Tribological Behavior of Hybrid Al6063 MMCs Reinforced with Gr/MoS_2 and SiC Particulates

A Dissertation Submitted
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by

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CERTIFICATE

I hereby declare that the thesis entitled **"Tribological Behavior of Hybrid Al6063 MMCs Reinforced with Gr/MoS_2 and SiC Particulates"** is an authentic record of my work 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 July, 2013 to 15 July, 2015. No part of 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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Abstract

Aluminium metal matrix composites are a class of advanced materials which have been developed for weight-critical applications in the aerospace and automotive industries. The present investigation aims to establish the Tribological behavior of Al 6063 hybrid metal matrix composite reinforced with hard SiC and lamellar structure particulates (Gr and MoS_2). Composites were fabricated by stir casting process and studied using a pin-on- disk apparatus under dry sliding conditions. The effect of various input parameters (composition, normal load, sliding distance, sliding velocity) on output responses (wear and coefficient of friction) have been analyzed using Analysis of Variance (ANOVA). The worn surfaces of the samples were analyzed using a Scanning Electron Microscope (SEM). The samples have been characterized by X-ray diffraction (XRD) to analyze the various elements present in the hybrid composite. Main effect plot and interaction plot has been used to determine the optimal design for each output response.

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Greek Symbols

μ	≡	Coefficient of Friction
ρ	≡	Density

Acronyms and Abbreviations

AMCs	≡	Aluminium Matrix Composites
ASTM	≡	American Society for Testing and Materials
ANOVA	≡	Analysis of Variance
DOE	≡	Design of Experiment
DOF	≡	Degree of Freedom
MMCs	≡	Metal Matrix Composites
SEM	≡	Scanning Electron Microscope
SS	≡	Sum of Squares
XRD	≡	X-Ray Diffraction
NS	≡	Not Significant
Al	≡	Aluminium
B_4C	≡	Boron Carbide
Cr	≡	Chromium
Cu	≡	Copper
Fe	≡	Iron
F_N	≡	Normal Force
F_F	≡	Friction Force
Gr	≡	Graphite
Mg	≡	Magnesium
Mn	≡	Manganese
MoS_2	≡	Molybdenum Disulphide

CHAPATER 1

INTRODUCTION

1.1 Introduction

With the ever increasing demands and sophistication of technology updates researchers and designers are constantly exploring the advanced and smart materials, light weighted and high-performance materials for its end use such as for the purpose of automotive and aerospace industries. It is too difficult to achieve these properties in a conventional material. Aluminum metal-matrix composites consists many advantages over monolithic materials, including high strength to weight ratio, high wear resistance, low cost, higher thermal conductivity, lower coefficient of thermal expansion and high toughness etc. and are used in structural application along with the aircraft, space, defense and automotive industries [Hunt, 1990].

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. Self-lubricated materials consists a lubricant constituent that can be released automatically during the wear process. Now a days, one of the most frequently used solid lubricant materials are Graphite and Molybdenum disulphide [Rohatgi et al., 1992].

Friction and wear is induced when the two bodies are in contact (sliding or rolling) with each other. The most of the energy of the system is dissipated by the cause of friction, and wear is responsible for the material failure. So it is very important to select an appropriate material for mating bodies. Solid and liquid lubricants are used to control the friction and wear. For the material design it is very important to understand a deeply knowledge of these two factor wear and friction, to select the appropriate material. Although, graphite is most widely used solid lubricant, one of the major disadvantage of using graphite as a solid lubricant material is to loss in strength of the whole composite.

Metal Matrix composites, now a days, are getting much attention for the enhancement of the properties of the base metals. Aluminium is the third most plentiful element on the Earth's crust, only oxygen and silicon exist in greater quantities [Smith, 1993]. Aluminium is used extensively in the modern world due to its corrosion resistance, high strength to weight density, thermal expansion, low melting temperature etc., as compared to other commonly used metals. Its application covers the variety of domains, like in the home appliances, transport, industry and commerce for their specific useful properties.

In the present study, hybrid Al6063-based metal matrix composite reinforced with graphite/ Molybdenum disulphide as a solid lubricant and SiC particle as a hard particulate, has been fabricated by stir casting process. The Tribological behavior is studied on a pin on disc apparatus. The major advantage of the Al/SiC/graphite hybrid composite is that it overcomes the problem of loss of strength due to graphite particles because hard reinforced SiC particles provides a strength to the composite and yet they are self-lubricating materials.

