TRIBO-EVALUATION OF SOME CANDIDATE AMMC DISCS SLIDING AGAINST AUTOMOBILE BRAKE PAD

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Submitted by

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Certificate

This is to certify that the work done in this thesis report entitled "**TRIBO-EVALUATION OF SOME CANDIDATE AMMC DISCS SLIDING AGAINST AUTOMOBILE BRAKE PAD**" submitted in partial requirement for the award of master of engineering degree in CAD/CAM engineering submitted in the mechanical engineering department of Thapar university Patiala, is an authentic record of work carried out by me under the guidance of Dr Hiralal Bhowmick, Asst. Professor , Mechanical engineering department, Thapar university, Patiala.

The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

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This is to certify that above declaration made by the student concerned is correct to the best of my knowledge.

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Abstract

Braking systems are one of the most important controlling systems used in the automobiles. Conventionally grey cast iron is used to make the Disc material. However, it is heavy which results in higher specific fuel consumption. Due to the ever increased competition regarding power consumption during the braking application, requirement of light weight technology and due to continuously changing brake friction material, now-a-days automotive sectors are shifting their attention on the alternative materials for brake rotors that can perform better than existing material in terms of tribological, thermal and mechanical aspects. Particulate reinforced aluminium MMCs are promising candidates for automotive applications since they offer high specific stiffness and strength, good wear resistance and suitable thermal properties; furthermore, they are readily available at reasonable prices and can be processed using conventional technologies and hence gained wide attention for the tribological development during the last decade. Although, a lot of research is done for the formulation of new brake friction material, however, relatively little study has been made till date on the brake disc material especially using composite material. Despite of the fact that AMMC is one of the most widely researched matrix materials amongst all the promising types of composites , however, a very few studies are available in the literature which investigated the tribological behaviour of Al-B_4C and Al-SiC-B_4C hybrid composites sliding against commercial brake pads. Hence, to replace the conventional CI as brake rotor material, further investigation can be carried out using various AMMCs as disc material.

The present research is carried out in this direction using four different types of AMMCs along with the commercial cast iron disc materials, all of which slides against the commercial brake pad. For this purpose, AMMCs are fabricated by stir casting, as well as commercial discs and pads are procured. Then they are subjected to mechanical and tribological characterization using hardness testing, Optical microscopy, SEM, EDS and XRD. The wear and friction response and worn surface morphology and elemental compositions on the wear tracks reveal some interesting facts about the AMMC-Pad tribopairs. The investigation shows that Al6061composite and its hybrid can be carefully developed for the desired tribological properties required for the brake rotor application for reliable, long life and high performance application. The research outcome will definitely help in understanding the meaningful market potential of developing AMMC disc in place of conventional CI rotor.

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Chapter 1

INTRODUCTION

1.1 Introduction

Composites are the combinations of two or more chemically and physically different phases separated by the distinct interface. Again, the overall properties of composites can be further improved by way of adding multiple reinforcements to the virgin metal matrix. This is called as the hybrid composite These different constituents of the composite have their own distinct properties and impart more mechanical strength to the composite by imparting these properties [1-2]. These distinct phases include matrix phase (primary component) and the dispersed phase (held by the primary phase). The dispersed phase (also called reinforcing phase) has more strength than the matrix phase. Composites have superior properties as compared to their base such as high stiffness and strength, high temperature stability, high electrical and thermal conductivity, corrosion resistance, improved friction response and wear resistance, etc. The need for a new wear resistant material for high performance tribological applications lead to the tribological development of particle reinforced aluminium composite during the last decade.

Braking systems are one of the most important controlling systems used in the automobiles. As power generated through the engines is kept on increasing, the braking action needed to be more effective, consistent, stable, more powerful and more reliable. In automobiles friction brakes are commonly used. These brakes uses friction force to convert mechanical energy into the heat energy, which propagates through rotor and brake pad and then into space. The aim of present work is to select and develop lightweight wear resistant materials for the application of brake disc, emphasizing on the substitution of the conventional cast iron. As Aluminum is one of the most widely researched matrix materials amongst all the promising types of composites, therefore it will be experimentally investigated for its potential application for the brake rotor disk along with the conventional brake pad.

1.2 Disc Brake

Today’s automobile brake system consists of disk brakes in front while it may be having either disk or drum brakes in the rear. In disk brakes, a disc which is mostly made up of cast iron, works as rotor which is attached to wheel. Mainly brakes are comprised of brake callipers, brake pads and brake rotors. When the brake is applied, the brake callipers/pads are made to make contact with disc, which in return increase the friction force between brake pad and disc which is then used to stop vehicle. Drum brake’s working principle is same as disc brake, however, instead of disc it uses a drum as rotor and brake pads are placed circumferentially. Now-a-days, automobile industries are shifting towards disc type rotor from the conventional drum type rotors due to reasons such as better cooling of disc as compared with drum, which can be very helpful in preventing phenomenon known as ‘FADE’. Fade is said to be happened when due to increase in temperature of interface between rotor and callipers, the coefficient of friction will start decreasing. That means to be able to work properly the temperature of brakes should be as possible as near to ambient temperature. Another reason for disc being used is ease of manufacturing.

Disc brakes are either hydraulically operated or pneumatically operated. In case of disc brakes, as shown in Fig. 1.1, braking signal comes from brake line as driver puts pressure on brake pedal. This signal pushes piston which in turn pushes calliper. Calliper then applies friction force on the disc of cast iron. This leads to stopping of the vehicle.

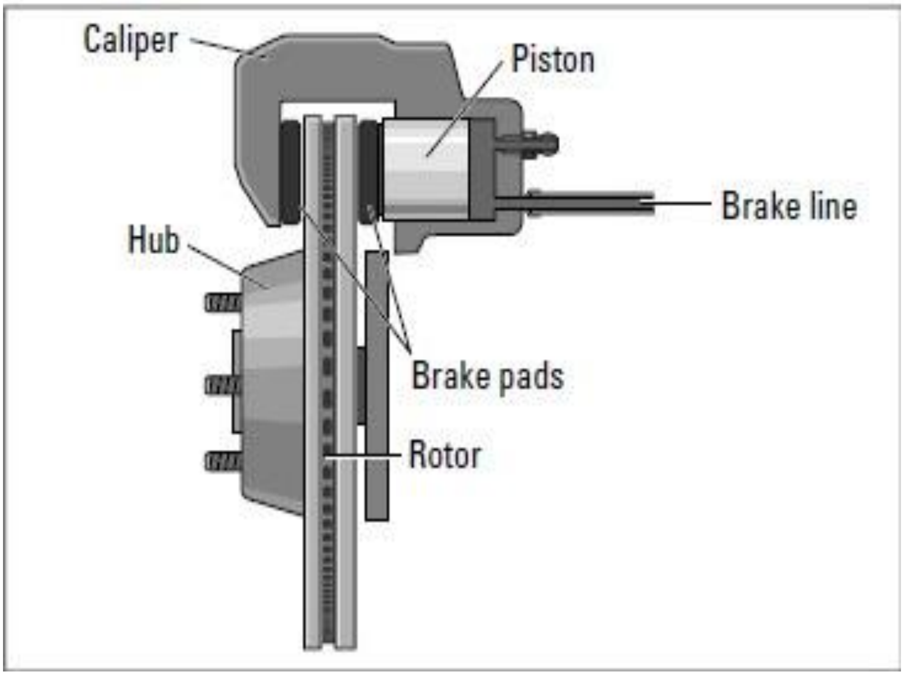


Figure 1.1 Set up for Disc brake [1]

The calliper houses pistons and is mounted to the torque plate and steering knuckle or wheel carrier. There are two calliper designs; floating calliper and fixed calliper. Brake pads are lined with friction material which comes in contact with the brake rotor and convert the kinetic energy of the car to thermal energy by friction. During contact when a brake pad is heated, pad and rotor then "stick" to each other, transferring small amounts of friction material to the disc, providing the friction that stops the vehicle. In order to achieve the desired properties, most brake pad materials are composed of composites of many raw materials may be more than 20. To ensure stable frictional and controlled wear rates of both pad and disc, the pad materials used may include metal, carbon, glass, Kevlar fibers or ceramic fiber. The literature shows that graphite powder when used as friction modifier helps in improving the thermal conductivity of the composite brake pad material. To reduce the hardness of brake pads sometime graphite powder can be used as friction modifier without affecting flexural properties.

There are various forms of discs used in the automotive industries

i. Plain solid discs: These are most commonly used disc brakes. Fitted in most of the application these days.
ii. Vented discs: There are two layers of the disc and space is vented out in between these two layers of the discs. Advantages are the better cooling hence prevention from the fade phenomenon. Ventilated discs are widely used in automobile disc braking system for improved cooling during braking. However, one of the major disadvantages is that it requires more space and is heavy as more material is required.
iii. Drilled and grooved disc: For proper cooling and increased air flow, a plain disc is made with grooves and drilled holes. This in turn, serves the purpose but also reduces the weight. However, they weaken the disc and failure starts from these grooves and holes that have been made.

1.3 Desired Properties For Brake Disc Materials

The brake rotors materials should have certain mechanical and thermal properties so that it can be highly effective during operation. Mechanical properties include high strength and hardness, stable friction and high wear resistance for service temperatures range. They should also be durable to withstand torque loads from braking. Desired thermal properties include high heat absorption capability, high thermal conductivity to dissipate frictional heat away from braking surfaces and minimum thermal expansion to reduce performance variability [1]. Besides, the material should possess high vibration damping capacity to minimize noise issues and higher corrosion resistance. Lastly the material should be inexpensive and processing costs should be less.

Gray cast iron has long been the material of choice for brake rotors due to its low cost and properties of which can be made up to desired level via heat treatment. Grey cast iron has better thermal properties, lower density, better castability, and better friction than martensitic stainless steel. However, Grey cast iron possesses some traits which make it less desirable than martensitic steel for brake disc applications. These include: it is more brittle, which means it is easier to crack, it has very low impact resistance, making it less durable under heavy braking and it has less hardness, so it wears more quickly. Also, if left uncoated, it is more susceptible to oxidation, which means it is more likely to rust. For a vehicle which weighs relatively little when compared to a car, the SS holds up great to the frictional/torsional forces created during the braking process. If we cast the grey cast iron in the same shape and size, it would not stand up to it. The main reason is, at that thickness, cast iron's brittleness would not stand up. In that case, the SS is a much better choice. Besides, brake rotor iron requires specific graphite morphology and strength to work for better performance in the operating temperature. Also, use of cast iron causes to consume much fuel due to its high specific gravity.

Development of automotive brake discs can be based on basic two philosophies. The first, used for family sized vehicles which operate on the principal of small diameter requires high strength discs with low thermal conductivity but sufficient inherent strength to resist any tendency of thermal cracking and distortion at high operating temperatures. The second type of discs can be large and low strength discs with high thermal conductivity.

1.4 Emerging Trends In The Development Of Brake Disc Materials

Due to increased power and high temperature rising during the braking application as well as requirement of light weight technology, automotive sectors are shifting their attention on the alternative materials from brake rotor materials. Hence researchers are investigating for the suitable hybrid composite material which is lighter than cast iron and has better mechanical and physical properties. One such material is C/C brakes, which has higher refractiveness and can perform at higher temperature. C/C composite is promising candidate for advanced braking system [2]. Researchers studies for C/C SiC brakes use in premier cars, but their disadvantage is high cost. As compared to grey CI, carbon/carbon or C/C-SiC composite exhibits high COF and thermal shock resistance, and extremely low wear rate. Some countries already have launched research drive for these new materials for braking system [3-6]. But these types of brakes are costly and cannot be made for general application of brakes. And the answer comes up with low cost composites materials.

Aluminium Metal-Matrix Composite (AMMC) is one of such potential candidate for automobile brake application for low to medium service temperature. Particulate reinforced AMMC s are promising candidate for the above applications since they offer improved mechanical properties such as high specific stiffness and strength and good wear resistance along with suitable thermal properties. Furthermore, they are readily available at reasonable prices and can be processed using conventional technologies. However, its cost is manifold to the cost of CI rotors. On the other hand, C/C and C/SiC composite materials are not limited by operational temperatures of rotor and frictional properties are better at higher temperatures, but its implementation cost is nearly a hundred times the cost of gray cast iron rotors. High strength glass fiber composites (HSGFC) are also another potential candidate for the above application.

Although, composites such as AMMCs have promising friction and wear behaviour for disk brake rotor application, however, a little study has been made till date for the replacement of cast iron for general purpose brake disc application by the composite materials.

1.5 An Overview On Metal Matrix Composites (MMC)

MMCs can be divided into many types of based on their composition i.e. their matrix material and their reinforcements [9]. This provides us lots of types of composites, which leads us to very complex classification. Hence a much broader classification i.e., based on type of reinforcement is presented below.

As shown in the above figure, MMCs can be classified on the basis of structure of reinforce provided in them. Accordingly, they can be particle reinforced MMCs, short fiber reinforced MMCs or continuous fiber reinforced MMCs. The matrix materials generally used are aluminium, titanium, steel to obtain new materials with good mechanical properties. In recent years, SiCp reinforced AMMCs have received significant attention in terms of their fabrication techniques as well as their desired mechanical properties.

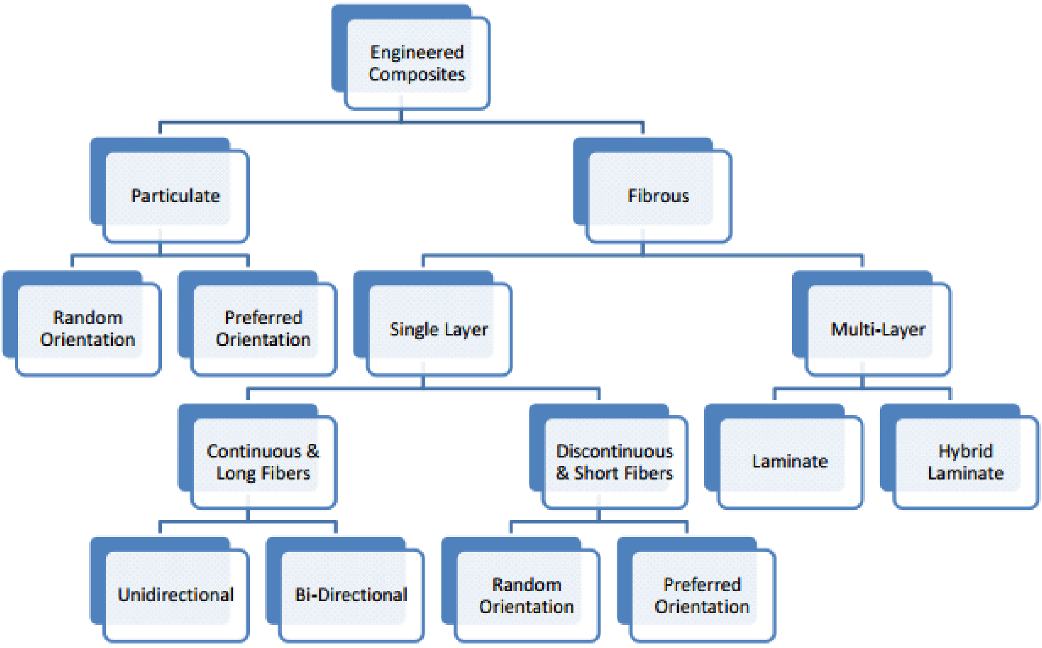


Figure 1.2 Broader classifications of MMCs [9]

Particulate composites have one or more type of particles embedded in a binding matrix. Particles may be reinforced with random orientation (ex: concrete) or with preferred orientation (ex: extruded plastics with reinforcement particles).

Fibrous composites have fibre of reinforcing materials distributed in binding matrix. They may be broadly categorized into single-layer and multilayer composites. Single-layer fiber composites are made of several layers of fibres all oriented in the same direction. In multi-layer composites, reinforcement is provided, layer- by layer in different directions. Table 1.1 provides information on the characteristics of various reinforcements used in MMCs.

Table 1.1 Characteristics of various reinforcements [9]

TYPE	ASPECT RATIO	DIAMETER (μm)	EXAMPLES
Particle	~1-4	1-25	SiC, Al_2O_3,BN,B_4C
Whiskers	~10-1000	.1-25	SiC, Al_2O_3,Al_2O_3+SiO_2,C
Continuous fiber	> 1000	3-150	SiC, Al_2O_3,C,B,W

Particulate reinforced composites have become more popular because they are inexpensive as compared to fiber reinforced composites. Also, they provide relatively isotropic properties.

Important metallic matrices include the alloys of aluminium, titanium, copper and magnesium. Aluminium alloys are in great demand in aerospace sector and automotive industry, because of their low density and excellent strength, toughness and resistance to corrosion (due to formation of Al_2O_3). Aerospace industry uses AMMCs for most of the aeroplane structure or aero structure. In case of automotive industry AMMCs found applications in disk brakes, or other type of brake lining. They are also used in engines pistons. Titanium is another important materials used in aerospace material because it has high strength to weight ratio and high modulus to weight ratio. It has relatively higher melting point which leads it to retain it strength at higher temperature. All these properties lead it to very good aerospace material. They are too much expensive for the commercial airlines, so they stick to the AMMCs. However, Titanium is used in strategic aeroplanes, i.e., combat aircraft, or missiles which are going to travel at very high speed , that is they are always travel at a speed higher than speed of sound, when skin temperature of aircraft is very high to sustain by any other element. They are used in the components of Jet Engines. In automotive industry they are used as technology demonstrator, i.e. in Formula-1 cars or Super Sports Cars where they found application in brakes. Cast of magnesium alloys are used in aircraft gearbox housings, chain-saw housing. Copper MMCs can be used in super-conductors.

Mechanical behaviours MMCs: No material is of any importance unless; we know its properties properly. Uni-directionally reinforced fiber MMC shows a linear increase in longitudinal Young’s modulus of the composites as function of fiber volume fraction. However, the increase in transverse modulus is very low. Similarly, particle reinforcement also shows the same trend for the modulus, however, the increase is much less than that predicted by rule of mixture. The prediction of strength is more complicated than the prediction of modulus for MMC. The rule of mixtures, says that the strength of the composites is a volume weighted average of the strength of the fibre and matrix. The toughness of MMCs depends on the matrix material and microstructure as well as the reinforcement type, size and orientation. In unidirectional fiber reinforcement, it is very easy to crack to propagate through it which can break the composite. Ceramics reinforcements have a co-efficient of thermal expansion greater than that of most metallic matrices due to which thermal stresses are generated when the composites are subjected to temperature change. This stress can be controlled by controlling the proportion of reinforcement and matrix and the distribution of the reinforcement in the matrix.

1.6 Fabrication Of AMMC

For the purpose of the work with the MMCs one of the most important steps is to fabricate MMCs according to our need. There are many ways to manufacture the MMCs. Most common of them are via liquid metallurgical route while another popular method is powder metallurgy which follows solid metallurgical route. Since in the present work is one of the liquid metallurgical route i.e., Stir casting will be used, so a brief background of this process is described below.

