

Study on The Tribology of Aluminium Metal Matrix Hybrid Composites Reinforced with SiC and Al₂O₃

A Dissertation Submitted

In Partial Fulfillment of the Requirements
for the Degree of

Master of Engineering
in
Production Engineering

by

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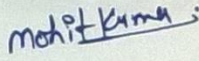
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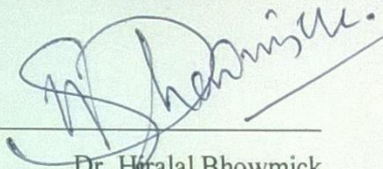
CERTIFICATE

I hereby declare that the thesis entitled "Study on The Tribology of Aluminium Metal Matrix Hybrid Composites Reinforced with SiC and Al₂O₃" is an authentic record of my study carried out as requirements for the award of the degree of **Master of Engineering in Production Engineering** at **Thapar University, Patiala** under the supervision of Dr. Hiralal Bhowmick, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala during 22 July, 2013 to 15 July, 2015. The matter embodied in this report has not been submitted to any other university or institute for the award of any degree.

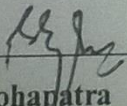
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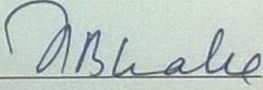

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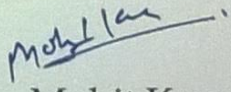

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Abstract

Aluminium alloy are used in many applications including Aerospace, Automobile and commercial industries due to its good strength to weight ratio and low cost. Aluminium has good mechanical properties, low thermal coefficient of expansion and low density. At present aluminium composites are used due to improved mechanical and wear properties over aluminium alloy. It is essential to provide a lubrication to reduce friction and wear. However, sometime it is too difficult to access a lubricant around the wear parts surfaces externally. The present study is focused on the improvement of coefficient of friction and wear rate of aluminium composites reinforced with Al_2O_3 and SiC. The composites were fabricated by stir casting process. Reinforcement is used in different weight percentage. Influence of hybridization on the improvement of hardness and microstructure has been also investigated in this study. XRD & EDS has done to investigate the composition and phase analysis of the fabricated composites. SEM has been done to evaluate the distribution of particles and defects. Dry tribology of the fabricated composites has been investigated to examine the effect of increased the weight percentage of reinforcement in matrix, effect of load and sliding distance on wear rate and friction for the composites sliding against EN31 disk.

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Nomenclature

μm	Micrometer
MMC's	Metal Matrix Composite
XRD	X-Ray Diffraction
SEM	Scanning Electron Microscopy

CHAPTER 1

INTRODUCTION

1.1 Introduction

To meet the ever increasing demand there is an unabated quest for new materials which will satisfy the specific requirements for various applications like structural, medical, household, industrial, construction, transportation, electrical, electronics, etc. Till recent years, metals and metallic alloys were the most commonly used materials in these applications. Aluminium alloys are widely used in aerospace and automobile industries due to their low density and good mechanical properties, better corrosion resistance and wear, low thermal coefficient of expansion as compared to conventional metals and alloys. In today's complex engineering environment single materials can't stand to full-fill the requirement. To achieve the better performance the use of composite materials with their unique properties in engineering application is in trend [1-2]. The excellent mechanical properties of these materials and relatively low production cost make them a very attractive candidate for a variety of applications. With improved and customized strength to weight, toughness, wear resistance, specific strength etc., composite materials are made to meet the variety of different demands.

Automobile producers had just begun to employ composites in the engine parts. Several engine parts are being made using aluminum-alloy matrix reinforced with aluminum oxide and carbon fibers. These are of less weight and oppose wear and thermal deformation. Besides, metal-matrix composite has been engaged in drive shafts, extruded stabilizer bars, and forged suspension and transmission components [3].

1.2 Composites

A composite material is defined as mixture or combination of two or more nano, micro or macro constituents which are chemically and physically different, with a boundary separating them. The fabricated material would still have identity of components as the different materials constituent. Usually, composite materials will consist of two different components, one is matrix and the other is reinforcement. The matrix is the primary component that holds

the reinforcement together to shape the bulk of the material [4]. The constituent materials in composite stay separately because they are chemically and physically dissimilar.

Alloy is a homogeneous or heterogeneous but composites are heterogeneous. There is at least one metal in alloy but in composites it is not necessary to have an alloy. In alloy the constituent elements do not retain their original properties after mixing where as in composites materials forming the composites retain their original properties.

When suitably designed, fabricated composites can be produced with high hardness, excellent strength to weight ratio, corrosion resistance, stiffness, toughness, high wear resistance, durability and high impact strength.

1.3 Constituents of Composites

As mentioned above, constituents of composites can be divided into Matrix and Reinforcement

Matrix Phase: The primary phase with a continuous medium is known as matrix. Matrix is usually more ductile and less hard phase and it holds the reinforced phase. The lighter metals such as aluminum, magnesium, etc are used as metal matrix for composites (MMC), and it provides to reinforcement a compliant support in structural applications. Co and Co-Ni alloy matrices are common metal used for high temperature applications.

Since this thesis work will be dealing with aluminium as matrix phase so it is worthwhile to provide a brief note on it at this juncture. Aluminium is the third most abundant element and is known for the low density, its ability to resist corrosion. In aerospace, transportation and industrial structure, aluminium and its alloy are widely used these days. Aluminium is a relatively soft, durable, lightweight, ductile and malleable metal with appearance ranging from silvery to dull gray, depending on the surface roughness. Aluminium has property of nonmagnetic and it does not ignite easily. When using in automobile it reduces dead weight, energy consumption and increase load capacity. Strength can be adapted by its modifying composites. Aluminium makes a oxide layer in contact with oxygen in air which in turn prevents from the corrosion. Aluminium is nice durable material in nature and having low acidic environment. Aluminium is excellent heat and electricity conductor and in relation to its weight is almost half as much as copper conductor having equal conductivity. Aluminium used in wires. Aluminium is a ductile material and having low melting point and density. Its ductility permits aluminium products to be formed near to

the product's end. Due to impermeability of Aluminium neither light, aroma nor taste out from it.

Reinforcement: The reinforcement material is the secondary phase of composite which is embedded into a matrix. The reinforcement phase is also known as dispersed phase. The dispersed phases change various properties of the resultant composite, such as thermal conductivity, hardness, coefficient of friction, or wear resistance. MMC's with discontinuous reinforcements can be worked with metal working techniques such as forging, extrusion and rolling. Monofilament wires or fibers (Carbon, SiC) are used for continuous reinforcement. Because the fibers are embedded in certain direction into the matrix that shows an anisotropic structure the anisotropy in various strengths of composites can be achieved via its alignment.

Silicon Carbide is the only chemical compound of carbon and silicon. Silicon carbide is an excellent abrasive. So over hundred years it has been producing many abrasive products and grinding wheel. Today silicon carbide with metal developed a high quality grade for improving mechanical properties of materials. The material can also be made an electrical conductor and has applications in resistance heating, flame igniters and electronic components. Structural and wear applications are constantly developing. It has low density, high strength and hardness, low thermal expansion, excellent thermal conductivity, high elastic modulus, excellent thermal shock resistance

Alumina is a chemical compound of aluminium with oxygen. Alumina is a good insulator but in compare of ceramic material it has high thermal conductivity. Due to its hardness it is use as abrasive and cutting tool components. Aluminium is very reactive with atmosphere then it reacts with atmospheric oxygen and makes a passivation layer of aluminium oxide at its surface. This layer helps the aluminium form further oxidization. Alumina is one of the most widely used and cost effective materials in the family of engineering ceramics. The raw materials are easily available with reasonable price from which this high performance technical grade ceramic is made, resulting in good value for the cost in fabricated alumina shapes.

1.4 Classification of composites

Composites can be broadly classified in the following manners.

1.4.1 Metal matrix composites

As the name suggests, MMCs consist of fiber as reinforced dispersed into the matrix of ductile metal. Aluminium and its alloys are principle matrix materials for metal matrix composites. Magnesium, titanium, copper, zinc and lead can also used as matrix for further special properties. These materials may be used at higher process temperatures than their base metal equivalent; furthermore, the dispersed phase may improve hardness, strength, thermal conductivity, specific stiffness, wear rate and dimensional stability of composites. MMCs have high overall cost, and, therefore, they restricted at several places.

Few combinations of these matrix–reinforcements are more reactive at high temperatures. Due to high processing temperature or elevated temperature during service of MMC's the degradation of MMC's occur. This problem is resolved either by coating the surface of reinforcement or by changing the composition of matrix alloy.

MMC's can be classified further, according to continuous reinforcement or discontinuous reinforcement. Production of MMC's with discontinuous reinforcements is less expensive than continuous fiber reinforced metal matrix composites, although mechanical properties show the benefits [5].

1.4.2 Polymer matrix composites

Polymer-matrix composites (PMCs) consist of a fibers as reinforcement disperse phase with polymer resin as the matrix. Polymer composites are most popular due to simple fabrication methods and their low cost. In polymer composites, reinforcement material is the principle load bearing member and the matrix provides a medium to binding and holds the reinforcement together into solid. Also it protects the reinforcement from environmental degradation. Linear polymer, thermoplastic polymer, thermosetting polymer and elastomers are amongst the different types of polymers [6].

Polymer composites are used to make bicycles of light weight for easier and faster to handle than standard ones, fishing boats that are resistant to corrosive seawater, turbine blades of light weight for efficiently generate the wind power.

1.4.3 Ceramics matrix composites

Ceramics matrix composite consists of ceramic reinforcement embedded in ceramic matrix. Ceramics composites have low density, superior chemical and thermal properties and high hardness. So ceramic composites highly attractive due to their good thermal and chemical properties and use in vast applications like internal engine components, exhaust system for fighter jet and missile structure etc. These composites are inherently resilient to oxidation. These materials are ideal candidates for use in severe stress and high-temperature applications, specifically for automobile component and aircraft gas turbine engines component. Ceramic materials have low fracture toughness value [7]. Recent developments in this category utilizes ceramic whiskers for the improvement of fracture toughness

1.4.4 Hybrid Composites

A relatively new fiber reinforced composite is the hybrid. When two or more fibers or particulates of different properties are reinforced in single matrix then the composites is called Hybrid composites. These composites have better mechanical and tribological properties than composites containing single reinforcement. Many fiber combinations composites are used, but most common fiber combination is carbon and glass fibers in polymer resin matrix. Glass fibers have low stiffness and also inexpensive. Carbon fibers are low density reinforcement, strong and relatively stiff, but they are expensive. So the combination of glass-carbon hybrid which has good impact resistance, toughness, and having lower production cost than either all glass composites or all fibers composites. Due to their improved properties the application of hybrid composites are air transport components, automotive parts, lightweight land and water [8].

1.5 Manufacturing and fabrication of composites

1.5.1 Liquid Phase Fabrication

Liquid state fabrication involves processing molten matrix metal with reinforcement, followed by its solidification. Good interfacial bonding (wetting) between the liquid matrix and reinforcement should be obtained to provide improved mechanical properties of metal matrix composites. Coating of reinforcement particles (fibers) results in improved wettability. Interfacial energy is reduced by proper coating. Chemical interaction between the matrix and dispersed phase is also prevented by proper coating.

The methods to fabricate liquid state of MMC's include Stir Casting process, Infiltration process, Pressurized Gas Infiltration, Squeeze Casting Infiltration, Pressure Die Infiltration, etc.

Stir Casting:-Stir Casting is a process to fabricate MMC's in liquid state. In stir casting process reinforcement (ceramics, fibers, and particles) is mixed with matrix (molten material) by using mechanical stirrer. Then molten mixture is cast into mould. The fabrication of liquid MMCs by stir casting process was initiated in 1968; R. Ray used alumina powder into molten aluminium alloy by mechanical stirring. The main step of stir casting process is mechanical stirring. The mechanical stirring process distributes the reinforcement into matrix phase. The distribution of reinforcement in matrix depends on strength of mixing, stirring parameters, melting temperature, geometry of stirrer, relative density etc [2].

Distribution of reinforcement can be improved when matrix is in semi-solid phase. This process is most effective for cost and simplest method to fabricated liquid phase composites. The stirring method in semi- solid state of matrix is known as **Rheocasting**.



Figure 1.1 Stir Casting Furnace [Photo courtesy: Thapar university campus, Patiala]

Infiltration: Infiltration is a process to fabricate liquid state matrix composites, in which reinforcement (fiber, ceramic particles, woven) is drawn in a liquid metal matrix, which filled the dispersed phase inclusion. Capillary force of the reinforcement is known as spontaneous infiltration and an external pressure such as mechanical, electromagnetic, gaseous, centrifugal or ultrasonic are applied to the liquid matrix phase called as forced infiltration. So, infiltration process has these two motive force. Infiltration process is one of the methods to prepared tungsten-copper composites [9].

Gas Pressure Infiltration: Gas pressure infiltration (Figure 1.2) is a unique process to fabricate the liquid matrix composite. In this process pressurized inert gas is applied on liquid matrix phase to infiltrate in reinforcement. Gas pressure infiltration is also known as forces infiltration method to fabricate liquid metal matrix composites, in which molten metal is forced to penetration into a preformed dispersed phase by applying pressure on it, using pressurized gas. For manufacturing the large composites part, gas pressure infiltration method is used mainly. The process is rapid and no limitation and rapid. In this method non-coated fibers are used due to less contact time of the hot metal with fibers. Other than mechanical forces method, gas pressure infiltration process results having less damage of fibers [7, 9].

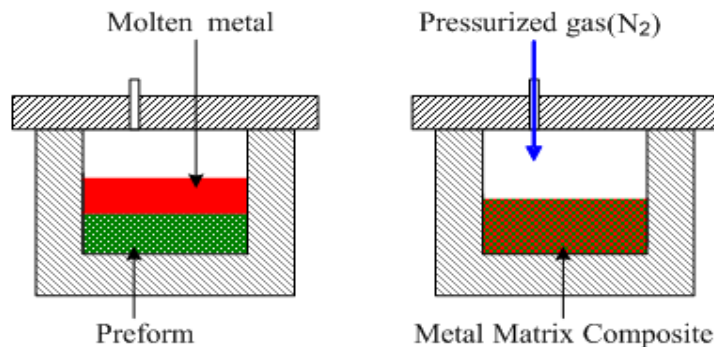


Figure 1.2 Gas Pressure Infiltration

Squeeze Casting Infiltration: Squeeze casting infiltration is also a forced infiltration method. This is used to fabricate liquid phase metal matrix composites. The molten metal is filled into lower fixed mold half part with reinforcement as shown in the figure 1.3. In this method ram is used for applying pressure on the molten matrix and forcing it to infiltrate into reinforcement. The solidification process of infiltrated material is complete

under the pressure. The ejector pin is used to remove the part from mold. It is used to produce net shape and small component. [7, 10]

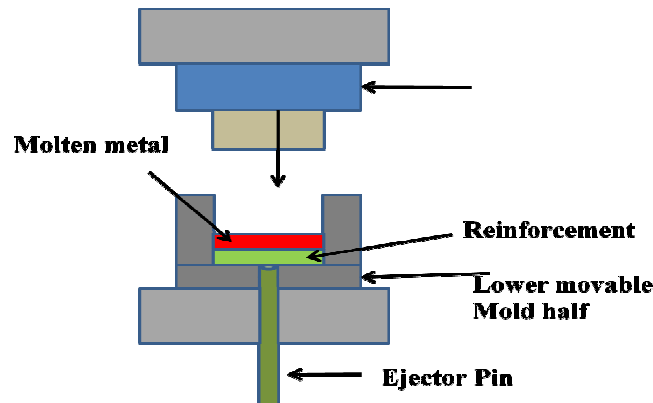


Figure 1.3 Squeeze Casting Infiltration

Pressure Die Infiltration: Pressure die infiltration is a forced infiltration method to fabricate liquid phase metal matrix composites. In this method, a movable piston (Plunger) is used to pressurized the molten metal. In die a performed dispersed phase is placed and molten metal is moved through sprue to penetrate the dispersed phase into die. This is followed by the removal of the cast material by ejector pins [11].

