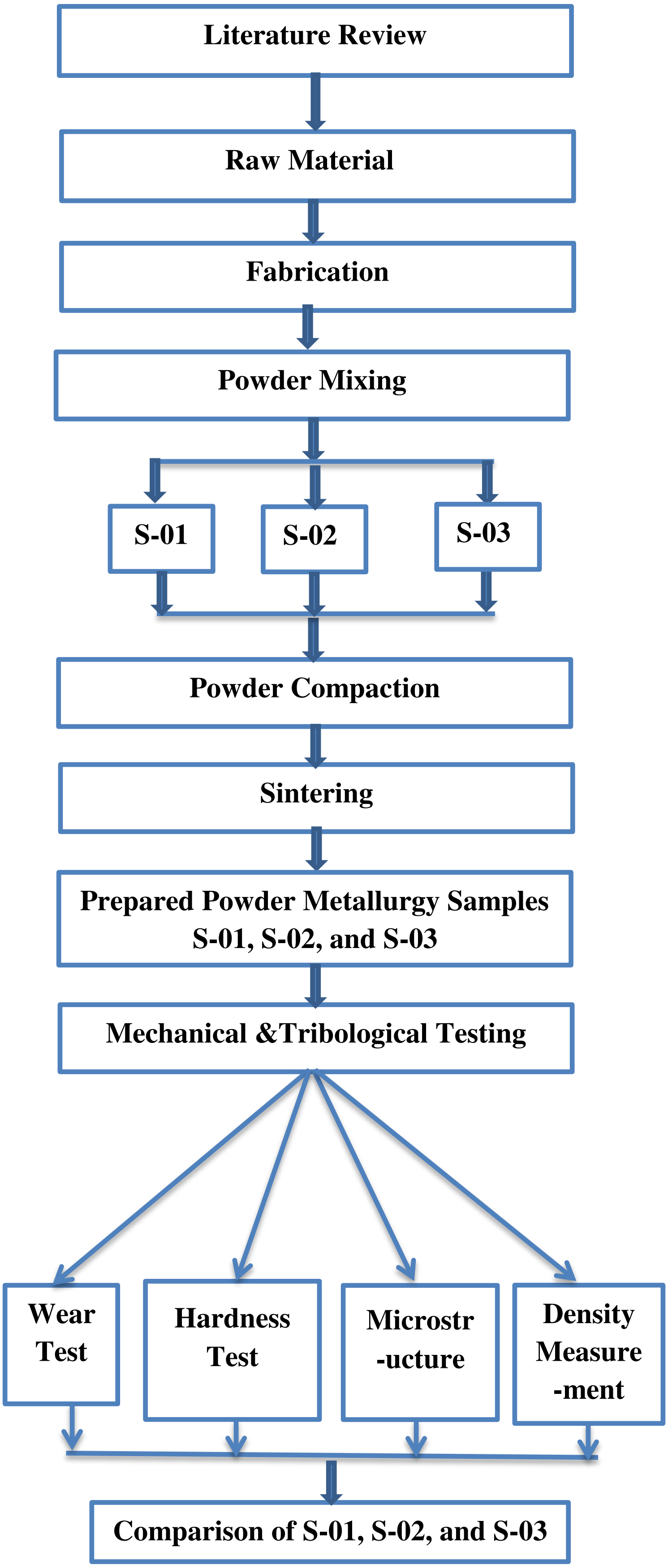


Figure 2: Research methodology

Chapter 2 LITERATURE REVIEW

2.1 Introduction

Brake pad is an essential component of braking system, these are a component of disc brake used in automotive, wind turbine, aircraft and other applications. Brake pads are steel backing plates with friction material bound to the surface that faces the disc brake rotor. The basic objective when using friction materials is to convert kinetic energy into thermal energy, promoting a decrease or total stop of movement. This thermal energy is usually dissipated by friction materials, and because of that they present good thermal conductivity. Besides this characteristic, friction materials present good friction coefficient and low wear rate, supplying the brake system with a high performance.

In order to achieve the properties required by brakes, most brake materials are not composed of single elements or compounds, but rather are composites of many materials. More than 2,000 different materials and their variants are now used in commercial brake components. According to Nicholson (1995), Herbert Frood is credited with inventing the first brake lining materials in 1897. It was a cotton-based material impregnated with bitumen solution and was used for wagon wheels as well as early automobiles. His invention led to the founding of the Ferodo Company, a firm that still supplies brake lining materials to this day. The first brake lining materials were woven, but in the 1920s, these were replaced with molded materials that contained chrysotile asbestos fibers a plentiful mineral. Resin-bonded metallic linings were introduced in the 1950s, and by the 1960s so-called ‘Semi-Mets’ were developed that contained a higher amount of metal additives. Table 1 lists the common brake materials in the early days.

Table 1: Historical Compositions of Automotive Friction Brake Materials [4]

MATERIAL DESCRIPTION	APPLICATION(S)	APPROXIMATE YEARS
Cast iron on steel	railroad car brake blocks and tires	1870
Hair or cotton belting (limited by charring at about 150°C)	wagon wheels and early automobiles	1897
Woven asbestos with brass and other wires for increased strength and performance	automobiles and trucks	1908
Molded linings with shorter chrysotile fibers, brass particles, and low-ash bituminous coal	automobiles and trucks	1926
Flexible resin binders developed along with more complex formulations	brake drum linings	1930
Resin-bonded metallic brake linings	industrial and aircraft applications	1950
Glass fibers, mineral fibers, metal fibers, carbon, and synthetic fibers to provide semi-metallics with higher performance than asbestos (beginning of safety issues with asbestos)	automobiles and trucks	1960
Non-asbestos (fiberglass) materials	brake drums on original equipment cars	1980

2.2 Types of Friction Material Used

Most common types of friction materials were used in practice are explained in fig 3.

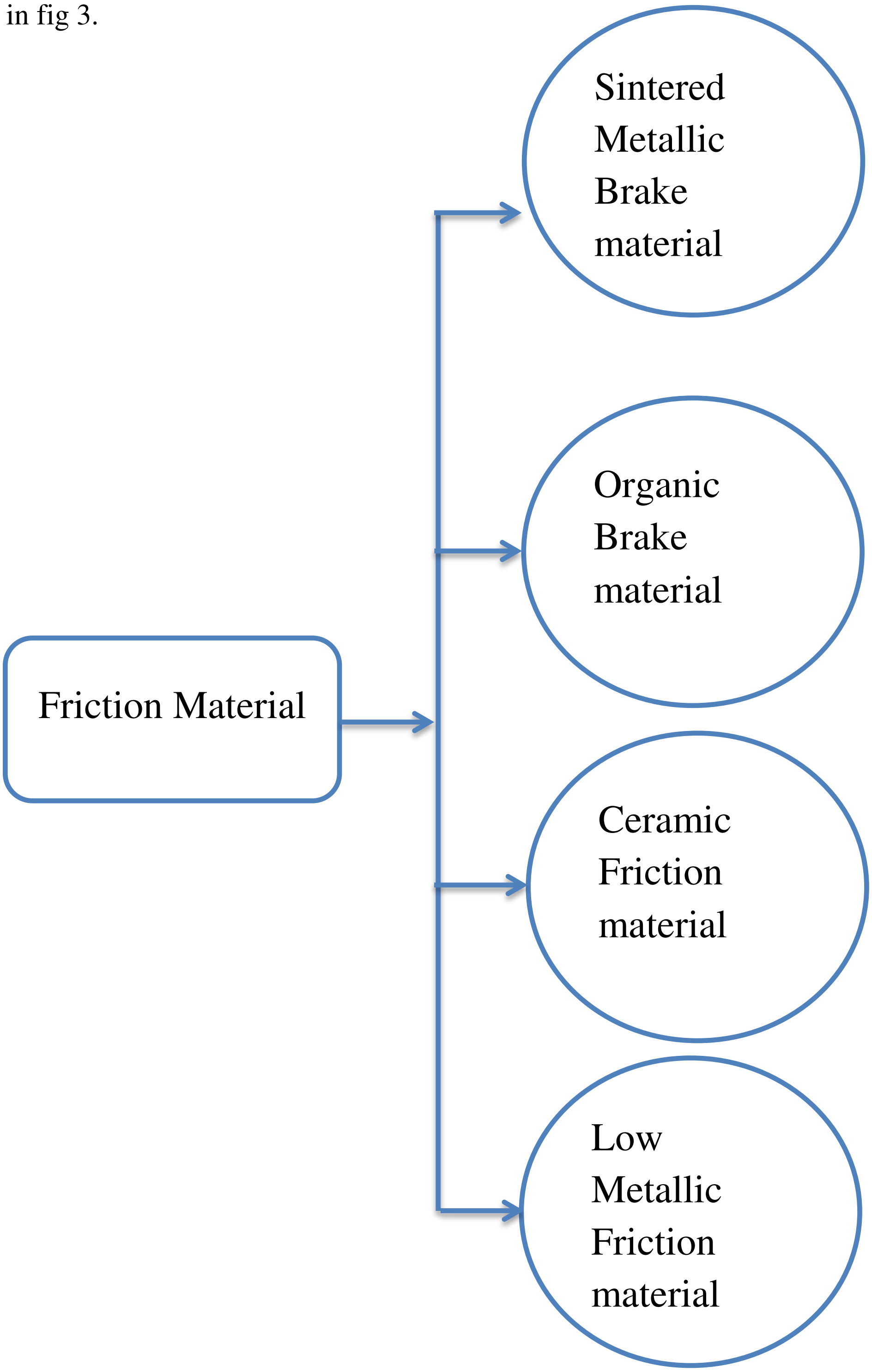


Figure 3: Types of friction materials

2.2.1 Sintered Metallic Brake Pad

Sintered metallic brake pad shown in fig 4, are metal matrix-ceramic composites., contain anywhere from 60-65% metal by weight, typically consisting of iron, copper, etc., combined with friction modifiers and fillers, as well as a graphite lubricant. Sintered metallic brake pads are arguably the most versatile style available, with the slight compromise being more noise and dust. They're also longer-lasting and more durable, and their metallic composition can help draw heat away from the rotor and aid in more efficient brake-cooling.