1.2 Composite Materials

A composite material is a material that is fabricated by artificially and which is composed of a suitably arranged mixture or combination of two or more Nano, micro, or macro constituents with an interface separating them that differ in form and chemical composition and are essentially insoluble in each other [Smith and Hashemi, 2008]. In other words, composite materials are engineered materials made from two or more constituent materials with significantly different physical, chemical or mechanical properties which remain separate and dissimilar on a macroscopic level within the finished structure [Callister, 2000]. If suitably designed these materials provide a better combination of properties as compared to conventional material. They possess at least one property which cannot be achieved by the single constituent.

The properties of composites are mainly dependent upon the properties of their constituent materials, their distribution, interfacial bonding and the interaction among them. Characteristics of a composites are not only depend upon the nature of the constituent materials but also influence the geometry of the reinforcement such as shape, size and uniformly distribution in the matrix material. The orientation, structure properties and weight/volume percentage of matrix affect the properties of the composite. The shape of the reinforced phase (which may be cuboidal, spheroidal or irregular), the size (micro, nano etc) and size volume fraction determine the interfacial area, which plays a significant role in determining the interaction and interfacial bonding between the reinforcement and the matrix material.

A composite material is composed of reinforcement and matrix. The primary phase, having a continuous character, is called matrix. Generally matrix are ductile in nature and it holds the reinforced phase in desired shape. The main functions of matrix is to bear the load and transfers it to the secondary phase or reinforcement. It binds the reinforcement and protects it from mechanical, chemical and handling damage. It also separates the individual reinforcement and to form the desired shape. The second phase is imbedded or dispersed in the matrix in a discontinuous form. A phase surrounds the matrix phase called dispersed phase or secondary phase. Generally dispersed phase is stiffer and stronger than the matrix phase, therefore sometimes it is called reinforcing phase. Reinforcement enhances the overall mechanical properties of the matrix.

1.2.1 Metal Matrix Composites (MMCs)

A metal matrix composite is composite material composed at least two distinct phases. One is a metal (aluminium, magnesium, copper etc) and the other material can be a different metal or another material, such as a ceramic (SiC, Al_2O_3 etc) or organic compound. When at least three different materials are present, it is called hybrid composite. MMCs have several advantages over the conventional material such as high thermal and electrical conductivity, good chemical resistance against an environment, high impact strength, erosion resistance etc. In addition, MMCs shows higher strength and stiffness as compared to the matrix alloy.

Application of composite can be grouped according to their need in different fields like as in home appliances, automobile industry, aerospace, defense, commercial and industrial area etc. Metal matrix composites play an important role in Aerospace applications due to their high strength to weight ratio. This is due to the quest for weight reduction for improved performance and payload capabilities combined with high value placed on weight savings. Examples of aerospace application are aircraft structure, aero engine, space structure and other space applications. In an automotive field, the desired properties of an automotive engineer include increased stiffness, low thermal expansion, corrosion resistance, wear resistance, and improved cycle fatigue resistance etc. Weight saving is also important in automotive applications for achieve a high performance improvements at a lower cost. Examples for automotive applications are engines, brake system, driveshaft and other automotive applications. In commercial and industrial sector, improved performance is highly valued. As a result many of materials that gain favor in aerospace industry market are also applied in this sector also. Examples for commercial and industrial sector are recreational, computer hard disk drives and other industrial applications. Among the various MMCs, aluminium matrix composites are widely used in diverse fields as automotive, aerospace, electronics, industrial equipment and sporting goods industries for their high strength to weight ratio.

The present work is concerned with the metal matrix hybrid composite, in which aluminium 6063 alloy is matrix and other constituents are ceramics (SiC) and inorganic compound (MoS_2). The major advantages of AMMCs as compared to unreinforced materials are high strength, more stiffness, reduced weight, high resistance of wear and lower coefficient of thermal expansion etc.

1.2.2 Particulate reinforcement

AMMCs can be classified into mainly three categories depend upon the type of reinforcement like as Particle Reinforced, Short fibre-reinforced, Long fibre-reinforced as shown in Figure 1.1

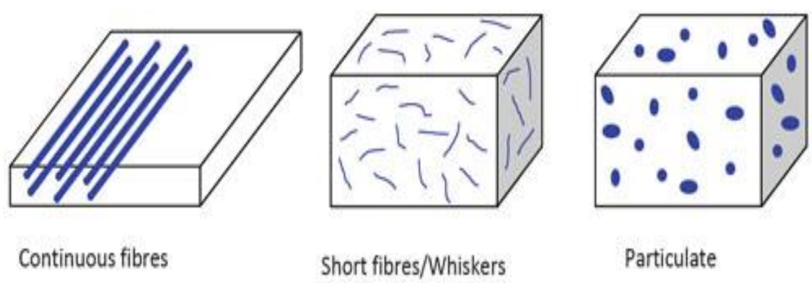

Figure 1.1: Different types of reinforcement.