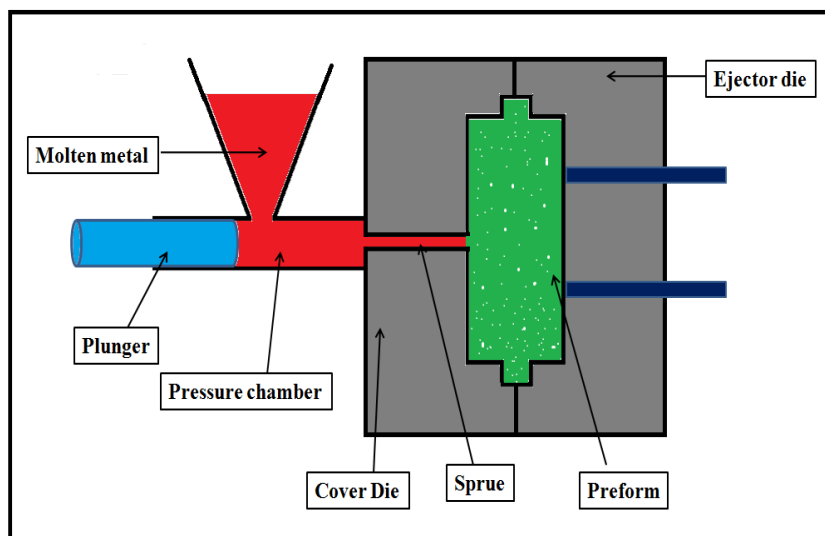


Figure 1.4 Pressure Die infiltration

1.5.2 Solid Phase Fabrication

Solid state fabrication of MMC's is the process in which mutual diffusion occurred at high temperature with high pressure and results the bonding of metal matrix and dispersed phase formed into Metal matrix composites. Solid matrix fabrication process as

compared with liquid matrix fabrication, depresses unwanted reactions on the boundary between dispersed (reinforcing) phases and the matrix phase. There are two types solid state fabrication of MMCs; Diffusion bonding and Sintering

Diffusion Bonding: In this method foils form of matrix and long fibers form of dispersed phase are stacked in a specific order and at high temperature pressed together. Simple shape parts are fabricated by diffusion bonding process. Roll bonding and fiber/wire winding are the alternative of diffusion bonding. In roll bonding process rolling (hot or cold) strips of two different metals is combined and revealed the results with formation of laminated composite material with a metallurgical bonding between the two layers. In wire/fiber winding process continuous ceramic fibers and metallic wires are wound at elevated temperature followed by pressing [10, 11].

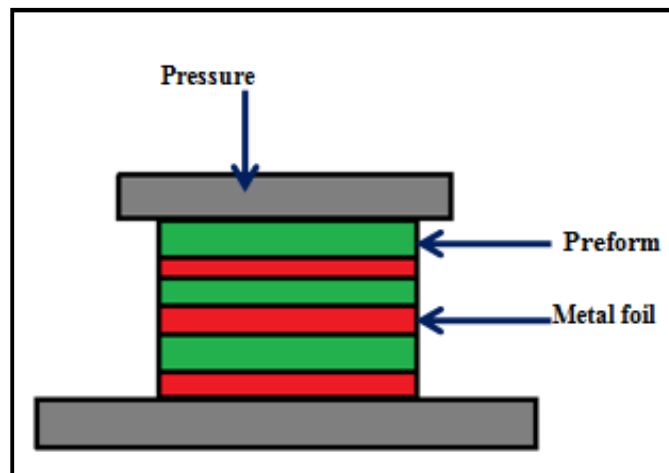


Figure 1.5 Diffusion Bonding

Sintering: This fabrication process of MMC is a process of powder metallurgy. Metal matrix in powder form is mixed with a powder of reinforcement in form of particles or short fibers followed by compacting and sintering in solid state. In sintering process the 'green' compact part is heated to elevated temperature below melting point for consolidation of power grains. Other than using liquid state fabrication of metal matrix composites, upto 50% dispersed phase is used by obtaining material through sintering method. [12]

1.6 Fundamentals of Friction and Wear

1.6.1 Theory of Wear

Wear is a progressive loss of material from a surface primarily by mechanical action due to interaction with mating surfaces in relative motion. Plastic deformation at interface generally leads to wear; it can also be caused by chemical reaction. All machines lose their reliability and durability due to wear. Wear is the system response, not an intrinsic material property. The presence of wear is characterized by detached wear particles, material and shape changes of surface under tribological load. Wear can be classified into various types; Adhesive, Abrasive, Fatigue, Fretting, Corrosive, Erosive, etc.

Adhesive wear occur when there is a localized bonding between two solid surfaces that leads the material transfer between surfaces or loss from either surface. In adhesive wear, it is necessary that both surface to be in intimate contact. Adhesive wear can be reduced by contacting of surface with lubricating films and oxide.

Abrasive wear occurs when interlocking of a curved or inclined, ploughing takes places between the contacts of two surfaces in sliding. Due to extraction a certain volume of surface material removed and abrasive grooves form on the weaker surface i.e., abrasive wear occur when one surface (harder than other) cut material from second surface.

Fatigue wear occurs due to repeated stress cycles. When number of contact cycle is high, then fatigue mechanism is expected to dominate in the wear mechanism. In this process wear occur by fracture arising from material fatigue.

Most of the metals are thermally unstable and get reaction with the atmospheric oxygen and make an oxide form, which developed a layer on surface of metal and alloy. Corrosion wear is gradual distortion of unprotected metal from surface by effect of acids, gas atmosphere etc. these types of wear occur due to chemical reaction. Fretting wear is expected within a short time interval with extremely short sliding motion.

Erosive wear is caused by impacts of solid or liquid particles against the object surface. When a solid particles impinge in a surface then metal removal process take place. This type of wear is known as erosive wear. Wear produced is closely analogous to abrasion due to small impingement angle.

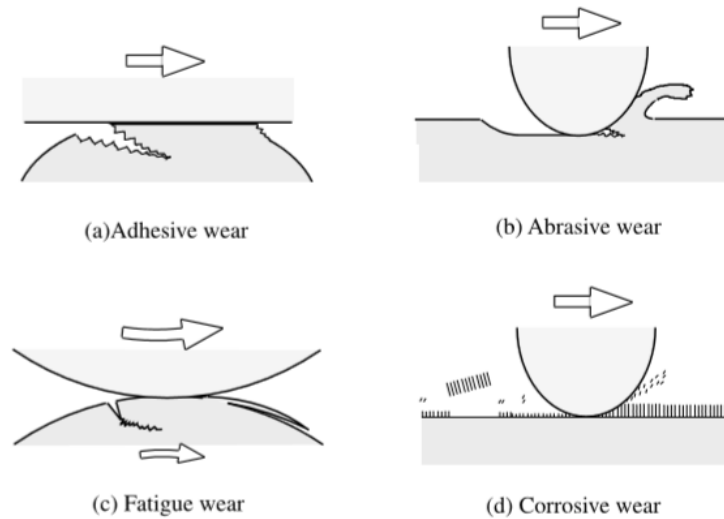


Figure 1.6 Types of wear (a) Adhesive wear (b) Abrasive wear (c) Fatigue (d) Corrosive wear

(Kato and Adachi, 2001)

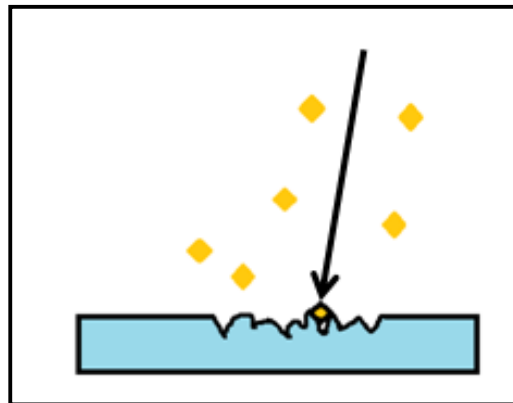


Figure 1.7 Erosive wear

1.6.2 Theory of Friction

Friction is resistance to relative motion by contact of two bodies i.e., when a body slides over another body the resistance to motion is known as friction. Friction is a result of energy dissipation at interface (sliding). The reason of friction is microscopic forces of molecular adhesion and microscope reasons of mechanical abrasion.

Coefficient of friction (COF) is defined as the ratio of friction force to the normal reaction (weight applied) acting on a body. It is not material property, it is a system property.

$$F = \mu N$$

Where,

F= Frictional force

N = Normal reaction

μ = Coefficient of friction

Coefficient of friction depends on Surface roughness, Lubrication, Contact stress, Contact geometry, Environment, Temperature. Friction is independent on area of contact between two bodies. Friction force is proportional to the load between surfaces. Static friction is known as the force required to start sliding motion of one object over another whereas kinetic friction is the force required maintaining the motion of one object over another. Static friction is always greater than kinetic friction.

There are two major types of mechanisms which are believed to be the causes of friction. a) Adhesion and b) Material displacement-either due to asperity interlocking or macro displacement.

When two surfaces are loaded together they can adhere over some part of the contact and this adhesion is therefore one form of surface interaction causing friction. Bowden and Tabor explained the adhesion theory of friction when metal surfaces are loaded against each other, they make contact only at the tips of the asperities. Because the real contact area is small the pressure over the contacting asperities is assumed high enough to cause them to deform plastically. This plastic flow of the contacts causes an increase in the area of contact until the real area of contact is just sufficient to support the load

If no adhesion takes place then the only alternative interaction which results in a resistance to motion is one in which material must be deformed and displaced to accommodate the relative motion. As per material displacement theory we have two types of interactions which are responsible for friction. In asperity interlocking motion cannot take place without deformation of the asperities. In macro displacement theory a hard sphere loaded against a softer cause displacement of softer material during motion. Ploughing is caused by asperities of a hard metal penetrating into a softer metal and plowing out a groove by plastic flow in the softer material. This is a major component of friction during abrasion processes and also it is probably important in cases where the adhesion term is small.

It is well known fact that both friction and wear can be minimized by modifying the contact conditions either by using lubricants or changing the surface properties of the contacting materials. Lubricants provide cooling between contact surfaces of two bodies and transports debris away from interface [13].

1.7 Summary of the Chapter

This chapter discusses the basic definitions and characteristics of the composites followed by the importance of hybrid aluminium matrix composite, their types, properties and fabrication technique. A brief description on the fundamentals on wear, friction and lubrication, is also presented here. Subsequent chapters will give an elaborate view of the research work using hybrid aluminium MMCs.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, an extensive literature survey of the worldwide research works carried out on the friction and wear studies involving metal matrix composites, hybrid composites, aluminium alloys and the use of different nanoparticles which might have beneficial for tribological behaviour when they are reinforced in the metal matrix of the composites. The composite material is composed of continuous phase of matrix and discrete reinforcement. This chapter also contains the literature survey in the field of casting to understand the concept of manufacturing and synthesis of various methods to cast the MMCs and change in their properties. The literature survey focuses, primarily on the particle reinforced metal matrix composites. Properties of these materials depend upon many process parameters and selection of matrix and reinforcement. The basic reason of metal reinforced with ceramics are to improved some properties like strength, hardness etc than its original material. The following section highlights findings of the various the author's work for better understanding.

2.2 Literature Review

Dry sliding metal-metal and metal-abrasive wear behavior of composite were investigated by Ahlatci et al., [14]. They studied on aluminium matrix hybrid composite fabricated by pressure infiltration technique. The composites were reinforced with 25 vol% of SiC and 37 vol% alumina and Mg upto 8wt%. Their result showed that as the matrix hardness and strength increased porosity and toughness decrease with increasing content of Mg. Metal-metal and metal-abrasive wear decrease with increasing Mg content. With increasing test temperature, abrasive wear rate of hybrid composite increase.

Prabu et al., [15] carried out their study with high silicon based aluminium metal matrix composites reinforced with silicon carbide. In their study the effect of stirring speed and stirring times was explored to synthesize 10%SiC composite. For the investigation of micro

structure and distribution of reinforcement particles they used optical microscope and scanning electron microscope. The hardness test was performed on composites from base to top of cast by Brinell hardness machine. Their results revealed that hardness of composite influenced by the stirring speed and stirring time. Microstructure analysis revealed that the particle clustering was more at lower stirring time with lower stirring speed. Increase in stirring speed and time pointed towards the better distribution of particles. Composite's hardness also affected by stirring speed and stirring time. At 600 rpm and 10 minute stirring time the uniform hardness of composites had been achieved. However, after certain stir speed the properties of composites degraded again.

Ramchandra and Radhakrishna [16] studied on aluminium (12wt% Si) as matrix and fly-ash as reinforcement at different percentage. The composite were fabricated by liquid metallurgy process. Tribological characteristics were studied by sliding wear test, slurry erosive test and fog corrosion test. For sliding wear test pin on disk machine was used at varying parameters viz. load, track velocity and fly-ash percentage. For slurry erosive wear, pH value of slurry and percentage fly-ash was used as varying parameters. For fog corrosion test fog of NaCl was used. Optical microscope and scanning electron microscope were used for analyze the worn surfaces. The result revealed that with the increase in fly-ash percentage, wear rate decrease. Wear rate increased with increase in track velocity and applied load which they suggested to be due to the micro cutting of base alloy. They also observed that corrosion resistance decrease with increasing fly-ash particles and slurry erosive wear decreases with increase in fly-ash content due to formation of passive layer on surface of specimens.

Fligier et al., [17] studied on two different modern fabrication method of composite material with aluminium and alumina as a matrix. The methods they followed are (a) powder metallurgy of aluminium EN AW-AlCu4Mg1 (alumina) and (b) pressure infiltration of liquid alloy EN AC-AlSi12 through porous medium (sintering alumina with porous forming agent-carbon fibers). The results showed that the composite fabricated by extrusion method bending of alumina particles parallel (longitudinal) to extrusion direction and there was agglomerations of alumina particles and their segregation.

Wahab et al., [18] performed their study on the mechanical characterization of aluminium matrix (with high silicon content) composites reinforced with aluminium nitride. Two types of mould used to cast the composites are graphite crucible and stainless steel permanent mould. Optical microscope was used to investigate the distribution of reinforcement particles and morphology of composites. The reinforcing particles were clearly shown present at the

edges and around grains of silicon primary, silicon needles and inter-metallic compound of $\text{FeMg}_3\text{Si}_6\text{Al}_8$. The hardness of Al-Si matrix was observed as 44 HV and increased to 89 Hv for an Al-Si composite reinforced with 5 wt.% AlN powder. Hardness was increased with the increasing amount of AlN particles into the matrix.

Swamy et al., [19] fabricated aluminium matrix composites with liquid metallurgy route. SiC was used as reinforcement in Al6061 alloy to improve its hardness, tensile strength and wear resistance. Al6061–SiC composites were fabricated by liquid metallurgy route with varying percentages of SiC as 4wt%, 6wt%, 8wt% and 10wt%. The cast composites had been subjected to solution zing treatment at a temperature of 530°C for 1 h followed by quenching in different media such as air, water and ice. The natural and artificial ageing had been done of quenched samples. Structural natures of composites were defined by micro structural studies. Mechanical properties such as micro hardness, tensile strength and wear resistance of both matrix Al6061 and Al6061–SiCp composites had been conducted before heat treatment and after heat treatment. Al6061–SiCp composites under heat treatment conditions show improved micro hardness, tensile and wear resistance when compared with Al matrix alloy.

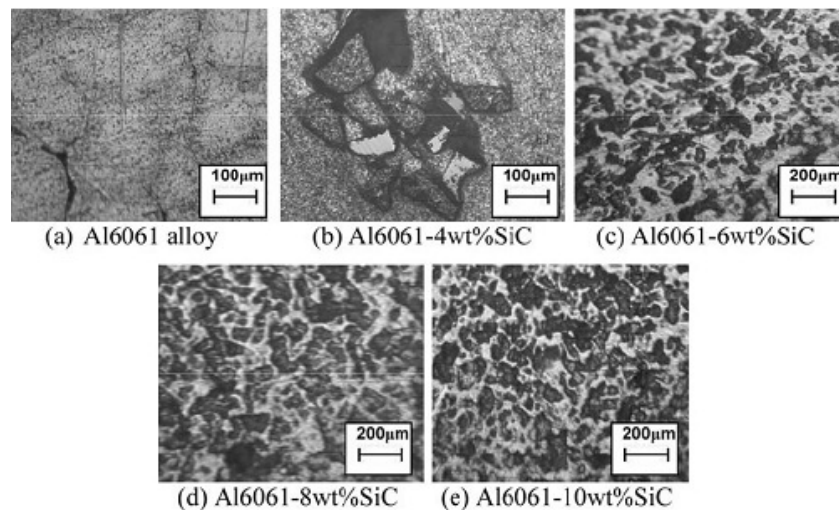


Figure 2.1 Optical microphotographs of base Al6061 alloy and Al6061–SiCp composites at 4, 6, 8 and 10 wt% SiCp [19].

Kumar et al., [20] studied on Al6061-SiC and Al7075- Al_2O_3 composites fabricated by liquid metallurgy technique. Mechanical properties such as tensile strength, hardness and tribological properties have been carried out on fabricated composites. As per ASTM standard the sample was prepared from all the composites for hardness, tensile strength, wear and microstructural tests. The increasing percentage of reinforcement content in composites revealed that hardness and density of their composites increases. Optical microscope revealed

that uniform distribution of reinforcement into the composites. According to rule of mixture for composites the experimental density value agreed with the theoretical density value of composites. It has been shown that Al6061-SiC reflects superior tensile strength than Al7075-Al₂O₃ composite. SiC contribute in improving the wear resistance of Al6061-SiC composites which was reflected by the low wear rate of composites.