Stir casting is the most convenient way to manufacture MMC material with any kind of particulate reinforcement. In this process metal used in MMCs is first melted in crucible placed inside a furnace. Then this melted metal is stirred with the help of graphite stirrer. During stirring due to rotation of metal a vortex is formed at middle of the crucible. Formation of this vortex is essential and critical for the whole process as this is where we will drop reinforcement. Turbulence in this vortex will decide that how much effectively any particulate reinforcement will mix in any meted metal.

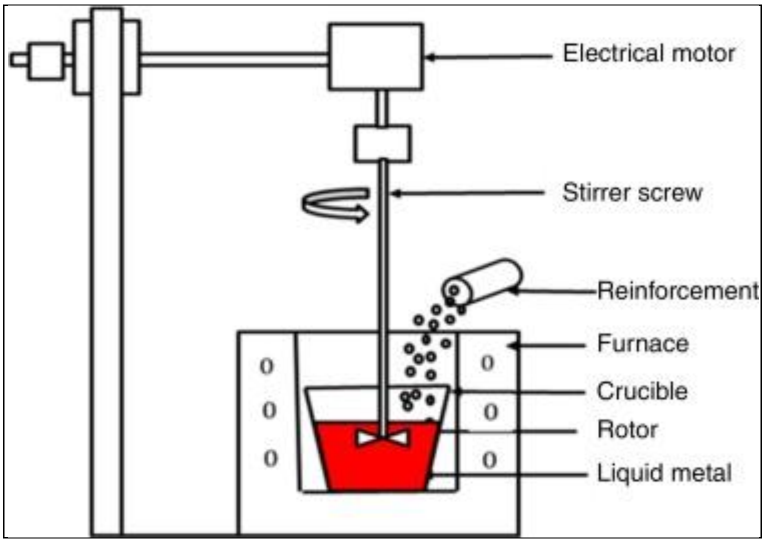


Figure 1.3 Stir Casting Set-up

There are a number of parameters involved that can be responsible for the good quality of casting. Some of them are discussed below.

- *Viscosity of liquid metal:* It has been seen that a higher viscosity will lead to a better mixing of reinforcement. So if for this purpose magnesium is added to melted metal. This will increase the viscosity and dispersion of the particulates will be more uniform.
- *Speed of the stirrer*: Speed of stirrer is an important parameter to be controlled as higher speed will push reinforcement particles against wall of crucible and they will

stick with it. And if speed is lesser then a proper vortex will not form and in spite of stirring mixing of reinforcement particle will not take place properly.

- *Design of stirrer*: For proper formation of vortex design of stirrer should be proper. Design of stirrer includes numbers of blades, Angles of Blades.
- *Rate of adding of reinforcement*: If addition of reinforcement is too much fast then coagulation/Lumps of reinforcements will form. Due to this a region of brittleness will form inside the casting, hence overall deteriorating quality of casting. If rate of adding is too slow then material will burnt out.
- *Temperature of molten metal*: If molten metal will exposed with too much high temperature. Metal will get fused and destroy the casting.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The most common procedure to manufacture different kind of MMC is stir casting. Different types of reinforcement used widely in composites for brake pads and brake disc material. In particle reinforced composite manufactured by stir casting many attempts are made by differentiating between reinforcing material and quantity of those material. These different compositions in the matrix affect the properties of composite. Here an extensive literature survey has been presented on the different procedures related to MMCs fabrication, mechanical and wear characterization of AMMC as well as the emerging trends of material development for brake disc and pad.

2.2 Tribological Behaviour of AMMC-Steel Contact

Many studies are available in the literature on the tribological behaviour of AMMCs sliding against ferrous materials [10-16]. Matejka et al. [10] acknowledged that applied pressure and sliding velocity, wear and frictional properties of the composite material can be affected from the particle size of reinforcement. Hence they tried to find relation between particle size and tribological properties of the composite material using three different particle sizes and four different compositions. Pins were made of composite material and disc is of cast iron. Their study revealed that friction material with finest SiC particles show lowest stable frictional coefficient. Wear rate was decreased with increase in percentage composition of SiC and hardness increased as expected. Ahmad *et al.* **[14]** used Al Alloy-242 reinforced with alumina 30% to fabricate the composite through squeeze casting and carried out tribological test with varying load and velocity. The SEM images of samples were studied for recognition of type of wear failure occurred on the surface. Comparison between the conventional brake disc material and Al-SiC composite was done for the comparison of wear rate and coefficient of friction. Akhlaghi et al. [15] studied the influence of graphite content on the sliding wear characteristics of sintered Al2024/Gr composite materials using a pin-on disc wear test. They used in situ powder metallurgy technique to fabricate the composites with 5–20 wt. % flake graphite particles as well as the base alloy. They found that for dry sliding, the base alloy exhibits the friction coefficients equal to 0.35 and decreases with increased graphite concentration reaches to 0.12 for composites containing 15 wt. % graphite. Veeresh Kumar [16] used Al6061+SiC and Al7075+Al_2O_3 for their study and compared the tribological characteristics sliding against EN31 chromium steel. Pins are made up of composite material and disk is of EN31. Their study concluded that density, hardness and tensile strength of both composite materials are increasing with reinforcement contents. Also, wear resistance of both the composite material was appeared to be increasing with increase in percentage of reinforcement.

Many more such works can be found in the literature involving the tribological behaviour of AMMC. However, these tests could not simulate the real tribological behaviour for brake rotor applications since most of the studies made were involved sliding against steel.

2.3 Significant Research on Composites as Brake Pad Materials

AMMCs is gaining interest for the wear resistant and light weight applications such as brake rotors and drums, cylinder liners, pistons, cylinder blocks, etc [1, 6]. **Prabhu et al. [17]** studied tribological and mechanical behaviour of Cu/SiC/Gr hybrid MMC as brake pad material taking Cast iron as the counter surface. MMC is made from powder metallurgy methodology. Composites were made in form of monolayer (SLCs) and multilayer (MLCs) which also include layer of pure Cu metal to increase density and dampening capacity of composite material pin. A dynamometer was being used for experiment making brake action at different sliding speed. Wear rate and braking performance was seen to be better in case of multi layered composite material. Smaller particle size was seen to have better braking behaviour and lower wear rate. Compression and flexural strength of the multi layer composite material was seen to higher than monolayer composite material. They believed that lower porosity, strain hardening of pure copper layer are reason of increased strength. It was also observed that crack growth is higher in case of monolayer composite as in case of multilayer composite material layer of pure copper hinders the growth of crack. **Mohammad A [18]** studied AMMC for the application of brake pad. He made two samples of Al/SiC composite material made from powder metallurgical method. After the experiment using Krauss type Rig friction tester with cast iron as the counter surface, results were compared with friction results of resin based brake part. Wear of resin based pad was observed to be higher than both of aluminium based composite material whereas coefficient of friction of resin based composite was higher and more constant than the AMMC. However, temperature rise of AMMC was much lower than the resin based composite.

Nagesh et al. [19] investigated some brake pads made up of a combination of friction material, wear resistant material, filler material and some binder material to bind all the material mentioned above, and then compared wear behaviour of different samples against the brake pad commercially available. In this way they predicted effect of composition of different material on performance of brake pad and also gave alternative composition of brake pads. **Jae hyun gwon et al. [20]** studied the effect of glass fiber in the brake friction material. Brake friction material consisting of chopped and milled glass fiber was made from powder metallurgy method. They observed that more adhesive contacts lead to high co-efficient of friction and wear rate due to stick slip phenomenon which in turn leaded to fiction force instability, more vibrations and more noise was produced during braking action.

Aranganathan and Bijwye [21] attempted to develop copper free brake friction material which replaced asbestos. Nowadays Cu dust is also found to be dangerous to human. The authors tried to compare two types of friction material one is Cu based other is Cu free friction material. Two new types of friction material are also tested, rock wool and thermo-graphite. Different composition of both alternative filler material is tested cofs were observed after a number of braking is calculated. **Aranganathan et al. [22]** studied organic brake friction material and effect of concentration of aramid fiber (AF) on friction and wear properties using brake inertia dynamometer. They checked for the sensitivity of COF with change in speed and pressure and temperature. It was concluded that wear resistance of composite with highest AF have higher wear resistance and co-efficient of friction behaviour is found to be vary with vary with speed.

Rathod and Umasankar [23] prepared samples of Al6061-SiC and carbon fiber, by powder metallurgy method for the purpose of friction material. Quantity of SiC is fixed and carbon fiber was kept variables. Afterwards different properties such as density, hardness, porosity and wear rate were measured. **Maleque and Atiqah [24]** had prepared four coconut fibre reinforced AMMC for automotive brake pad. Binder, friction modifiers, abrasive material and solid lubricant were also used in the developed AMMC. From their investigation, they observed that 5 and 10% coconut fiber composites exhibit the better mechanical and physical properties. **Gultekin et al. [25]** made sintered Cu-MMC with graphite with varying percentage brake pad and Al reinforced with SiC-20% as brake rotor. Pad was made from powder metallurgical methodology while rotor was made via stir casting method. Constant sliding speed with varying load was taken for experimentation. They observed a stable COF for all composition but decreasing COF with increasing load. In their experimental results COF found to be varied from 0.2 to 0.45, depending upon graphite content, applied load and sliding distance. Higher value of COF was observed for 2 N load which was least in all the experiments. They attributed it due to lesser graphite dissipation to interface and non formation of triboxide layer. Worn surface for lower load had been seen with groove formation and ploughing. They concluded that for higher load wear mechanisms changes into plastic deformation induced delamination. Friction layer on pad was found with Cu and Graphite. Wear of rotor was found to be less than wear of pad due to presence of hard SiC particle in the disc.

2.4 Composites as the Brake Disc Materials

AMMC, C/C-SiC and Cu-MMC are the potential candidates for brake disc as will be shown by the following literature review. It is worth mentioning here that research on C/C-SiC is limited by their cost, Cu-MMC is limited due to the health concern, whereas AMMC though found to have enormous scope of replacing existing CI disk, however, research on the same for brake disk application has still left with huge scope. Researchers, in most of these AMMC for brake disk has explored by reinforcing SiC. Hybrid AMMC is yet be explored.

Maleque M.A. [26] recognised that in literature, there is no proper method that has been proposed to develop and select the proper brake disc material among some candidate material. So he developed a method based on the weighing method of properties. He considered some properties of the brake disc material and assigned some weight to them according to the importance of the properties, then applied the proposed method to some of the candidate materials. They calculated the performance index($\boldsymbol{\gamma}$) as

$$\boldsymbol{\gamma = \sum_{i=1}^{n} \beta i \alpha i}$$

Where, βi is scaled property value and αi is weighing factor. They suggested that the more will be the performance index, better will be the material for a particular application.

Daoud et al. [27] tested A359/20% SiC for the brake disc rotor. They fabricated a MMC disc rotor and tested it against semi-metallic brake pad within range of a load and speed. They found that wear-rate of existing CI disk is lower than the fabricated MMC disk while wear-rate of MMC and brake pad was found to first decrease and then increase with load. Wear rate of friction material against cast iron is slightly lower as against MMC. In some cases layer of friction material was found adhered to composite disc and hence provide some wear resistance and lubrication against further wear.

Bian G. [28] investigated C/C-SiC rotors and observed that there are two main regions of friction layer i.e. transfer layer and SiC over which a friction layer is formed. Transfer layer comprised of material from brake pad, which means that it is transferred from brake pad. There was no chemical bonding between transfer layer and brake disk material. Transfer layer and friction layer material were densely compacted inside the craters of brake disc material. SiC particles got detached from friction layer developing the plastic deformation slips which gave possible reason of detachment of SiC particles.

Rehman et al. [29] tried to find suitability of AMMCs for application of composite drum brake on the basis of coefficient of friction. ADC 12 aluminium alloy with two different wt composition of SiC were used, followed by heat treatment under T6 conditions. Commercial semi-metallic brake pad was used as counter surface. They studied the effect of load and speed on coefficient of friction. The researchers also observed formation of transfer layer due to transfer of brake pad material onto the brake drum composite material. They studies effect of this transfer layer on COF and wear resistance. It was observed that it has lubricating effect on friction between surfaces and increased wear resistance.

Mohan Kumar [30] recognised the need of new brake disc material. He studied 5 different compositions Boron Carbide (B_4C) in A359 Aluminium alloy using pin on disc test. Their experimental result revealed that specific wear rate decrease with the increase in load and wear behaviour improved with inclusion of boron carbide.

Natrajan et al. [31] studied dry sliding tribological behaviour of grey cast iron and A356/25% SiC (discs) sliding against semi metallic brake shoe lining (pins). Wear rate for disc and semi metallic brake pad were measured for varying sliding speed and varying load. Wear rate of brake pad was slightly higher than cast iron disc. Wear of the proposed MMCs was less than the wear of cast iron and wear of brake pad was more in case of MMC. Frictional force was found higher for MMCs.

Straffelini et al. [32] investigated the effect of load on the dry sliding friction and wear behaviour of AMMCs. The counter surface was taken as a semi-metallic friction material. They have found that wear resistance of AMMC brake rotors can be superior to those of cast iron rotor if the structure and composition of lining material are correctly modified. **Uyyuru et al. [33]** studied the friction and wear behaviour of Al-SiC disc sliding against automobile friction pads. They found that the wear rate increases and friction decreases with the increase in the normal load while both wear and friction decreases with increase in sliding speed. Similar studies were also performed by Zhang et al. [34] using 25 vol% SiC particles. Blau et al (35) simulated dry sliding wear using CI, MMC and ceramic composites. They have reported that average friction coefficients were similar for the sliding couples involving cast iron and the ceramic composite but were lower for the MMC.

2.5 Summary of Literature Review

A considerable development has been made for the brake pad and rotor materials. In the recent years a few studies also indicated the potential use of MMCs for braking applications. However, in brake applications the rotor material slides against automotive friction material, whereas limited information is available in the open literature which deals with the tribological interactions between composite discs and commercial brake pads. In the last few years, some researchers have tried to use AMMC, C/C-SiC and Cu-MMC as the potential candidates for brake disc and pads. In some cases researchers also came up with some encouraging results. Hard reinforcements such as SiC were added in aluminium matrix in quantity between 10% to 40% by weight. With increase in hard reinforcement, wear resistance of MMC increases but COF decreases. So researchers tried to strikes a balance between these two contradicting properties. Some results are successful in doing so. It is worth mentioning here that research on C/C-SiC is limited by their cost, Cu-MMC is limited due to the health concern, whereas AMMC though found to have enormous potential for replacing existing CI disk. AMMC technology exhibits a remarkable fit, in addressing all of these areas simultaneously while offering valuable rotating mass reduction. However, before making any conclusion it has to be explored further, to determine whether this component can be translated from laboratory stage to commercial production with meaningful market potential.

2.6 Research Gaps

Thus, based on the literature available a list of potential gaps is summarized that has helped in defining the objectives the present research work.

- The information on the development and application of the materials selection method for the design of automotive brake disc is limited in the literature.
- Many researchers have conducted the study on aluminium based MMCs with SiC, alumina, zirconia, boron carbide etc., as the reinforcements. But very few studies are

there which have investigated on hybrid composite sliding against automotive friction materials.

- Also, it is found that a lot of research is done for the formulation of new brake friction material as compared to the development of the brake rotor materials. Hence, to develop brake rotor materials to replace the conventional CI, further attempts can be made and adequate benchmark can be set to realize the actual wear behaviour of the AMMCs sliding against automotive friction materials. AMMC with other than SiC reinforcement, as well as hybrid AMMC for brake rotor application can be further explored.
- To the best of our knowledge, there is possibly no study available which compares the friction and wear of brake discs in one frame of work where disc is made of Al-SiC, Al-B_4C, Al-SiC-B_4C and Cast iron. Further investigation in this aspect will definitely help in understanding the meaningful market potential for developing AMMC disc in place of conventional CI rotor.

2.7 Research Objectives

It’s been a long time since researchers had been trying to get the benefits of composite material to be included into the different part inside an automobile. Composite materials have been included in different application such as Piston, piston rings, Bearings etc. Some researchers as we have seen in the previous chapter are trying to use composite material for the formation of disc material and brake friction material in a automobile braking system due to forever increasing demands for the braking system of the automobile. These new demands arise from continuously changing environmental norms for vehicle and due to continuously increasing power of the vehicle. Due to continuous demand for change in brake friction material, it is necessary to form a new brake disc material that can perform better than existing material in terms of tribological, thermal and mechanical aspects.

From the literature it is found that there are some mentions of hybrid composite material in the context of the candidate brake disc material. However, there is no proper research on the evaluation of tribological behaviour of these hybrid materials sliding against automotive pad friction liners.

In the present work an attempt is made to fabricate some candidate AMMCs and characterize their tribological behaviour against commercially used friction pad, for the purpose of potential candidate materials for brake rotor application. Subsequently, following research objectives are defined for the present research.

- Selection of suitable candidate materials for the brake disc application
- Friction and wear behaviour of automobile brake pad sliding against used and unused commercial cast iron disc.
- Development of AMMC for brake rotor with SiC, B_4C and SiC+B_4C reinforcements, by stir casting method.
- Mechanical and morphological characterisation of developed discs, commercial CI disc and an automobile brake pad.
- Investigation on the comparative friction and wear behaviour of the CI, Al-SiC, Al-B_4C and Al-SiC-B_4C discs with different compositions, sliding against a commercial pad.

Chapter 3

MATERIALS AND METHODOLOGY

3.1 Introduction

This chapter describes the selection of material used to fabricate the composite, the method of fabrication, experimental equipment and facilities used for characterizing the samples, friction and wear studies and any other methodology that has been followed to achieve the objectives.

3.2 Work Plan

To accomplish and attain the research goals mentioned in the previous chapter following plan of work is developed.