2.2.2 Organic Based Brake Pad

The production process usually used for organic-based friction materials is the hot pressing. Organic-based brake pads as shown in fig 5 are usually made of composite materials. Ten to twenty different components are used, but the following structural components are necessary:

- Structural materials: for the supply of mechanical resistance. Metallic fibers, carbon, glass, etc. are usually the ones used;
- Additives: for lubrication and stabilization of friction materials (graphite or metallic sulfides) or to promote cleaning of the disc surfaces through grind ability (alumina and silica);
- Fillers: to improve the production cost (silicon base oxide and barium sulphate) and,
- Bonds: for bonding and the fulfillment of the pad materials, forming a thermally stable compound (phenolic resins) where sometimes anti-noise (elastomer) materials can be added.

Figure 4: Sintered metallic brake pad [1]

Figure 5: Organic based brake pad [5]

2.2.3 Ceramic Brake Pad

The comparative new kind on the block is the ceramic brake pad. Ceramic pads are composed of a dense ceramic material (like pottery fired in a kiln) with embedded copper fibers. In use since the 1980s, ceramic pads were developed as an alternative replacement for organic and semi-metallic brake pads. At the time, these types produced too much noise and dust. Ceramic pads are also generally easier on rotors than semi-metallic pads. Figure 6 shows image of ceramic brake pads.

Pros:

- Quieter than semi-metallic pads, they emit noises that are above the range of human hearing.
- Produce finer, lighter-colored brake dust which does not stick to wheels.
- Longer lifespan than organic or semi-metallic.
- Stable under a wide range of temperatures for consistent performance.

Cons:

- Typically, the most expensive type of brake pad.
- Do not produce as much cold bite as semi-metallic pads, may not be ideal in extremely cold climates.
- Do not absorb heat as well as semi-metallic pads, which can increase brake system temperatures.
- Good all-around braking characteristics, but were never designed as heavy-duty or racing brake pads.

Figure 6: Ceramic based brake pad [5]

2.2.4 Low Metallic Brake Pad

Typically contain ferrous and nonferrous metals, inorganic and organic fibers, aggressive abrasives, lots of carbonaceous and sulfide lubricants. Some important points about low metallic friction material:

- Higher coefficient of friction levels ~ 0.38 –0.50
- Good pedal feel and braking confidence
- Good fade and high speed performance
- High pad/rotor wear
- Good for high speed wear
- Lots of wheel dust
- Inferior noise and life.

2.3 Review of Past Work

To accomplish the desired braking effect, various compositions of different materials for brake pad were tested at different decades. Most of the researches has done to obtain superior performance of brake pad material for automotive applications of braking system ,but limited work has reported on the brake pad material for wind turbine & aircraft applications. There is a scope of research in advancement of quality or properties of brake pad for wind turbine applications.

Some of past works on brake pad for wind turbine applications are as following:

- **(Jorge Alberto Lewis Esswein Juniora, Fabiano EdovirgesArriechea, Lírio Schaefferb:2008) [6]**

Samples of organic based brake pad & sintered metallic brake pad were tested for small wind energy convertors, both of these samples were tested for wear test, density test, and compression test & graphs have plotted for the test. The conclusions came from the research carried out were that the sintered brake pad proved to be more efficient than the organic-based pad because it presents a relatively lower wear rate as well as a higher friction coefficient. The wear rate in the sintered material was lower due to the good ductility of its metallic matrix. Due to the presence of SiO_2, it was possible to obtain an increase of the friction coefficient in the sintered material. In order to obtain an even greater wear resistance of the sintered material, it is necessary to increase its hardness. This can be done using a sintering process under pressure. To improve the thermal conductivity of the material, it is important to decrease the matrix porosity, so that it is possible to improve the brake pad efficiency.

- **(Thiago Santos, Inácio Regiani, Roberta Jachura Rocha, José Atílio) [7]**

Sintered metallic brake pad material with variant graphite content was tested. The conclusions came out from the research were that, the graphite content affected the sintering process, regardless whether the compaction pressure is significantly greater. Its reduction (graphite) caused an increase in density by 18% and increased mechanical resistance up to 62%. The increase in compacting pressure improved mechanical strength, with more pronounced effect on the composition with a lower graphite content. Although the strength of composites that contain hard particles (ceramics) increases with the volume percentage of particles in the composite, an increase in sintering temperature resulted in greater mechanical resistance due to a higher densification. From the microstructure analysis, it was observed that the ceramic particles hindered the sintering process by the agglomeration of ceramic inclusions in the Cu-Fe, Cu-Cu and Fe-Fe interfaces. Increasing the sintering temperature to 1050°C made possible the production of a compound with a moderate level of graphite without severely affecting the material properties.

- **(G. S. Darius, M. N. Berhan, N. V. David, A. A. Shahrul& M. B. Zaki) [8]**

Brake pad with different material composition were prepared & tested for wear, hardness, & density for comparison with commercial brake pad. It concluded that, with an increase of Iron & Barium content in brake pad composition the coefficient of friction increases & wear rate decreases.

- **(Samir Butkovi , MirsadaOru , Emir ari, Muhamed Mehmedovi , 2011) [9]**

Stainless steel powder compact samples were prepared at different sintering temperatures and operating conditions & properties of materials were tested. It concluded that, the density of the heat-resistant stainless steel GX40CrNiSi 25–20 produced by the MIM process depends mostly on the sintering temperature. Increasing the average density from 7.09 g/cm^3 to 7.73 g/cm^3 was achieved by increasing the sintering temperature from 1200 °C to 1310 °C. Sintering in hydrogen and argon resulted in higher densities and better ductility of the sintered parts compared to the nitrogen atmosphere. Also ,it is very important to emphasize that the prolongation of the sintering time at a temperature of 1200 °C, from 3 h to 6 h, increased the sintered density from 6.91 g/cm^3 to 7.26 g/cm^3, which is still much less than the density achieved at a temperature of 1310 °C. This is very important during the optimization of the sintering profile and indicates the importance of using a higher temperature to reduce the sintering time and the sintering Costs.

- **(Ahmed Sahib Mahdi , Mohammad SukriMustapa,MohammadAmrylajis, and MohdWarikh) [10]**

Powder metallurgy based sample of material AA6061Al alloy was prepared at different compaction pressures& mechanical properties of the prepared sample were tested. Based on investigations it was concluded that When compaction pressure was increased, the compression strength and micro-hardness increased. The relationship between compaction pressure & mechanical properties were obtained linear in nature. In addition, the increasing of compacted pressure has led to decreasing of the pores and increasing of contact points. So, direct proportion was detected between the compaction pressure and the hardness.

Table 2 represents some important specific past work on sintered metallic brake pads.

Table 2: Review of past works

Author	Experimental Detail	Conclusions
Thiago Santos, Inácio Regi, Roberta[7]	Sintered metallic brake pad material with variant graphite content was tested.	Reduction in graphite caused an increase in density and increased mechanical resistance.
Samir Butkovi , Mirsada Oru , Emirari, Muhamed Mehmedovi , 2011[9]	Stainless steel powder compact samples were prepared at different sintering temperatures and operating conditions & properties of materials were tested.	Increasing the average density from 7.09 g/cm^3 to 7.73 g/cm^3 was achieved by increasing the sintering temperature from 1200 °C to 1310 °C. Sintering in hydrogen and argon resulted in higher densities and better ductility of the sintered parts compared to the nitrogen atmosphere.
Ahmed Sahib Mahdi ,Mohammad Sukri Mustapa, Mohammad Amrylajis, and Mohd. Warikh [10]	Powder metallurgy based sample of material AA6061Al alloy was prepared at different compaction pressures & mechanical properties of the prepared sample were tested	When compaction pressure was increased, the compression strength and micro-hardness increased. In addition, the increasing of compacted pressure has led to decreasing of the pores and increasing of contact points.