R.D. Pruthviraj [21] studied on the fabrication and mechanical characterization of aluminium (zinc based) metal matrix composites reinforced with silicon carbide particles. The composite was cast in sand moulds with different metallic chills like copper, steel and cast iron respectively. The silicon carbide of size 50-100 μm was reinforced to matrix. The cast composite were characterized for hardness, strength and wear rate. Their microstructural studies revealed that matrix and dispersoid have great bonding between and uniform distribution of reinforcement into matrix. They found that small amount of silicon carbide particles are sufficient for change in mechanical properties. Composites with SiC 9wt% content showed maximum strength and hardness. Their study also revealed that the wear resistance (dry and slurry wear) is affected by the reinforced quantity. Increasing in reinforcement results with increasing wear resistance.

Sujan et al., [22] studied the performance of stir cast alumina and silicon carbide reinforced metal matrix material to evaluate the physical and mechanical properties. Two sample of MMC were prepared for this purpose. First one is aluminium-alumina with composition of 5%, 10%, 15% and other is alumina-silicon carbide with 5%, 10%, 15% reinforcement. Their composites were characterized with improved physical and mechanical properties such as high hardness, impact strength, high tensile strength and low coefficient of thermal expansion as compared to single materials. It also has been found that new material exhibits higher wear resistance against abrasive wearing with increasing reinforcement's weight percentage in aluminium.

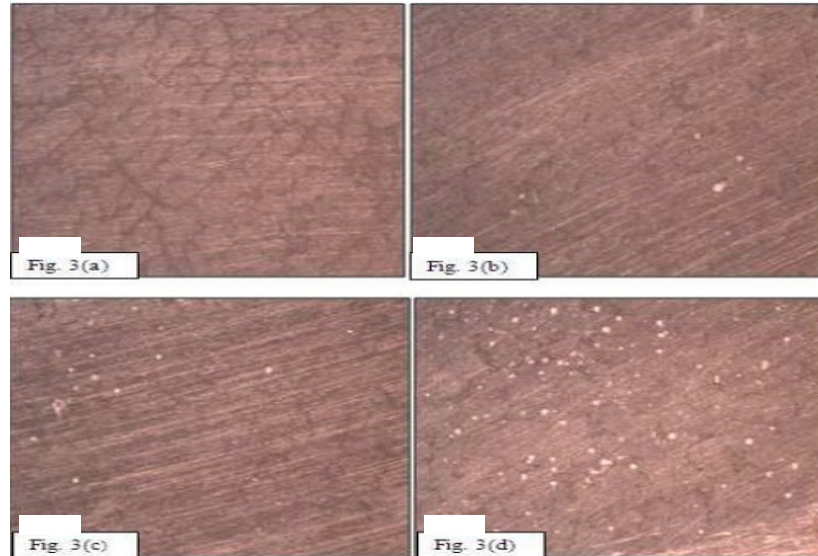


Figure 2.2 Optical micrograph of alloys and composites (x35) (a) Aluminium at pure state (b) 5 wt% Al₂O₃ reinforcement (c) 10wt% Al₂O₃ reinforcements (d) 15wt% Al₂O₃ reinforcement [22]

Aluminium matrix composites at different process temperature with varying holding time was fabricated by Sozhamannan et al., [23] to find out the effect of process parameter on distribution of particles in matrix and relative mechanical properties. For producing discontinuous particles reinforced metal matrix composites, conventional stir casting process has been used. The major problem of this process was found to be attainment of sufficient wettability of particles with liquid matrix and get homogeneous dispersion of ceramics particles. The particles were distributed uniformly in the composite at process temperature 750°C and 800°C. Viscosity decreases with increasing of processing temperature of Al matrix. The tension test indicated that ultimate strength increased gradually up to 800°C and starts to decrease gradually due to the distribution in the Al matrix. Increase in holding time decreased the ultimate tensile strength of metal matrix composites.

Ahmad et al., [24] investigated wear behavior of alumina particles reinforced Aluminium Matrix Composites (AMCs). Wear rate was characterized under dry sliding condition at room temperature by using pin on disc type wear testing machine. At 25, 50, 75, 100 N the wear rate measured with sliding speed of 250, 500, 750, 1000 rpm and concluded that percentage difference in weight loss of AMCs was approximately 52%. At lower load, for both the materials, coefficient of friction was almost same but at higher load percentage difference in weight loss decreased.

Ezatpour et al., [25] studied on aluminium based metal matrix composite with two types of fabrication process. Alumina in nano and micro size in different weight percent was used as reinforced particles. The two melt techniques such as compo-casting and stir-casting were used to fabricate the metal matrix composite. Scanning electron microscopy and optical microscopy were used for surface morphology and micro structural characterization. Mechanical properties of composites such as hardness, tensile strength and compression test were carried out. The results of micro structural study revealed the uniform distribution of reinforcement, grain refinement and low porosity in micro and nano-composite specimens. The mechanical results showed the increasing tensile strength, compression strength, yield strength and hardness due to addition of alumina (micro and nano). It was indicated that particle size and type of fabrication process have a great effect to influencing on the mechanical properties. The best mechanical properties were obtained at Compo-casting process with small particle size.

A review of stir casting process, its parameter and preparation of metal matrix composite was performed by Bhandare et al., [26], using aluminium as matrix and SiC and Al₂O₃ as reinforcement. The result indicates that mechanical stirrer's blade should be 4 and blade angle should be 45° for uniform dispersion of material. Maintaining the operating temperature at 630°C for Al (6061) will give good wettability and to reduce the porosity, preheat the mould.

Behera et al., [27] studied on wear behavior of three different composites reinforced with alumina, titanium dioxide and copper. Powder metallurgy technique was used to prepare the composites by using increasing furnace temperature from 100°C to 700°C with the rate of 3°C/min. Wear results showed that wear rates decrease with increasing the sliding velocity for all three composites. Wear rate is affected by the content of alumina and titanium dioxide. Alumina had shown the high wear as compared to other combination.

Surendran et al., [28] aluminium alloy LM25 reinforced with alumina by Die casting method for their study. The composition of reinforcement was 0%, 1%, 1.5%, 2.5% and 5%. To find out the properties of fabricated composites tensile test, wear test, hardness test, impact test were carried out. The LM25 Al alloy reinforced with 5% of alumina displayed superior characteristics as compared to the other composition of metal matrix composites. Pin on disk wear test result with pure aluminium reinforced with 1%, 1.5%, 2.5%, 5% alumina showed that wear rate decrease with increasing percentage of reinforcement. It was observed that MMC samples with higher percentage of reinforcement shows higher hardness.

Khanna et al., [29] studied the effect of production parameters on wear resistance of Al–Al₂O₃ composites. Aluminium powder used with 3, 12, 30, 48 μ particle size of alumina. Alumina powder up to 20% was added in sintering process. The sintering process used at different range of sintering temperature of 500°C, 550°C and 600°C and time is taken as 30, 45, 60 and 90 minutes respectively. It revealed that the density, hardness and homogenization of microstructure increased as the sintering temperature increased. However at certain sintering temperatures and time, considerable grain growth and reduction of hardness value occurred, leading to the degradation of wear resistance. The results showed that the relative density of composites increase with high alumina content. First, the relative density of composite initially increases and then drops to lower values due to raising the alumina particle size. The hardness and wear resistance improved with increase in the weight percentage of alumina particle in aluminium composites. The alumina particles had a similar effect on hardness and the wear resistance. Finally, a high amount and low size of alumina particles observed as finer grain size.

Padmavati and Ramakrishnan [30] focused on wear and friction behavior of Al6061 with various percentage volumes of multiwall carbon nano tube and silicon carbide reinforcement by stir casting and die casting. By pin on disc method wear test was performed and observed that for all values of applied load there is an increase in coefficient of friction with % of MWCNT and decrease in specific wear rate. As hybrid ratio increases, hardness of composites increases.

Table 2.1 coefficient of friction value for 3 samples

Load	Al-15%SiC	Al-15%SiC-0.5%CNT	Al-15%SiC-1%CNT
0.5	.532	.404	.263
1	.569	.487	.382
1.5	.589	.535	.486

Krishna and Xavier [31] found that the weight fraction is greatly influenced by mechanical properties such as tensile strength. It was observed that density increased with SiC and decreases with SiC/Gr hybrid particulates.

Prabhakar et al., [32] fabricated aluminium-boron carbide metal matrix to analyze the tribological behavior of composites. The boron carbide 5wt% with particle size 33 μ m was reinforced in aluminium by stir casting process. Uniform distribution of reinforced particles was examined. Wear test was conducted by pin-on-disc tribometer with Taguchi's L-27 orthogonal array. The three process parameters are taken such as load (10N, 20N and 30N), velocities (1m/s, 2m/s and 3m/s), and sliding distances (1000m, 1500m and 2000m). Result revealed that wear rate and coefficient of friction increases with increasing the load and inversely related to the sliding distances and velocities.

James. S.J. et al., [33] carried out a study on machining parameters and mechanical properties of hybrid aluminium metal matrix composites. The composites were prepared at different composition of silicon carbide and titanium di boride. Optical microscope was used to morphology and reinforcement particles distribution in composites. Hardness test has been carried out using Vickers hardness to find out the hardness of composite. Turning operation has been done with different parameters such as: feed rate, cutting speed, wt% of TiB₂ influence on surface roughness, dept of cut was examined. Results revealed that cluster formation take place as increasing the wt% of reinforcement. Wear resistance behavior increase by TiB₂ particles of hybrid metal matrix. Taguchi method was used as such parameters for best surface of value at cutting speed 120m/s, depth of cut 0.5mm, 0% reinforcement of TiB₂. It has been observed that abrasive and adhesive actions, low cutting speed with high depth of cut and increased wt% of TiB₂ are main cause of high tool wear.

Pawar et al., [34] fabricated and studied metal matrix composites aluminium as a matrix and silicon carbide as reinforcement. The composition of reinforcement was taken as 2.5%, 5%, 7.5% and 10%. Microstructure and hardness test were conducted for mechanical properties. Stir casting process was used to fabricate the composites. These composites were fabricated to propose a material for continuous loading power transmitting element. CATIA and ANSYS 14.0 were used modeling and finite element analysis. From their results they found that hardness of composites is much better than aluminium. The hardness of composites was increased as the reinforcement mass% increased.

Ramnath et al., [35] studied on the mechanical behavior of aluminium matrix composites reinforced with alumina and boron carbide. Stir casting process was used for fabricated composites by mixing reinforcement at required quantities for excellent hardness and toughness. Three sample were prepared at different composition of composite such as aluminium-alumina 3%- boron carbide 2%(Sample-1), aluminium-alumina 2%- boron

carbide 3%(Sample-2), and aluminum(Sample-3). The results showed that tensile strength of sample-1 is higher than other samples. Sample-3 has higher flexural strength. Sample-2 has higher hardness than other two samples. Scanning electron microscope shows the uniformly distribution of the reinforcement into the composites.

Walczak et al., [36] studied on tribological behavior of $F_3S_{.20}S$ aluminium material (20% SiC and AlSi9Mg alloy). The tests were carried out on raw sample (without heat treatment) and with T6 thermal treatment. Ball on disc wear test has been used for tribological studies. $F_3S_{.20}S$ composite after heat treatment show the low coefficient of friction with significantly high wear resistance. Micro cutting or ridging with spalling of SiC particles were attributed to the cause of weight loss of $F_3S_{.20}S$ composite during Ball-on-disk wear tests.

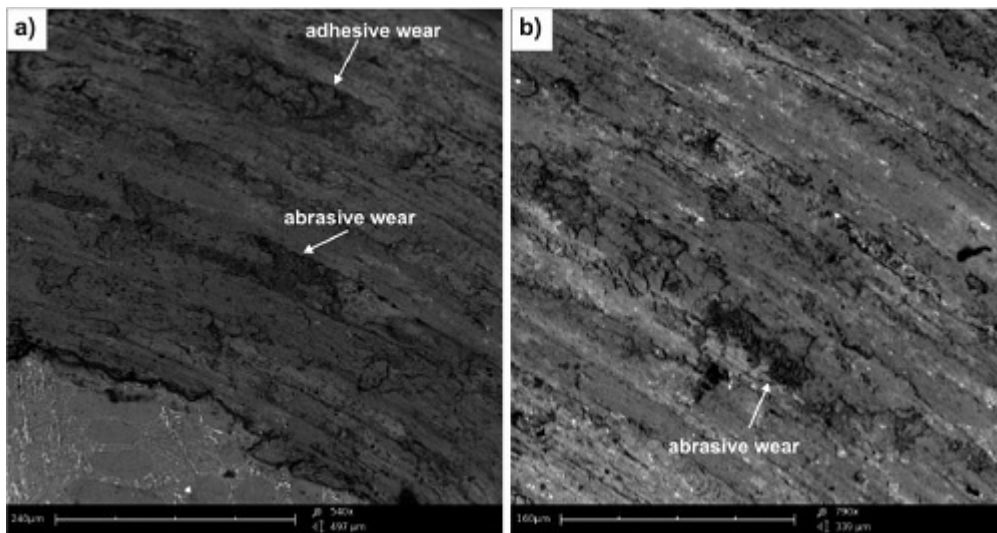


Figure 2.3. SEM microstructure of AlSi9Mg alloy: (a) wear trace edge and (b) wear trace centre.

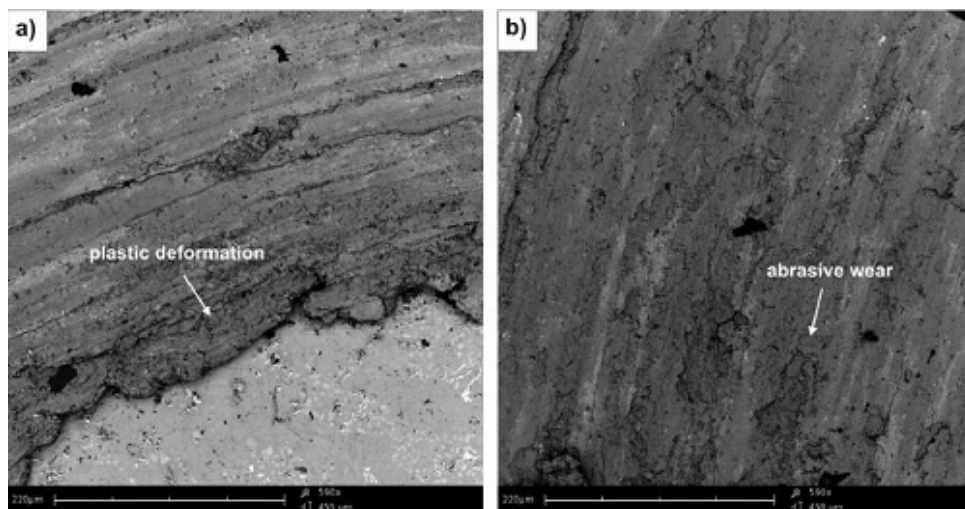


Figure 2.4 SEM microstructure of AlSi9Mg alloy after T6 heat treatment: (a) wear trace edge and (b) wear trace centre

2.3 Summary of Literature Review

From the literature survey it is found that most of the works on MMCs have been carried out using aluminium matrix with different types of reinforcements, different particles size and manufacturing processes. For the manufacturing of MMCs, the conventional processes such as die casting, stir casting, friction stir processing and common methods to prepare it were studied. The mechanical properties and metallurgical characterization must be carried out for cast composites at different compositions. Scanning electron microscope and optical microscope are used to find out uniform distribution of reinforcement into matrix, surface morphology and grain structure.

Most of the works used either alumina or silicon carbide particles for reinforcement. It is now clear fact that various properties of MMCs can be improved if the synthesis and fabrication of the composites are carried out keeping in mind the desired application.

The importance of further research on MMC can be well understood keeping in mind the various end uses of these composites. Aluminium MMCs are gaining attention in the aerospace area, in aircraft structure, aero engine, space structure and other space applications where weight reduction for improved performance and payload capabilities are the major criteria. In Commercial area, Aluminium-graphite composites are use to manufacturing of electronic module due to low density, coefficient of thermal expansion and high thermal conductivity. In industries AMMC's are used in reciprocating and high speed machinery, and precision equipments. In automotive engineering metal matrix used in reciprocating and static engine component and breaking system of all vehicle and train also.

Effects of the reinforced materials with their varying percentage were studied. The reinforcement changes the microstructure and grain growth of the composites. The overall result revealed that increasing the percentage of reinforced particles improves the hardness, tensile strength, impact strength of composites. Size of particle also has a great influence in these properties. Small size particles were found out the best with increasing percentage quantity. Mg particles improve the porosity of cast composites which improve the hardness of composites. Increasing in percentage of reinforcement the wear resistances improve for all cases. Also, it is found that composite with different percentages of reinforcement influence the wear rate differently.