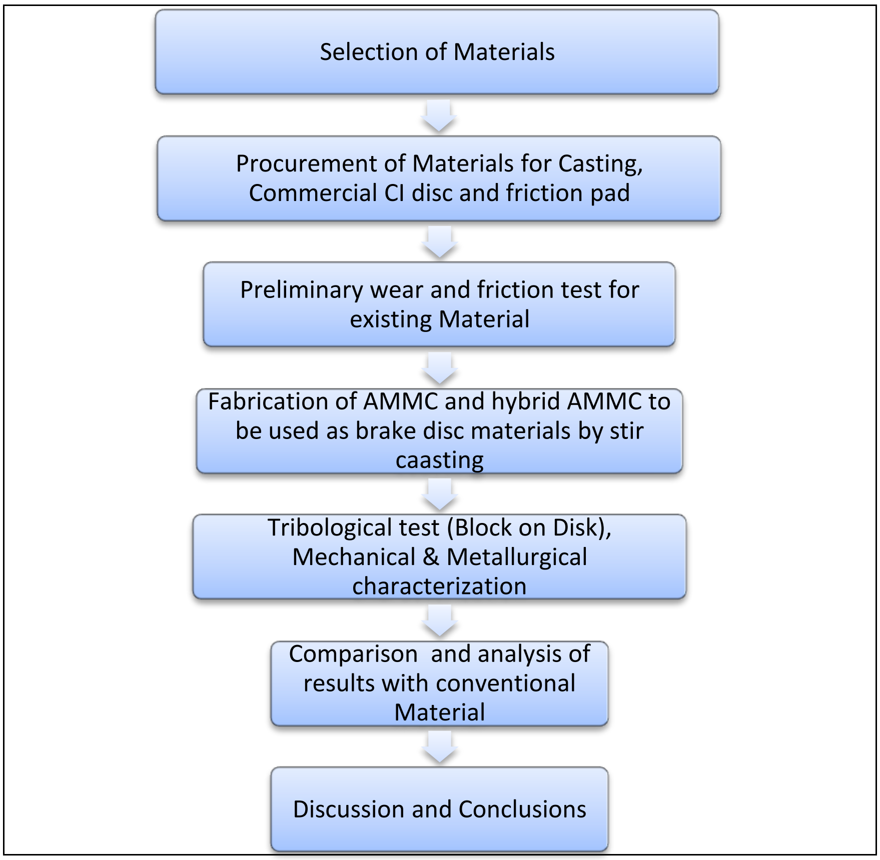


Figure 3.1 Flow chart of work plan

3.3 Material Selection

Material selection process may lead to several possible solutions to the same problem. Also, for the given application the material of the components should be selected in such a way that it should behave in conditions (mechanically or environmentally) in the way we anticipated. It is very important criteria as all the thermal or mechanical stresses our product is subjected to, is to be borne by the selected material. Coefficient of friction can vary depending on the type of material used for the brake rotor.

- **Conventional Disc:** Traditional material for automotive brake rotor is the cast iron due to its cost, relative ease of manufacture and thermal stability. However, the specific gravity or density of cast iron is higher which consumes much fuel due to high inertia.
- **MMC as potential candidate:** As discussed earlier MMCs, especially AMMCs has shown great promise for brake rotor applications. Following section discusses the few alternatives for matrix and reinforcement materials and subsequently reason of selection of aluminium alloy for the purpose of our study.

Matrix: The other potential candidate materials for the brake disc application include cast iron, aluminium alloy, titanium alloy, etc. Aluminium alloys alone would be very soft to use. However, it is corrosion resistance durable, light weight, excellent thermal conductivity, ductile and malleable material. These materials have a lower density, high strength-to-weight ratio and higher thermal conductivity as compared to the conventionally used gray cast irons. As a result use of these materials can reduce weight up to 50-60% in brake systems. So, the composite of aluminium undoubtedly is one of the great options for many industrial applications including the material for brake disc. Titanium alloys are lighter element and having excellent thermal properties. It is lighter but not as lighter as aluminium alloys but thermally better then aluminium and its alloy. It is much more expensive then the aluminium and cast iron. Hence, it may be applied only to expensive automobile.

In the present study, for the purpose of primary phase in composite material, Al 6061 is chosen as Al 6061 is also available in abundance due to application in aircraft industry. Also, it shows a very good corrosion resistance as compared to other aluminium alloys [36]. The selected aluminium with alloyed content (Al6061) has the following composition:

Table 3.1 Composition of Al 6061 [37]

Component	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Si**	**Ti**	**Zin**	**Al**
Wt. %	0.04-0.35	0.15-0.4	Max. 0.7	0.8-0.12	Max 0.15	0.4-0.8	Max 0.15	Max 0.25	Balance

Reinforcements: A number of potential reinforcements are surveyed before selection of the same for our purpose. Some of the already prepared and discussed composite materials from the literature are being discussed. The potential hard reinforcements for our research includes SiC, B_4C, TiC amongst the others.

Silicon carbide is used as reinforcements due to its hardness and Tensile strength. They both are higher than the Aluminium 6061. And hence addition of reinforcement into a primary phase i.e. Aluminium alloys will enhance both properties. And also SiC has a very good shock resistance. Thermal property such as thermal conductivity is also very good. Chemically, it is a very inert Material and improves chemical inertness of composite material. Boron carbide is one of the hardest material exist in nature. It has very excellent thermal conductivity. It is chemically inert material. It is more costly than the SiC but is harder than the SiC. Also, it is having lesser density then SiC and aluminium. This means that it will further decrease the weight of the composite material. Hence it will make a lighter composite material but hardness of composite material will improve as well when it will be compared with SiC composite material. TiC is extremely expensive as reinforcement to be used. But when used in Aluminium matrix it forms a intermetallic compound named titanium Tri-Aluminium which is very much brittle and hard material. It is known for having a needle type structures which becomes very abrasive in nature. Due to formations of these compounds there is decrease in ductility and tensile strength of the matrix [38]. These compounds are of course very hard and corrosion resistant at elevated temperature. But these compounds are very poor when it comes to ductility. They are very brittle in nature. Due their very high hardness during tribological test they do have very catastrophic effect on counter surface also. And also on impact titanium aluminide compounds tend to break out from the matrix. So over all hardness will increase but it is not a guarantee that wear rate will also decrease.

Due to the above limitation of TiC, in our study it is discarded and instead SiC and B_4C are used as the hard reinforcements for aluminium matrix. SiC reinforcements are the most tested reinforcement material. It is being tested for mechanical, thermal and as well as tribological properties against commercial brake friction material. It is tested at different composition, sizes of particle etc. Due to requirement of higher wear resistant, in the literature composition tested is started from 13 % and goes up to higher composition such as 40 %. But optimal value is recognised as 20% to 25 %. Recently, M. Govindan et al. [39] carried out a study of Al-SiC MMC brake disc and suggested that even 10% SiC reinforcement can suit for brake disc application. On the other hand not much work is available for B_4C as compared to SiC. Properties of the selected SiC and B_4C particles are shown below.

Table 3.2 Properties of SiC and B_4C particles [40]

Properties	SiC	B_4C
Density	3.21 gm/cc^3	2.5g/cm^3
Hardness	2800 kg/mm^2	2900-3580 kg/mm^2
Fracture toughness	4.6 MPa	2.9 - 3.7 MPa
Thermal conductivity	120 W/m.K	30-42 W/m.K
Specific Heat	750 J/kg.K	840 J/kg.K
Size	37 µm	37 µm

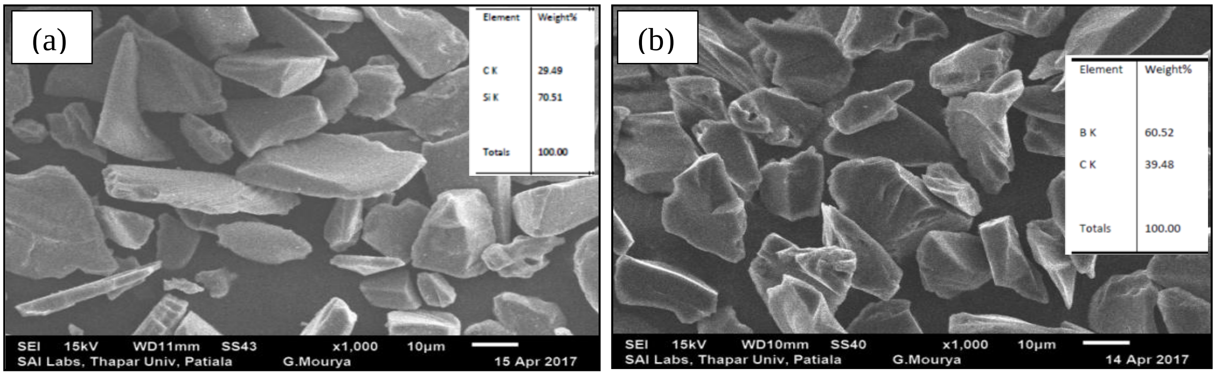


Figure 3.2 SEM micrographs of a) SiC b) B_4C

In case of hybrid composite material between Al+SiC+B_4C it is observed that when B_4C component of reinforcement is increased as compared with SiC, mechanical properties of composite material is observed to increased [41]. This also shows us that we can use two types of reinforcement together for the development of hybrid AMMC disc.

3.4 Fabrication of Composites

It is one of the most important steps required for the subsequent experimental study. The composites were fabricated by Stir Casting method. Al 6061 alloy rods are cut into 150 mm length and melted in a resistance heated muffle furnace at the temperature of 750^{0}C for 2-3 hours. Then in the mean time, reinforcement particles were heated separately in a baking oven to a temperature of 200^0C to remove moisture from the powders. Then the magnesium ribbon was put into the molten metal for the wettability and after some time the boron and/or silicon carbide were mixed into the molten metal. The mixture was stirred by using mechanical stirrer for about 10 minutes. The stirring speed was 400 rpm and the melt temperature was maintained at 750^0C during addition of the particles. Cast blocks of 150mmx75mmx50mm size was prepared in this manner which is then processed further for our required samples for different experimental purpose. This same procedure was followed for all the composites prepared.

Table 3.3 Parameter of casting

S. no.	Parameters	Value (in respective units)
1	Temperature Metal (˚C)	750
2	Preheating temperature (˚C)	200
3	Stirrer speed	400 rpm
4	Stirring time	10 minutes (2 + 5 + 3)

For the purpose of casting, electrical resistance furnace was used which can attain up to a temperature of 1100 ˚C. A graphite stirrer comprised of 4 blades is used to make a proper vortex during the stirring which helps in proper mixing of reinforcement and we get a macroscopically homogenous mixture. Stirrer is attached to a stainless steel rod which is then attached to electric motor.

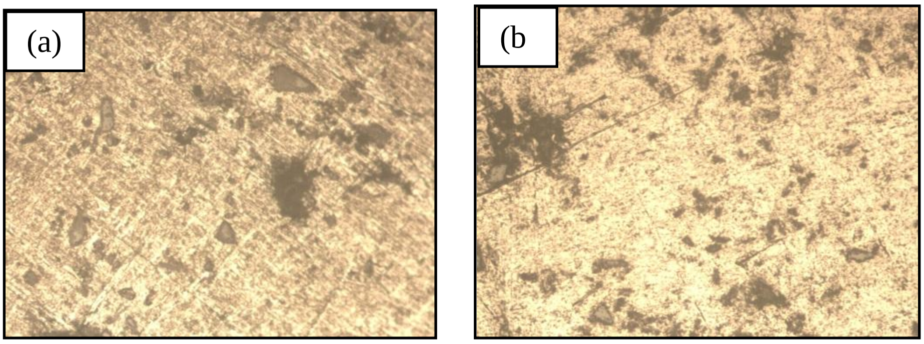


Figure 3.3 Optical Micrographs of Cast Samples (a) Al/10% SiC Composite material, (b) Al/25 % SiC Composite material

While casting stirrer is placed near the bottom of the crucible so that those reinforcement particles don't get settled down inside the crucible. Crucible is made up of a ceramic to be able to withstand high temperature. After stirring the aluminium melt is poured into a cast iron mould, which has been designed to push out the cast later.

3.5 Metallurgical Characterization

X-ray diffraction (XRD) was used to establish the structure of composites and wear tracks. X-rays are produced with high speed electrons from a hot tungsten (W) filament act as cathode. The anode is a water-cooled block of copper (Cu). Reflections of these X-rays are detected based on which material characterization is done. The facility is available in SAI Labs, Thapar University Campus, Patiala.

In SEM high energy electron focus beam used for generate different variety signals to get information about sample morphology, chemical composition, and crystalline structure.

The SEM used for this study is a highly accurate and precise instrument (Make: JSM-6510LV, JEOL Ltd, Tokyo, Japan) for fast characterization and imaging of fine structures and has a magnification range from 5–300,000 X (printed as a 128 mm x 96 mm micrograph). It was used to study the worn surfaces and investigate the wear mechanism. This facility is available at SAI Labs, Thapar Technology Campus, Patiala.

Optical microscope is used to observe the internal structure of the metals at different scale and provide a qualitative and quantitative description. In the present study metallurgical microscope is used to analyses the shape, size and dispersion of the reinforcement particles in the matrix alloy. Before examining the structure of the composite, samples are well polished with the help of fine grade emery paper and then etched with etching solution for 20 to 40 seconds.

3.6 Tribology Study

Friction and wear testing by Pin-on-Disk Tribometer: To perform the experiments for our research work the pin-on-disk apparatus (Model: TR-201LE, DUCOM make) was used to examine the dry sliding wear characteristics and the coefficient of friction of the composites. Pin is made in form block of 6 mm x 6 mm cross section and of variable length based on the shape of the brake pad. Disc is made up of Conventional material and Stir casted at various compositions and different material. Disc is made up of diameter 45 mm and height 5 mm. The pin is made up from a commercial brake pad procured from BOSCH agency in Patiala. Block are being flattened and polished with a fine grit size emery paper (up to 1000 Grit size paper) before experimentation. Disc surface is also being polished so that a proper contact surface can be established between the brake pad and disc surface. For each test run, disc and pin was cleaned with acetone or hexane. The friction forces were directly obtained from the automatic digital reading and then calculated coefficient of friction. Samples were weighed before and after the test using a digital weighing balance. So that we can measure wear rate by mass loss method.

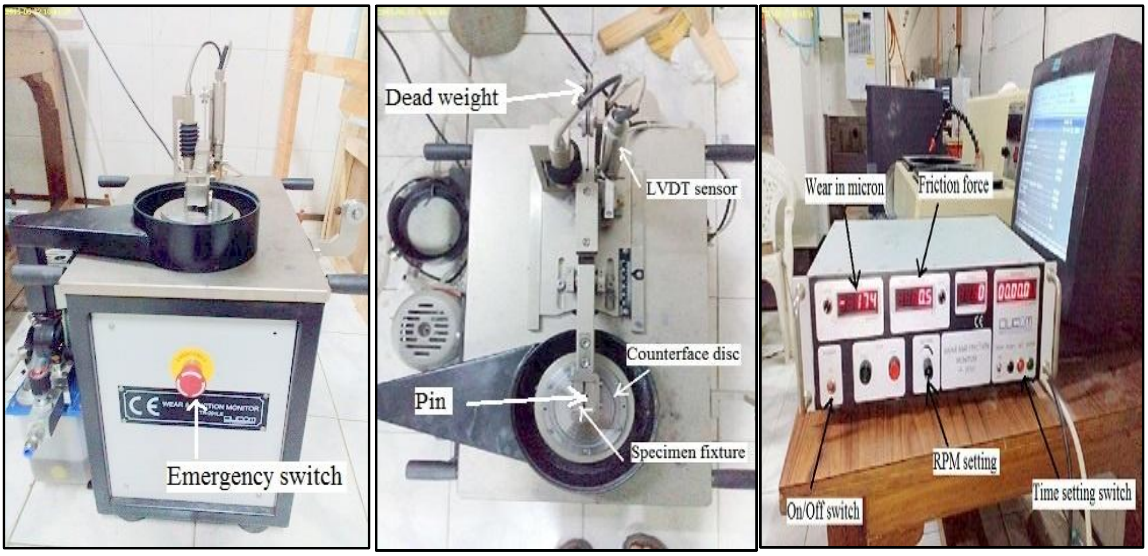


Figure 3.4 Components of pin-on-disk test apparatus

Samples were weighed before and after the test using a digital weighing balance (Make: Mettler-Toledo, Greifensee, Switzerland) with least count 0.0001 g. This facility is available in Chemical Engineering Department, Thapar University, Patiala.

The following equation was used to obtain the wear rate for the pin and disc:

Wear rate (mm^3/m)=Mass loss (g) /Density (g/mm^3)xSliding distance (m)

Design of experiment: The tests were carried out for different sliding speeds and loads at the constant sliding distance of 1800 m (Table 3.4). Sliding speed is taken as 0.25 m/s, 0.5 m/s, 1 m/s. Different loads were 10 N, 30 N and 50 N. There were five different types of disc materials sliding against the same type of friction pad pin.

Table 3.4 Operating Parameters and sliding conditions for sliding wear tests.

Parameters	**Description**
Apparatus	Pin-on-disc Tribometer
Wear test standard	ASTM-G99
Wear pin	Material: Semi-metallic brake pad
Counter disc	Material: CI, Al-SiC, Al-B_4C, Al-SiC-B_4C
Normal load	10, 30, 50 N
Sliding velocity	0.25, 0.5, 1.0 m/s
Sliding distance	1800 m
Lubrication condition	Dry sliding
Temperature	25±2°C

3.7 Hardness Characterization

Hardness is probably known as the resistance of a material to localized deformation or simply referred as resistance to indentation or scratch. The deformation can be in the lot of forms like indentation, cutting, scratching, elongation, bending. In case of ceramics, metals and polymers deformation is considered as plastic deformation of the surface. Hardness can be measured through various techniques such as Rockwell's, Brinell's and Vicker's hardness test are the most significant and important. Composition of mixture plays very important role in approximation of hardness. The reinforcement with Silicon Carbide (SiC), Alumina (Al_2O_3) and aluminized preferred for imparting higher hardness. The size, shape as well as the concentration of the particle influences the hardness. With increase in the filler content, hardness as well as the load bearing capacity of composites increases. Higher Hardness of the material will lead to the brittleness of the material. The micro hardness tester used for calculating the hardness is shown in Fig. 3.5.

Figure 3.5 Micro-hardness tester [Photo Courtesy: Thapar university campus, Patiala]

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

As discussed in the previous chapters, after acquiring the cast iron disc and commercial brake pad and post fabrication of composite discs, they are subjected to various experimental investigations. Hardness measurements for all the materials are performed using Vickers hardness tester. Metallurgical characterization has been done through SEM-EDS and XRD techniques. The materials are then subjected to tribo-evaluation. The following sections present and discuss all the experimental works carried out in the present research.

4.2 Hardness Characterization of AMMCs and Brake Pad

A micro hardness test has been conducted on all the material being used for the tribological test. Samples under investigation were lightly polished so that indent can be visible during the test. The hardness data for each material shown in the Table 4.1 is averages of at least ten readings on different locations of each sample. For all test usually indent locations are selected in the vicinity of reinforcement boundaries so that their effect on the matrix can be characterized adequately and representative values can be obtained thereof.

Table 4.1 Micro hardness for different materials used in the present investigation

Material tested	Average Hardness (VHN)
Commercial Brake Pad	78.2
Cast Iron	242.8
Al6061+ 10% SiC	102
Al6061+ 10% B_4C	150.8
Al6061+ 25% SiC	162
Hybrid (Al6061+15% SiC+ 10% B_4C)	191.8

From the Table 4.1 it is obvious that the hardness of commercial brake pad is much lower than the corresponding cast iron disc. In practice this hardness difference is required maintain so that disc wears out less than the pad. However, in developing new materials for brake disc for the same brake pad we need to be very careful in maintaining the hardness as well as the wear resistance properties of the disc materials. From the table it is clear that Cast iron has the highest hardness of all the tested disc material and with hard reinforcement in the matrix, the hardness of composites gets improved. With increasing percentage of the reinforcement there is also increase in hardness of the composite. The highest improvement is found in case of hybrid composite consisting of SiC and B_4C reinforcements. This is highly desirable because besides the hardness improvement to a great extent it also reduces the overall weight of the composite as compared to the SiC reinforcement only. It is to be noted that density of Boron carbide is lower than both aluminium alloy as well as SiC.