The composite with reinforcement in particle form is called a particulate composite. Particulate reinforcements are those which are in the form of particles having a size of few microns in diameter. The particles mainly increase the strength and decrease the ductility of matrix materials. In particulate reinforcement composites, the load is shared by both particles and matrix materials. However, the load shared by the particles is much larger as compare to the matrix material. In a present work silicon carbide, graphite and molybdenum disulphide particulates are reinforced in the aluminium metal matrix and to fabricate a hybrid composite.

1.2.3 Liquid State Fabrication of MMCs

Liquid state fabrication is a common technique which is used to fabricate a Metal Matrix Composites in which the dispersed phase is mixed with the matrix in liquid form and then allowed to solidify it. It possess a high range of mechanical properties of the composite, a strong interfacial bonding (wetting) between the secondary (dispersed phase) should be obtained. Wetting is the commonly problem in liquid state fabrication. It can be improved with provide a coating on the dispersed phase (reinforcement). Coating is used to reduce the interfacial energy and to prevent the chemical reaction between the reinforcement and the metal matrix. In present work magnesium ribbons are used to improve the wettability of the matrix material.

1.2.4 Fabrication of Composite by Stir casting process

In the present work, stir casting process as shown in Figure 1.2 is used to fabricate the hybrid metal matrix composite. Stir Casting is the simple and the most economical process of liquid state fabrication. The liquid composite material is then cast in the sand casting mold and allow to solidify it. The appropriate temperature range is maintained to mixing or avoid some chemical reaction between the reinforcement and matrix material. The temperature range and stirring time is the most critical parameter in stir casting process because it influence the structure and the properties of the composite.

In the present work stir casting process is used where the reinforcement particulates (SiC, Gr, MoS_2) are mixed in the liquid state of matrix phase (Al6063 alloy) by means of mechanical stirring action. This method is used due to its inherent advantages as mentioned below. Stir casting process is relatively simple and low cost. Distribution of reinforced phase can be improved if the process parameters are optimized, like as reinforcement is mixed in the matrix is in semi-solid condition, use of optimum speed of the stirrer to form a vortex, to reduce the surface tension of the matrix, to improve its wettability etc. The method of mixing reinforcement phase in a semi-solid state is called Rheocasting. It has been found that the mixing of the reinforcement particles are better at high viscosity of the matrix, as compare to the low viscosity.

However, Stir Casting is characterized by few limitations which should be given due considerations while processing. In a stir casting process it is very important to pay an attention in the uniform dispersion of the reinforcement phase in the matrix. In a stir casting process, sometime the particles are often tend to form agglomerates, due to the difference in density of reinforcement and matrix which can be mixed completely by high speed stirring. The content of the reinforcement phase should not more than 30% by volume. However, the access of the environmental gases into the melt must be absolutely avoided, because atmospheric gases are react with molten metal and to form oxides and unwanted porosities, and due to this strength of the material is affected. To avoid the reaction between the atmospheric gas and molten metal, an envelope of inert gas can be provide to their surroundings.

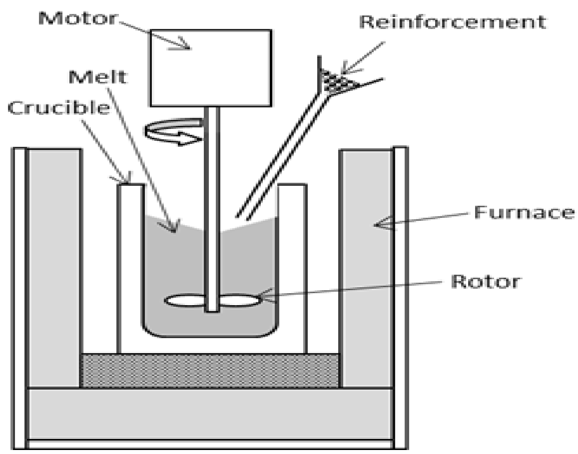

Figure 1.2: Stir casting process [www.substech...]

1.3 Concept of Tribology

The word Tribology is derived from the Greek word ‘tribos’ which means rubbing or sliding. Tribology deals with the friction, wear and lubrication of interacting surfaces in relative motion. Tribology is an interdisciplinary science which involves in various fields like as mechanical engineering, fluid dynamics, chemistry and chemical engineering, material science and other related branches. There is no mechanism, no machine and no equipment that is not affected by wear and friction problem. Approximately 70% mechanical components during their function are failed due to wear and friction problems. One third of world’s energy resources are wasted due to friction in one form or the other and then most of these result in wear. So, it is of prime importance to study the wear behavior of materials.