However, these composites suffer a great loss in ductility and toughness due to the incorporation of non-deformable ceramic reinforcements which limits their wide applications

to a certain extent. Hence, instead of going on increasing the wt% of single reinforcement there is a need of optimizing the properties of composites by hybridization. Such an attempt for the investigation of hybridization is also presented here. Researchers are now trying to explore the hybrid composites to improve their properties. A few research on the hybrid composites hints that the wear rate do not depend on type of reinforcement only, but the compatibility of reinforcements into MMCs and interactions amongst themselves. Increasing the reinforcement weight percentage in hybrid composites it is seems that abrasive wear resistance of the component might be significantly improved.

Thus, it is evident that a numbers of properties can be enhanced further by fabricating the MMCs through suitable combination of materials and process parameters. In the field of wear resistance, it is essential to provide a lubrication to reduce the wear. However, sometime it is too difficult to access a lubricant around the wear parts surfaces externally to reduce the wear.

2.4 Gaps from Literature Review

After going through the reported literature by different authors, research gaps are formulated. A lot of work has been reported regarding the enhancement of the properties of Aluminium Matrix composite but still lots of scope is left in the field of composite fabrication for the desired application. Following gaps are found after surveying the literature-

- A very limited works are available in the literature which deals with the fabrication and characterization of metal matrix hybrid composites and on these process parameters while manufacturing of hybrid composites.
- Majority of the works found in the literature are more concerned with the improvement of the mechanical properties. A very limited research has been noticed in the field of the complete tribological characterization of the MMCs, especially the hybrid composites, which explains the wear mechanisms, counter face wear, different parameter that influences the wear loss and the role of the reinforcement phases.
- Moreover, studies on the mechanism of friction involving hybrid composites are in its infancy stage.
- There is a vast potential and opportunities for the researchers still left to improve friction and wear properties of aluminium composites by varying parameter associated with wear such as reinforcement particle size, adding different

reinforcement hybrid composites and changing ratio of them, changing fabrication technique and parameters associated with that

The above gaps provide the background for the concept generation and what is going to be aimed at, through this research work. Accordingly, the problem is formulated and plan of work is proposed.

2.5 Scope and Objective of Present work

Now a day's composite materials are in a demand to full fill the specific requirement like as high strength to density ratio, wear resistance, high toughness etc. in automobile and aerospace industries.

The main objective of the present research is to optimize the process parameters and material combination in the fabrication of Al-SiC, Al-Al₂O₃ and a Hybrid composite by investigating the tribological behavior as well as mechanical, microstructural and surface properties.

To fulfill the above general objective, the present research is carried out to achieve the following specific objectives-

- To fabricate AMMC composites by an efficient and easily available infrastructure.
- Hybridization of the particulate reinforcement in the fabricated composite to enhance the properties.
- To carry out the microstructural and metallurgical characterizations of the composites using SEM, EDS, Optical microscope and XRD techniques.
- To investigate the macro and micro-hardness of the fabricated composites
- To study the friction and wear behavior of the base metals, and the reinforced composites using pin-on-disc tribometer.
- To estimate the effect of various influencing parameters such as composition of reinforcement particle, load, sliding distance, on wear and friction in dry sliding conditions.

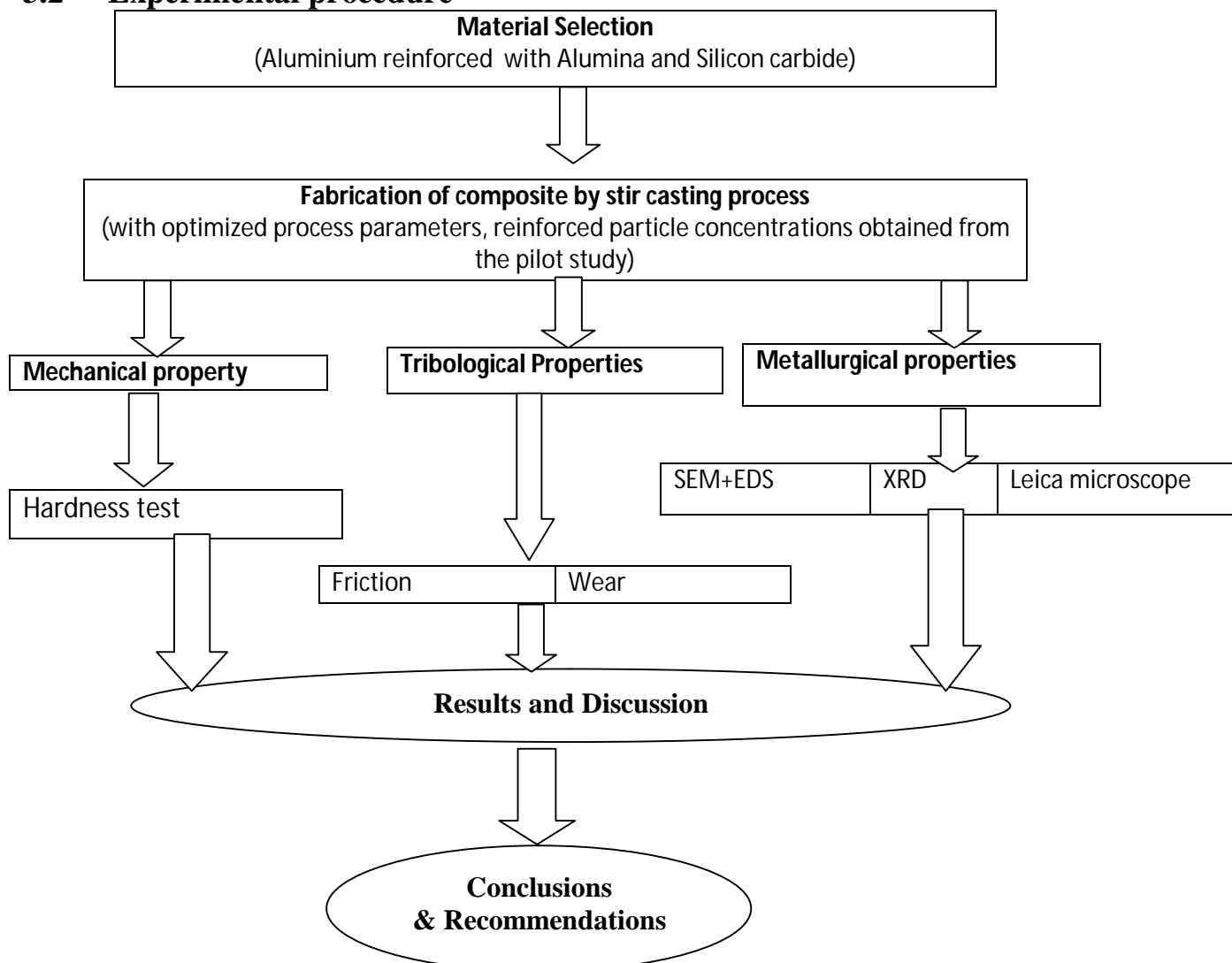
CHAPTER 3

METHODOLOGY

3.1 Introduction

Once the objectives are defined an experimental set up is prepared for the pilot study. Based on the observations of the pilot study a set of experiments are designed and carried out to achieve our goal through this research work. Prior to fabrication of composites by casting, the process parameters for the preparation of mould are optimized using green sand and molasses, sand percentage, clay percentage and water percentage. Then, the selection of constituent materials to prepare the sample with varying composition of reinforced material into matrix was carried out. This is followed by mechanical, metallurgical, surface and tribological characterization of the cast AMMCs.

3.2 Experimental procedure



3.2.1 Material selection

Aluminium is selected as metal matrix for the composite due to its abundance, low cost and already proven track record for the similar purpose. It is relatively soft, durable, lightweight, ductile, malleable metal and has high corrosion resistance, excellent heat conductivity. The selected aluminium with alloyed content (ADC12) bears the composition as shown in the following table (Table 3.1).

Table 3.1 International Standard composition of ADC 12 [www.leekeegroup.com]

Silicon carbide (Si) %	Iron (Fe) %	Copper (Cu) %	Manganese (Mn) %	Magnesium (Mg) %	Nickel (Ni) %	Zinc (Zn) %	Tin (Sn) %	Aluminium (Al) %
9.6-12	1.3 max	1.5-3.5	0.5 max	0.3 max	0.5 max	1.0 max	0.3 max	Balance

Silicon Carbide is taken as one of the particulate reinforcement for the composite considering the facts that it has high strength and hardness, excellent thermal conductivity, high elastic modulus, excellent thermal shock resistance and superior chemical inertness.

Properties of the selected silicon carbide particles are shown below.

Table 3.2 Properties of the selected silicon carbide particles (<http://accuratus.com/silicar.html>)

Density	3.21 gm/cc ³
Hardness	2800 kg/mm ²
Fracture toughness	4.6 Mpa
Thermal conductivity	120 W/m.°K
Specific Heat	750 J/kg.°K

Alumina is the second a chemical compound used for the fabrication of the hybrid composite. Alumina is one of the most widely used and cost effective materials in the family of engineering ceramics. The raw materials are easily available and have high hardness, good wear-resistant; at elevated temperature it resists strong acid and alkali

attack, excellent thermal conductivity, excellent size and shape capability, high strength and stiffness.

The materials used here bear the following technical properties

Table 3.3 Properties of the selected Alumina particles (<http://accuratus.com/alumox.html>)

Density	3.95 gm/cc ³
Hardness	1500 kg/mm ²
Thermal conductivity	15 W/m.°K
Melting properties	2015°C
Specific Heat	920 J/kg.°K

3.2.2 Fabrication of composites

Aluminium alloy (ADC 12) was melted in graphite crucible by heating in the muffle furnace at the temperature at 850°C for 3-4 hours. The alumina and silicon carbide particles preheated at the temperature of 350°C and 400°C respectively to make their surface oxidized. First the temperature of furnace raised above the melting temperature of ADC 12 which is about 730°C to melt the metal completely and then cool down to keep slurry in semi solid state. Radial drilling machine is used for stirring process for an appropriate time at stirring rate of 200 RPM. Preheated alumina or silicon carbide particles will add to crucible during stirring process. The reinforced materials mixed into base material equally distributed in 3 or 4 times. After stirring process, the process temperature was controlled within 750°C± 10°C. Then the mixture of molten metal is poured into mould to get the desired shape of specimen. Following figure shows the cast composite.



Figure 3.1 Cast composites [Photo courtesy: Thapar university, Patiala]

Same process will use for all different composition of Silicon carbide and alumina with aluminium. A brief overview on the equipments and components which are used in stir casting process are given below.

- **Muffle Furnace:** It is used to melt the base material to achieve desired temperature by the conduction, convection and black body radiation from electrical resistance heating elements. The temperature of muffle furnace was raised about 850 °C. Fig.3.7 is shown a Casting furnace have a maximum temperature range of 1100⁰ C



Figure 3.2 Muffle Furnace [Photo Courtesy: Thapar university campus, Patiala]

- **Graphite Stirrer:** The function of stirrer is to agitate liquid for speeding up reaction. The stirrer is designed to get homogeneous mixture of metal in liquid and liquid-solid form with reinforcement. This stirrer is connected with electric motor (range 22-480) with help of Stainless steel rod. The stirrer is positioned near the bottom of crucible while mixing.



Figure 3.3 Designed Graphite stirrer

- **Ceramic Crucible:** A crucible is a refractory container used for metal, glass production which can withstand temperature high enough to melt or otherwise alter its contents.

Historically, the crucible is made of clay, but now it is made of graphite keeping in mind its inherent advantages.

- **Sand mould:** It is used for cast the MMCs as the pattern shape. It is made of different type of sand compositions which can withstand with high temperature. The liquid-solid metal is poured into mould (having a pattern shape) to cast the MMCs.



Figure3.4 Ceramic crucible



Fig.3.5 Sand mould

[Photo Courtesy: Thapar university campus, Patiala]

- **Power Hack Saw:** A power hacksaw (electric-saw) is a type of hacksaw that is powered by its own motor. A hacksaw is fine tooth saw with blade under tension in a frame used for cutting materials such as Aluminium into small piece so it to keep metal into crucible.



Figure 3.6 Power Hacksaw [Photo Courtesy: Thapar university campus, Patiala]

- **Baking oven:** A baking oven is thermally insulated box used to baking, heating and drying the substances. Reinforcement is preheated in oven to get moisture-less (dry). Because dry reinforcement (powder) mix properly in liquid metal. The range of baking oven is 500°C.



Figure 3.7 Baking oven

3.3 Characterization of metallurgical properties

3.3.1 X-Ray Diffraction (XRD)

The structure of composites could typically be established using X-ray diffraction (XRD) analysis. Due to its easiness and availability, XRD is the most commonly used tool to probe the composite structure. X-rays are produced whenever high speed electrons collide with a metal target. The source of electrons is a hot tungsten (W) filament and a high accelerating voltage between the cathode (W) and a target. The anode is a water-cooled block of copper (Cu) containing desired target. By monitoring the position, shape and intensity of the reflections from the atomic layers, the composite structure may be identified.

The atomic planes of a crystal cause an incident beam of X-rays to interfere with one another as they leave the crystal. This phenomenon is called X-ray diffraction (XRD). It is based on Bragg's diffraction law which states that

$$2d\sin\theta = n\lambda$$

Where

λ = wavelength of beam

d= distance between lattice planes

θ = angle of diffracted waves

n= numeric constant known as order of diffracted beam



Figure 3.8: X-Ray Diffractometer
(Photo courtesy: SAI Labs, Thapar Technology Campus, Patiala)

3.3.2 Scanning electron microscope (SEM)

In SEM high energy electron focus beam used for generate different variety signals to get information about sample morphology, chemical composition, and crystalline structure. Scanning electron microscope (SEM) is focused electron monitoring to get the chemical and structural information at point by point of an interested region of specimen. The high resolution of SEM makes it powerful tool for surface characterization of sample at nano level. The electron gun or source forms a stream of electrons which are accelerated towards the specimen using a positive electrical potential. A series of lenses are used for control the beam diameter and also focus the beam on specimen. The beam of electrons also scanned across the surface of the sample. The electron beam is affected by the interactions that occur inside the irradiated sample, which are detected and transformed into an image or signal. In this way SEM provides the information about surface morphology and topology.

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). Specimens can be observed in high vacuum, low vacuum, dry conditions (in environmental SEM), and at a wide range of cryogenic or elevated temperatures. It was used to study the worn surfaces and wear mechanism. This facility is available at SAI Labs, Thapar Technology Campus, Patiala.



Figure 3.9 Scanning Electron Microscope

(Photo courtesy: SAI Labs, Thapar Technology Campus, Patiala)

3.3.3 Optical Microscope

Metallurgical microscope shown in Figure: 3.10 is an optical microscope which uses a visible light and a system of lenses is to magnify the images of small samples. The images from an optical microscope are captured by normal light-sensitive cameras to generate a micrograph. Optical microscope is used to observe the internal structure of the metals at different scale and provide a qualitative and quantitative description. In a 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.



Figure 3.10 Metallurgical Microscope

(Courtesy: Advanced metallurgical lab, Thapar University, Patiala)

3.3.4 Characterization of friction and wear

Friction and wear testing by Pin-on-Disk Tribometer

A pin on disc tribometer consists of a stationary "pin" contact with a rotating disc under an applied load. "In Tribometer, a sphere or flat pin is loaded onto the rotating disc with a precisely known force. The pin can have a specific contact, but for contact geometry spherical tips are often used. The ratio of the frictional force to the loading force on the pin gives the coefficient of friction. The stiff lever (frictionless force transducer) connected with pin. Deflection of the elastic arm gives the result of friction coefficient. Wear rate of the pin and disk is calculated by the volume of material lost or weight loss during the wear test. The study of friction and wear for solid state material with or without lubrication is facilitates by this method. The condition of real life for a practical wear is reproduced by controlling of the test parameters such as load, speed, time, contact pressure, frequency and the environmental parameters (lubricants, humidity and temperature).

To perform the experiments for research work, the pin-on-disk apparatus (DUCOM make), shown in Figure 3.11 were used to examine the dry sliding wear characteristics and the coefficient of friction of the metal matrix composites.