4.3 Morphological and Microstructural Analysis of Discs and Brake Pad

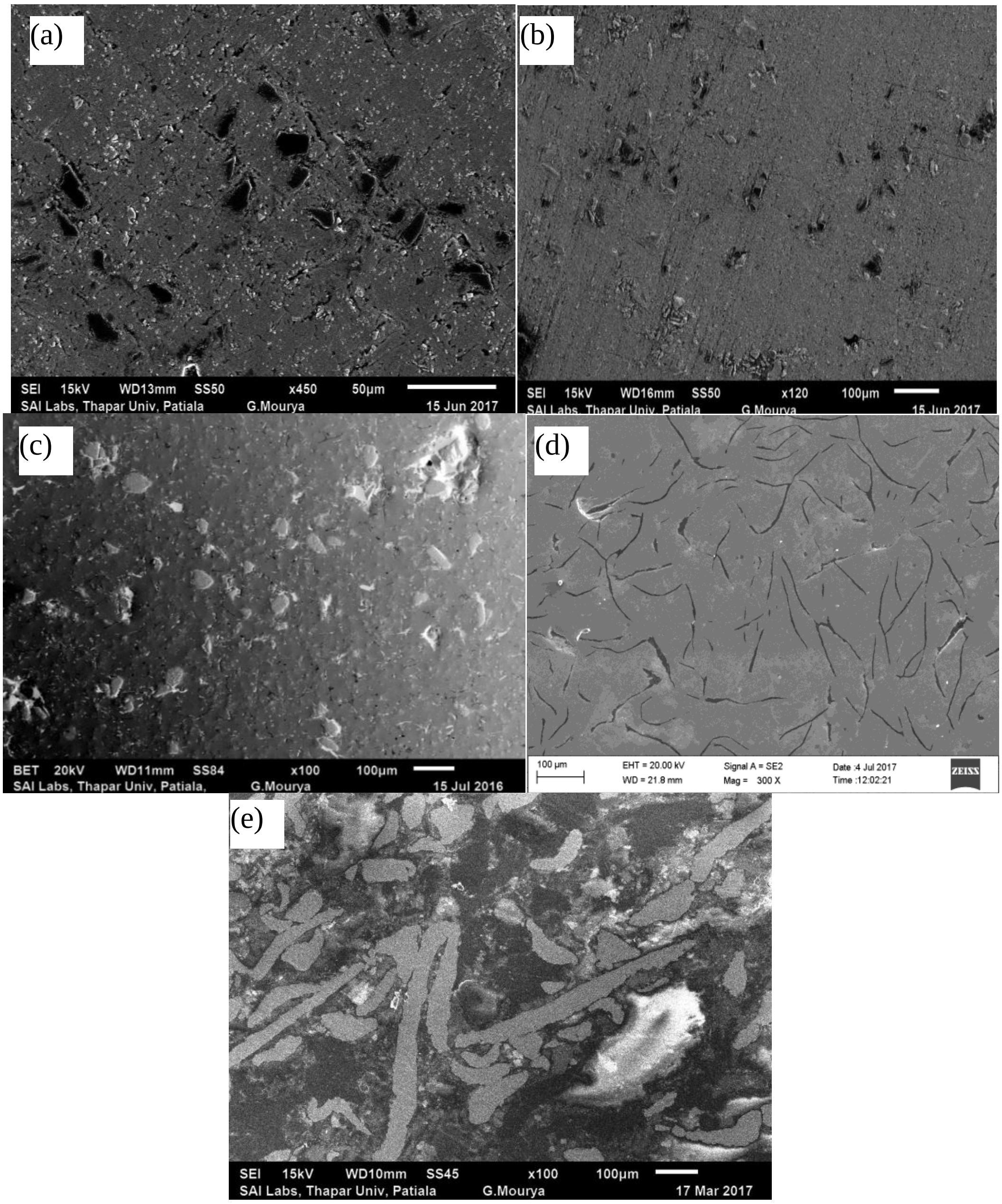
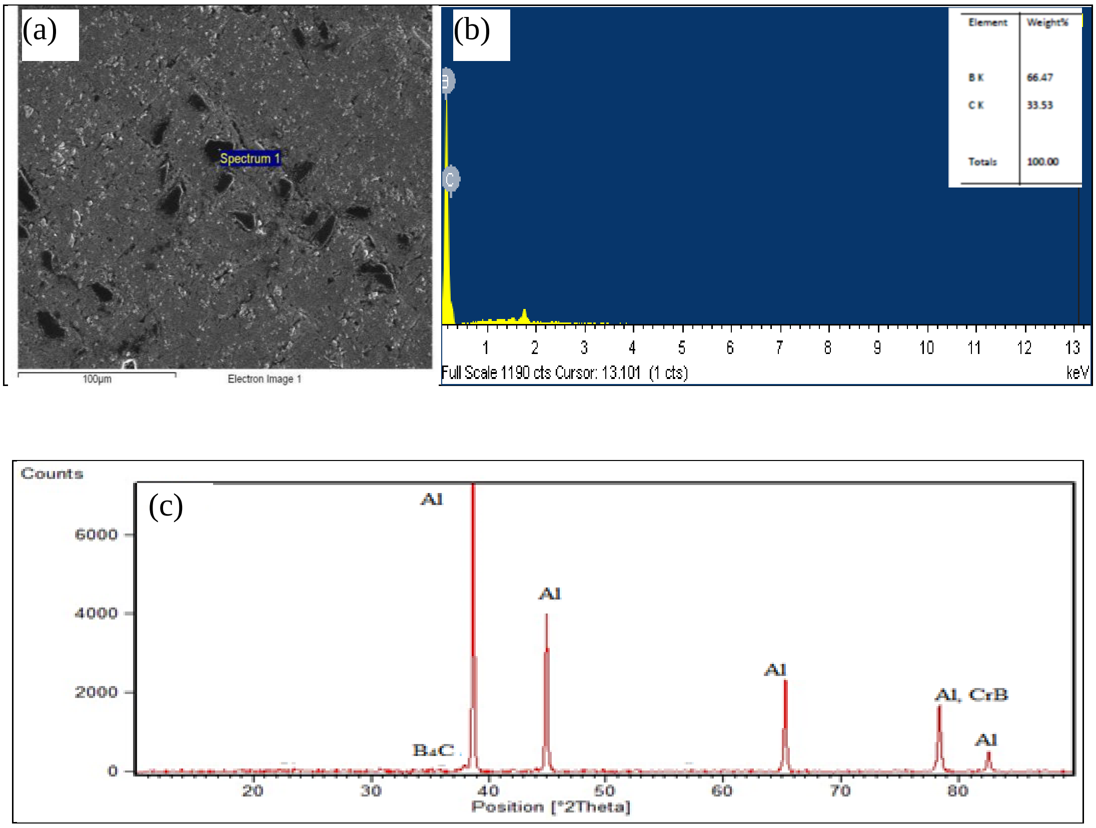


Figure 4.1 SEM micrograph of (a) Al-B_4C (b) Al-SiC-B_4C (c) Al-SiC (d) Cast Iron (e) Brake pad

The micrographs shown in Fig 4.1 demonstrate the microstructures of the fabricated disc as well as of cast iron disc and brake pad. The micrographs from Fig. 4.1(a-c) clearly show the uniform distribution of various reinforcements into the matrix. This is the reason why the mechanical properties such as hardness of the case composites are significantly improved. Figure 4.1(d) shows the microstructure of the cast iron surface, while Fig. 4.1(e) is for brake pad which is a composite of multiple reinforcements which will be confirmed by the EDS analysis.

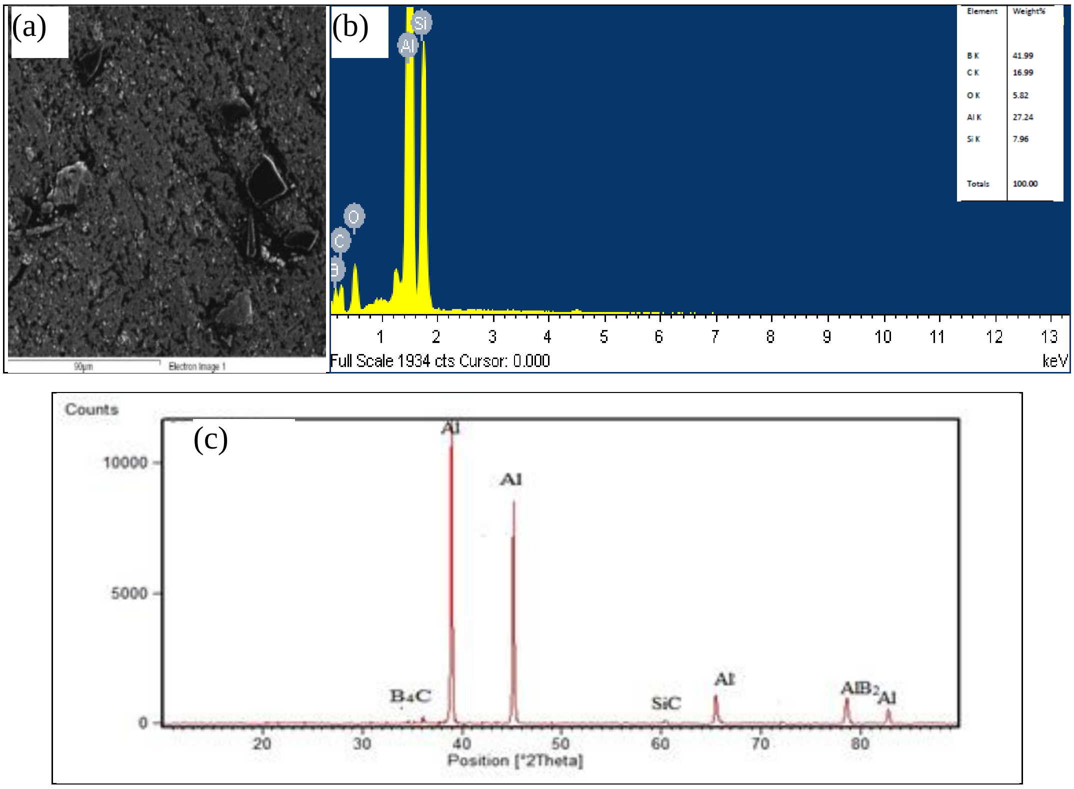
Figure 4.2 shows the elemental analysis of fabricated Al-B_4C composite done by EDS and XRD. The spectral peaks from EDS and XRD clearly show the significant amount of Al and B_4C. Besides, some trace amount of bromides can also be found which is formed after reaction of corresponding element contributed from the matrix and reinforcement.



Element	Weight%
B K	66.47
C K	33.53
Totals	100.00

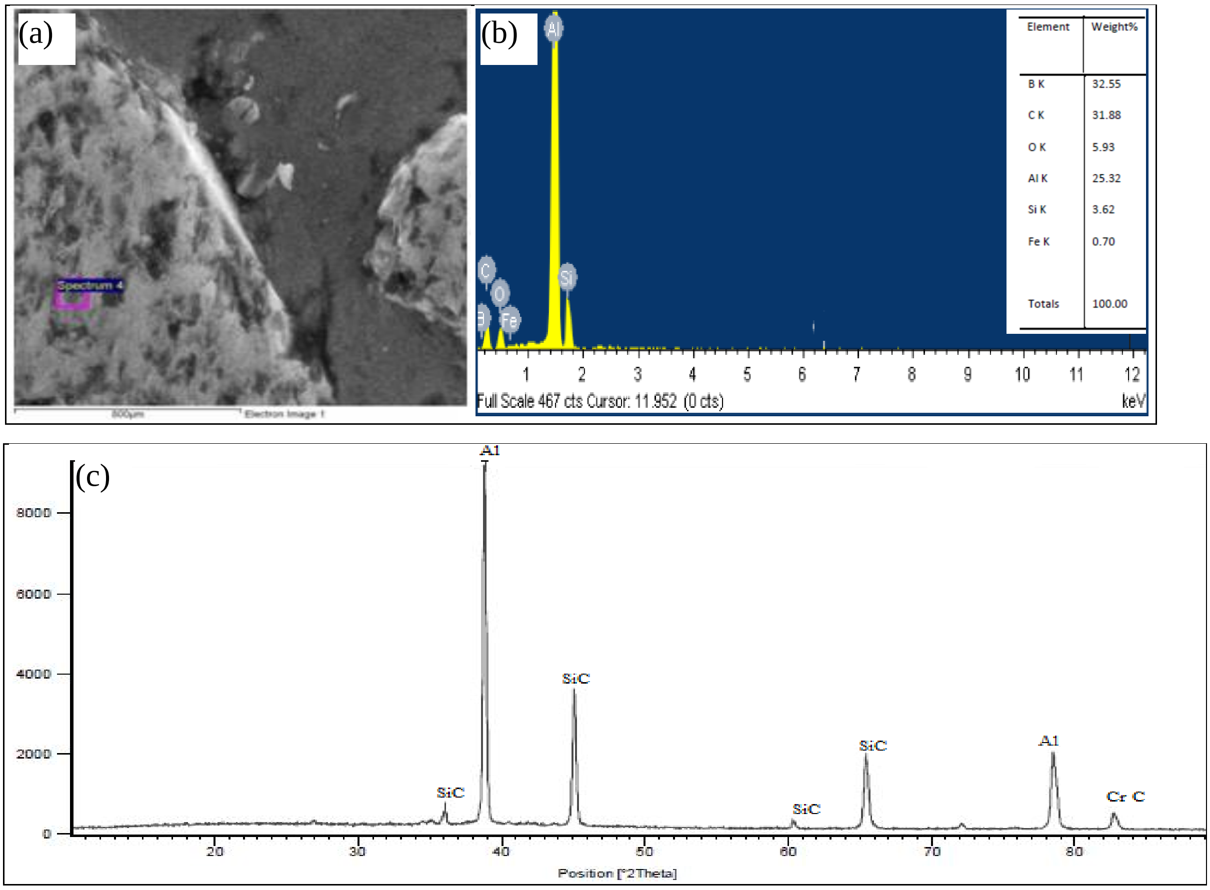
Figure 4.2 (a) Selected region for EDS (b) EDX spectrum and (c) XRD for Al-B_4C

Similarly, Fig. 4.3 shows the elemental analysis done by EDS and XRD for fabricated Al-SiC-B_4C hybrid composite. The spectral peaks from EDS and XRD clearly show the significant presence of Al, SiC and B_4C. Besides, some trace amount of CrB_2 can also be found which is formed after reaction of corresponding element contributed from the matrix and reinforcement.



Element	Weight%
B K	41.99
C K	16.99
O K	5.82
Al K	27.24
Si K	7.96
Totals	100.00

Figure 4.3 (a) Selected region for EDS (b) EDX spectrum and (c) XRD for Al-SiC-B_4C



Element	Weight%
B K	32.55
C K	31.88
O K	5.93
Al K	25.32
Si K	3.62
Fe K	0.70
Totals	100.00

Figure 4.4 (a) Selected region for EDS (b) EDX spectrum and (c) XRD for Al- SiC

Similarly, Fig. 4.4 shows the elemental analysis done by EDS and XRD for fabricated Al-SiC-B_4C composite. The spectral peaks from EDS and XRD clearly show the significant presence of Al and SiC.

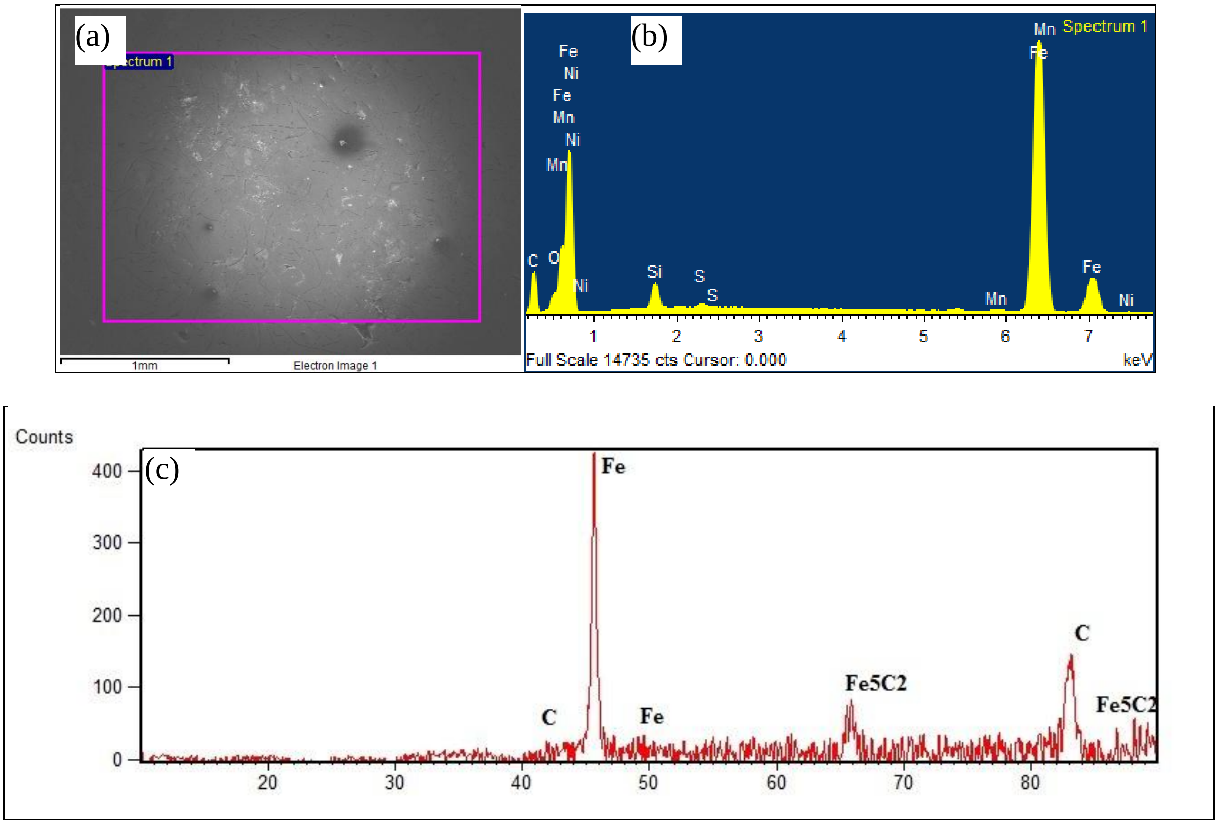


Figure 4.5 (a) Selected region for EDS (b) EDX spectrum and (c) XRD for Cast iron

Figure 4.5 shows EDS and XRD of the CI disc which was used as the reference disc for wear studies. Besides the peaks shown for Fe and C in XRD, negligible amount of elements such as Mn, P, S and Si were also detected in it.