1.4 Wear

Wear is a process of progressive loss of a material from operating surfaces of solids, subject to contact and sliding. The detached material forms a loose wear debris. When the material is removed from one or both of two solid surfaces in relative motion (sliding, rolling or impact) is termed as wear. Wear takes place either by mechanically abrasion action, chemical reaction, or by combination of both processes and is generally increase at very fast rate by the increment of temperature. It is very important to understand the wear behavior in aluminium metal matrix composite to prevent the failure of the useful machine components in automotive applications. Wear mechanism can be classified into a number of categories as mentioned below.

1.4.1 Abrasive Wear

Abrasive wear takes place when material is removed from one surface by the harder material, and leaving particles between the two surfaces. It is also called a scratching and depends up on the severity of wear. Abrasive wear further classified into two categories; Two body abrasion and Three body abrasion. In two body abrasion, one surface is harder than the other and harder surface remove the material on the softer surface shown in Figure 1.3 Machining, cutting, and grinding operations are the example of two body abrasion. In three body abrasion process a third body, generally a small unwanted particle of grit or abrasive, lodges between the two softer rubbing surfaces, abrades one or both of the surfaces.

In a micro scale, the abrasive wear process is due to the contact of asperities of the harder surface press into the softer surface, and the plastic flow of the softer surface takes place around the harder asperities. This condition is also known as micro ploughing, micro cracking, and micro cutting. Abrasive wear can be reduced by providing a hydrodynamic or elasto hydrodynamic lubricants between the contact surface at various film thicknesses to separate the surfaces or prevent the high degree of metal to metal contact.

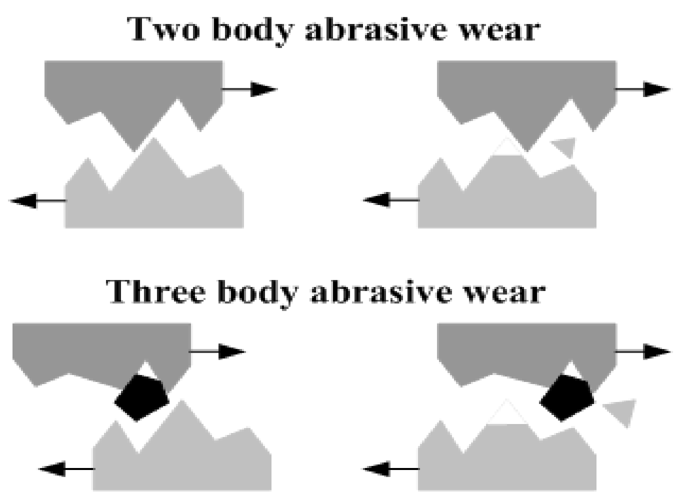

Figure 1.3: Abrasive wear [www.substech...]

1.4.2 Erosive Wear

The bombardment of solid particles or small drops of liquid or gas as shown in Figure 1.4 often cause an erosion of materials and components. In the case of erosion, a solid hard particles moving with a velocity, impacts on the solid surface at a certain angle, then slide along the surface and finally bounce off, cause an erosive wear. An especial attention is required on impact of abrasive hard particles on the surface, in the field of aerospace industry to prevent the failure of a useful component. [Wang et al., 1992]. The erosion of jet engines and of helicopter blades are some examples of erosive wear. Due to the impingement of the abrasive particles on solid surface creates a cut scratches grooves, and produce wear debris. A material is removed on a soft surface by the impact of hard irregular shape particles results an erosive wear. The volume of the removed material on the soft surface is directly proportional to a high velocity or power of the abrasive.

Material removal or surface damages also occur in liquid state due to the phenomenon of cavitation. Cavitation takes place in fluid flow systems due to the difference in the pressure or a negative pressure is exists in that region. Cavitation damage generally occurs in such fluid-handling machines such as marine propellers, hydrofoils, dam slipways, gates, and all other hydraulic turbines, according to [Bhushan and Gupta 1991]. Due to the cavitation erosion fine pin holes are generate on the surface.

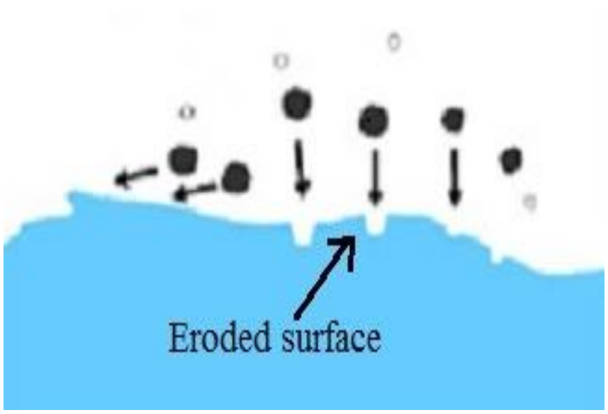

Figure 1.4: Erosive wear [www.substech...]