2.4 Effect of composition on properties of brake pad

The effects of changing in composition are as follow:

1) **Copper (Cu)** – Copper having higher value of thermal conductivity about 385 W/m-K, which should have to result as an increase in heat dissipation rate and due to that wear loss should be decreases.
2) **Graphite** – Graphite is a lubricating material, the addition of which imparted lubricating ability of the material and makes it soft. The decrease in graphite content of sintered metallic brake material should result in a decrease in the softness of material and simultaneously a decrease in wear loss.
3) **Silicon Carbide (SiC)** – Silicon carbide is a frictional additive, the addition of this should have to results as, an increase in the hardness of the material and as well as an improved frictional properties.

2.5 Identified Research Gap

Following research gaps were identified based on the review of the past work done on sintered metallic brake pad

- No work has been reported on the addition of copper content in to the iron based sintered metallic brake pad material.
- Limited work has been reported on the change in graphite content of sintered metallic brake pad material.

Chapter 3 EXPERIMENTAL DETAILS

3.1 Introduction

The sintered metallic brake pad samples were prepared by powder metallurgy method. Powder metallurgy (PM) is the process of formation of materials or components by using metal powders. In powder metallurgy, metals are mixed in powder form in a definite proportion & then compacted using compaction press followed by the heating effect. The flow chart of fabrication process through powder metallurgy is represented in fig 7.

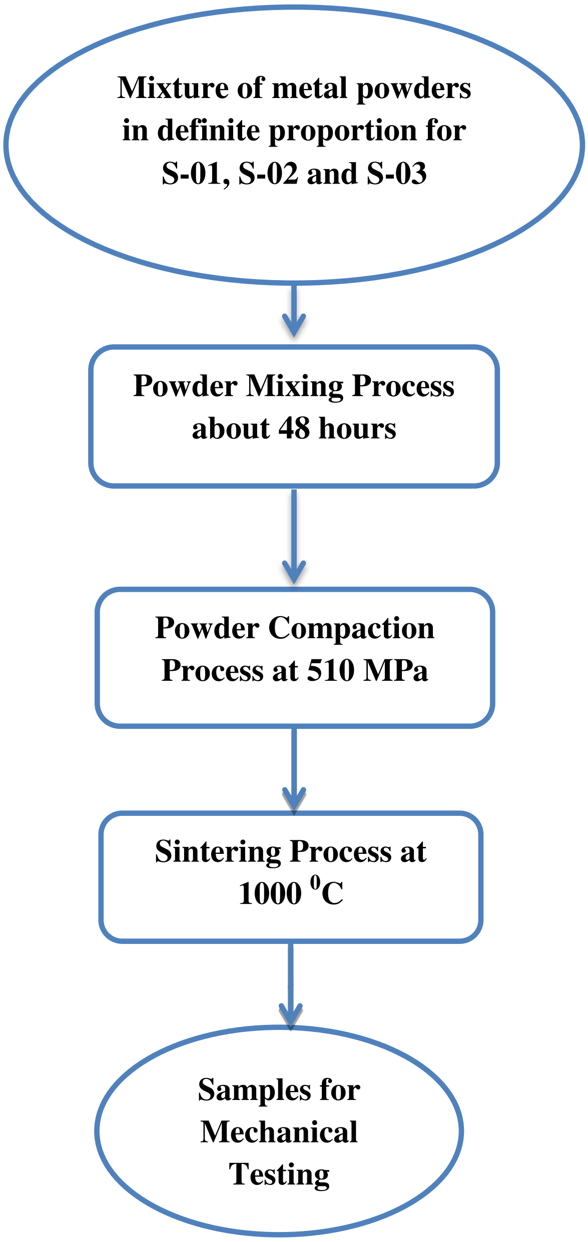


Figure 7: Fabrication process

3.2 Material Composition & Powder Mixing

Three different samples (S-01, S-02 and S-03) were prepared with different compositions of material constitutes sintered metallic brake pad. Generally conventional sintered metallic brake pads are formed by metal matrix (basically either Fe-based or Cu-based), non-metallic constituents such as carbides and ceramics (like SiC), and solid lubricants (like graphite).

In this research iron is used as the base metal of metallic matrix, because it is having good frictional and wear properties. Silicon carbide (SiC) is used as a frictional additive, which increases coefficient of friction. Graphite is used as a lubricating agent & some other additives.

3.2.1 Material Composition of Samples

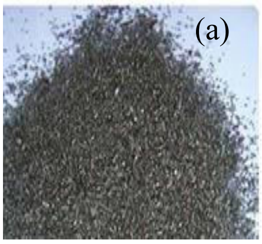
Material compositions for all of the samples prepared are listed below in the table 3.

Table 3: Material composition of sintered metallic brake pad samples S-01, S-02 and S-03

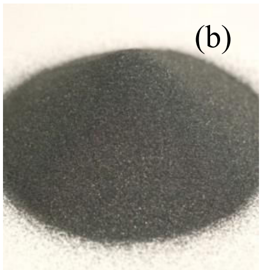
Material	Weight (%)		
	S-01	S-02	S-03
Iron (Fe)	70	70	60
Copper (Cu)	-	-	10
Silicon Carbide (SiC)	08	10	10
Graphite	12	10	10
Barium Sulphate ($BaSO_4$)	06	06	06
Tin (Sn)	04	04	04

3.2.2 Powder Mixing Process

Powder Mixing is an essential and initial process of powder metallurgy .In this process all the components are mixed either manually or by using mixing/blending machine. Mixing process give a homogenous mixture of components having different particle size. In this experiment powder form of all metallic and non-metallic constitutes were mixed in different proportion of amount by their weight percentage according to the requirement of samples S-01, S-02 and S-03.Mixing was done manually by using a silica crucible up to 40 to 45 hours uniformly at random time to ensure that the powder constitutes were thoroughly intermingled. Figure 8 (a) to (e) shows the powder used for mixing process & their particle size.

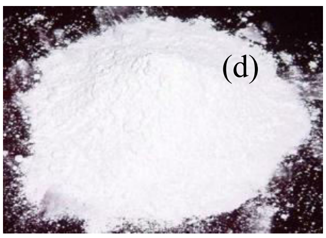


Iron Powder,
grain size- 200µm

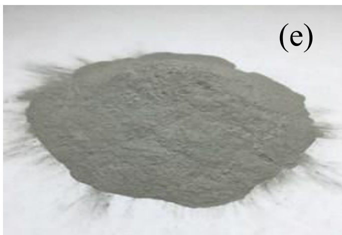


SiC Powder,
grain size- 80µm

Graphite Powder,
grain size- 80µm



Barium Sulphate,
grain size- 4.8µm



Tin Powder,
grain size- 210µm

Figure 8: Powder component used in the experiment with their particle size

The powders of different material mixed in various steps, in very first step the silicon carbide (SiC) powder were mixed with barium sulphate ($BaSO_4$) in an ethanol medium to prevent it from any oxidizing effect. The mixture prepared in first step is then made dry in an electric heater at an operating temperature of about 120 degree centigrade up to 2 hours, this dry heated mixture then pulverized into small size particle by using small grinder for the duration of 4 hours. The dry pulverized mixture of silicon carbide (SiC) and barium sulphate ($BaSO_4$) then mixed thoroughly up to 28 hours with iron (Fe) powder. The iron mixed powder finally intermingled with graphite powder & zinc stearate ($C_{36}H_{70}O_4Zn$) manually for a time interval of 12 hours to get desired homogenous powder mixture of Fe/SiC/Graphite hybrid composite. The flow chart of the powder mixing process is shown in fig 9.