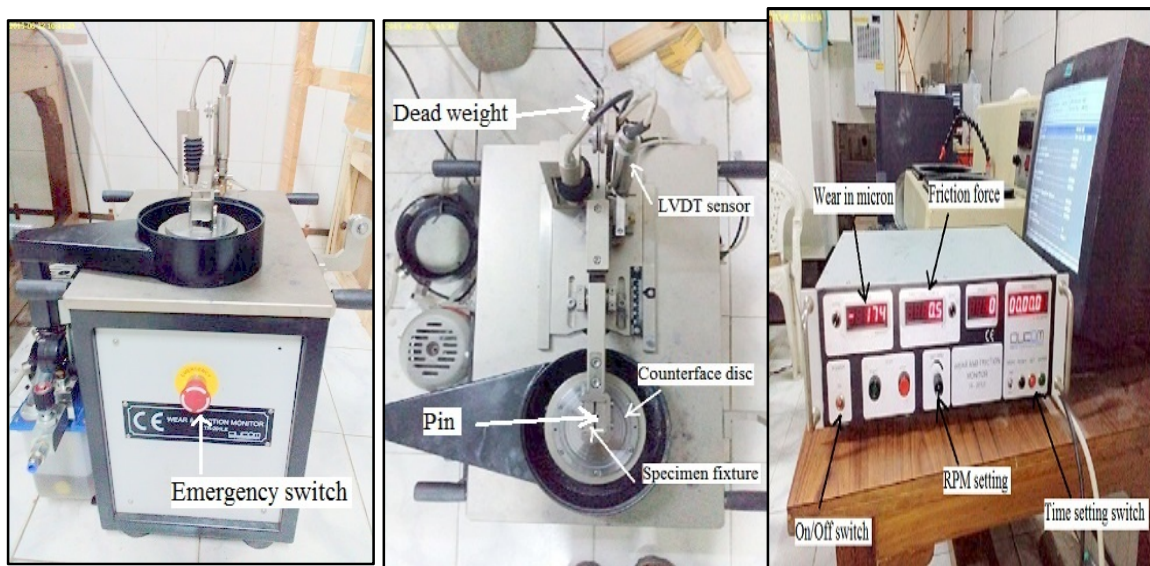


Figure 3.11 Components of pin-on-disk test apparatus

3.3.5 Profile projector

The main function of profile projector is to project the image of an area to be selected on to the screen using diascopic illumination. It magnifies the profile of object and display on to built-in-projection screen. On the screen there is grid which rotates the image at 360° in X-Y

directions. The screen display profile of object and magnifies it for ease of calculation of linear measurements. The object is opaque then light will not pass through it but it will form a profile of object. In this study this facility is used for the profile study of the worn out and freshly made pin ends.



Figure 3.12 Profile projector [Photo Courtesy: Thapar university campus, Patiala]

3.3.6 Hardness Measurement

It is property of material that resists it to deformation usually by penetration or indentation and scratching. Hardness of material mainly depends on strain, ductility, elastic stiffness, strength, plasticity, viscoelasticity, toughness and viscosity. Hardness is generally measured by three techniques;

- (a) Scratch: It measures fracture and plastic deformation due to friction from sharp object. Most common test is Mohs scale.
- (b) Indentation: It measures the sample's resistance to deformation of material due to compressive load from a sharpened object. Most common indentation tests are Rockwell, Vickers, Shore and Brinell.
- (c) Rebound: It is also called dynamic hardness. It measures height of the 'bounce' from a fixed height onto a material. It is measured by a device called scleroscope. It is generally measured by Leeb rebound test and Benett hardness scale.

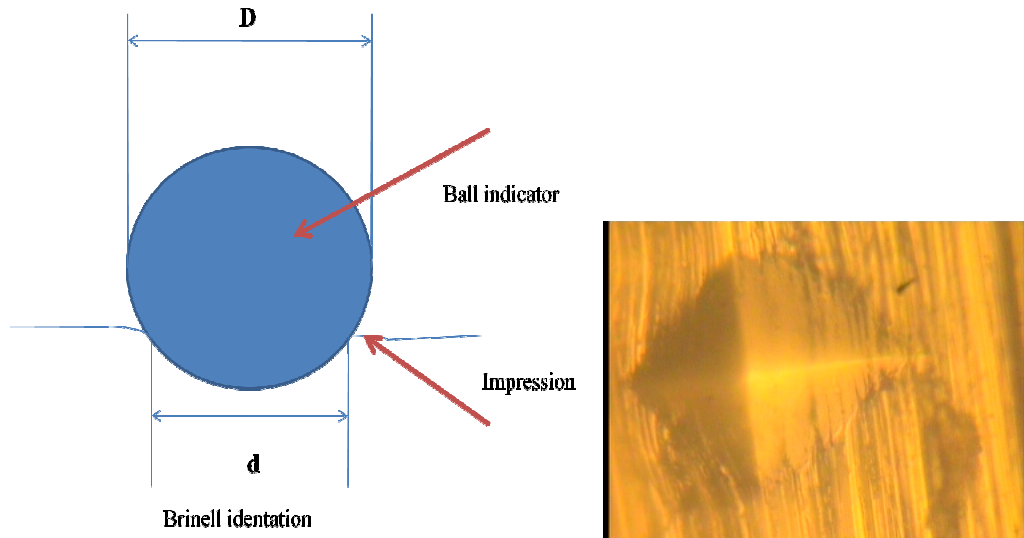


Figure 3.13 Brinell hardness testing

In the present study Brinell hardness test is used. Brinell hardness test are less influenced by surface scratches and roughness than other hardness tests and best for achieving the bulk and micro hardness of material, particularly for those material having heterogeneous structures. The hardness test was carried out by Brinell hardness tester. Constant load of 100 gm with dwell time of 15 sec was applied on each sample. To get more precise result testing was carried out at 5 different points on each sample. It gives average value of two indentation at right angle, set up shown in Figure 3.13 above,

Brinell hardness number (BHN OR Hb) is expressed as a load P divided by surface area of indentation

$$\text{BHN} = \frac{P}{\pi d/L} (D - \sqrt{D^2 - d^2}) = \frac{P}{\pi Dt}$$

Where, $(D - \sqrt{D^2 - d^2})$

P- Applied load, Kg

D- Diameter of ball, mm

d- Diameter of indentation, mm

t- Depth of impression, mm

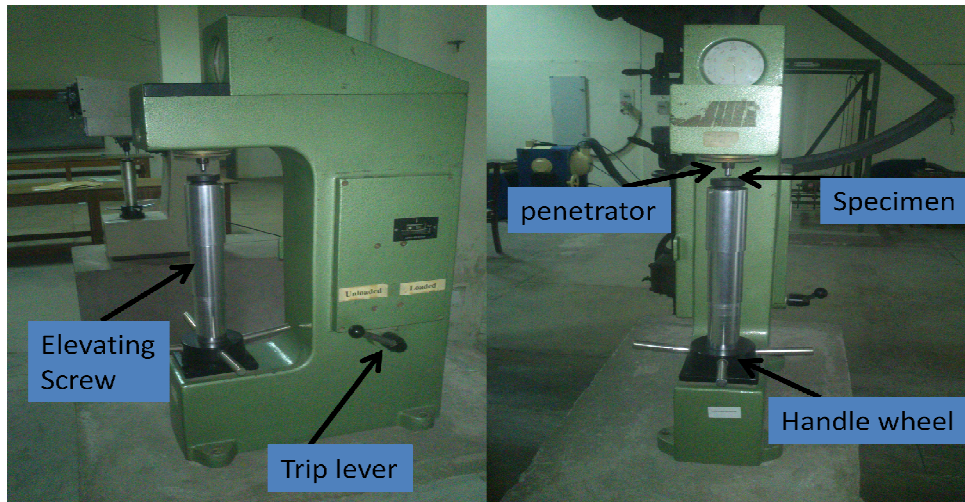


Figure 3.14 Brinell hardness Machine

[Photo Courtesy: Thapar university campus, Patiala]

3.4 Sample preparation for experimental studies

The mould for casting was prepared of 10×9×1.5 cm of length, width and height respectively. Following table shows the compositions of fabricated MMCs.

Table 3.4 Different composition of metal matrix composites

S.N.	Aluminium (gm)	Silicon carbide (gm)	Alumina (gm)	Remarks
1	380.70	0	0	Pure al. alloy
2	373.09	7.61	0	2% SiC
3	361.67	19.04	0	5% SiC
4	342.63	38.07	0	10% SiC
5	342.63	19.04	19.04	5%SiC+5% Alumina

All samples were prepared from this cast as per their dimensions. For SEM and XRD the sample of 10mm×10mm×5mm of length, width and height respectively cut from cast. For hardness testing samples are cut of 10mm×10mm×10mm of length, width and height respectively. Sample for tribometer of 6mm×6mm of square were cut from cast material with

different height. The shape was giving like as hemisphere from its contact with disk for samples of tribometer. Once the samples are cut for different experiments then the following procedure was taken before all characterization.

- Sample prepared for Brinell hardness was polished by using 180, 320, 400, 600, 800 and 1000 grades emery papers.
- For microstructure Lieca microscope was used for sample morphology. Samples were also prepared by etching process. Etchant was prepared by using chemical composition (methanol 25ml, hydrochloric acid 25 ml, nitric acid 25 ml.). The etching process was done for 1 min/sample.
- For SEM and XRD, samples were polished by using emery papers 320, 400, 800, 1000, 2000 and 3000 grades. Then etching process was done on these samples.
- Wear testing pin samples were prepared spherical ended. The dimensions of sample were calculated by using profile projector. Then the roughnesses of samples were calculated and then profile projector was used to get the shape of samples.

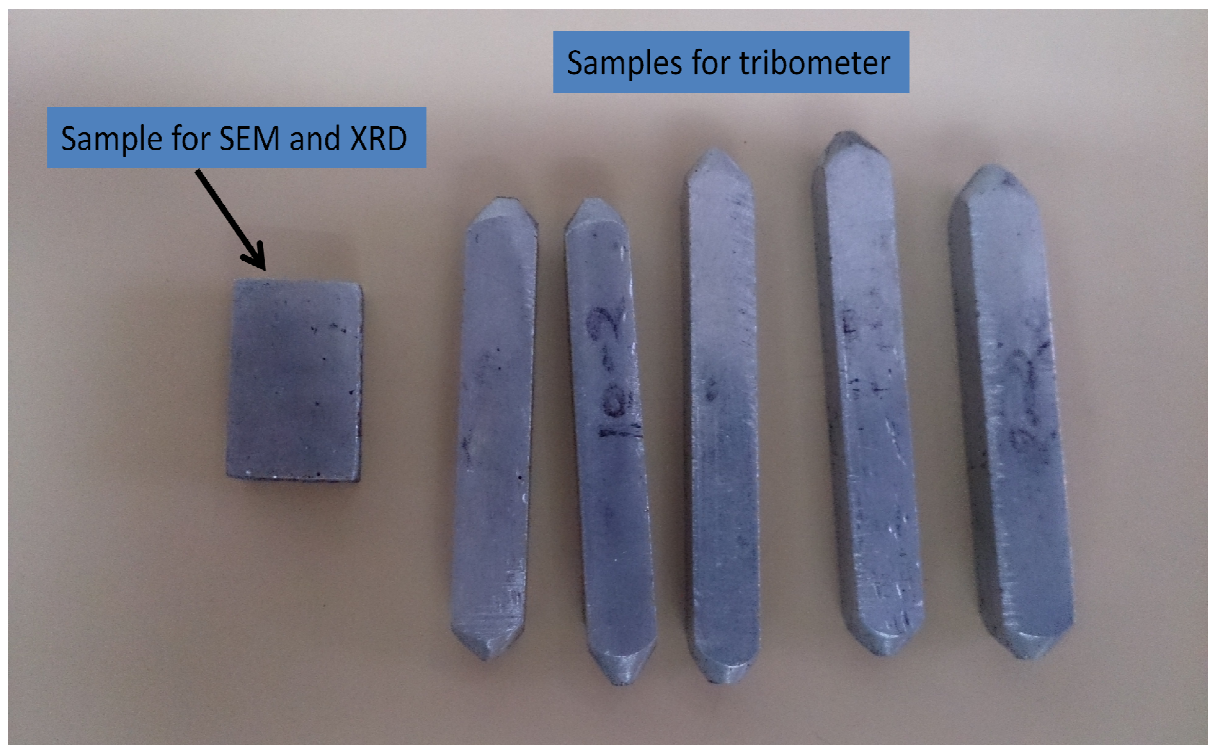


Figure 3.15 Prepared Samples

3.5 Friction and wear testing runs for pilot study

The following table shows the set of runs selected for the friction and wear testing of base materials. The selection of independent factors to investigate the dry sliding wear and coefficient of friction of the selected composite is based upon the understanding of process and literature survey. This will be followed by a full factorial testing of overall tribology studies. The next chapter will deal with the results and detailed discussion of the works performed in this research work.

Table 3.5 Runs set for tribological studies

Run trail	Load-P (Kg)	Diameter-D (mm)	Sliding velocity-v (m/s)	N (r.p.m.)	Time (min.)	Sliding distance (meter)
Run 1	0.5	10	0.1	191	30	180
Run 2	0.5	40	0.5	239	30	900
Run 3	0.5	70	2	546	30	3600
Run 4	1.5	20	0.1	95	30	180
Run 5	1.5	50	0.5	191	30	900
Run 6	1.5	80	2	477	30	3600
Run 7	2.5	30	0.1	64	30	180
Run 8	2.5	60	0.5	159	30	900
Run 9	2.5	70	2	546	30	3600

3.6 Summary of the Chapter

This chapter has discussed about the work plan and methodology to achieve our target including the materials selection, machine and equipment's used to process and fabricate the hybrid metal matrix composite and the various characterization techniques to be used for the study

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the detailed results of mechanical, metallurgical and tribological properties of the fabricated metal matrix composites. The effect of various influencing parameters of dry sliding wear and coefficient of friction on metal matrix composites and hybrid metal matrix composites are presented.

4.2 Hardness Results

The hardness test was carried out on Brinell hardness tester. Constant load of 100 gm with dwell time of 15 sec was applied on each sample. To get more precise result testing was carried out at 5 different points on each sample. The result of Brinell hardness test for aluminium alloy (ADC 12) and composites with different compositions of silicon carbide and alumina are shown below (Table 4.1 and Figure 4.1).

Table No 4.1 Brinell hardness of composites of different composition

S.N.	Sample Name	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	% increase
1	Al alloy ADC 12	85	83	88	87	83	85.2	-
2	Al+ 2.5% SiC	92	93	94	92	95	93.2	9.4
3	Al+5% SiC	100	103	99	101	103	101.2	18.8
4	Al+10% SiC	116	113	115	114	115	114.2	34.0
5	Al+5% SiC+5% Al ₂ O ₃	106	109	107	110	107	107.8	26.5

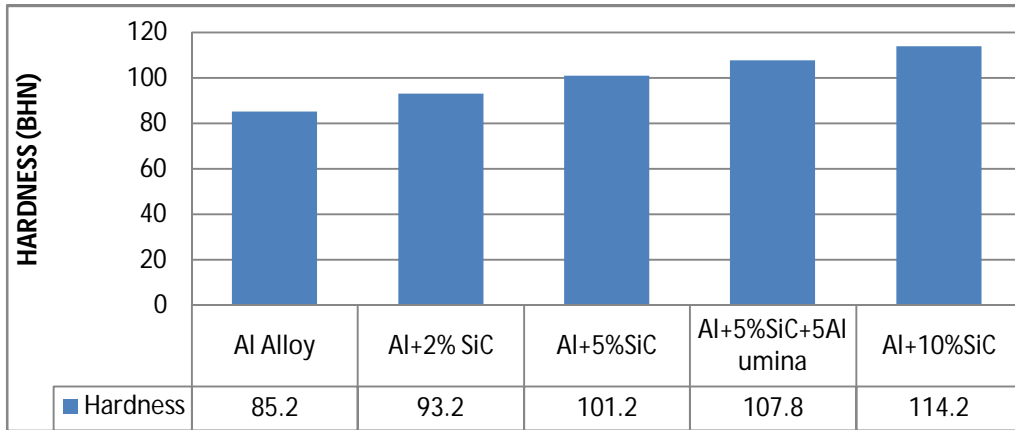


Figure 4.1 Hardness values of different composition

Referring to the base metal, we can see that the hardness value is well in agreement with the reported value. Figure 4.1 shows the hardness distribution in the base alloy and composite. The average hardness of fabricated composite is 34% higher than that of the aluminium alloy. From the above Table 4.1 the hardness results revealed that the hardness of aluminium composites increase with the increase in wt% of silicon carbide particles. This is due to the fact of uniform dispersion of hard silicon carbide in matrix (SEM images of the same will reveal the same) which increases the resistance to deformation. The hybrid composites reinforced with 5% silicon carbide and 5% alumina shows improved hardness as compared to 5% silicon carbide composites (by more than 10%). The combination of silicon carbide and alumina also increases the hardness of composites due to their property of hard ceramics in nature. The increase in wt% of these materials thus increases the overall hardness of the composite.

The possible strengthening mechanisms which may include: a) Work hardening may occur due to the strain misfit between the hard reinforcing particles and the plastic matrix, during casting, b) due to the fine dispersion of SiC/Al₂O₃ particles and good bonding to matrix alloy.