1.4.3 Adhesive Wear

Adhesive wear occurs when two nominally flat and similar solid surfaces are in sliding contact. Due to the contact at the interface between the two surfaces asperities come with contact and bonding takes place due to adhesion shown in Figure 1.5. According to [Bhushan and Gupta 1991] when a normal load is increased, the local pressure at the surrounding of asperities are become very high. Often the value of contact stress reaches yield stress and due to this the asperities on the surface are deformed until the real area of contact is sufficiently increased to support the applied load.

In the absence of lubricants, asperities are cold-weld together and form new junctions. This wear mechanism destroys the sliding surfaces and generate wear particles, can lead to the failure of the component. An appropriate supply of lubricant can reduced the adhesive wear problem between the two sliding surfaces. Under nominally unlubricated sliding or dry sliding often the presence of naturally formed surface oxides and other interfacial contaminants may act in a slippery manner, reducing the adhesive wear.

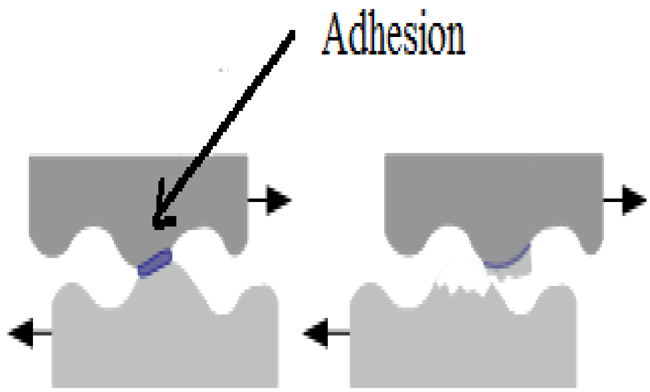

Figure 1.5: Adhesive wear [www.substech...]

1.4.4 Surface Fatigue

Surface-fatigue wear is occurred by repeated high stress, when machine component move in cyclic motion, stresses are induced on the metal surface and then often leading to fatigue failure of the material. All repeating stresses in a rolling or sliding contact are the main cause of fatigue failure. In a fatigue failure, it is not necessary the material will be failed due to the direct contact, sometime high stresses are induced below the surfaces under consideration is shown in Figure 1.6 When the relative motion is occurred between the two surfaces at a high load, the shear stresses are induced some distance below the contact surface, cause a formation of micro cracks in the localized region and leads to failure of the component. These cracks are start slowly at a point, where maximum shear stress is occurred and spread all over the surface. Sometime the formation of cracks are due to the reason of inclusion, porosity and some material defect present in the material and these defects are helps to initiate a surface fatigue.

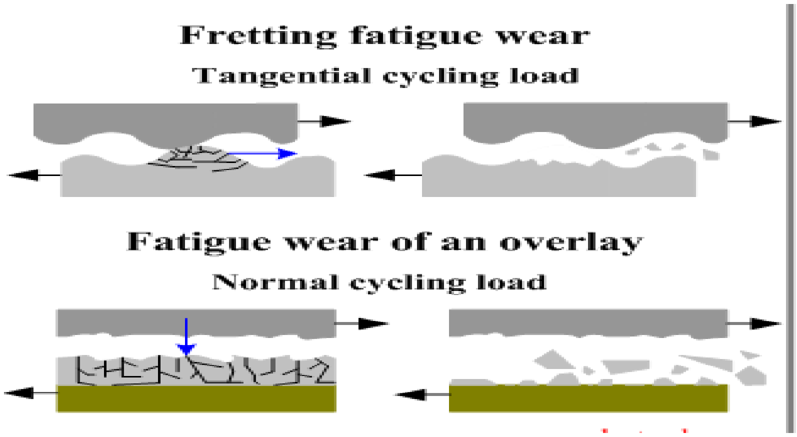

Figure 1.6: Surface fatigue [www.substech...]

1.4.5 Corrosive Wear

Corrosive wear takes place whenever a gas and liquid chemically attacks on a surface left exposed by the sliding process shown in Figure 1.7 When any surface is corrode by the influence of environment factors (moisture, temperature etc.) and these products of corrosion are stayed on the surface, are the main cause of further corrosion at a very high rate. If the regular sliding takes place on the corrode surface, the corrode products are removed automatically otherwise a protective coatings are required to prevent the chemical attack of corrosive wear.