As depicted in Fig. 4.6, brake pad is a composite of many elements and components, the major component being Fe and graphite, C. Due to the presence of large variety of mineral species; XRD peaks give rise to overlapping leading the very difficult interpretation of these peaks. Other compounds detected in insignificant amounts include $BaSO_4$, Fe_2O_3, Al_2O_3, $CaCO_3$, MgO, $ZrSiO_4$, Sb_2S_3, ZnS, $CuFeS_2$, FeS_2, MnS_2, CuS, etc.

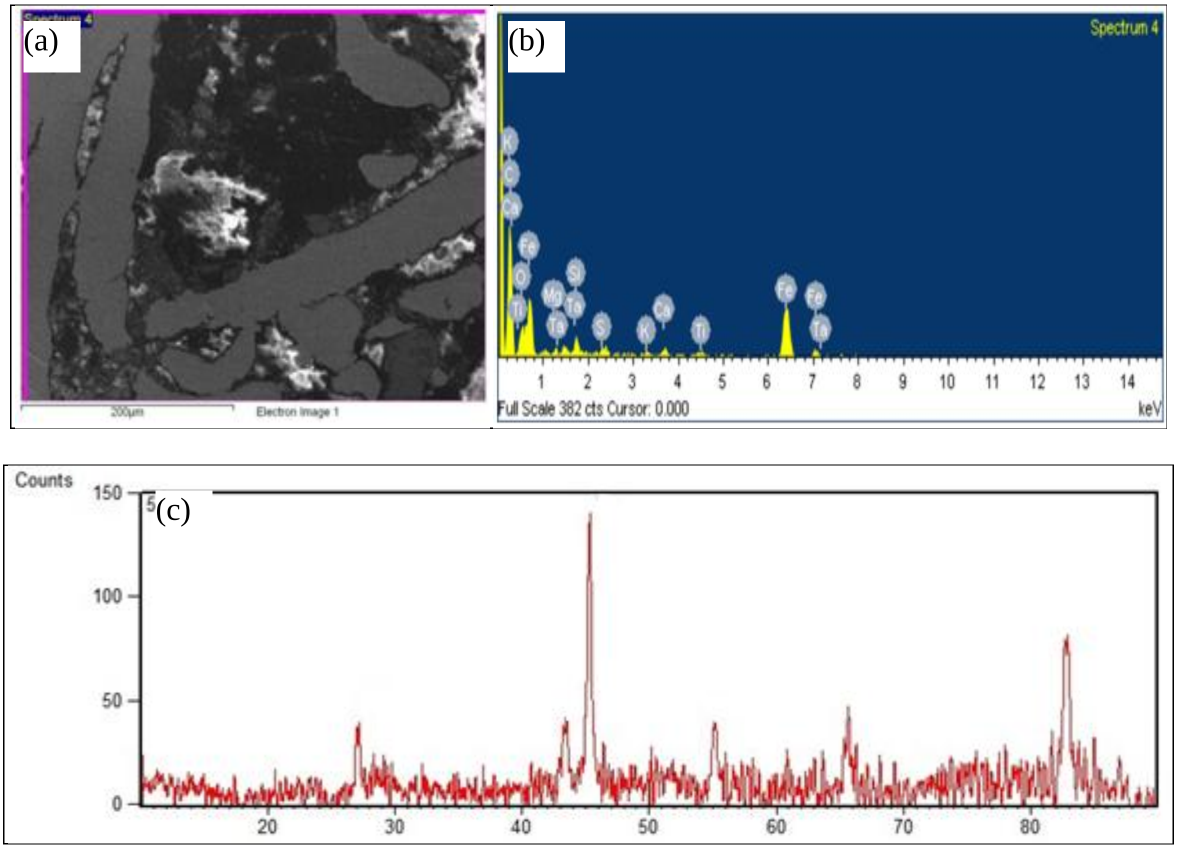


Figure 4.6 (a) Selected region for EDS (b) EDX spectrum and (c) XRD for Brake pad

Thus, the brake pad is characterized by huge amount of complex elements and compounds which is very difficult to interpret and careful analysis is required separately if the pad is to be formulated. However, in the present study, since the pad material is kept same and disc material performance analysis is being carried out, so we will primarily focus on the disc material and worn out disc characterization in the subsequent sections. The above analysis also indicates that friction materials of selected brake pad are directly hooked to the metallic support in combination with coarse carbon particles.

4.4 Wear and Friction Behaviour

A number of different conditions such as load and sliding velocity are being utilised to study the behaviour of the different brake disc materials against a standard brake pad material. Both the wear rate of brake pad and brake disc material has been calculated. Table 4.2 shows the wear rate of brake pad sliding against the various brake discs whereas Table 4.3 shows the corresponding disc wears.

Table 4.2 Wear Rate of brake pad sliding against various discs

	Wear Rate (mm^3/m)			
Counter Surface	**Load (N)**	**Sliding speed (m/s)**		
		0.25	**0.5**	**1**
Cast Iron	10	$1.65*10^{-04}$	$3.53*10^{-04}$	$4.02*10^{-04}$
	30	$4.94*10^{-04}$	$5.85*10^{-04}$	$6.91*10^{-04}$
	50	$6.22*10^{-04}$	$8.88*10^{-04}$	$11.8*10^{-04}$
Al-10%SiC	10	$1.32*10^{-04}$	$1.65*10^{-04}$	$2.01*10^{-04}$
	30	$2.82*10^{-04}$	$2.92*10^{-04}$	$5.59*10^{-04}$
	50	$3.66*10^{-04}$	$6.25*10^{-04}$	$7.99*10^{-04}$
Al-10%B_4C	10	$1.32*10^{-04}$	$1.88*10^{-04}$	$2.19*10^{-04}$
	30	$3.76*10^{-04}$	$3.84*10^{-04}$	$4.94*10^{-04}$
	50	$4.39*10^{-04}$	$7.57*10^{-04}$	$8.23*10^{-04}$
Al-25%SiC	10	$2.30*10^{-04}$	$3.29*10^{-04}$	$4.39*10^{-04}$
	30	$4.23*10^{-04}$	$5.85*10^{-04}$	$7.57*10^{-04}$
	50	$5.84*10^{-04}$	$9.21*10^{-04}$	$10.5*10^{-04}$
Al-SiC-B_4C Hybrid	10	$2.30*10^{-04}$	$3.47*10^{-04}$	$4.61*10^{-04}$
	30	$5.92*10^{-04}$	$7.05*10^{-04}$	$7.68*10^{-04}$
	50	$6.05*10^{-04}$	$7.6*10^{-04}$	$9.15*10^{-04}$

Table 4.2 and Fig. 4.7 shows that when the brake pad slides against harder material then wear rate of the pad is higher as compared to the others. In case of hybrid composite as the disc there is some improvement in the brake pad wear rate. This may be due to the interparticle third body interaction during sliding and surface hardening throughout the contact. From the table 4.2 and Fig. 4.7 it is also clear that when the load is increased the wear rate also increases almost linearly for the brake pad materials for all sliding seeds. The same type of trend is also observed for increased sliding speed with constant load. At this point, prior to the detail investigation of worn surfaces the possible causes may be attributed to the increase in contact pressure and temperature rise due to which more ploughing and abrasion of hard asperities from counter surface takes place with rise in load. In case of higher speeds the transfer film, if any, is destroyed at a faster rate. Further investigation on the worn surface will reveal the wear mechanism and is discussed in detail in the subsequent section.

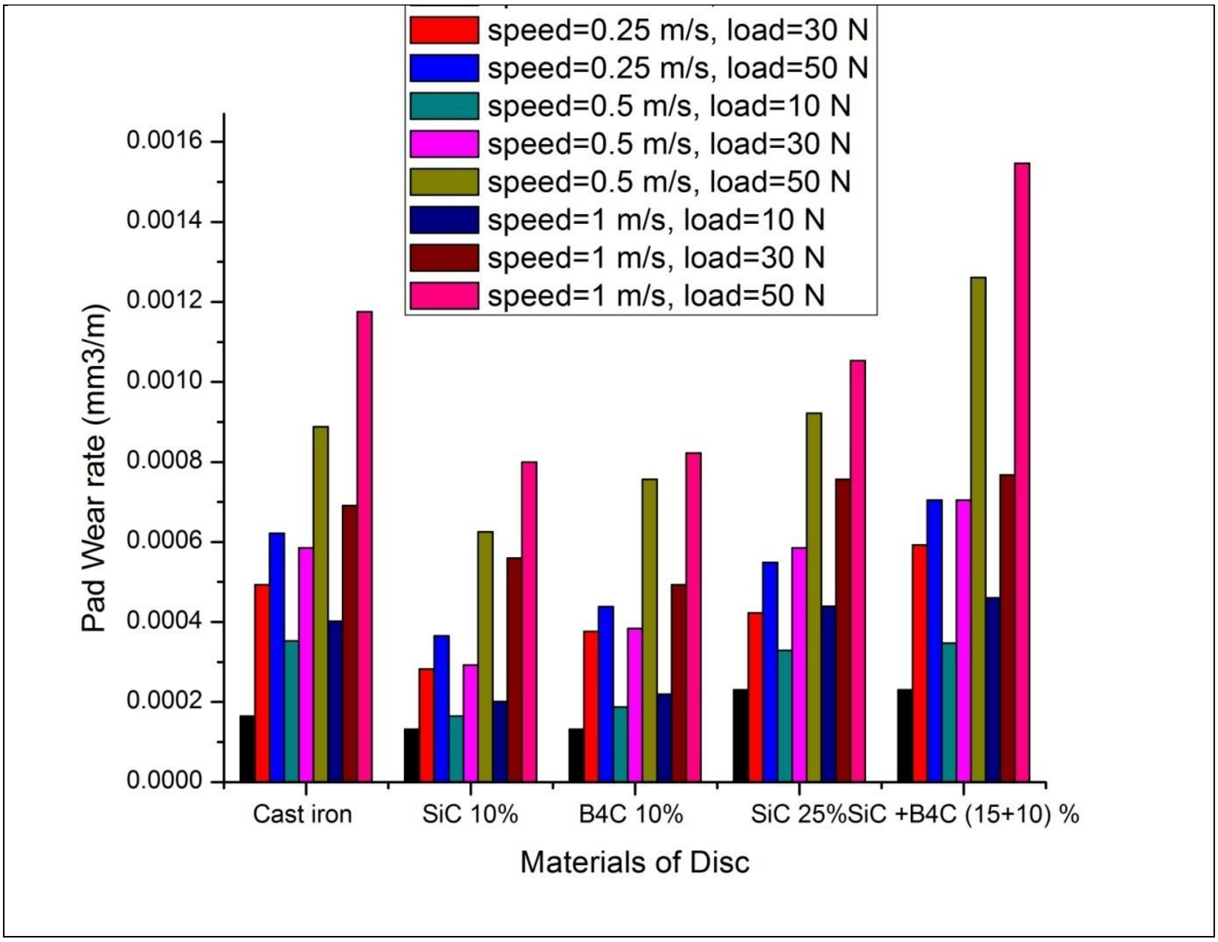


Figure 4.7 Brake pad wear rate in different operating conditions

From the above figure it is also observed that the wear rate of brake pad for Al-SiC10% and Al-B_4C10% lower than the Al-SiC25%. This is due to the fact the large amount of hard reinforcements in the composite contribute to the predominant abrasion effect onto the counter brake pad. However, since CI is much harder than the brake pad so when it rubs against the relatively soft brake pads, the brake pad is wearing out more. However, in case of hybrid composite with relatively higher content, as in the present investigation, contributes lesser wearing of brake pad as compared to the CI and Al-SiC25% disc. The cause of this interesting finding can only be revealed when the worn surface analysis is carried out.

If we compare the wear rate of brake pad and brake disc (Figs. 4.7-4.8), it can be easily found out that in the entire load and sliding speeds range the wear rate of brake disc is one order less than the wear rate of brake pad, especially in case of CI, Al-SiC25% and Al-SiC-B_4C discs.

Also, if we compare all the composite materials, wear rate are in accordance with the hardness of that material. That means the harder the material, lesser is the wear rate for that material. However, for Al-SiC10% and B_4C 10% discs, due to the low reinforcement concentration, and subsequent inadequate development of hardness and wear resistance in some operating conditions these discs are found to be associated with significantly higher wear rate. However, the dependence of wear rate on the sliding speed and load is similar to that of brake pads.

Table 4.3 Wear Rate of various discs sliding against brake pad

	Wear Rate (mm^3/m)			
Disc Materials	**Load (N)**	**Sliding speed (m/s)**		
		0.25	**0.5**	**1**
Cast Iron	10	$2.85*10^{-05}$	$3.05*10^{-05}$	$3.95*10^{-05}$
	30	$5.08*10^{-05}$	$4.74*10^{-05}$	$7.12*10^{-05}$
	50	$7.12*10^{-05}$	$8.54*10^{-05}$	$9.15*10^{-05}$
Al-10%SiC	10	$7.23*10^{-05}$	$15.5*10^{-05}$	$24.1*10^{-05}$
	30	$18.1*10^{-05}$	$26.1*10^{-05}$	$43.4*10^{-05}$
	50	$32.1*10^{-05}$	$54.2*10^{-05}$	$67.1*10^{-05}$
Al-10%B_4C	10	$7.26*10^{-05}$	$10.4*10^{-05}$	$22.2*10^{-05}$
	30	$15.6*10^{-05}$	$22.2*10^{-05}$	$36.3*10^{-05}$
	50	$30.3*10^{-05}$	$43.6*10^{-05}$	$59.7*10^{-05}$
Al-25%SiC	10	$3.61*10^{-05}$	$5.16*10^{-05}$	$10.0*10^{-05}$
	30	$12.9*10^{-05}$	$20.0*10^{-05}$	$25.3*10^{-05}$
	50	$18.0*10^{-05}$	$28.9*10^{-05}$	$32.5*10^{-05}$
Al-SiC-B_4C Hybrid	10	$3.62*10^{-05}$	$6.03*10^{-05}$	$7.24*10^{-05}$
	30	$7.24*10^{-05}$	$10.3*10^{-05}$	$14.1*10^{-05}$
	50	$8.3*10^{-05}$	$11.1*10^{-05}$	$12.7*10^{-05}$

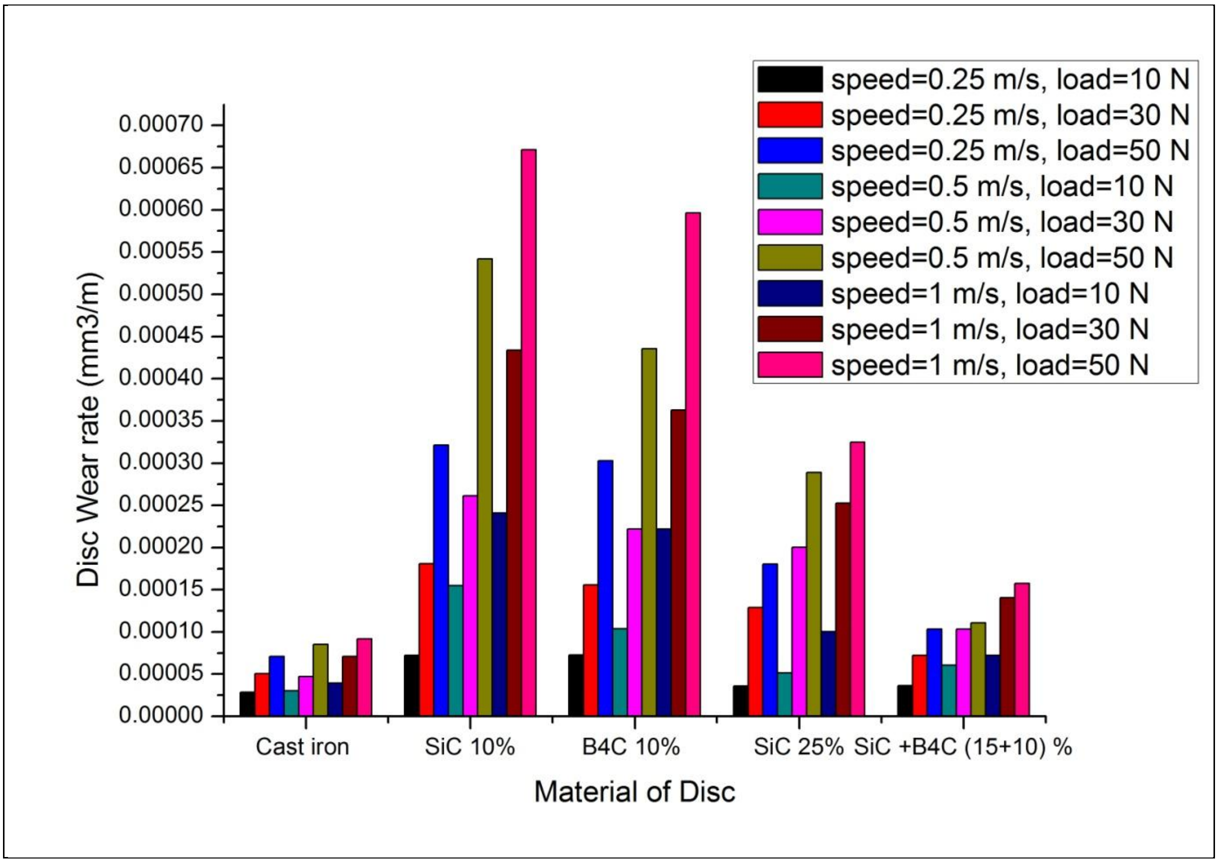


Figure 4.8 Disc wear rates for different operating conditions

Table 4.4 Coefficient of friction for various sliding discs-brake pad tribopairs

	Coefficient of friction			
Disc Materials	**Load (N)**	**Sliding speed (m/s)**		
		0.25	**0.5**	**1**
Cast Iron	10	0.32	0.325	0.34
	30	0.335	0.34	0.35
	50	0.35	0.365	0.40
Al-10%SiC	10	0.30	0.31	0.33
	30	0.32	0.325	0.34
	50	0.32	0.33	0.35
Al-10%B_4C	10	0.32	0.33	0.34
	30	0.33	0.335	0.36
	50	0.34	0.35	0.37
Al-25%SiC	10	0.27	0.28	0.30
	30	0.29	0.29	0.31
	50	0.31	0.29	0.315
Al-SiC-B_4C Hybrid	10	0.33	0.335	0.34
	30	0.34	0.35	0.36
	50	0.35	0.37	0.38