Also, there is a slight reduction of hardness when 10% particles in the hybrid form are embedded in the matrix than as compared to the single particle (SiC) addition. This is due to the fact that alumina is less hard than SiC. Thus, it is obvious fact that with increase in reinforced particles hardness of the composite can be improved. Similarly, microhardness results also displayed the similar trend in the variation of hardness for different composites, which indicates that the reinforcement is well dispersed in the matrix with our processing parameters.

4.3 Density of Composites

The density of composite can be calculated as

$$\rho_c = \rho_m V_m + \rho_p V_p$$

Where,

ρ_c = density of composite (gm/cm³)

ρ_m = density of matrix (gm/cm³)

V_m = volume fraction of matrix

ρ_p = density of particle (gm/cm³)

V_p = volume fraction of particle

$$V_m = \frac{\text{volume of matrix}}{\text{volume of composite}}$$

$$V_p = \frac{\text{volume of particle}}{\text{volume of composite}}$$

The Density of silicon carbide particulates (3.21 g/cm³) and alumina (3.98 g/cm³) is higher than the ADC (2.82 g/cm³) and hence the increase in silicon carbide and alumina content in Al matrix will increase the density of the composite. Density of the composites was also verified by measuring liquid volume displacement in graduated tube based on the Archimedes Principle.

Table 4.2 Density of composites

Composite	Density (gm/cm ³)
Al Alloy	2.82
Al + 2% SiC	2.83
Al + 5% SiC	2.85
Al + 10% SiC	2.87
Al + 5% SiC + 5% Al ₂ O ₃	2.90

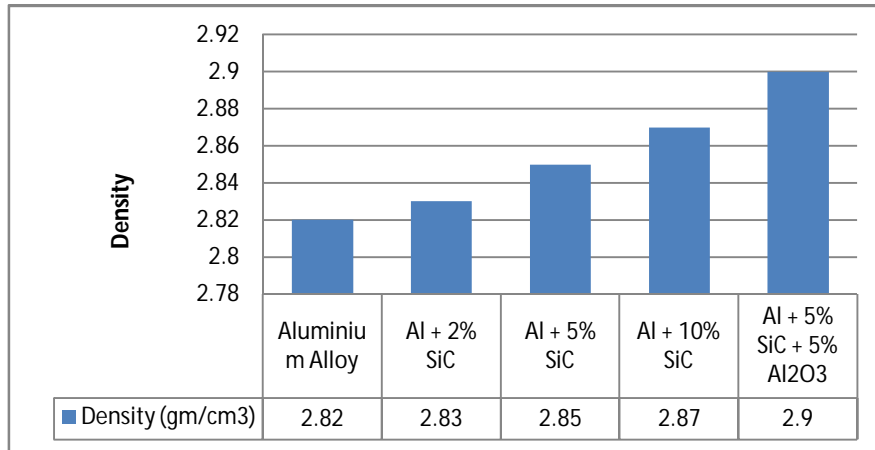


Figure 4.2 Density of Different composites

4.4 Microstructure and composition analysis

4.4.1 XRD Results

Figure 4.3 represent the XRD (X-Ray Diffraction) graph of Aluminium composites reinforced with different wt% of SiC and Al-SiC-Al₂O₃. XRD peaks identify the different phases present in the composites. The results of XRD reveal that in Al-SiC composite the presence of aluminium (in the largest peaks), the presence of silicon carbide particles (second largest peak). Composites with 2% SiC show the constituents Al, Si, SiC with maximum wt. fraction of aluminium. Results show that there is no oxygen reaction in the samples during the casting process because compounds of aluminium oxide are not found. Composites with 5% SiC show the constituents Al, SiC, SiC and SiO₂ with maximum wt. fraction of SiO₂. Composite with combine SiC-Al₂O₃ shows Al, SiO₂, Si and Al₂O₃ with maximum weight fraction of Al₂O₃. Results show that there is oxide formation in the samples during the casting process because compounds of aluminium oxide are not found. It means Al change into Al₂O₃ due to chemical reaction thus it become harder. Composites with 10% SiC show constituents Al, Si, SiC and SiO₂ with maximum weight fraction of Al.

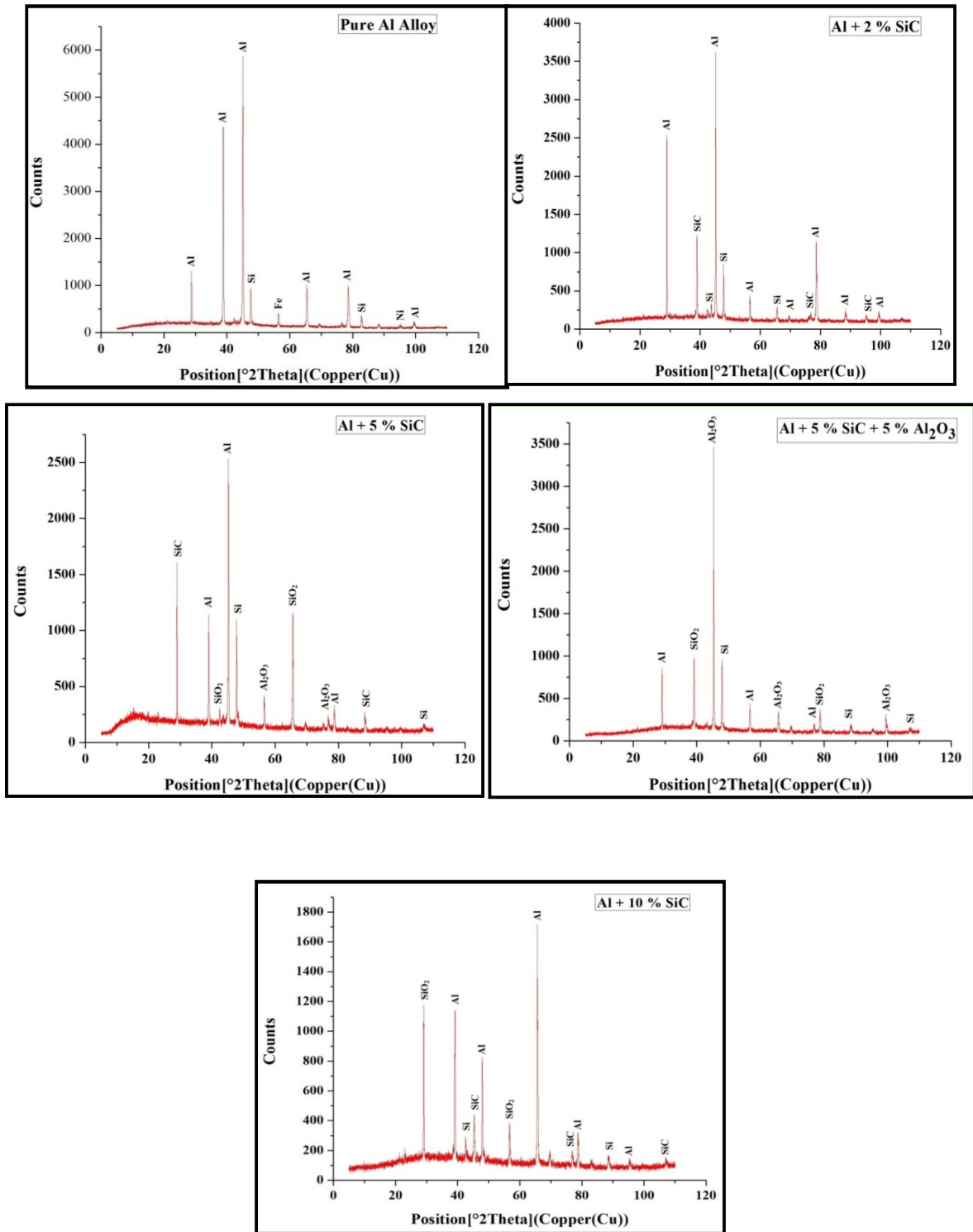


Figure 4.3 XRD spectra for a) Al Alloy, b) Al with 2% SiC, c) Al with 5% SiC, d) Al with 5% Al₂O₃+ 5% SiC and e) Al with 10% SiC

So overall results show that the increased in weight% reinforcement increased the constituent of that particle as compared to each other. 10% SiC composites show the constituent related to Si is more as compared to SiC of 2%, 5% composites.

4.4.2 SEM and Optical Micrographs of fabricated composites

Figure 4.4–4.8 represents the SEM (Scanning electron microscope) images of fabricated composites at different magnification.

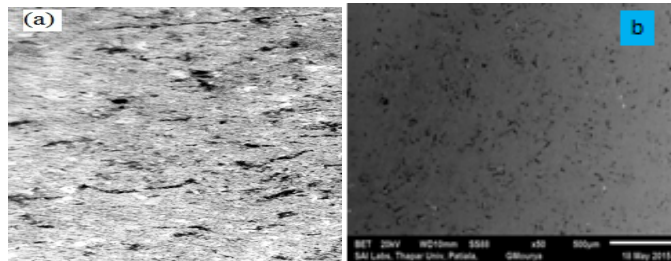


Figure 4.4 a) Optical, b) SEM micrographs of Aluminium Alloy ADC 12

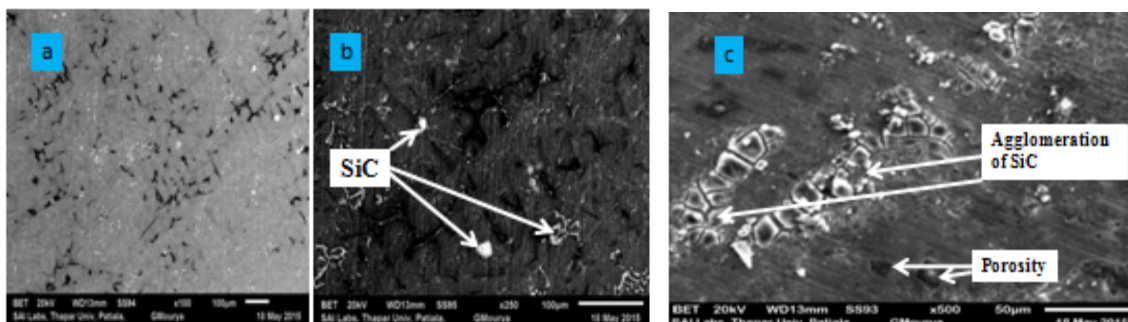


Figure 4.5 SEM micrographs of Aluminium ADC 12 with 2% SiC

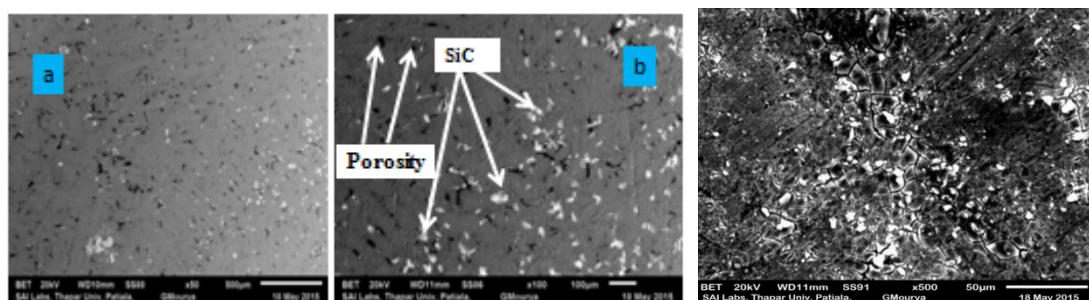


Figure 4.6 SEM micrographs of Aluminium ADC-12 with 5% SiC

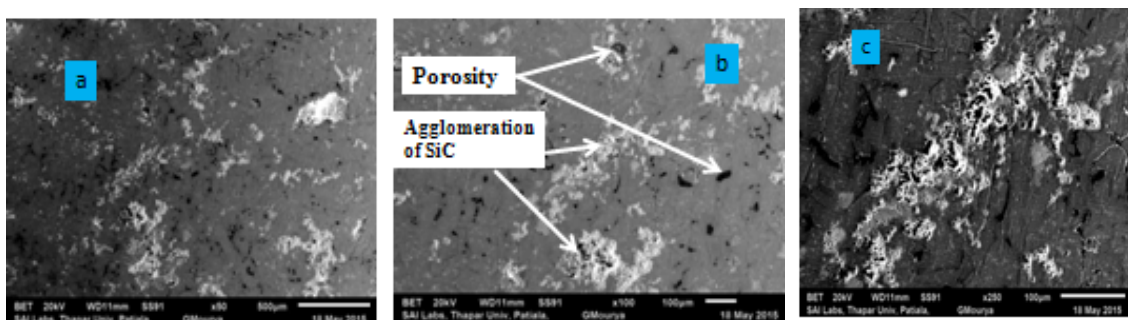


Figure 4.7 SEM micrographs of Aluminium ADC-12 with 10% SiC

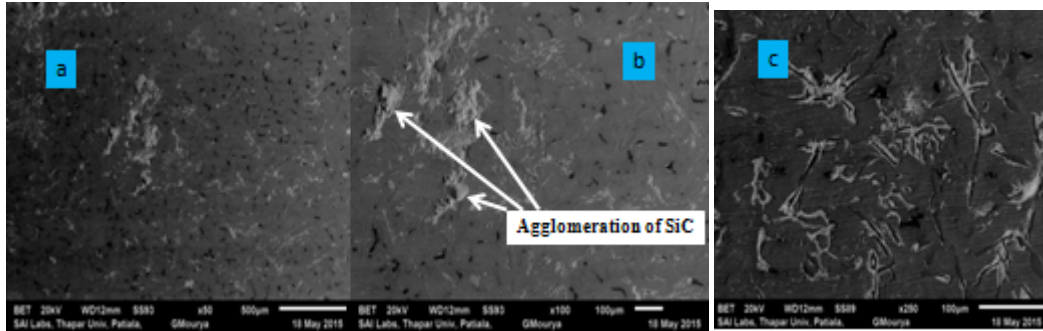


Figure 4.8 SEM micrographs of Aluminium ADC-12 with 5%SiC and 5% Al₂O₃

It is observed from the above figures that all reinforcement particles (SiC, Al₂O₃) are uniformly dispersed in the matrix which may be due to the effective stirring action and the use of appropriate process parameters. The micrographs reveal the shape and structure of the SiC particles. It is clearly observed in micrographs there is no cracks and little agglomeration found in the matrix when the ceramic concentration is low to medium. The reinforcement particles show homogeneous mixture because they were preheated before mixing in matrix. The uniform distribution of reinforcement improve mechanical properties of composite. However, at high particle concentration, agglomeration of particle starts as in for 10% SiC and Al₂O₃ particles and holes due to porosity, air or moisture in SiC particles.

4.5 Friction and Wear Analysis

Wear can be expressed in weight loss or volume loss where as wear rate can be expressed either in mm³/m, mm³/s, kg/hr, mm³/N-m, etc.

Volume loss can be calculated either from weight loss or from its geometric dimensions. Although, weight loss is subjected to the precision of the measurement whereas later method provides the more accurate values, still due to ease of calculation weight loss is quite often used for wear calculations.

$$\text{Volume loss (mm}^3\text{)} = \frac{\text{Mass Loss}}{\text{Density}} \times 1000, \text{ where Mass loss (gm), Density (gm/cm}^3\text{)}$$

Or

$$\text{Volume of wear} = (\pi \times (\text{Radius of pin point})^2 \times \text{Depth of penetration})$$

When wear rate is expressed in mm³/s, it can be calculated as

$$\text{Wear Rate (mm}^3/\text{s)} = \frac{\text{Volume loss}}{\text{Time}}, \text{ where volume loss (mm}^3\text{), Time (second)}$$

$$\text{Wear Rate (mm}^3/\text{m)} = \frac{\text{Volume loss}}{\text{Sliding distance}},$$

Where Sliding Distance = (2 x π x Radius of wear circle)

$$\text{Specific Wear Rate (mm}^3/\text{Nm)}, k = \frac{\text{Volume loss}}{\text{Load} \times \text{Sliding distance}} = V/F_n \cdot L,$$

Where V the wear volume, F_n the load, L the sliding distance and k the wear rate)

The wear rate expressed in $\text{mm}^3/(\text{Nm})$ usually based on Archard's abrasive wear model. In other word, if our experiments verify the linear model $V = k \cdot F_n \cdot L$ we should use the specific wear rate k expressed in $\text{mm}^3/(\text{Nm})$, because it takes into account the contact conditions. Otherwise, there is no reason to use the $\text{mm}^3/(\text{Nm})$ because the wear volume V won't follow a linear trend with $F_n L$.

Again, one should use caution and discretion for predicting wear behavior of a material by Archard's wear coefficient. This is applicable only in the cases where the wear mechanism is abrasive or predominantly abrasive. As we know in actual contact conditions, there is no single mechanism of wear but a complex combination of several mechanisms simultaneously in play, so, on the prediction of wear, use of specific wear rate should be used very carefully.