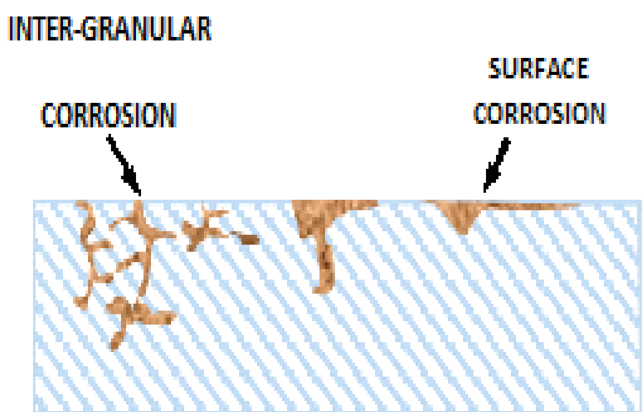

Figure 1.7: Corrosive Wear [www.substech...]

1.5 Friction

The friction force always act opposite to the relative motion in a direction parallel to the area of contact. The friction force (F_F) depends on the normal force (F_N) and the nature of the surfaces involved (μ). The friction force **does not** depend on the surface area (contact area). Friction force is expressed as $\mathbf{F_F = \mu F_N}$.

Based on the relative motion of the contact surfaces friction are classified into two types, Static friction and Kinetic friction. The friction that exists between two surfaces that is not moving relative to each other is called static friction. It can be any value up to or equal to that maximum amount, i.e., $F_F \geq \mu_s F_N$. The friction that occurs between two surfaces which are moving relative to each other is given by $F_F = \mu_k F_N$ (μ_s is static, μ_k is kinetic).

1.5.1 Causes of 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 causes displacement of softer material during motion. Plowing 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.

1.6 Solid lubricants

Solid lubricants are those materials which are in solid phase and generally used to reduce the coefficient of friction between the two sliding surfaces without any need of liquid medium. Some time it is difficult to stay the liquid lubricant due to decomposed it at high temperature, then solid lubricants are used for fulfill the specific requirements. Some solid lubricants such as graphite and molybdenum show good lubricating properties under a high load and high temperate range approximately 1100^0C. Graphite and molybdenum disulfide are the predominant materials used as dry lubricants. Solid graphite provides good lubrication in high humidity, high temperature stability, protect against fretting corrosion, low coefficient of friction under extremely high loads. A molybdenum disulfide consist an excellent adhesion property, decreasing friction at higher loads, high load carrying capacity, stick slip prevention, protection against fretting corrosion etc.

The size of the lubricant particles also influence the coefficient of the friction. A large size lubricant particulates shows a better result in rough surface at low speed and a fine lubricants particles performs best on smooth surfaces at high speed. These particles can be used in the liquid lubricants to enhance their properties. Other compounds which are shown similar behavior of useful solid lubricants include boron nitride, polytetrafluorethylene (PTFE), talc, calcium fluoride, cerium fluoride, and tungsten disulfide etc.

Solid lubricants are preferred over liquid lubricants for some special conditions when conventional (generally) lubricants are inadequate, such as:

- Reciprocating motion: A typical application is a reciprocating motion in which one surface slides over the other and it requires lubrication to prevent or minimize a wear for example piston in cylinder bore, in gears and chain lubrication. Liquid lubricants will squeezed out and decomposed against a high temperature while solid lubricants do not escape and maintain a stable layer at a high load and prevent a high ratio of metal to metal contact.
- Ceramics: when another application is for cases where chemically active lubricant additives have not been found for a particular surface, such as polymers and ceramics.
- High temperature: Graphite and MoS_2 act as lubricants at high temperature and in oxidizing atmosphere environments, whereas liquid lubricants typically will not survive. A typical application include fasteners which are easily tightened and unscrewed after a long stay at high temperatures.

- Extreme contact pressures: The lamellar structure orient parallel to the sliding surface resulting in high bearing load combined with a low shear stress. Generally a solid lubricant is used in forming process involve plastic deformation especially in extrusion process where dies are lubricated with the help of solid lubricant.

1.6.1 Lamellar structure-friction relationship

The lubricity of many solids is attributable to a lamellar structure like as graphite shown in Figure 1.8 and MoS_2 shown in Figure 1.9 The lamellae orient parallel to the surface in the direction of motion and slide easily over each other resulting in low friction and preventing contact between sliding components even under high loads. These lubricants, due to the weak bonding between the layer in a microscopic level helps to maintain a low friction between the contact surfaces. Such layers are able to slide relative to each other with minimal applied force, thus giving them their low friction properties. That is why, graphite and MoS_2 find their use in many engineering applications.