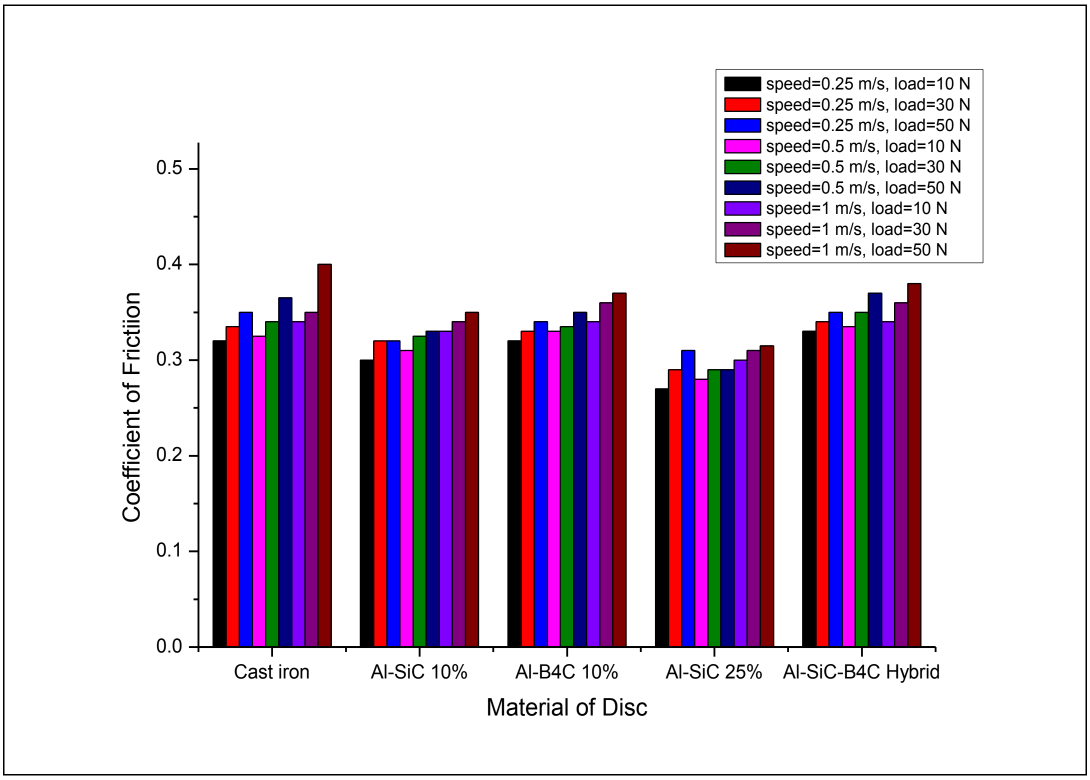


Figure 4.9 Coefficient of friction with various disc materials under different operating conditions

The variation of friction coefficient for various discs and lining material pair is shown in Figure 4.9 and Table 4.4. It is observed that the friction coefficient increases with increase in applied loads. This is because the transfer film, if any, is found to be stable at lower loads and also the temperature rise is low. At higher loads, the plastic deformation of matrix increases as a result of which load is shifted from the hard reinforcement to the metal matrix. This will increase chances of contacts of aluminium with the brake pad leading to the more adhesive and abrasive wear. Similarly, for all loads the friction coefficient is found to increase with increase in sliding velocity as shown in Figure 4.9. At higher speeds the transfer film is destroyed at a faster rate which requires time again to rebuild and the temperature rise is also high.

Further investigation is carried out on the worn surfaces to understand the exact friction and wear mechanism for each of the contact pair. Since the primary friction and wear phenomena is expected to be same for all loads and speed given the same material pairs, so to investigate further the fractography an worn surface analysis is carried out for all the tribopairs operating in high load and speed conditions, in the present case it is **(**1 m/s speed and 50 N load). Table 4.5 shows the performance and physical parameters for the selected set

Table 4.5 Performance and physical parameters of the candidate disc materials against friction pad (sliding speed=1 m/s, load=50 N)

Properties Materials	Friction coefficient	Wear Rate of Disc (x 10^{-5} mm3/m)	Wear Rate of Pad (x 10^{-4} mm3/m)	Specific Gravity
Cast iron	0.40	9.15	11.8	7.2
AMMC(10%SiC)	0.35	67.1	7.99	2.75
AMMC(10%B_4C)	0.37	59.7	8.23	2.65
AMMC(25%SiC)	0.315	32.5	10.5	2.85
Al-SiC-B_4C Hybrid	0.38	12.7	9.15	2.74

Figure 4.10-11 show the wear rates of brake pad and discs and coefficient of friction for the various contacts in the selected operating conditions. From Fig. 4.10 it is evident that the disc wear rate for hybrid composite is comparable to that of CI whereas the brake pad wears out is significantly reduced in case of hybrid disc. Similarly, we can see that with the optimized hybridization of the composite we can achieve the coefficient of friction up to the desired level which is in the present case as per the commercial cast iron disc.

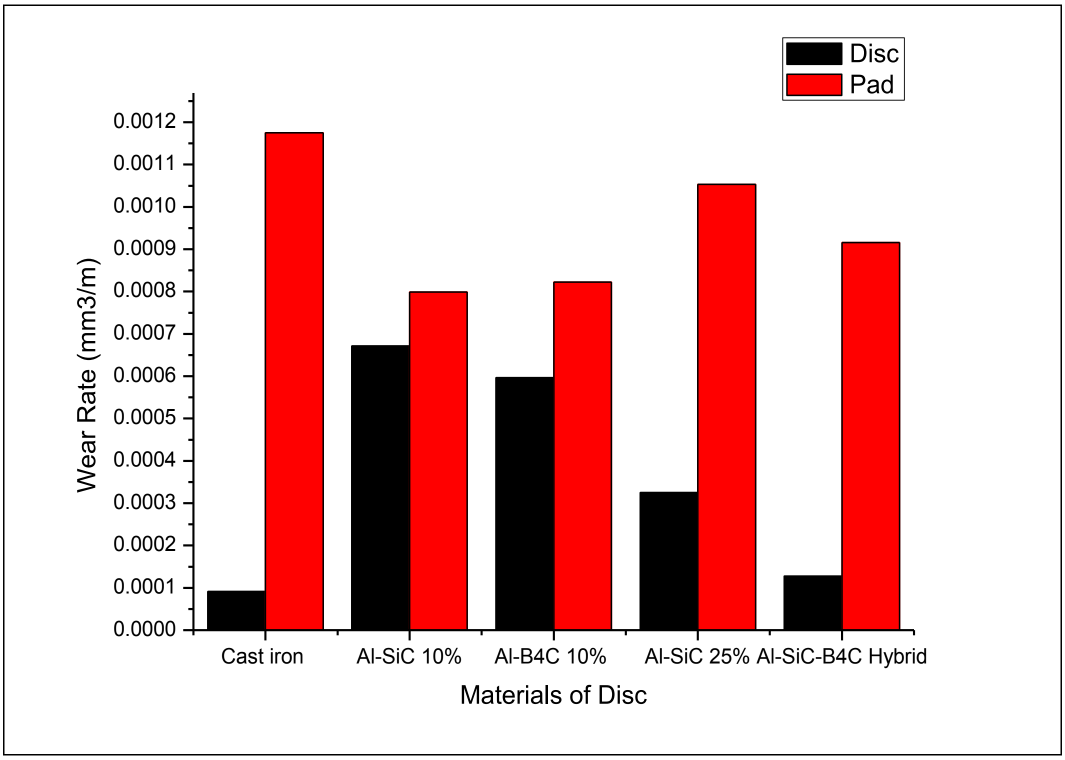


Figure 4.10 Wear rate of brake pad and disc for 50 N load and 1 m/s sliding speed

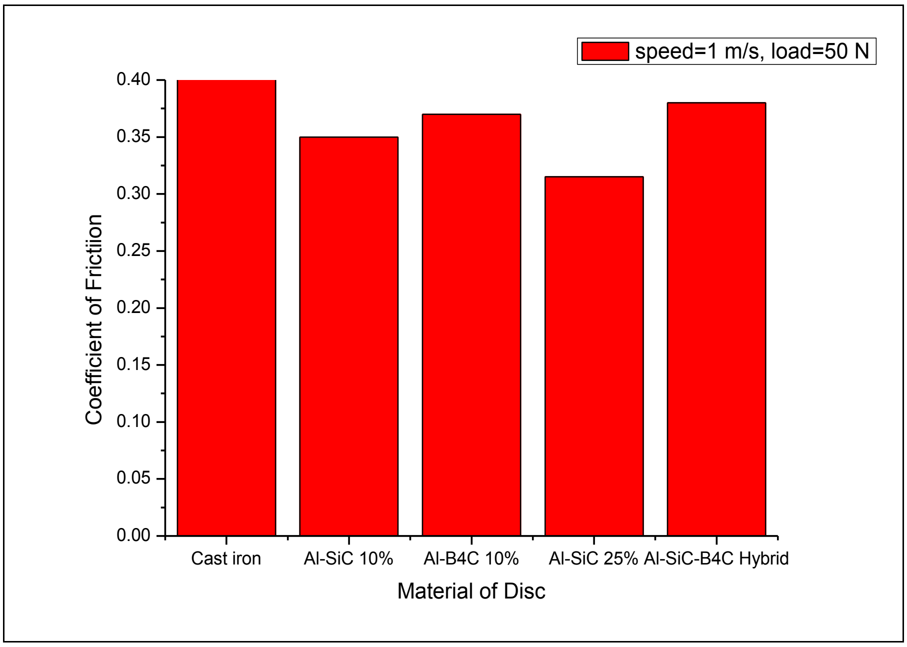


Figure 4.11 Coefficient of friction for various discs and brake pad contacts at 50 N load and 1 m/s sliding speed

Figure 4.12-13 show the friction and wear responses of the various materials with time for the selected set of operating conditions.

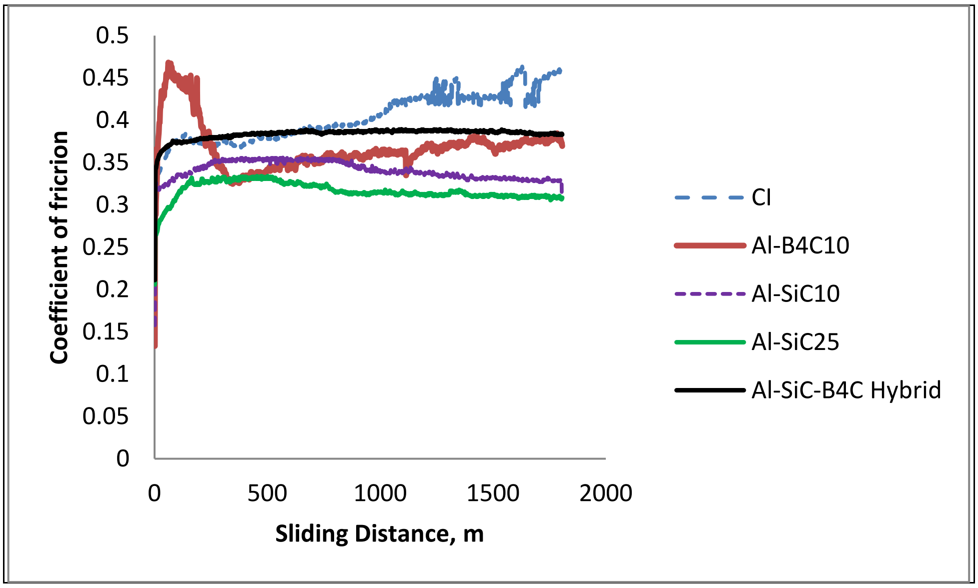


Figure 4.12 Friction behaviour with sliding distance of various disc-pad pairs at 50 N load and sliding speed of 1 m/s

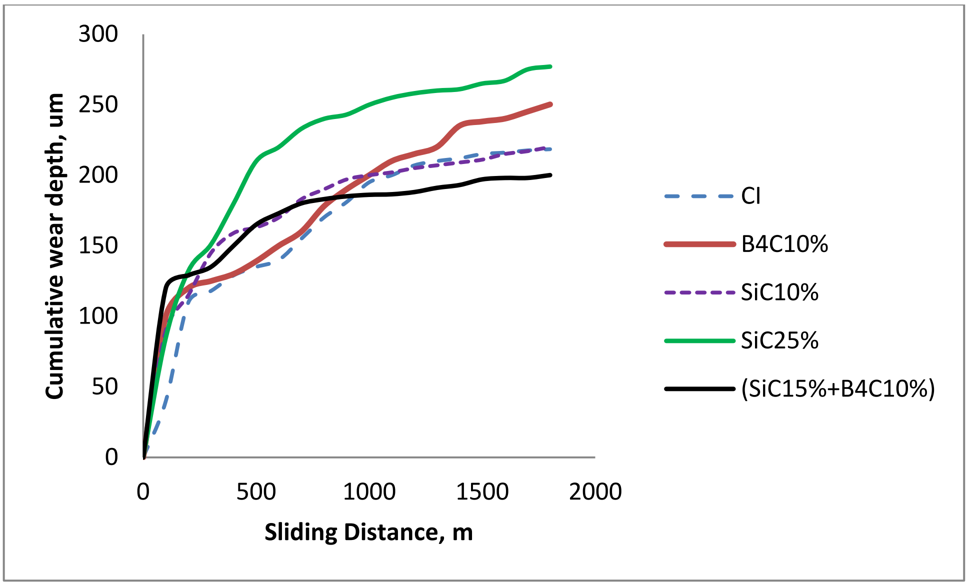


Figure 4.13 Cumulative wear depth with sliding distance of various disc-pad pairs at 50 N load and sliding speed of 1 m/s

4.5 Worn Surface Morphology

4.5.1 Brake Pad sliding against Cast Iron Disc

In the subsequent sections the worn surface analysis is carried out in detail for each of the tribopairs, for the selected operating conditions, to validate the friction and wear mechanism discussed in the previous sections.

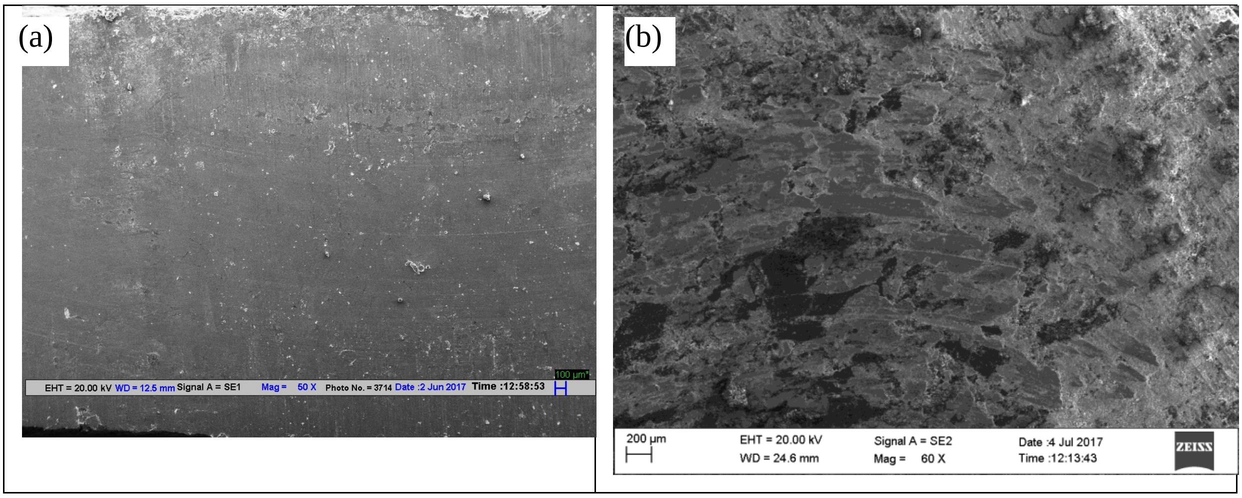


Figure 4.14 SEM micrographs of worn out surfaces (a) Cast Iron Disc (b) Brake pad

Figure 4.14 shows the SEM micrographs of worn out CI disc and pad. The micrographs reveal that there insignificant wear out on disc surface whereas the pad is characterized by the severe wear consisting of the grooves and sheared out phases.

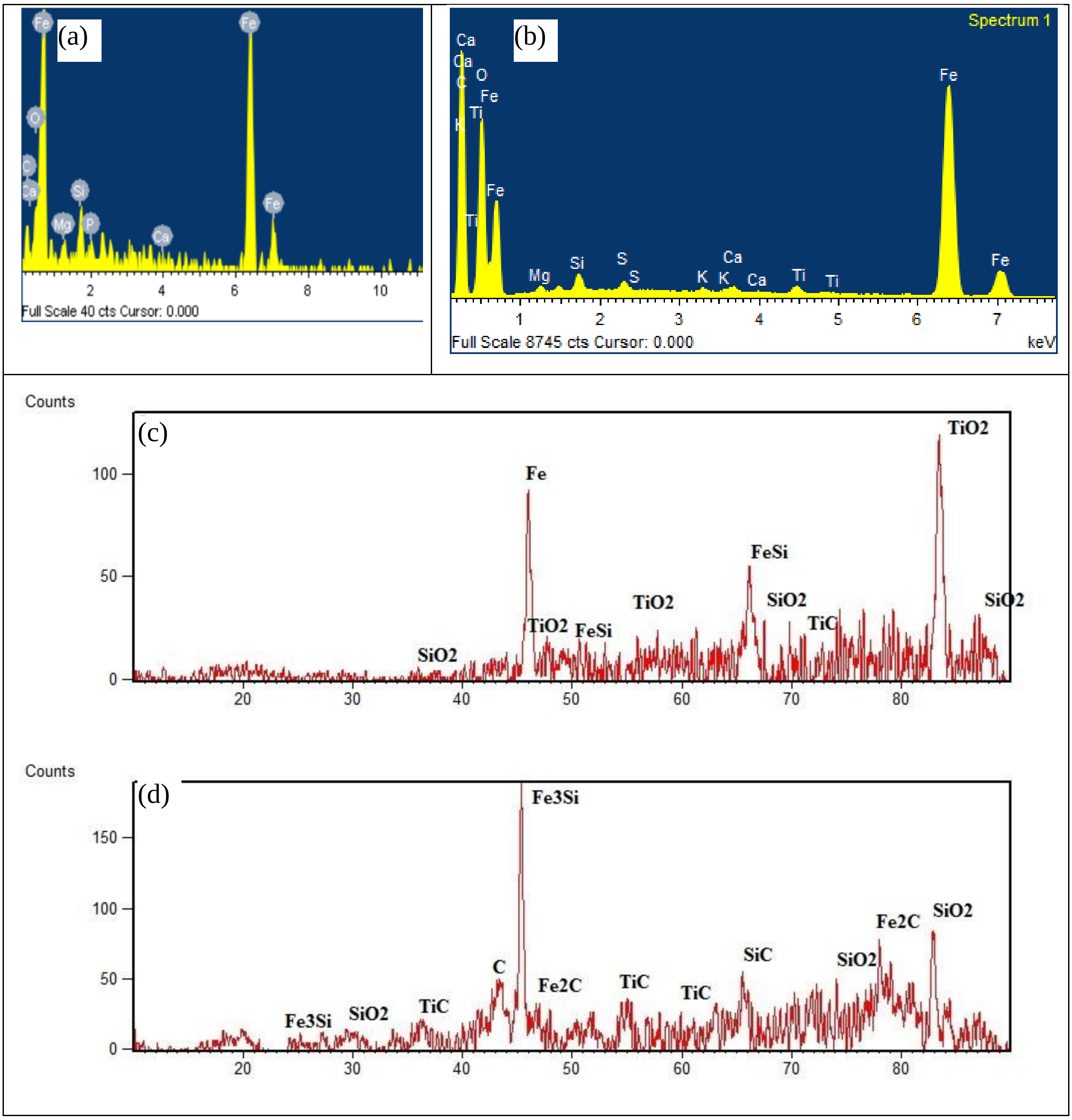


Figure 4.15 CI/Pad wear tracks: (a) EDS on CI disc (b) EDS on pad (c) XRD on disc and (d) XRD on pad

Also, above EDS and XRD characterization (Fig . 4.15a,c) clearly shows us that some of the material that were not present initially, in the cast iron disc are now present on the disc. These materials prove that there is a mechanical as well as chemical transfer of the material from the brake pad to the brake disc. Some hard components are also formed due to this transfer of the material from the pad such as TiC, SiO2 and TiO2, due to which the overall increase in the wear resistance of the Cast Iron disc.