As a thumb rule, if operational parameters (load and sliding distance) are variables then we should use wear rate so that we can compare the tribological performance of the different materials used. But if operational conditions are not changing and only material is changing (its geometry, dimensions, chemical composition, etc) then wear volume must be used for comparing the tribological performance of the different materials used. In the present study since the operating conditions are changing, we will use wear rate for the comparative study with different composites. Also, use of specific wear rate will be investigating the validity of Archard model in the present contact conditions.

The wear and coefficient of frictions for the various conditions and compositions are shown in the table 4.3.

Table 4.3 Wear and friction for values for different operating conditions and composites

Composite	Run	Initial weight (gm)	final weight (gm)	mass loss (gm)	volume loss (mm ³)	wear rate X 10 ⁻⁴ (mm ³ /s)	Wear rate (mm ³ /m) X 10 ⁻³	Specific Wear rate (mm ³ /N-m) x10 ⁻⁴	COF
Al Alloy	1	6.3678	6.3659	0.0019	0.67	3.72	3.722	7.589	.332
	2	4.0243	4.0218	0.0025	0.87	4.83	0.967	1.971	.350
	3	5.0484	5.0441	0.0043	1.52	8.44	0.422	0.861	.290
	4	5.6588	5.6563	0.0025	0.89	4.94	4.944	3.360	.322
	5	4.9982	4.9944	0.0038	1.34	7.44	1.489	1.012	.315
	6	5.5667	5.5597	0.007	2.48	13.8	0.689	0.468	.301
	7	6.211	6.2078	0.0032	1.13	6.28	6.278	2.560	.317
	8	5.8369	5.8306	0.0063	2.23	12.4	2.478	1.010	.323
	9	5.7146	5.7036	0.011	3.9	21.7	1.083	0.442	.319
Al + 2% SiC	10	5.5499	5.5482	0.0017	0.6	3.33	3.333	6.796	.291
	11	5.8367	5.8344	0.0023	0.81	4.5	0.900	1.835	.301
	12	4.8356	4.8318	0.0038	1.34	7.44	0.372	0.759	.270
	13	5.1298	5.1274	0.0024	0.84	4.67	4.667	3.171	.263
	14	5.3579	5.3548	0.0031	1.1	6.11	1.222	0.831	.287
	15	5.0156	5.0098	0.0058	2.05	11.3	0.569	0.387	.279
	16	5.7077	5.7048	0.0029	1.02	5.67	5.667	2.311	.281
	17	4.964	4.9585	0.0055	1.94	10.8	2.156	0.879	.276
	18	4.8663	4.7653	0.0101	3.57	19.8	0.992	0.404	.292
Al + 5% SiC	19	5.8375	5.8362	0.0013	0.46	2.56	2.556	5.210	.239
	20	4.3687	4.3666	0.0021	0.74	4.11	0.822	1.676	.252
	21	4.9755	4.972	0.0035	1.23	6.83	0.342	0.697	.261
	22	5.6358	5.6339	0.0019	0.67	3.72	3.722	2.530	.243

	23	5.4159	5.4129	0.003	1.05	5.83	1.167	0.793	.267
	24	5.9112	5.9056	0.0056	1.96	10.9	0.544	0.370	.247
	25	5.3554	5.5512	0.0028	0.98	5.44	5.444	2.220	.257
	26	5.5897	5.5845	0.0052	1.82	10.1	2.022	0.825	.249
	27	4.3695	4.3614	0.0081	2.84	15.8	0.789	0.322	.269
Al + 10% SiC	28	5.5263	5.5257	0.0007	0.24	1.33	1.889	3.851	.158
	29	5.0084	5.0069	0.0015	0.52	2.89	0.733	1.495	.183
	30	4.9252	4.9224	0.0028	0.98	5.44	0.306	0.623	.140
	31	5.1126	5.1113	0.0013	0.45	2.5	2.667	1.812	.183
	32	5.4687	5.4661	0.0026	0.91	5.06	1.111	0.755	.136
	33	5.0019	4.9981	0.0038	1.32	7.33	0.508	0.345	.128
	34	5.7785	5.776	0.0025	0.87	4.83	5.000	2.039	.138
	35	5.3571	5.3536	0.0035	1.22	6.68	1.956	0.797	.159
	36	5.6621	5.655	0.0071	2.47	13.7	0.700	0.285	.144
Al + 5% SiC + 5% Al ₂ O ₃	37	6.285	6.284	0.001	0.34	1.89	1.333	2.718	.203
	38	5.3858	4.3851	0.0019	0.66	3.67	0.578	1.178	.210
	39	4.3018	3.2725	0.0032	1.1	6.11	0.272	0.555	.197
	40	5.3358	5.3344	0.0014	0.48	2.67	2.500	1.699	.208
	41	5.7489	5.746	0.0029	1	5.56	1.011	0.687	.203
	42	5.3549	5.3496	0.0053	1.83	10.2	0.367	0.249	.211
	43	5.2725	5.2699	0.0026	0.9	5	4.833	1.971	.205
	44	4.3851	4.38	0.0051	1.76	9.78	1.356	0.553	.199
	45	5.5275	5.5202	0.0073	2.52	14	0.686	0.280	.209

4.5.1 Comparison of wear for Al alloy and composites with different SiC wt%

- At constant load:

Figure 4.9 shows the variation of wear rate for different composites with various SiC concentrations. Time remain constant as 30 minute for every run.

It is observed that in pure Al alloy there is a large severe plastic deformation as compare to the composites. The worn surface indicates the existence of detachment and abrasion of material near the contacting surface. The main reasons of the severe plastic deformation are full contact between the pairs, low hardness and more ploughing action on Al. with increase in SiC content, the hardness of composite is increased and subsequently due to the uniform distribution it increases the wear resistance.

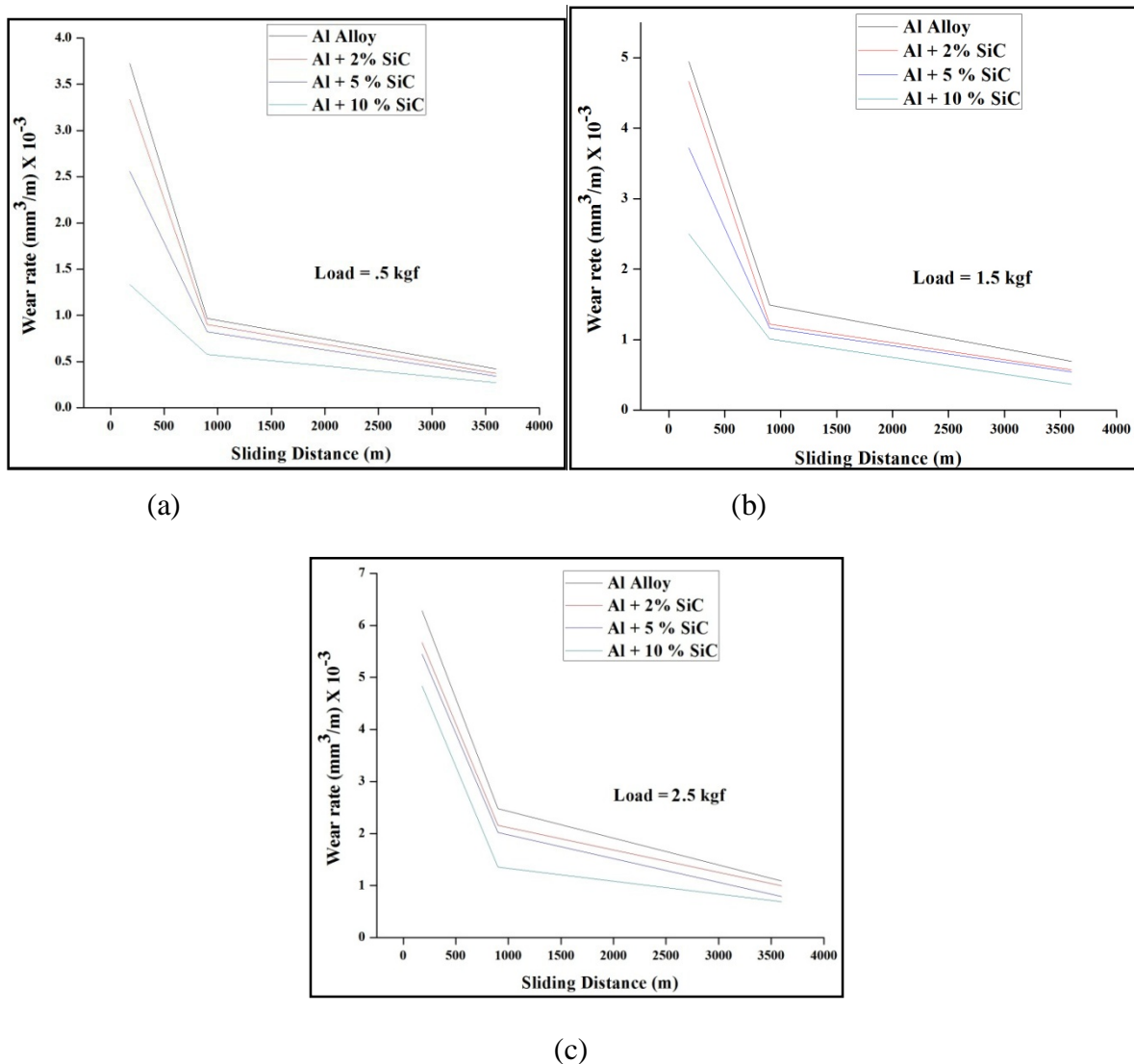
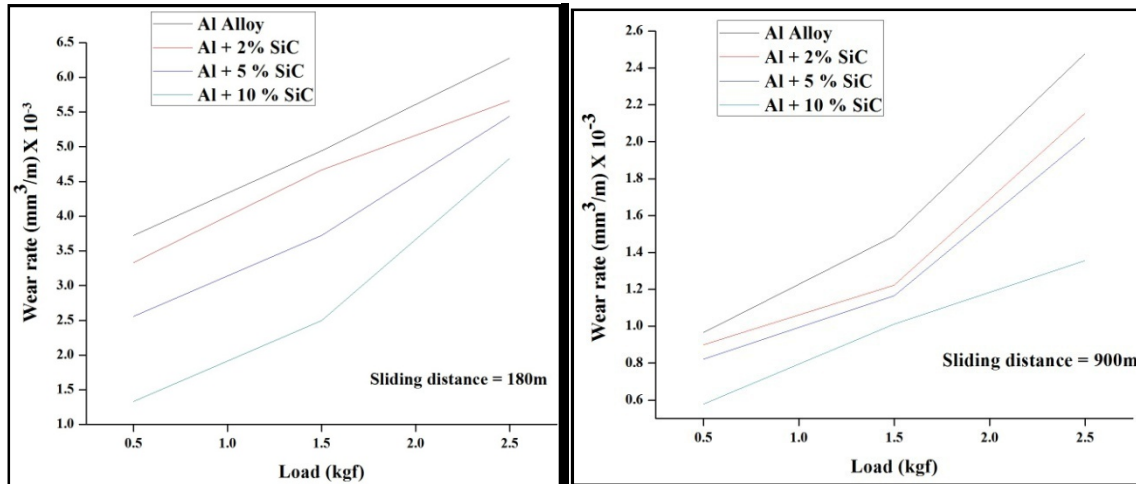


Figure 4.9 Wear rate at Figure a) 0.5 kgf load, b) 1.5 kgf c) 2.5 kgf load

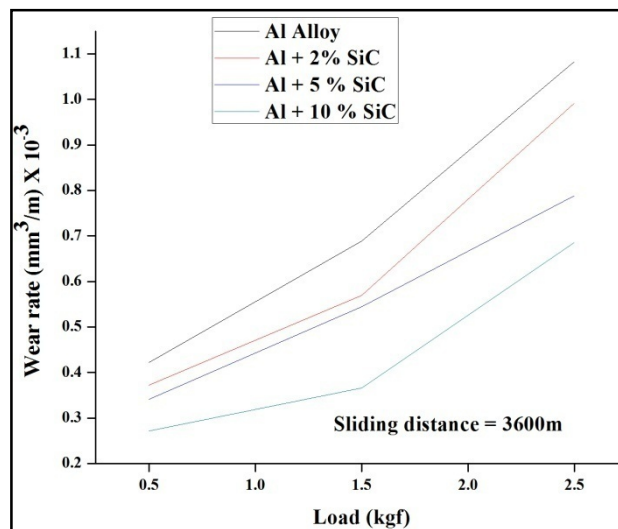
It is also observed that with increase in sliding distance wear rate decreases for all the loads. This is attributed to the oxide layer formation in the contact. The hard layer acts as protective layer and prevents further wear until it again breaks, thus decreasing the wear rate.

- **At constant sliding distance**



(a)

(b)



(c)

Figure 4.10 Wear rate at sliding distance (a) 180 m, (b) 900m and (c) 3600m

From figure 4.10, it can be observed that wear rate increase with increasing load at all sliding distances. The reason is that when load increases then the deformation and contact of area between pin and disk increase.

4.5.2 Comparison of wear for Al alloy, SiC Composite and Hybrid composites

- At constant load

Figure 4.11 represents the wear rate with respect to load and sliding distance of aluminium with 5 wt% of SiC particles and combined 5wt% SiC and Al₂O₃. Time remain constant as 30 minute for every run.