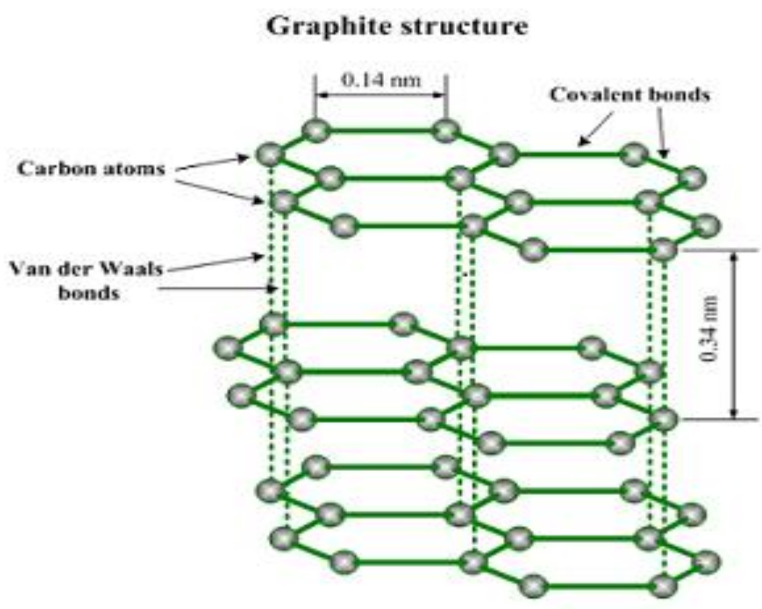

Figure 1.8: Structure of graphite [www.goo…]

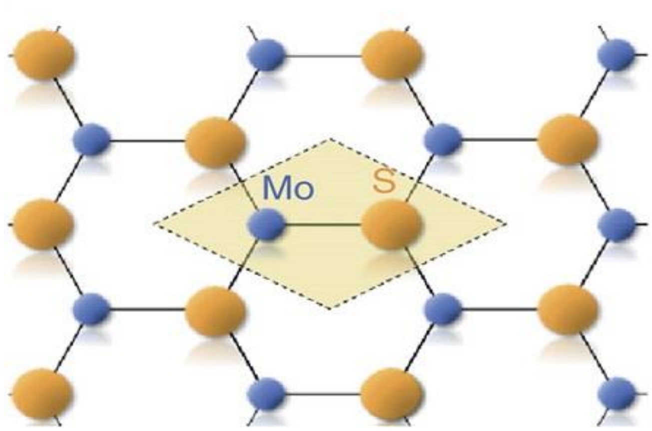

Figure 1.9: Structure of MoS_2 [www.goog…]

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 have been highlighted in this chapter. The chapter also provides a brief information about the principles of wear, friction and lubrication. The chapter also comments about the properties, structure and applications of the solid lubricants. Subsequent chapters will give an elaborate view of the research work on hybrid aluminium MMCs processing and its testing.

CHAPATER 2

LITERATURE REVIEW

2.1 Literature Review

This section presents the summary of work carried out by different researchers for improving the tribological and mechanical properties of Metal Matrix Composites. The selection of matrix material, reinforcement used and manufacturing methods of hybrid composites are discussed in this chapter. This survey includes the different statistical methods to analyze a wear and coefficient of friction behavior of the hybrid composites.

Chu and Lin [2000] fabricated and analyzed the wear behavior of Al6061 metal matrix composites, reinforced with a 10 vol.% of SiC and soft lubricant natural graphite and nickel coated graphite particles (0, 2, 5, 8, and 11 vol.%). The composite was made by powder metallurgy route. The results reveal that the use of the electroless nickel film was better and beneficial to reduction in wear rate of the composites as compare to the pure graphite. It has been found that the coefficient of friction was reduced at lower load, with the use of nickel coated graphite.

Guo and Tsao [2000] studied the wear behavior of self-lubricated 6061 aluminium /10%SiC / graphite hybrid composites, containing 2, 5 and 8 vol. % of graphite. The composite was fabricated by the semi-solid powder densification (SSPD) method. Results shows that the hardness and fracture energy decreases with the addition of vol. % of graphite. Wear results show that the seizure occurred in unreinforced alloy is more as compare to Al/SiC and Al/SiC/Gr composites. Amount of graphite released during the wear test depended upon the vol. % of graphite addition and formed a layer which prevents the contact between the pair. It has been found that the wear behavior becomes more stable as the graphite % was increased.