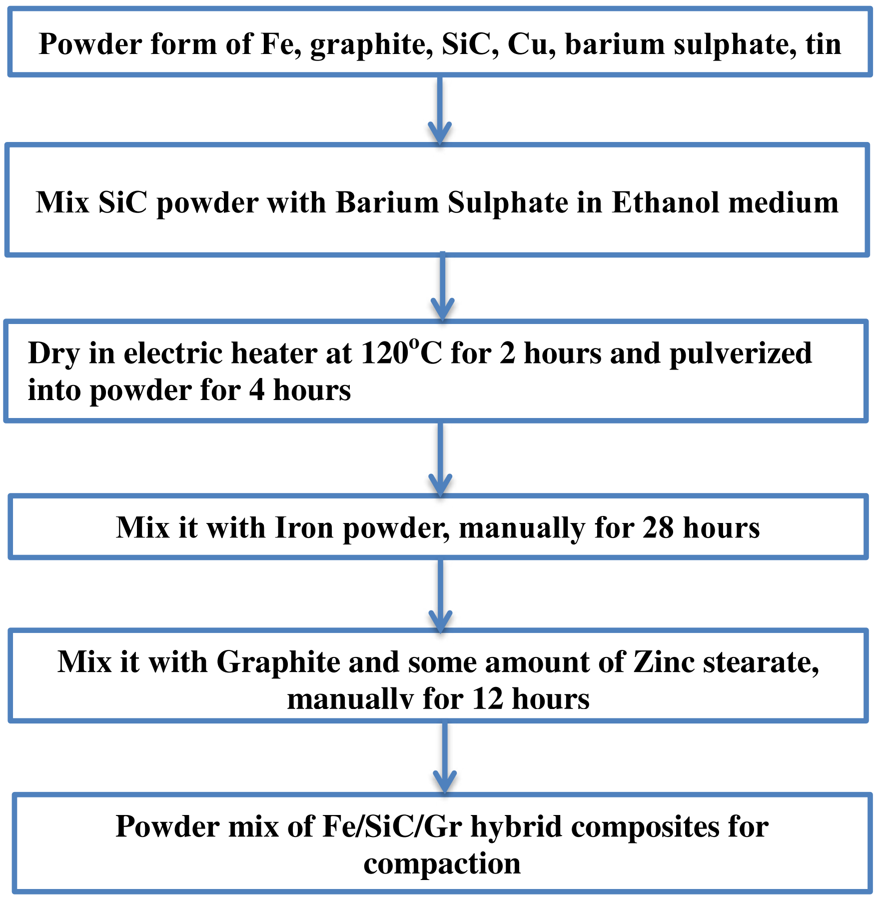


Figure 9: Procedure of mixing powders

3.3 Powder Compaction Process

Cold compaction is a process in which powder materials are compressed at room temperature so that the deformation mechanics associated with high temperatures, such as dislocation and diffusion creep, can be neglected. In this process, the powder is compacted by axially loaded punches in rigid dies that usually are made of steel. The compaction pressure is depend upon the major component of the mixture, for different types of materials the range of compaction pressure is listed below in table 4.

Table 4: Range of compaction pressure for different materials [11]

Application	Pressure (MPa)
Porous metal and filter	40 -70
Refractory metal and Carbides	70 – 200
Porous bearing	146 – 350
Machine part (medium density iron and steel)	275 – 690
Low density iron and steel parts	250 – 275
High density iron and steel parts	690 – 1650

3.3.1 Calculation of Force Required to Compact

Sample size required was of the dimension of Φ 15 mm. All of the samples were compacted at the pressure of about 510 MPa. Figure 10 shows principle of calculation of force required in compaction process.

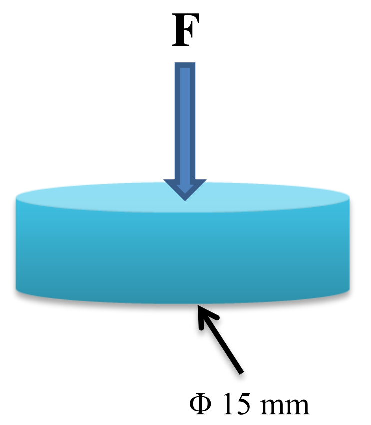


Figure 10: Force calculation for compaction process

$$\mathbf{F=P\times(\pi/4))\ d^2}$$

P= 510 MPa
d= 15mm

$$\mathbf{F = 510\times(\pi/4)\times(15)^2}$$

F = 90.0785 kN
F ≈ 90 kN

3.3.2 Process Parameter

The process parameters were taken during the process is listed below in table 5.

Table 5: Process parameter for compaction process

Process Parameters	Operating Value
Sample Diameter	15 mm
Compaction Pressure	510 MPa
Compaction Force	90 kN
Operating Temperature	atmospheric

3.3.3 Procedure of Compaction Process

Cold compaction equipment was used to compact the homogeneous materials after the milling process. The loose powder was compressed at room temperature, and it was moulded into a shape that is known as a green compact or green body. High density and the uniformity of that density throughout the compacted materials generally are desirable characteristics. During compaction, the powder particles move primarily in the direction of applied force, and the approach that was used is referred to as a powder metallurgy method. Compaction is the most important criterion in the powder metallurgy method. It starts from bulk powders that contain very small amounts of lubricants or binder material, and sometimes there is none of either. In this research, powder compaction via the cold press technique was used with the appropriate tools and dies (moulds). Normally, a die cavity that is closed on one end (vertical die, bottom end closed by a punch tool) is filled with powder. Figure 11 shows schematic of powder compaction process.

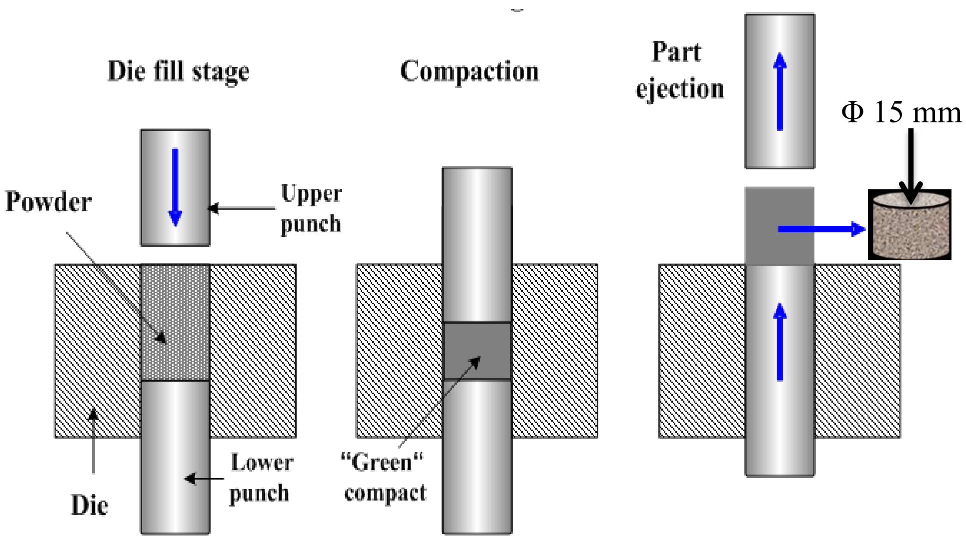


Figure 11: Powder compaction process [12]

After all of the ingredients of the brake pad had been milled to form a homogeneous mixture, this mixture was ready to be placed in the mould and compacted However, before placing it in the mould, a lubricant, such as WD-40 was sprayed on the mould to lubricate it and prevent the powder from sticking to the surface of the mould. After the lubricant had been applied to the mould, the homogeneous mixture of ingredients produced by the ball mill were placed in the mould and compacted with a pressure of 510MPa, using a uni-axial, hydraulic press machine. The compaction process produced brake pad ingredients that were compacted into the shape of the mould at room temperature (23 ^{o}C) and these compacted materials were ejected from the die cavity (mould). Both of the specimens were compacted into cylindrical shape with diameters of 15 mm, as shown in Figure 11. Their size and shape were established according to the design of the mould. The compacted samples are known as green bodies of the brake pad composite materials. These green bodies were compacted further and cured.

The equipment used for this process is shown below in fig 12.

Figure 12: Powder compaction press

3.4 Sintering Process

Sintering is a thermal treatment, below the melting temperature of the main constituent material, which a powder compact into a bulk material containing, in most cases, residual porosity. The process of sintering brings about certain physical as well as chemical changes in the material. The chemical changes can be illustrated as:

i) Change in composition or decomposition

ii) New phase formation or decomposition followed by phase change

iii) New phase formation due to chemical changes

Sintering process is to provide extra bonding between atoms. The atomic diffusion takes place and welded areas formed during compaction will increase the connection by sintering process. The sintering will be controlled over heating rate time; temperature and atmosphere are required for reproducible results. The equipment used during sintering process is tube furnace, the inert gas used during the process is Argon gas. Then, enter the specimen metal into the tube furnace, The temperature used is followed by sintering profile Figure.

3.4.1 Calculation of Sintering Temperature

Sintering Temperature was taken according to the rule. It should be kept between 70 % -90% of the melting point of main constituent.

Sintering Temperature (T_S) = (0.7-0.9) T_m

Where, T_m = melting point

Here the main constituent is iron & melting point of iron is about 1811K or 1538°C

Take, $T_S = 0.7\ T_m$

, $T_S = 0.7\ (1811\ K)$

, $T_S = 1267.7\ K = 994.7\ ^oC$,

, $T_S \approx 1000^oC$

3.4.2 Parameters and Temperature Profile of Sintering Process

Sintering was done at operating temperature of 1000°C for all samples in a tube furnace as shown in fig 13. The process parameter is listed below in table 6 and the temperature profile of sintering process is shown in fig 14.