From Fig. 4.15(b, d), we can see a number of metal carbides such as TiC, Fe_3C and Fe_2C. And also we can observe non metal carbides and oxides, such as SiC and SiO_2. These types of carbides will impart additional wear resistance to brake pad. Also Iron is present in form of Fe_3Si. Fe will give rigidity to brake pad that is needed and helps in proper bearing of force applied on brake pad [42].

Due to the presence of these transfer layers on the both surfaces, the adhesion between metallic contacts is reduced. The effect of these tribofilms can be clearly seen from the friction and wear response of CI-pad contact with time as shown in the Fig. 4.12 and 4.13. Once the tribofilm is formed then the wearing out of the surfaces are reduced and friction gets stabilized. However, due to the destroying of these films at faster rate at high speed and load there may be faster and make and break situation which leads to the fluctuation of friction and wear behaviour.

4.5.2 Brake Pad Sliding Against Al-SiC10% Disc

The worn out surfaces of discs and pad are shown in Fig.4.16(a, b). The micrographs show some scattered indentation marks on the disc due to the sliding of hard surface asperities in contacts from the pad materials. On the other hand, the brake pad surfaces are seen having large grooves caused by the abrasion of the hard SiC from the composite. On the both the surfaces patches of some layered materials can be clearly seen.

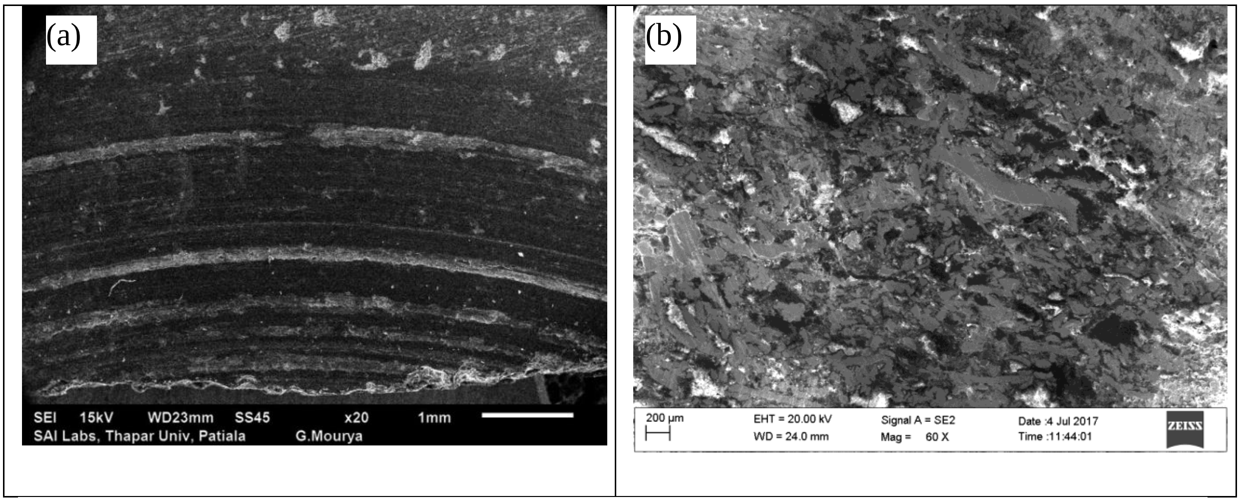


Figure 4.16 SEM micrographs of worn out surfaces (a) Al-10%SiC Disc (b) Brake pad

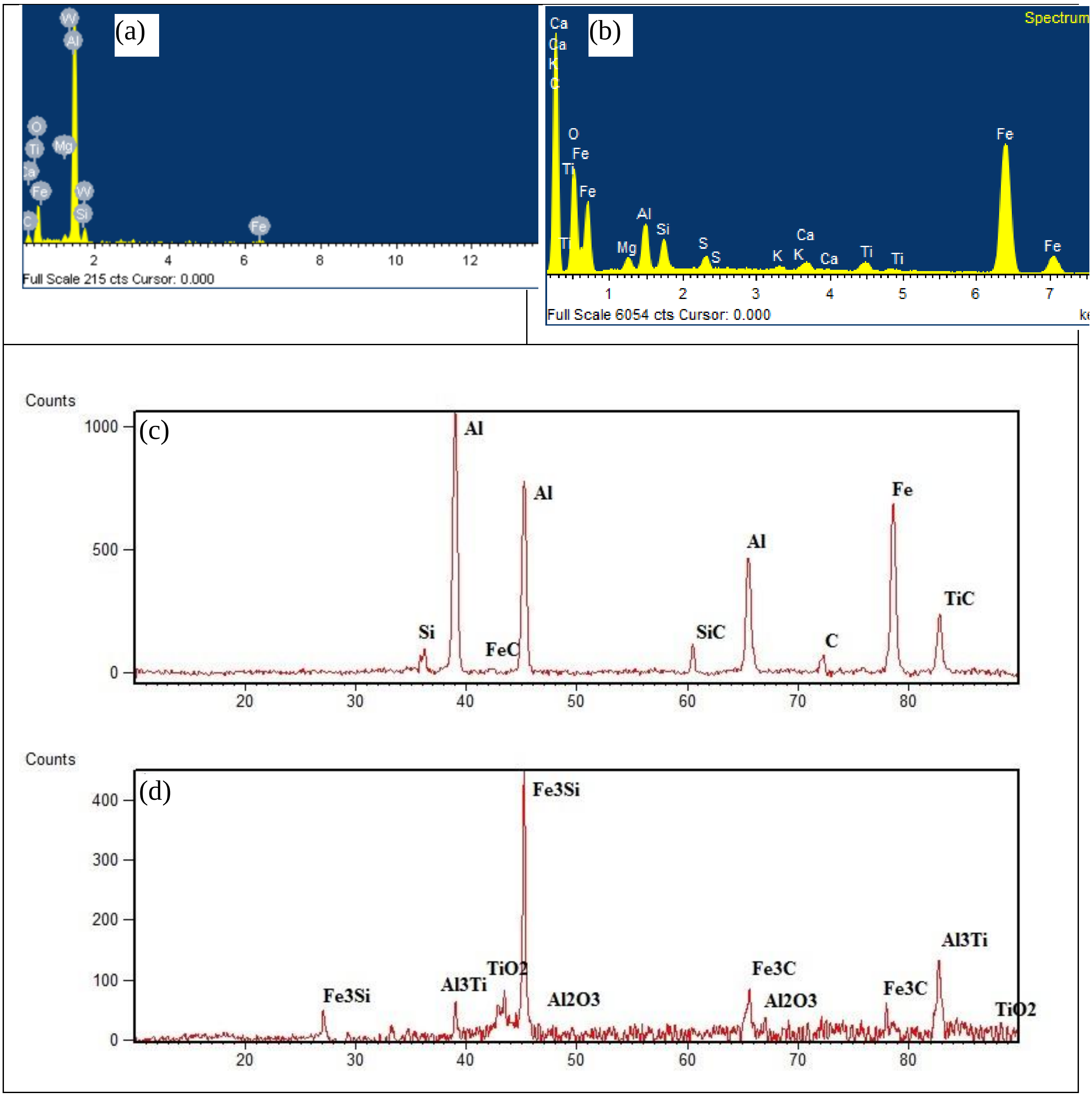


Figure 4.17 Al+10% SiC/Pad wear tracks: (a) EDS on disc (b) EDS on pad (b) XRD on disc, (d) XRD on brake pad

From the EDS and XRD plot (Fig. 4.17a,c) of the wear track on Al-SiC composite it can be seen that the surface of the disc is not significantly changed after the wear test. This means that during the start of the sliding the hard reinforcement SiC from matrix caused the high abrasive wear on the pad surface. The greater wear of friction material during initial period is attributed to the presence of the hard SiC particulates. Initially the SiC particles are sharper and harder, and because of the greater degree of sharpness of the SiC particles, a higher amount of stress acts on the pin material; therefore the wear rate of pin material is more. Moreover, due to the presence of SiC in small amount in the matrix so under the influence of load and sliding speed, the hard asperities from the counter surface can make it easily detachable from Al matrix causing its plastic deformation and then enter the thin tribofilms if any, which helps to abrade the brake material.

The wear of pad is mainly due to cutting actions of hard SiC particles. Hence we can observer higher wear rate during run-in period. However, with time these sharp particles are pulled out due to the inadequate adhesion between the matrix and reinforcements or due to the plastic deformation these get smoothened. The pulled out particles along with the worn out matrix particles get reacted with the elements from the pad surface. Figure 4.17(b, d) shows the EDS and XRD of the wear tracks of the pad. There are a lot of compound that are formed during the tribological test. Presence of Al_3Ti and Al_2O_3 is the proof of material transfer and oxidation of that material during experimentation. Titanium Trialuminide and Alumina are hard material and helps in imparting wear resistance to surface. Also oxidation of material present in the brake pad produces TiO_2 which is also a hard material. Iron of the brake pad also forms Fe_3Si and Fe_3C compounds. Fe_3Si imparts rigidity and Fe_3C imparts additional hardness to the brake pad. Addition of these materials will enhance wear resistance of the material [43]

Due to these coatings on the pad surface wear rate of pad gets reduced, however, due to the low hardness and shortage of SiC in disc, it subsequently increases the wear out of the disc surfaces. On the other hand once these protective layers are formed on the pad surface, the coefficient of friction is seen to be stabilized.

4.5.3 Brake Pad Sliding Against Al-B_4C10% Disc

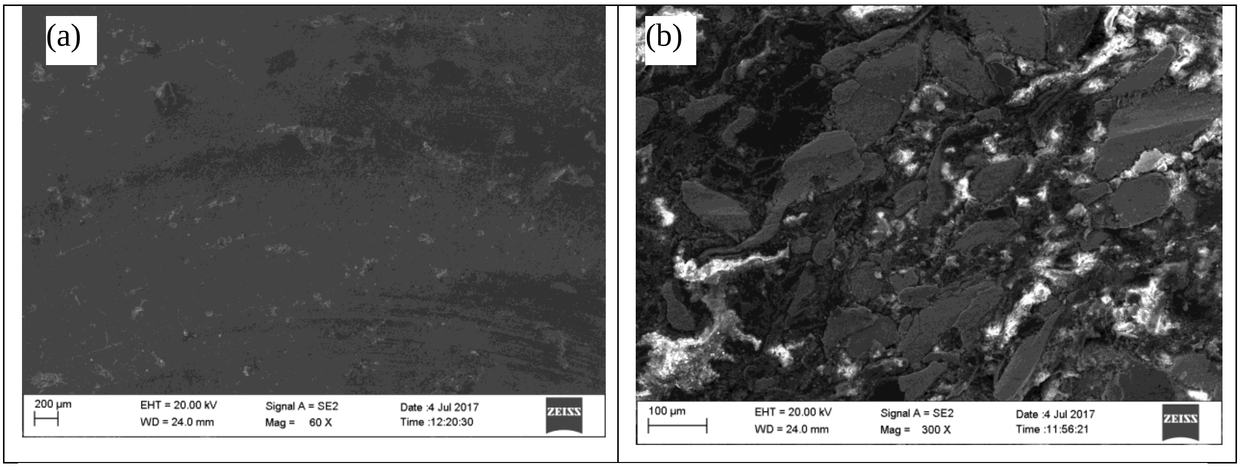


Figure 4.18 SEM micrographs of worn out surfaces (a) Al-10%B4C composite disc (b) Brake pad

Similar to the Al-SiC10% composite disc, due to the presence of hard B_4C reinforcement in the al-matrix and their contact with the pad surface asperities the run-in wear of pad surface is much higher than the disc surface. However, again due to the scarcity of these reinforcements and pulling out of hard particles from matrix especially at higher loads and speeds the wear resistance of the disc gradually decreases. However, as we seen earlier that the hardness of this composite is relatively higher than Al-SiC10% composite, so the wearing out disc in this case is relatively lower than that of Al-SiC10% disc.

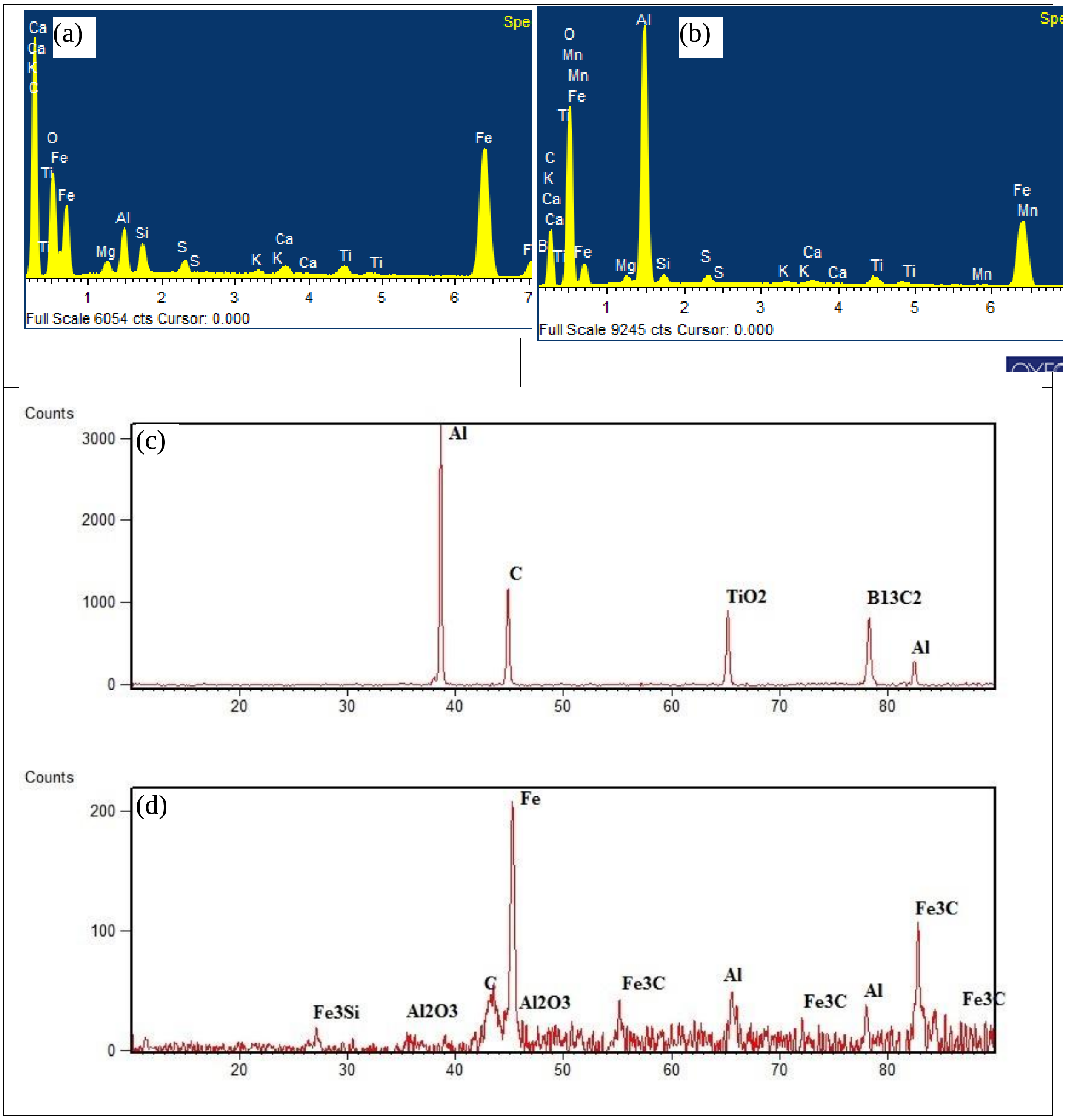


Figure 4.19 Al+10% B_4C/Pad wear tracks: (a) EDS on disc (b) EDS on pad (b) XRD on disc, (d) XRD on brake pad

On the other hand, since B_4C is much harder than the SiC particles so due to the direct contact as well as by third body abrasion it enhances the wearing out of pad. Similar to the Al-SiC composite, due to the presence of B_4C in small amount in the matrix so under the influence of load and sliding speed, the hard asperities from the counter surface can make it easily detachable from Al matrix causing its plastic deformation and then enter the thin tribofilms if any, which helps to abrade the brake material.. However, as seen in the Fig.4.12 and 4.13, there is a change in the slope of the wear and coefficient of friction. So there may be possibility of formation of tribofilm in-between the contacts. Figure 4.19 shows the elemental composition of the worn out surfaces of the Al-B_4C disc and pad. XRD plot of disc (Fig. 4.19a,c) shows us that some material being transferred from the brake pad to disc in the form of TiO2 which will impart wear resistant to the brake disc. Carbon in form of graphite will provide friction stability for the tribological applications. $B_{13}C_2$ is form of boron carbide which is carbon deficient and less hard than B_4C. Hence it is a possibility that loose carbon comes from the boron carbide. Figures 4.19(b, d) show that material is being transferred from the aluminium disc as aluminium is not originally present in the brake pad. Similar to the Al-SiC composite the presence of Al_2O_3 and Fe_3Si in the later stages of sliding and formed after triboreaction helps in preventing in reducing the wear rate of pads. However, since these are formed in discrete patches so the overall reduction of wear rate is not realized during the test duration further is also forming due to oxidation of the aluminium. Alumina will provide extra wear resistant to the pad. The presence of the free carbon on the pad surface work as solid lubricant and helps in friction stabilisation at the later stages of the test run as shown in Fig. 4.12.