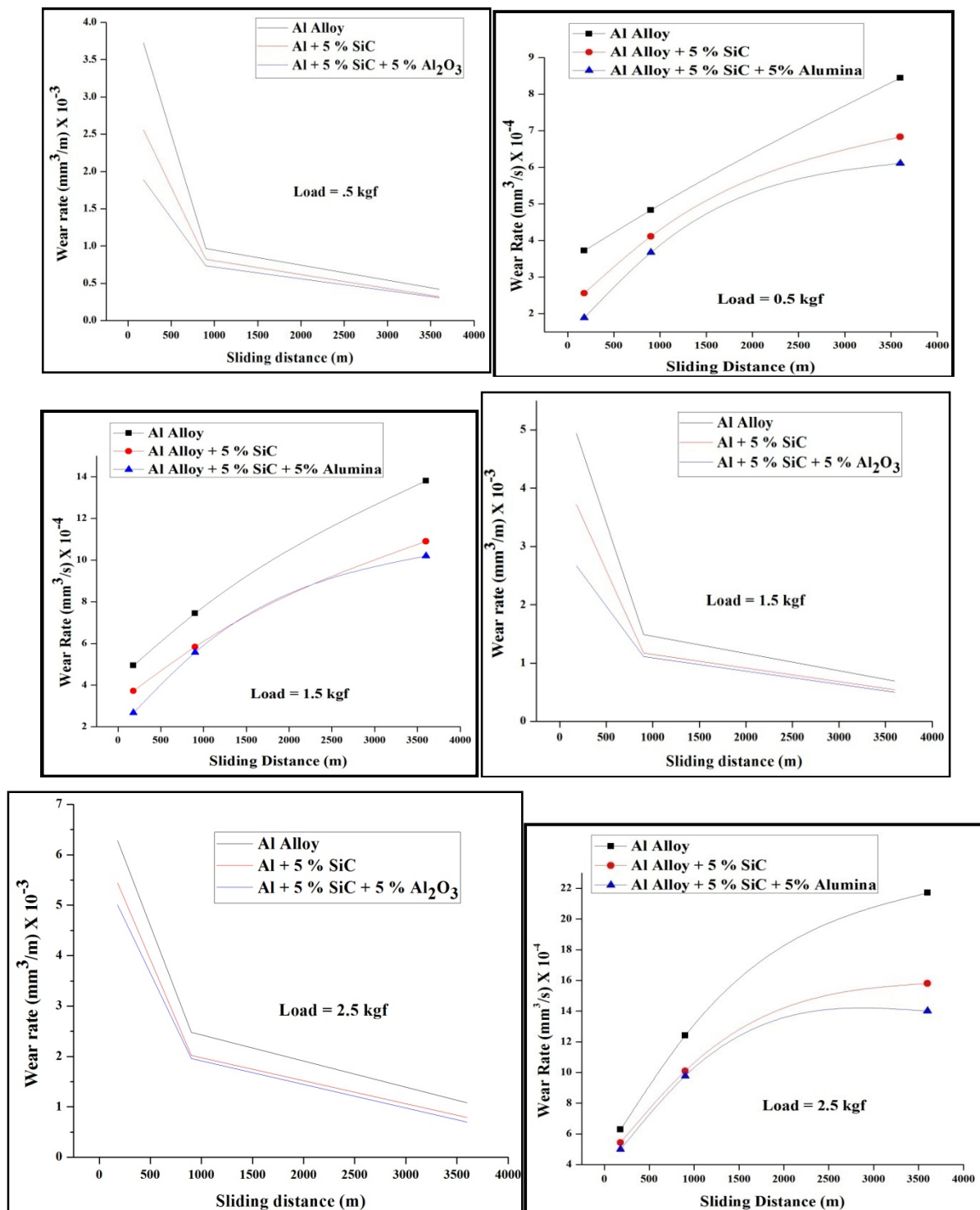


Figure 4.11 Wear rate at (a) 1.5 kgf load, (b) 2.5 kgf load and (c) 0.5 kgf load

- At constant sliding distance

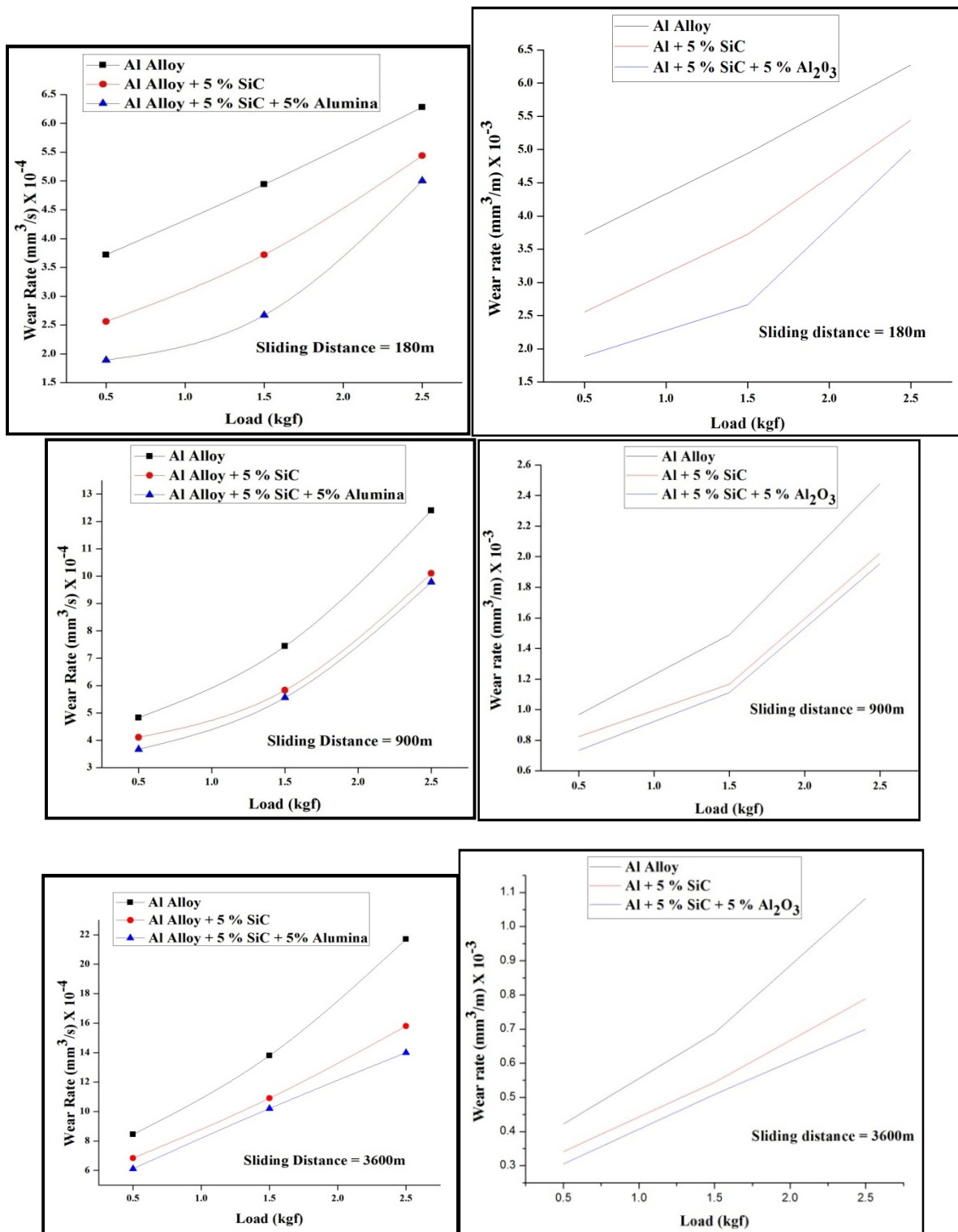


Figure 4.12 Wear rate at sliding distance (a) 180m, (b) 900 m and (c) 3600 m

From figures it can be observed that wear rate increase with increasing load at constant sliding distance and decreases with increasing sliding distance at a constant load. The reason is explained for the previous set of experiments. However, here, Aluminium-SiC-Al₂O₃

hybrid composites exhibits the lowest wear rate as compared to same wt% of SiC particles with aluminium. The reason is that in this fabricated hybrid composites SiC and Al₂O₃ show good interlocking with aluminium and each other. So the hardness as well as wear resistance of the hybrid composite is increased as compares to single reinforced matrix. Also, we have seen already that in addition to its hard nature, it also is having high oxide content which forms tribolayer between the contact.

4.5.3 Wear behaviour at constant load and speed

Here, we will compare both the wear rate and specific wear rate proposed by Archard. From the figure it is evident that both the wear rate and specific wear rate decreases with hybridization of the composite. As expected, aluminium is characterized by high wear rate and specific wear rate. Hybrid composite is displaying superior wear characteristics than the single particle reinforced composite, despite of being less harder than their counterpart.

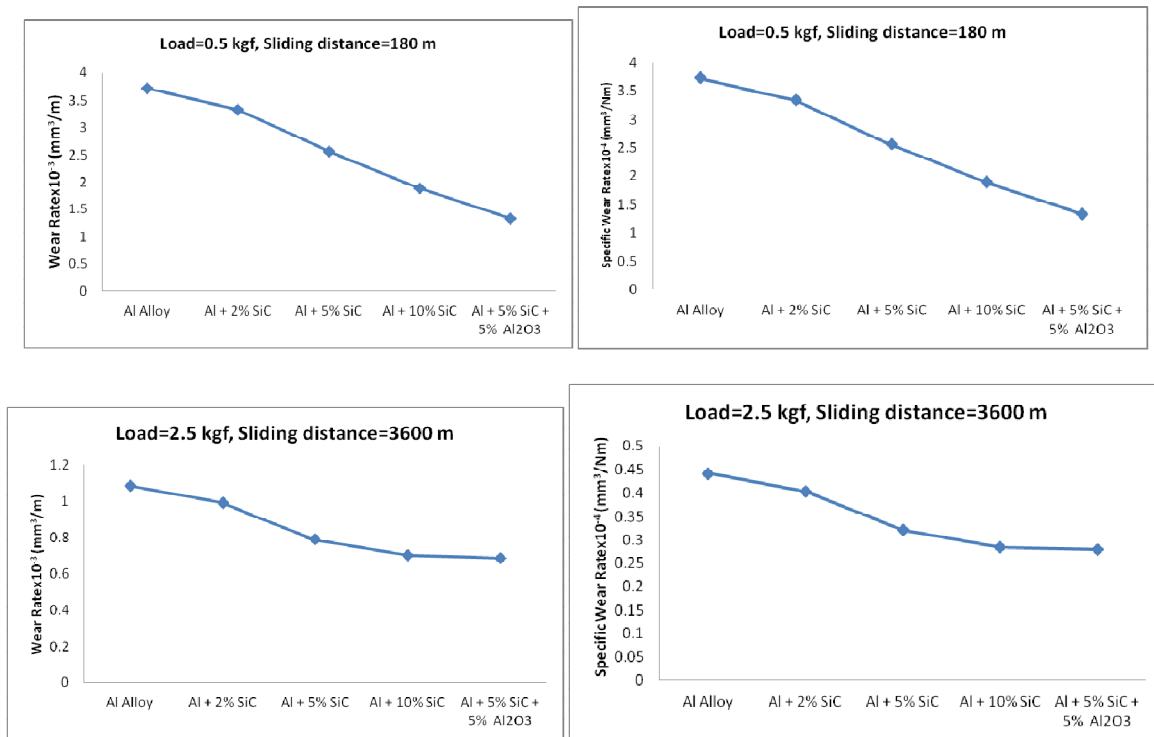


Figure 4.13 Wear rate of different composition at constant load and sliding distance

4.5.4 Micrographs of worn out surfaces

Following micrographs obtained from optical microscope depicts the wear mechanism already explained in the previous sections for base material and different composites.

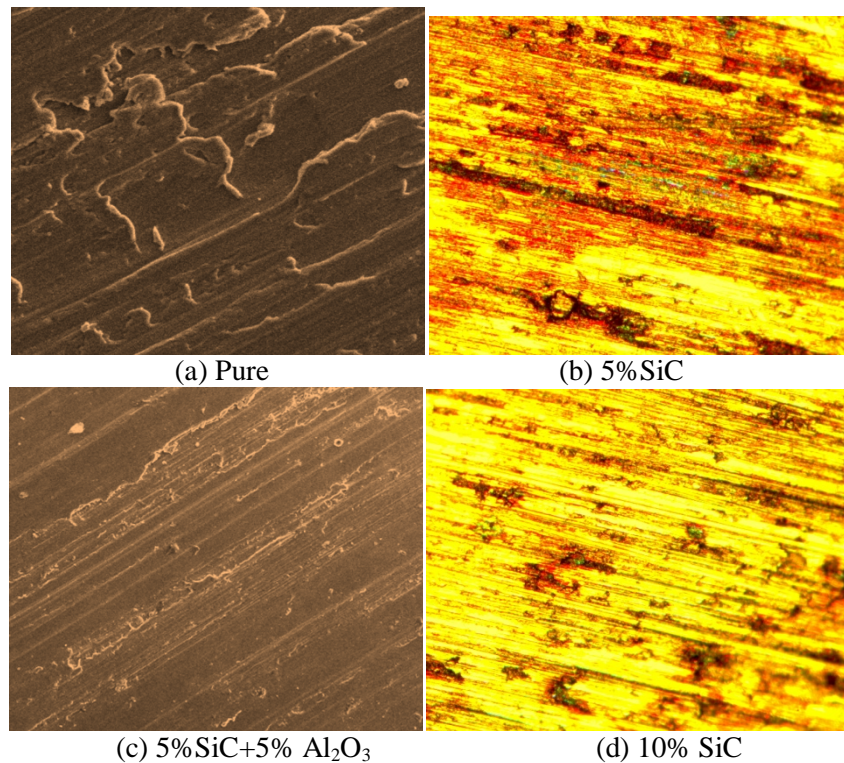


Figure 4.14 Optical Micrographs of wear tracks for different composites at 2.5 kgf load and 3600 m sliding distance

4.5.5 Comparison of coefficient of friction

Figures 4.16-4.17 show the friction behaviours of different composites. As expected, due to the reasons discussed in the wear mechanism, in this case also hybrid composites shows better friction response than the SiC composite of same wt%. Also, it is seen that it should be further improved for dry sliding condition as SiC itself can provide lower coefficient of friction by increasing the particle concentration.

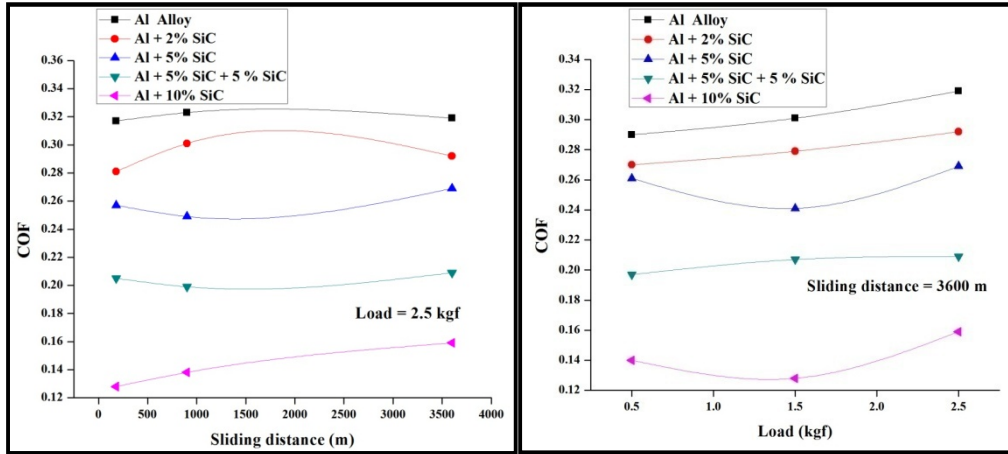


Figure 4.15 COF of different composites at (a) load of 2.5 Kgf and (b) sliding distance of 3600m

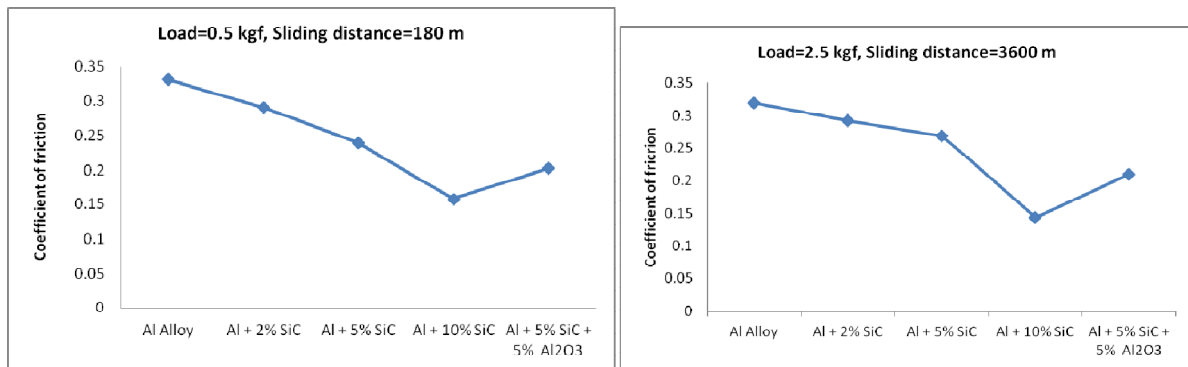


Figure 4.16 COF of different composites at (a) load of 0.5 Kgf, sliding distance of 180 m and (b) load of 2.5 kgf, sliding distance of 3600m

The result revealed that load and sliding distance have little influence on COF. It remains about constant for single composition either increasing load or sliding distance. at low but variable load for a fixed sliding speed the nature remains similar until frictional heat is not considerable and if load is higher than the friction heat will contribute to increase in friction. The COF affected by weight percentage of reinforcement. The COF decreases with the increasing weight percentage of reinforcement. It is due to the fact that due to the increase in the hardness of composites with increasing weight percentage of SiC particles, there is less ploughing and adhesive components in the steel-composite interactions.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

In the previous chapters, the details of preparatory research to finalize the different process parameters and their working range for main experimentation and main research work have been discussed. After analyzing the results obtained from present studies the overall conclusions made are following:-

- Composite reinforced with combine SiC/Al₂O₃ show superior hardness as compare to composite with same weight % SiC particles.
- Uniformly distribution of reinforcement show improved hardness of composites
- Stir casting process parameters also influence the distribution of particles in the matrix. These process parameters should be optimized while casting the composites. In the present study these parameters are optimized through initial trials runs for composites and finally it is observed that the homogeneous mixture of reinforcement of SiC/ Al₂O₃ in the matrix, which subsequently improved the desired properties. SEM result supports this fact of uniform distribution of particles in the matrix.
- It is obvious from the present work that the hardness of composites is increased with increasing the weight percentage of reinforcement. This is attributed to the strengthening mechanisms such as work hardening due to the strain misfit between the hard reinforcing particles and the plastic matrix, during casting and due to the fine dispersion of SiC/Al₂O₃ particles and good bonding to matrix alloy.
- It is observed that wear rate decreases with increasing hardness of composites, increase with increase load at constant sliding distances and decrease with increase sliding distance at constant load.
- XRD result shows the presence of different phases of Al, Si and SiC and presence of oxide phases such as Al₂O₃ and SiO₂.

- Wear studies reveal the fact that as the weight % of ceramic particles are increased in the composite, abrasive wear mechanism plays the predominant role in the dry sliding conditions.
- Friction studies revealed that the presence of oxide layer reduces the coefficient of friction. But since this layer at high load is make and break in nature, so the reduction is relatively not so significant in dry sliding condition. Also, as the relative hardness difference between the tribocontacts is reduced by increasing the reinforcement content there is decrease in the coefficient of friction.

5.2 Future Scope of work

In addition to present work, further works can be carried out on following issues:

- Heat treatment can be done to improve the fabricated Metal Matrix Composites and this requires further studies in that direction.
- Properties of fabricated composites can be further enhanced by adding suitable nano particles.
- Effect of nano size solid lubricant particulates of Gr and MoS₂ in hybrid metal matrix composite
- Tribology study can be made more conclusive by studying the friction and wear behavior in the wet condition and observing the influence of tribofilm.

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