Table 6: Process parameter of sintering

Process Parameters	Operating Condition
Sintering Temperature (**T_S**)	1000°C
Time Duration	90 min
Operating Pressure	0.3 mmHg
Atmosphere	Argon gas

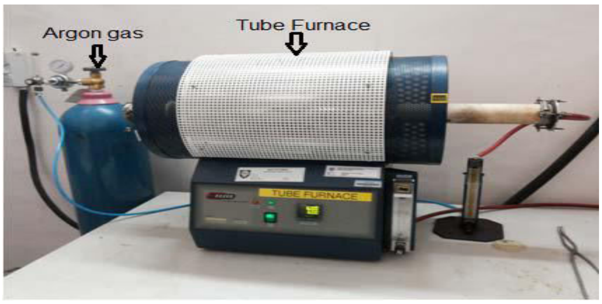


Figure 13: Sintering furnace

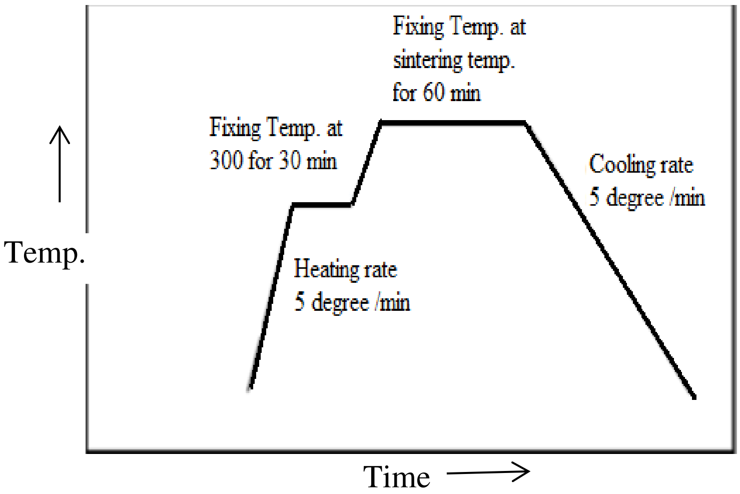


Figure 14: Temperature vs Time profile of sintering process

Chapter 4 RESULTS & DISCUSSION

4.1 Microstructure

4.1.1 Evaluation of Microstructure

Before taking microstructure on microscopy, materials get polished by using emery paper followed by diamond pest to acquire good finished surface. After that it etched to get required microstructure.

- Polishing~grit220-grit2500 of SiC emery paper & diamond polish of particle size 1µm.
- Etching~ Nital (nitric acid + ethyl alcohol)

Figure 15(a), (b) and (c) shows polished surfaces of samples and fig 16 Show Polishing process.

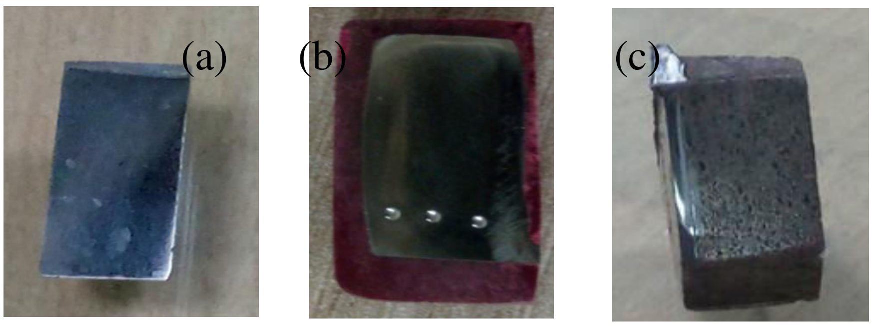


Figure 15: Polished Surfaces of Samples (a) S-01, (b) S-02, (c) S-03

Figure 16: Polishing Process

4.1.2 Microstructure

Microstructures were taken on inverted optical microscopy at different magnifications of 10x and 50x, fig 17 shows the microstructure of different samples at 10x and 50x magnifications.

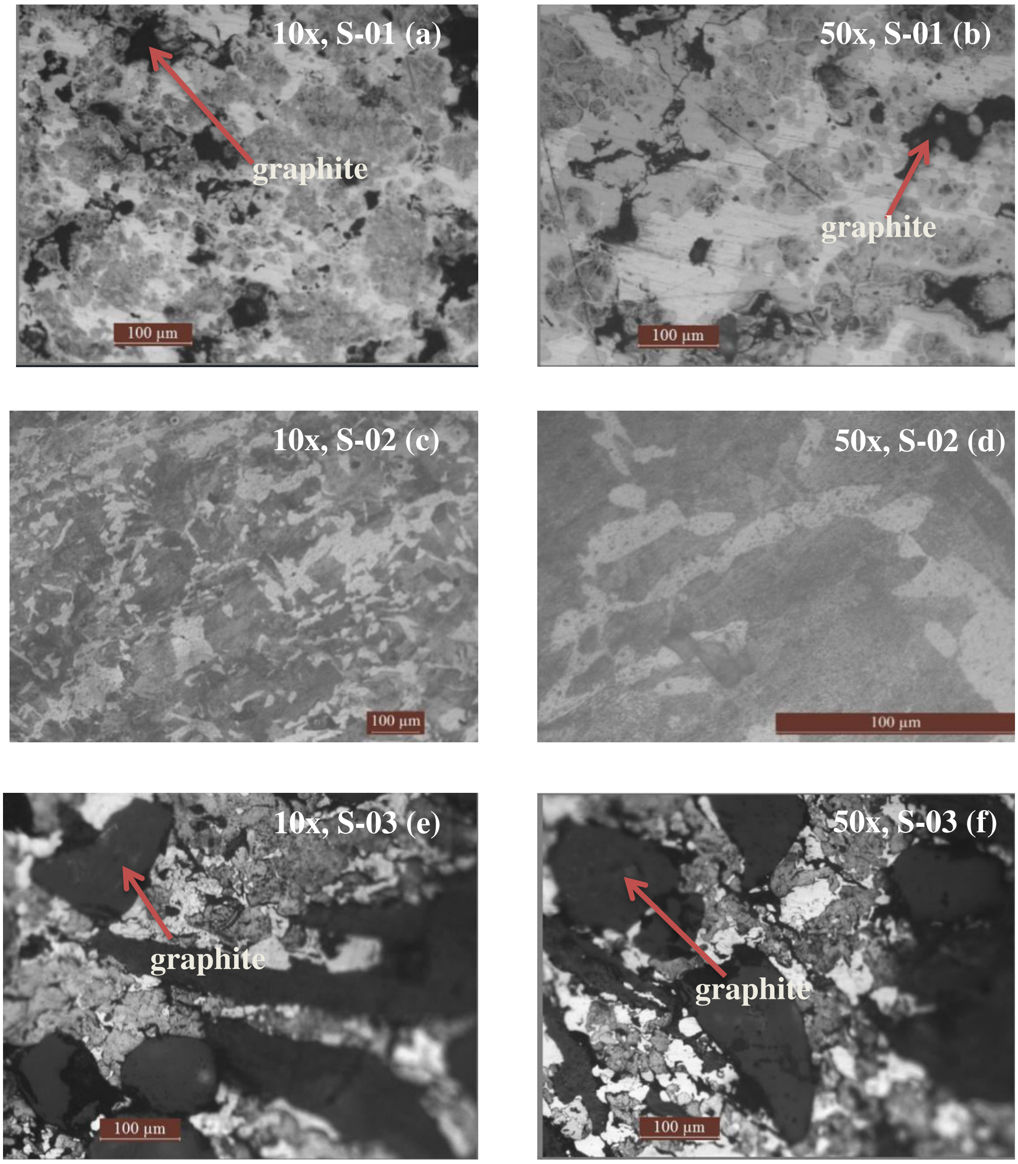


Figure 17: Microstructure of, (a) &(b) brake pad sample S-01 at 10x and 50x, (c) & (d) brake pad sample S-02 at 10x and 50x, (e) & (f) brake pad sample S-03 at 10x and 50x

4.2 Density Measurement

Density is a physical property of matter, it is defined as the mass per unit volume of a substance. The densities of the samples of the brake pad composite material can be determined by weighing the samples on a digital weighing machine, measuring their dimensions using a vernier caliper, using those dimensions to calculate the volumes of the samples, and obtaining the ratio of mass to volume. In this experiment densities of samples were measured by using Archimedes principle. Archimedes' Principle aids in the determination of density by providing a convenient and accurate method for determining the volume of an irregularly shaped object. According to Archimedes principle, a floating or submerged solid body in a fluid displaced an amount of fluid having weight equal to the weight of that solid body. Figure 18 shows Archimedes principle of density measurement.