4.5.4 Brake Pad Sliding Against Al-SiC25% Disc

The worn out surfaces of Al-SiC25% disc and the corresponding brake pad is shown in the Fig. 4.20. The figures clearly shows that although the surface of the disc is got smoothened but the pad the surface is hugely abraded by the hard reinforced particles of the disc. Due the higher percentage of the reinforcement contents the matrix is strength hardened. Due to the strong bonding between the particle and matrix the particles from the matrix kept on indenting and ploughing of materials from the pad surface. This is evident from the SEM micrograph as shown in Fig. 4.20(b). On the other hand the deep grooves observed on the pad track area show that abrasion is dominant.

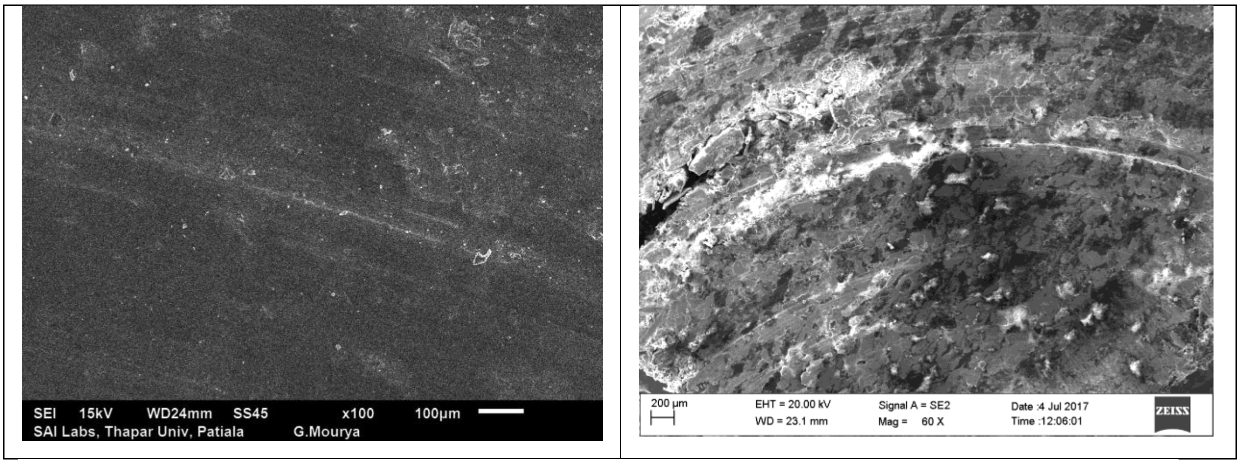


Figure 4.20 SEM micrographs of worn out surfaces (a) Al -25% SiC disc (b) Brake pad

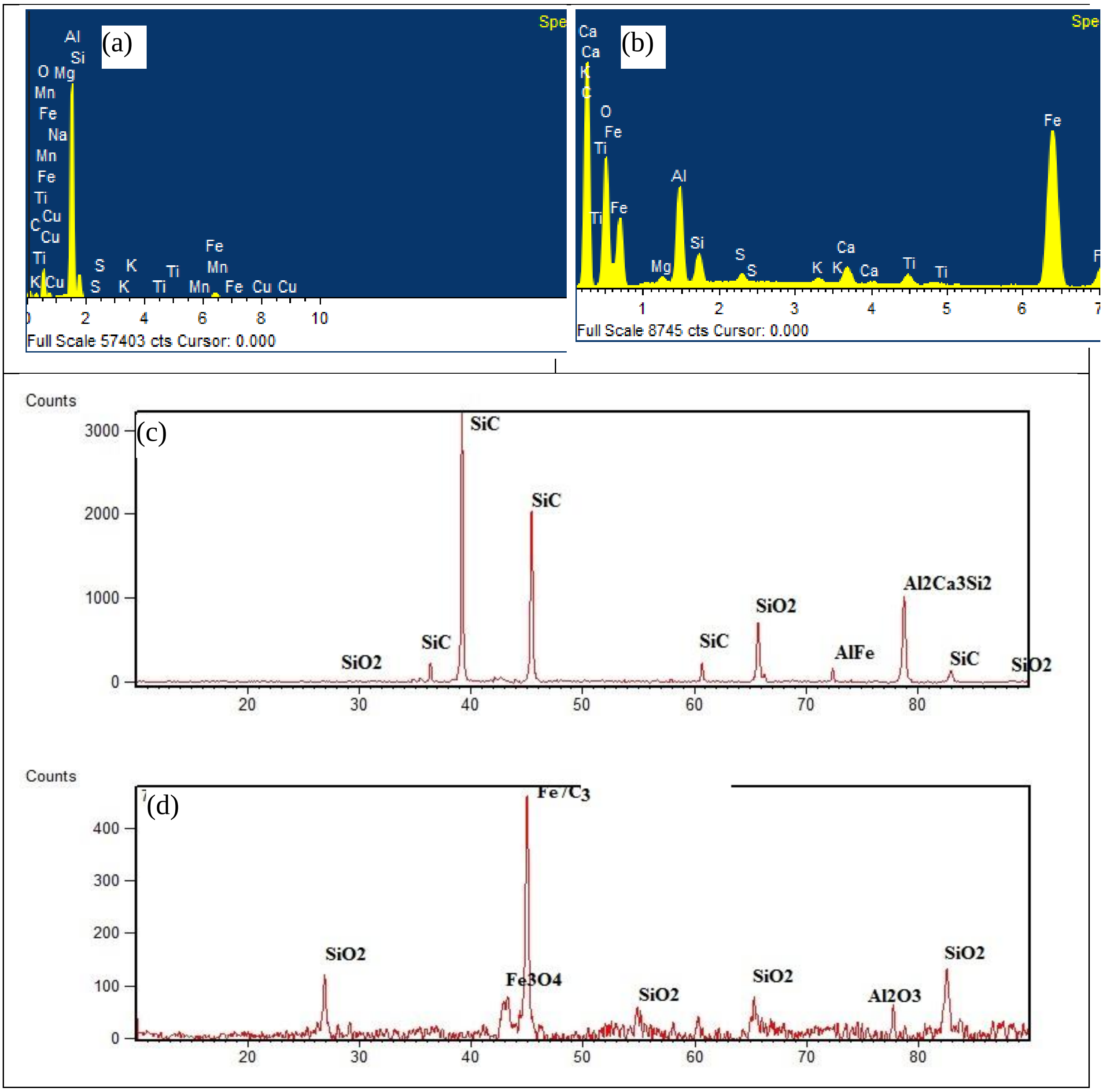


Figure 4.21 Al+25% SiC/Pad wear tracks: (a) EDS on disc (b) EDS on pad (b) XRD on disc, (d) XRD on brake pad

The XRD plot of Al-SiC25% disc (Fig. 4.21c) shows the huge presence of SiC, SiO2, besides AlFe. The oxides and carbides on the surface of the disc enhance its wear resistance, whereas the presence of AlFe which is having very low shear modulus helps in reduction of friction coefficient. However, from the elemental analysis of pad surface from Fig. 4.21 (b, d) it is found that there is also an abundance of Al_2O_3, Fe_3O_4 Fe_7C_3 which is brittle and imparts hardness to pad surface. Since it is not being transferred to the disc surface, there is a high possibility of third body abrasion when these are subjected to the load by the SiC particles and SiO2 layers from the counter surface. As a result of these enhanced abrasion action the wearing of both the surface does not get stabilized leading to the overall large wear rate of this material pair. Also, the huge presence of SiC particles in the counter face destroys the transfer film of the lining material, if any.

4.5.5 Brake Pad Sliding Against Al-SiC-B_4C Hybrid Disc

Figure 4.22 shows the worn out surfaces of the pad and hybrid disc. We can see that some blackish-gray shade of some material on to the disc material that has been transferred from the brake pad. The wear track of disc does not show any major grooves of craters. Similarly there are some white patches appearing on the brake pad.

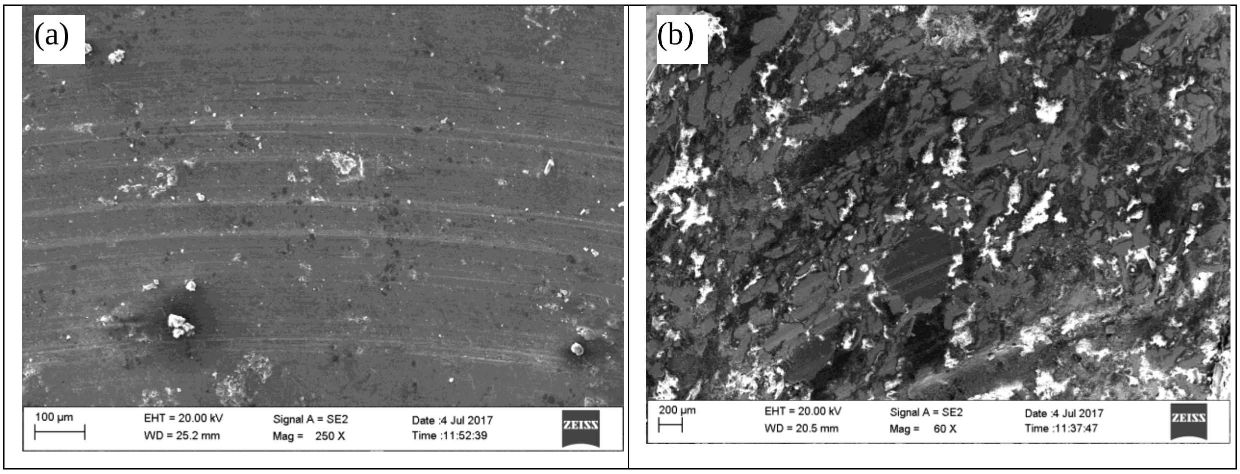


Figure 4.22 SEM micrographs of worn out surfaces (a) Al-SiC-B_4C Hybrid composite material (b) Brake pad

In the hybrid composite the mixture of SiC and B_4C is found to have a significant effect in decreasing the wear rate of both the surfaces. The increase in the hardness of the composites due to the presence of both the particles has improved the hardness of the composite. This may be due to both the interlocking of hard particles within themselves as well as the strong bonding between the matrix and reinforcements. Since the B_4C particles are strongly bonded with the matrix, they protect the surface against severe destructive action of the counter face. Under the influence of loading and repeated sliding even if SiC particles are pulled out or fracture, the presence of B_4C in the matrix prevents the matrix by sharing the load by them. It is due to the strong interface bond of B_4C which helps in crushing and shearing of any intermediate hard contacts that come into contact with the composite, plays a critical role in transferring loads from the matrix to hard particles, results in less wear of the composite disc. Besides Hence, the composite with higher B_4C particles can withstand high load irrespective of the sliding velocity.

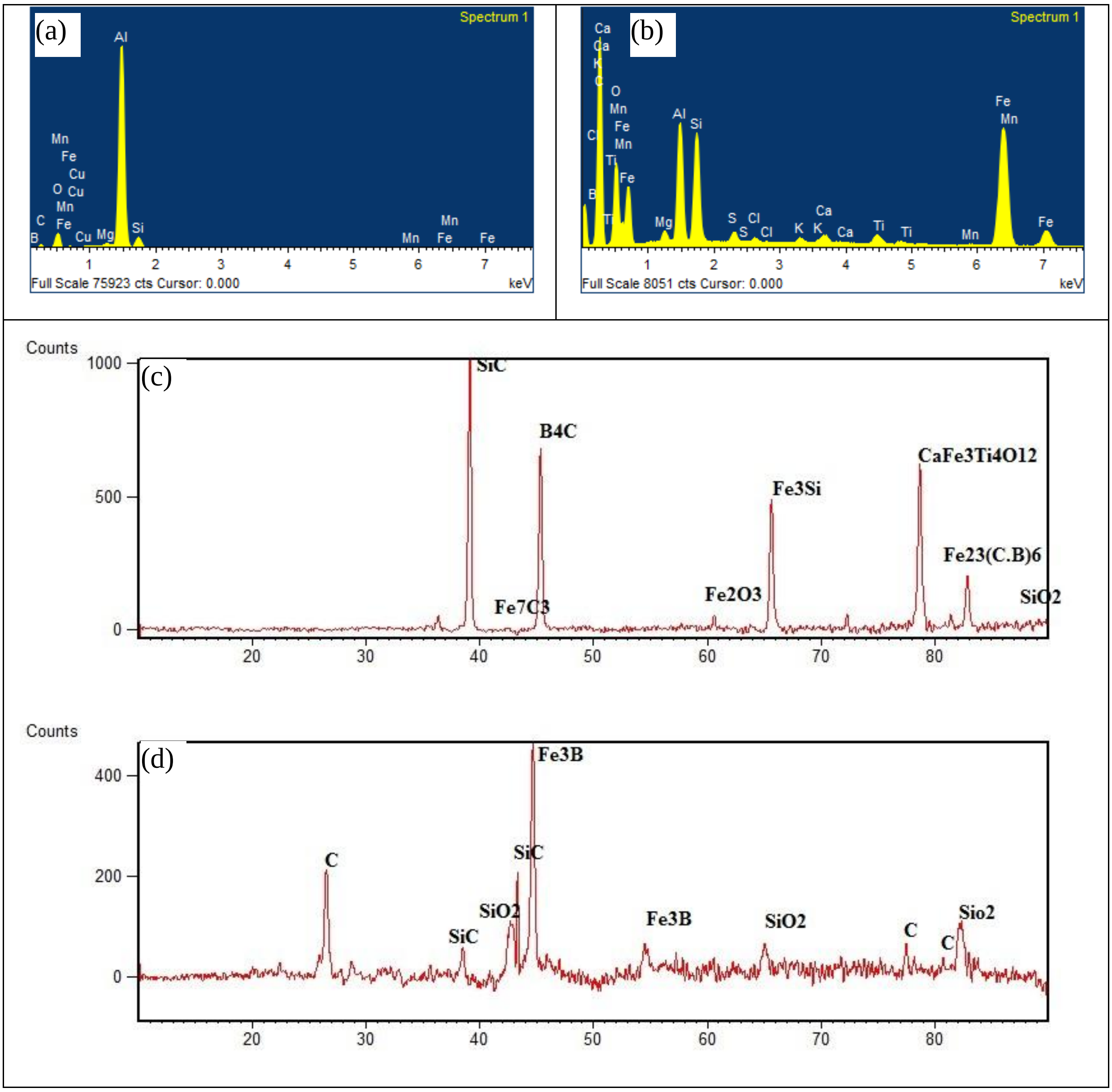


Figure 4.23 Al-SiC-B_4C hybrid/Pad wear tracks: (a) EDS on disc (b) EDS on pad (b) XRD on disc, (d) XRD on brake pad

On the other hand, the fractured or pulled out SiC under compression with B_4C gets impregnated into the pad materials forming some tribolayer or mechanical mix layers. This is evident from the huge presence of SiC in the XRD of pad as shown in Fig. 4.23(d). During sliding, due to the interaction of these interlocked materials a stable and high coefficient of friction is achieved. Higher friction can be attributed to the fact that part of the SiC particles had entered in between the pin and the MMC disc under the influence of load and compaction by strongly bonded B_4C particles. This possibly leads to three-body abrasion, particle interlocking and hard tribolayer formation, resulting in surface roughness between contact surfaces which subsequently increases the coefficient of friction.With further increase in sliding speed and load the temperature rise increases to a critical value at which the SiC particles act as lubricating agent, thus reducing the wear rate of friction material, and consequently the frictional heating. Besides, as shown in the EDS and XRD of both the disc and pad there is a huge presence of oxide and carbide layers in both the surfaces which protects the parent materials of both the surfaces, leading to the less wear rate. Also the presence of graphitic carbon is detected in brake pad which causes friction stabilisation into the tribological pair.

Chapter 5

CONCLUSION

5.1 Conclusions

In the previous chapters, some of the candidate materials that can be considered as composite material that can be used as brake disc material is discussed. Some results are really encouraging from mechanical and tribological point of view. From the present investigation it is observed that the different disc material behaves differently against a common brake pad. The MMC discs show a comparable friction coefficient and wear rate as compared with C.I, provided they are carefully formulated.

Major findings and conclusions of present thesis work is provided below:

- In the present investigation, the hybridization results in the more effective improvement of the hardness than the single particle reinforcement in aluminium metal matrix. Hybrid composite of 25 % reinforcement is found having 18.39 % harder than the 25 % SiC reinforced composite.
- It is seen that when we compare wear rates of 10% SiC and 10% B_4C composite discs the wear rate of Al-SiC disc is higher. Wear rate of SiC 10% disc are found to be 10 to 15 % higher than the wear of B_4C 10 % Disc.
- Hardness of B_4C composite is found more than the SiC composite which indicates that harder material wore out less against the same brake pad. Hardness of 10% B_4C is 47 % higher than the 10% SiC composite.
- The hardness improvement has been found to influence the wear resistance of the disc materials during their initial run in time. Wear rate of the brake pad also increases with increase in the hardness of the composite brake disc material.
- At a lower concentration of SiC and B_4C material, coefficient of friction in case of AMMC disc is found to be approaching the value for CI, however, in these cases disc is found to be wearing out severely (about 5-6 times that of CI).
- The coefficient of friction for hybrid composite is found significantly higher than that of the other composite discs and comparable to the CI disc. However, the present investigation leads to relatively lower coefficient of friction against the desired value for real world braking application.

- Wear rate of the hybrid composite brake disc material is found comparable to that of cast iron. However, the brake pad wear rate of pad is found lesser in case of hybrid AMMC as compared to the CI disc.
- The investigation revealed the fact that it is the tribolayer or compact mechanical mixing layer which finally governs the friction and wear mechanism. When the tribolayer or transfer film generates, the friction and wear mechanism changes accordingly.
- Transferred material layer has been found in all the cases but it is more visible in case of composite material. As they have more irregular surface as compared with cast iron. Due to these irregularities transferred material found places to stick onto the surface.
- The investigation results that Al6061 hybrid composite can be carefully developed with good mechanical and tribological properties which is required for the automobile brake disc applications for reliable, long life and high performance.
- Finally, it is possible to reduce the overall weight and cost of the braking system to approximately two-third of the existing system by replacing CI disc with suitably developed AMMC.

5.2 Future scope

Based on the observations made during present research my work some future scope of work can be as follows.

- Further work can be done using various combination and concentration of reinforcements to come up with optimized properties required for brake disc applications such as higher and stable COF (0.45-0.5) along with lower wear rates.
- A very important aspect in braking system is the dissipation of generated heat during braking system. So one can carry out the detailed investigation on this aspect for the developed composite to make is more suitable for real application.
- The effectiveness of the braking system also depends on the pad materials. In this work a single type of brake pad is used. To gain the deep insight for the generalized formulation of brake disc materials further study required involving pads with variety of compositions of pads of different manufacturers.
- Also due to requirement of higher braking torque, a higher braking load can also be tested at higher speeds by using brake dynamometer, if possible.

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