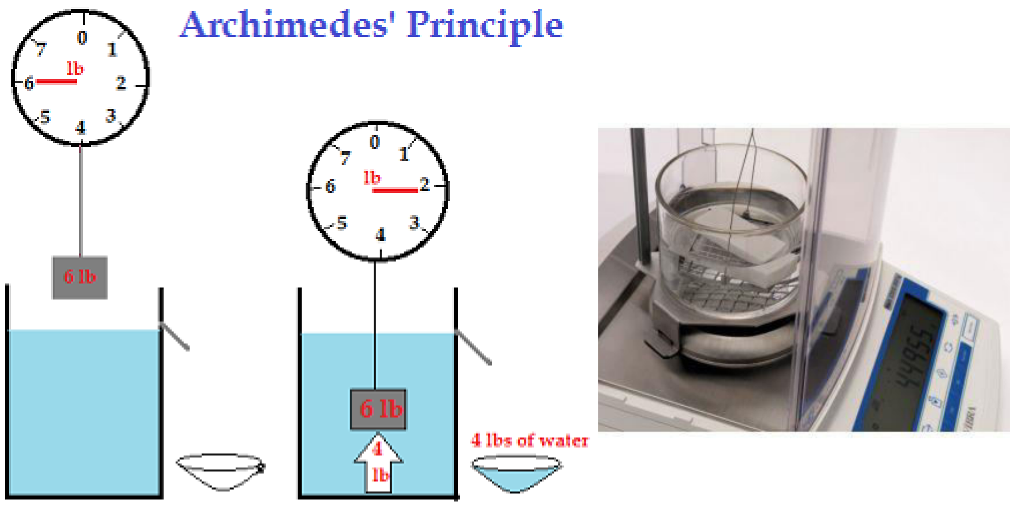


Figure 18: Archimedes principle of density measurement [13]

4.2.1 Principle of Density Measurement

Let, $\boldsymbol{\rho}$ = Density of material, m_1 = Weight or Mass of material in Air, m_2 = Weight of material in Water

Difference in weight of material in air & water = weight of displaced water =

$(m_1 - m_2)$ gm

For water density = 1 g/cm^3

Hence , volume of water displaced = (m_1 - m_2) cm^3

Volume of object = volume of water displaced = (m_1 - m_2) cm^3

Hence, density of material , $\rho = m_1 /(m_1 - m_2)$ g/ cm^3

Using this methodology densities of samples were evaluated, which are listed below in table 7.

Table 7: Density of different samples

Material	Density(g/cm^3)
Sample S-01	5.0519
Sample S-02	6.8634
Sample S-03	8.6081

4.3 Hardness Test

4.3.1 Methodology & Process Parameters

Hardness is a property of material by virtue of which it resists the indentation and scratches on it.

Hardness value is an expression that usually is applied to describe the durability of the friction material. It is generally perceived that a hard brake pad is more suitable for race conditions.

In this study, Rockwell hardness test was performed on the testing samples by using a Digital Rockwell Hardness tester, shown in fig 19.The Rockwell hardness test method consists of indenting the test material with a diamond cone or hardened steel ball indenter. The indenter is forced into the test material under a preliminary minor load F0 (fig 20 A) usually 10 kgf. When equilibrium has been reached, an indicating device, which follows the movements of the indenter and so responds to changes in depth of penetration of the indenter, is set to a datum position. While the preliminary minor load is still applied an additional major load is applied with resulting increase in penetration (fig 20 B). When equilibrium has again been reach, the additional major load is removed but the preliminary minor load is still maintained. Removal of the additional major load allows a partial recovery, so reducing the depth of penetration (fig 20 C).

Figure 19: Digital Rockwell Hardness Tester

The permanent increase in depth of penetration, resulting from the application and removal of the additional major load is used to calculate the Rockwell hardness number.

$$\boxed{\mathbf{HR = E - e}}$$

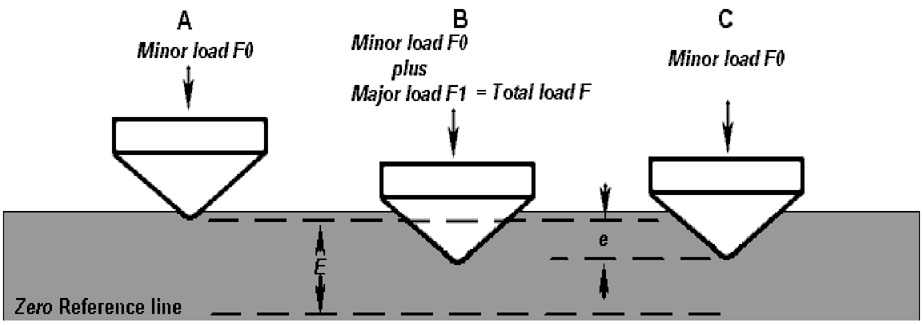


Figure 20: Rockwell principle [14]

F0 = preliminary minor load in kgf

F1 = additional major load in kgf

F = total load in kgf

e = permanent increase in depth of penetration due to major load F1 measured in units of 0.002 mm

E = a constant depending on form of indenter: 100 units for diamond indenter, 130 units for steel ball indenter

HR = Rockwell hardness number

D = diameter of steel ball

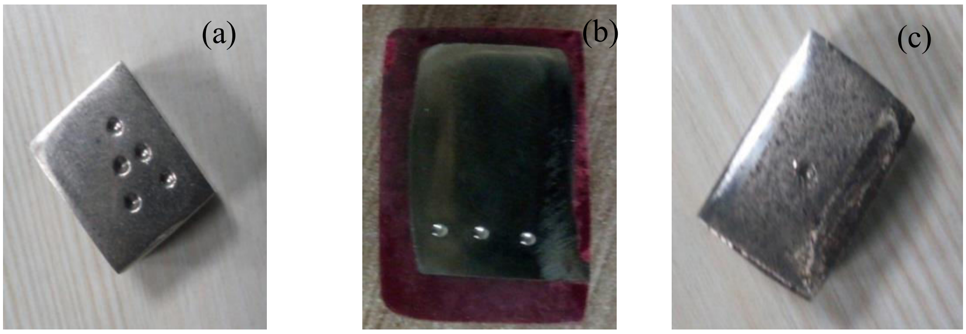
In this experiment a hardened steel ball has taken as indenter with a diameter of 1/16" or 1. 5875 mm. The other test parameters are listed below in table 8.

Table 8: Digital Rockwell hardness test parameters

Indenter ball diameter	**1.5875mm**
Test force	100Kgf
Minimum limit	20HRB
Maximum limit	70HRB

4.3.2 Hardness Test Results

The Rockwell hardness values for brake pad samples S-01, S-02 and S-03 are listed below in table 9. Figure 21 (a), (b) and (c) shows the images of indentation on all of these three samples. It is clear from the results, that brake pad sample S-03 has high value of hardness from other two, but on the other hand it can also be seen that brake pad sample S-02, having higher hardness value compare to S-01.



Indentation on brake pad sample S-01

Indentation on brake pad sample S-02

Indentation on brake pad sample S-03

Figure 21: Indentation on samples

Table 9: Rockwell Hardness value of samples

Material	Hardness Value
Brake pad sample S-01	21.2 HRB
Brake pad sample S-02	33.1 HRB
Brake pad sample S-03	49.5 HRB

4.4 Wear Test

Wear is a process of interaction between surfaces, which causes the deformation and removal of material on the surfaces due to the effect of mechanical action between the sliding faces. Wear also refers to the dimension loss of plastic deformation. Plastic deformation leads to wear; it causes the deterioration of metal surfaces, which is known as "metallic wear". Wear is the result of many things such corrosion, erosion, abrasion, chemical processes, or combinations of these factors. The processes of wear are studied in the field of tribology.

In this research wear tests was performed on Fretting wear (linear reciprocating) tribometer. In these type of tribometers the counterpart (a ball of tungsten carbide or steel), which is mounted in an anvil, allows to comes into the contact of testing surface with a definite amount of required load. This counterpart moves linearly (reciprocating) on the testing surface & wear out the surface by adhering that.

4.4.1 Parameters of Wear Test

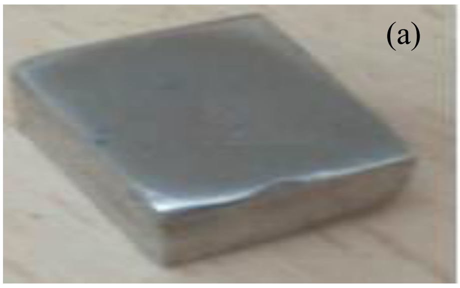
Wear tests were performed on brake pad samples S-01, S-02 and S-03, by using fretting wear tribometer. All the parameters used in test are listed below in table 10.

Table 10: Wear test parameters

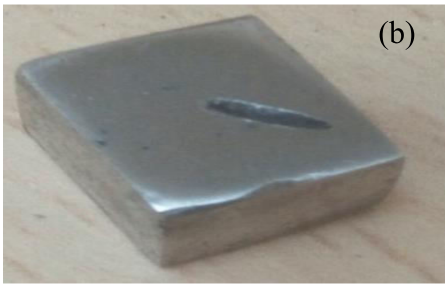
Parameters	Numerical Value
Mating Surface	Tungsten Carbide (Ball)
Ball Diameter	6 mm
Load	2.3 Kgf
Frequency	20 Hz
Stroke Length	0.5mm
Time Duration	15 minute

4.4.2 Wear Test Samples

Wear tests were performed on sintered metallic brake pad samples S-01, S-02 and S-03. The images before & after wear test of these samples are shown below in fig 22 (a) to (f).

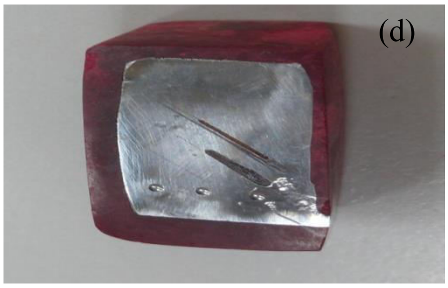


Brake pad sample S-01 before wear



Brake pad sample S-01 after wear

Brake pad sample S-02 before wear



Brake pad sample S-02 after wear

Brake pad sample S-03 before wear

Brake pad sample S-03 after wear

Figure 22: Images before & after wear test of sample S-01 (a) & (b), S-02 (c) & (d), and S-03 (e) & (f)

4.4.3 Wear Calculations

Wear rate of the tested samples were evaluated by using wear formula, which is represented as, **$K = \Delta m/(F \times s)$**

Where, K= wear rate in g/kN-m or g/kJ

Δm= loss in mass due to wear in (gm)

F= Force applied in (N)

S= Sliding distance in (m)

Sliding distance was calculated as follow,

- Sliding distance, $\boldsymbol{s = l \times f \times \mathrm{t}}$

s = (0.5mm)× (20Hz)×(15×60sec)

s = 9000mm=9 m

Where, l = stroke length

f = frequency of tribometer

t = time duration of wear test

- Wear calculation for sample S-01,

Sample Size, **1.5cm×1cm×1.1 cm**

Mass before test=8.3351g

Mass after test = 8.3336g

Wear rate , **K = Δm/(F×s)**

K = (8.3351g-8.3336g) / (2.3 ×9.81×9)

K = 7.3864 g/MJ =7.3864 g/MN-m

- Wear calculation for sample S-02,

Sample Size,**1.2cm×0.9cm×1 cm**

Mass before test=8.6647g

Mass after test = 8.6636g

Wear rate ,**K = Δm/(F×s)**

K = (8.6647g-8.6636g)/(2.3 ×9.81×9)

K = 5.4169g/MJ =5.4169 g/MN-m

Wear calculation for sample S-03,

Sample Size, (**1.2cm×0.9cm×1cm)**

Mass before test=9.2968g

Mass after test = 9.2963g

Wear rate ,**K = Δm/(F×s)**

K = (9.2968g-9.2963g)/(2.3 ×9.81×9)

K =2.4616 g/MJ =2.4616 g/MN-m

Figure 23 represent fretting wear tribometer used for wear test.

Figure 23: Fretting wear tribometer

4.4.4 Results of Wear Test

4.4.4.1 Graphs of Coefficient of Friction (COF) vs Sliding Distance (SD)

Figure 24 represents the graphs between Coefficient of friction & Sliding distance for brake pad samples S-01 (a), S-02 (b) and S-03 (c)

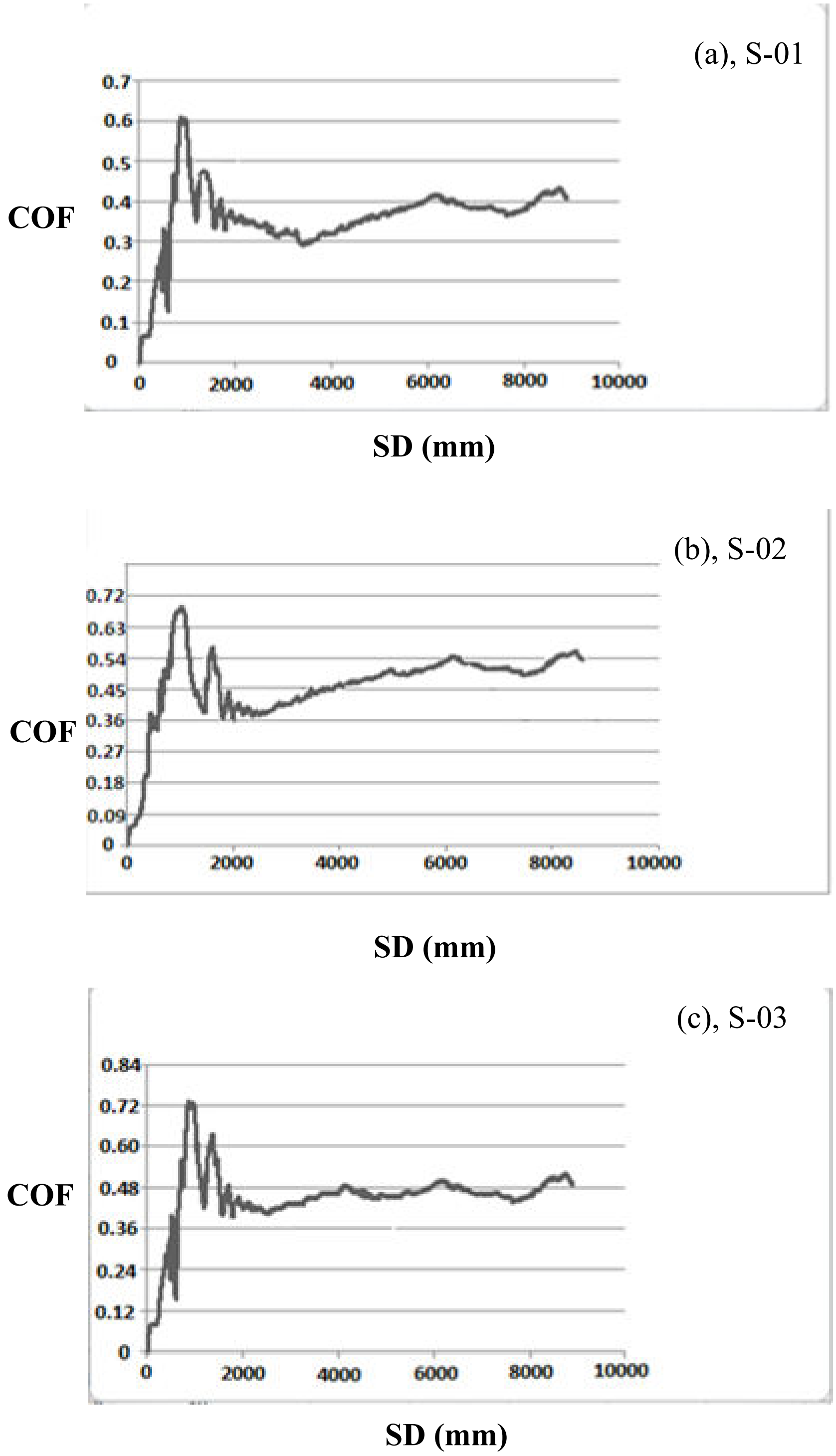


Figure 25: Graph between Coefficient of friction & Sliding distance for brake pad samples (a) S-01, (b) S-02 and (c) S-03

4.4.4.2 Graphs of Friction Force (FF) vs Sliding Distance (SD)

Figure 25 represents the graphs between frictional force and Sliding distance for brake pad samples S-01(d), S-02 (e) and S-03(f)

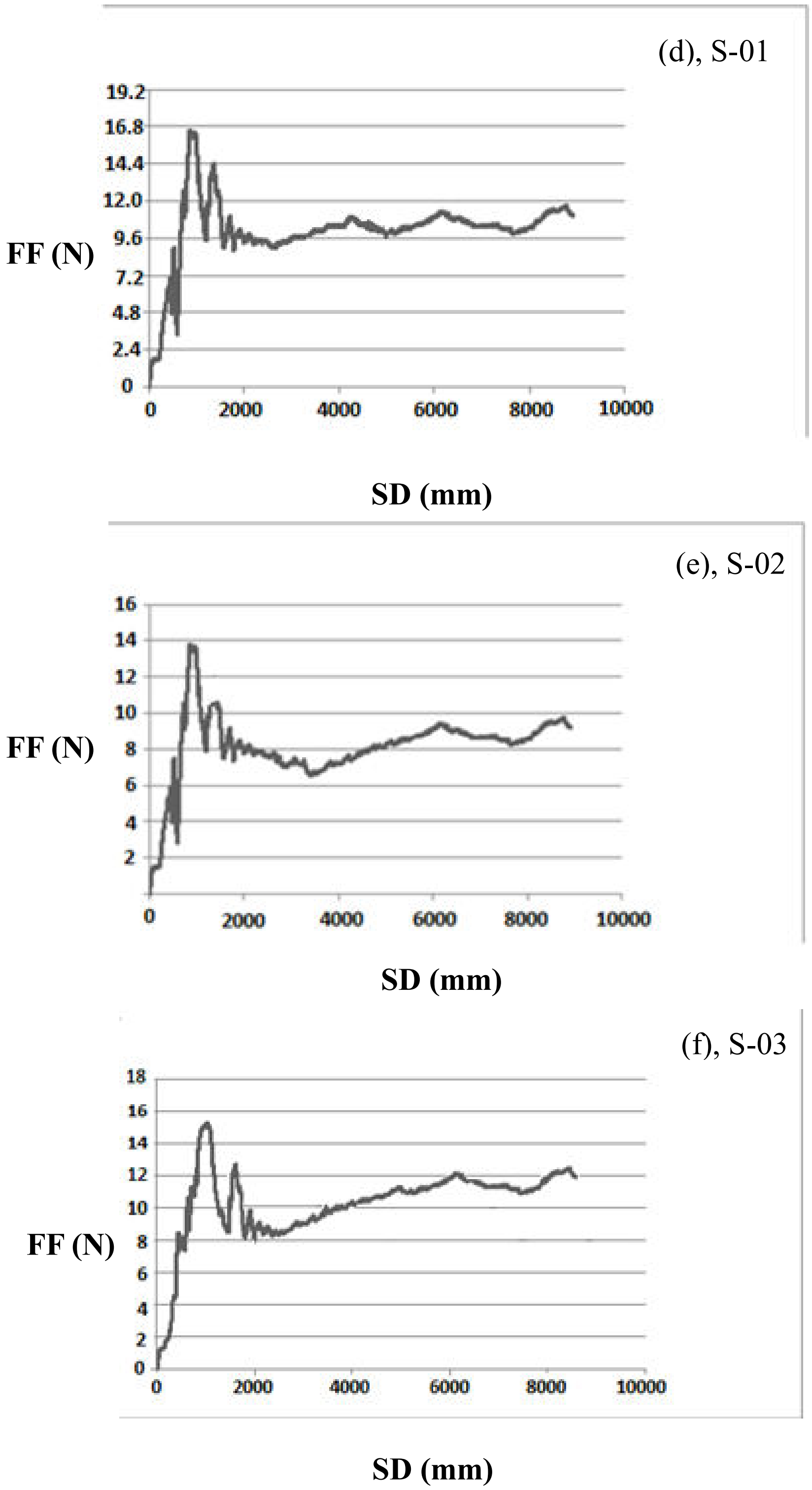


Figure 27: Graph between frictional force& Sliding distance for brake pad samples (d) S-01, (e) S-02 and (f) S-03

4.4.4.3 Comparison of Wear Test Results

Wear rates obtained by wear test performed on the brake pad sample S-01,S-02 and S-03, are shown below in table 11.

It can be seen by the table, that the wear rate of the brake pad Sample S-02 (5.4169 g/MJ) is comparatively less than that of the brake pad Sample S-01 (7.3864 g/MJ).That's mean is, on modifying the composition wear get reduced, & frictional properties of the brake pad materials.

Table 11: Wear rate of the samples tested

Material	Wear rate	COF (max)
Brake Pad Sample S-01	7.3864 g/MJ	0.60
Brake Pad Sample S-02	5.4169g/MJ	0.66
Brake Pad Sample S-03	2.4616 g/MJ	0.72

4.5 Comparison of All Test Results

Table 12 shows the comparison of results obtained in various test performed for different samples.

Table 12: Comparison of results obtained

Properties	**S-01**	**S-02**	**S-03**
Hardness	21.2HRB	33.1 HRB	49.5HRB
Wear Rate	7.3864 g/MJ	5.4169 g/MJ	2.4616g/MJ
Density	5.0519 g/cm^3	6.8634 g/cm^3	8.6081 g/cm^3

The results shows that sample S-03 with an addition of copper content has low wear rate and high value of hardness(2.4616g/MJ & 49.5HRB) as compared to the other two samples S-01 (7.3864 g/MJ &21.2HRB) and S-02 (5.4169 g/MJ &33.1 HRB) .

Chapter 5 CONCLUSION & FUTURE SCOPE

5.1 Conclusion

In this research three different samples were prepared with different compositions of graphite, SiC and copper to study the effects of these constituents on mechanical and tribological properties of sintered metallic brake pad.

At first a sample of sintered metallic brake pad S-01 was prepared with a material composition of as follow, Iron (Fe)-70% , Silicon carbide (SiC)-08% ,Grapphite-12%, Barium sulphate ($BaSO_4$)-06% ,& Tin (Sn)-04%. The compaction pressure & sintering temperature for fabrication of this sample was kept 510MPa & 1000 ^{0}C respectively. After fabrication this sample was tested for wear test, hardness test, density test, and microstructure evaluation.

After that another sample of sintered metallic brake pad S-02 was prepared with modified composition to getting better results with enhance properties of brake pad material. In this sample the composition of graphite was decreased from 12% to 10% & for compensates it, content of barium sulphate ($BaSO_4$) was increased from 8% to 10%. The material composition used for this sample was , Iron (Fe)-70% , Silicon carbide (SiC)-10% ,Grapphite-10%, Barium sulphate ($BaSO_4$)-06% ,& Tin (Sn)-04%.

Then at last, a sintered metallic brake pad sample S-03 was prepared with an addition of copper content in brake pad composition, compensated by a decrease in iron content in it. The compaction pressure & sintering temperature for fabrication of this sample was kept 510MPa & 1000 ^{0}C respectively.

Finally all these samples were tested for wear, hardness, density and microstructure evaluation & compared the results with each other. It is found that brake pad sample S-03 have superior wear resisting properties and having high hardness value as compare to other samples S-01 and S-02,& along with these it has also found that brake pad sample S-02 have improved mechanical and tribological properties as compare to sample S-01. The conclusions get from these observations are as follow :

1) A reduction in graphite content about 2% and increase in silicon carbide content up to 10 %,causes an increase in the density value of about 35 % ,as well as an increase in the hardness value and decreased in the wear loss from 21.2 HRB to 33.1 HRB and 7.3864 g/MJ to 5.4169 g/MJ respectively. The graphite content affected the sintering process. The increase in compacting pressure improved mechanical strength, with more pronounced effect on the composition with a lower graphite content. Although the strength of composites that contain hard particles (ceramics) i.e., SiC increases with the volume percentage of particles in the composite, an increase in sintering temperature resulted in greater mechanical resistance due to a higher densification. From the microstructures analysis, it was observed that the ceramic particles hindered the sintering process by the agglomeration of ceramic inclusions in the Fe-Fe interfaces.
2) An addition of copper content results in an increased wear resistance properties and reduced wear loss from 5.4169 g/MJ to 2.4616 g/MJ. These is due to the higher value of thermal conductivity of copper (385 W/m-K), which results in higher heat dissipation rate from the interface of brake pad and disc material. Due to these the temperature at the brake pad surface does not go up to an elevated level and brake pad material does not become softer which results in less wear loss i.e., superior wear properties and high hardness value. Hence the heat dissipation rate plays a major role in the performance of sintered metallic brake pad material.

5.2 Future Scope

During the braking action high amount of heat liberated at the interface of brake pad & disc surface, due to that an elevated temperature achieved by brake pad surface. Due to that high temperature the brake pad material becomes soft & the material removal rate of the pad material due to abrasion i.e., wear rate has increase. If by some means we further increase the heat dissipation rate then it will results in an improved wear properties of brake pad with low wear rate & less brake fade.

For this improvement in properties brake pad material can be made as functionally graded.

An idea introduced here about functionally graded SMBP. Functionally graded (FG/FGM) material shown in fig 26, possess different properties at different locations.

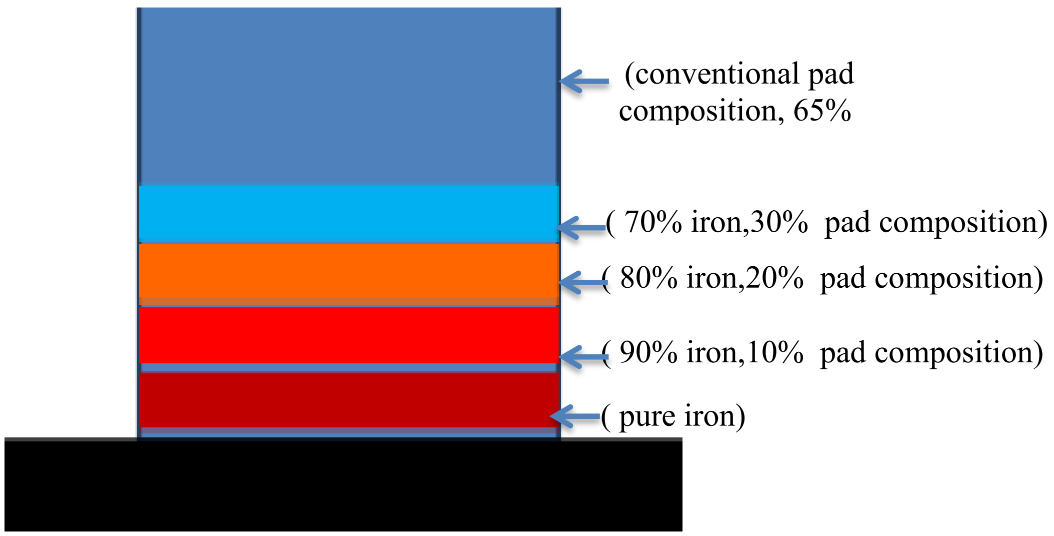


Figure 28: Functionally graded material

Functionally graded material prepared as follow:

- Laying the pure iron powder for specific thickness as bottom layer, followed by laying the mixture (iron-copper-graphite-silica-Barium sulphate-tin) of powder with decreasing iron composition, as shown in the figure.
- Iron percentage of the pad is from 100% at one end to the composition of a conventional pad at other end.
- This functionally graded material possesses different properties at different layer.
- FGM will results in increase heat dissipation rate, which causes reduction in brake and increase in wear resistant properties.

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