Riahi and Alpas [2001] fabricated and investigated the wear behavior of A356 Al–10% SiC–4% Gr and A356 Al–5% Al_2O_3–3% Gr composites. The graphitic composites were developed for the application of cylinder liner application. The composites were prepared by stir casting process. The investigation was mainly focused on the formation of tribo-layer between the contacting surfaces during the sliding wear. Three main wear regimes, namely, ultra-mild, mild and severe wear were observed. A protective tribo-layer was formed in almost every low sliding condition load in mild regime. The upper tribolayer consist an iron-rich layers and the remaining tribo-layer consisted of fractured SiC and Al_3Ni particles and thin films of the graphite. It was shown that the formation of thicker and more stable tribolayer in A356 Al–10% SiC–4% graphitic composite. The hardness of a tribolayer was increased with the increase in applied load and sliding speed. It has been found that higher transition from mild to- severe wear for all load and sliding speed combinations, as compare to A356 aluminium alloy and the nongraphitic A356 Al–20% SiC composite.

Singh et al. [2002] studied the dry sliding wear behavior of Al-Si12Fe /SiC composites. Composite samples were fabricated by stir casting process. It has been found the wear rate of the composite and unreinforced alloy is increased with increase of applied load and the abrasive size. Wear resistance of the composite was found low in case of fine particles of SiC as compared to the coarse particles. Their results showed that the wear rate decreases with increase in sliding distance due to the clogging and work hardening on the surface.

Balasivanandha et al. [2005] investigated that optimum stir process and stir time in the stir casting technique. The high silicon content aluminium alloy with 10% SiC composite was fabricated by stir cast technique by using a various stirring speeds and stirring times. The microstructure of the composite was examined by optical microscope and SEM. The stirring speed and stirring time influenced the microstructure and the hardness of the composite. It has been found that at lower stirring speed with lower stirring time, the particles were agglomerated in the casting. Increase in stirring time and speed, shows the better dispersion of the particles. The uniform hardness valued was achieved at 600 rpm with 10 min stirring time, but above this stir speed the properties degraded again.

Basavarajappa et al. [2006] studied the mechanical properties of hybrid metal matrix composite in which the matrix is Al 2219 were reinforced with SiC and graphite particles. Composites were fabricated by liquid metallurgy route. Dry sliding wear behavior of Al/SiC/Gr was compared by Al/SiC. Designs of experiment were arranged in a control way on the basis of Taguchi Technique. The parameters such as reinforced composition, load, sliding velocity, sliding distance were influenced the wear and analyzed by ANOVA. The results showed that the addition of Graphite reduces the wear volume loss due to formation of lubricant layer in between the Pin and their counter face. Sliding distance is the highest wear factor that influenced both the composites. The interactions between the wear factors have statistical significance but do not have any physical significance.

Goto and Uchijo [2007] studied the effect of environment on the Wear and Friction of Al-Si Alloy impregnated Graphite Composite. Wear and friction test were conducted in different environments like air, deionized water, argon, oxygen, water vapor, and liquid water and investigated the behavior of aluminium graphite composites. The pin-lifting process was continuously measured during the experiments. The results show that the mean of coefficient of friction and wear rate in the matrix are independent on relative humidity, but it is drastically changed in case of aluminium graphite composite. Friction coefficient is high in air than argon at low relative humidity and decrease with increase relative humidity. Wear rate was lower in argon as compared to air and oxygen indicated a small effect on wear resistance. The pin lifting was due to the deposition of film on the disc.

Elmadagli et al. [2007] investigated the relationship between wear resistance and microstructure of Al–Si alloys. Wear characteristics were analyzed on three grades of Al–Si alloys, a die cast 383 with 9.5 wt. % Si, spray cast alloy with 18.5 wt. % Si and a sand cast A390 with 25 wt. % Si in a dry sliding condition on a block-on-ring type tribometer. Heat treatment were used to enhanced the hardness and modify the microstructure. It was indicated that Si particles size and shape effects the wear coefficients. The small size and spherical Si reinforcing particles clearly influence in the reduction in wear rate and increased in transition load.

Kumar et al. [2008] presented the tensile and wear behavior of Al–7Si/TiB_2 composite reinforced by 0, 5 and 10 wt. % TiB_2 fabricated by salt route. Halide salt K_2TiF_6 flux was added in the matrix to improve their wettability. It has been found that the improvement in hardness and tensile strength with the addition of TiB_2. The mechanical and wear properties of Al–7Si/TiB_2 composite were better as compare to those reported earlier with SiC reinforcement. Results showed that wear was increased with increase of load and sliding distance. Their observation of worn surfaces indicated the detachment of mechanically mixed layer which caused primarily due to the elimination wear mechanism under higher applied load. The worn surfaces were examined with the help of scanning electron microscopy and SEM micrographs showed a wear pattern which helped them to determine the wear mechanism of the worn surfaces.

Das et al. [2008] found that the wear rate of Al-Si12Cu / SiC composite is less than as compared to their unreinforced alloy and it is decreased with the increasing in SiC wt. %. Further the wear resistance decrease with the increase of SiC particles size. The effect of SiC particle size was found insignificant if the abrasive size was less than 60 micron. The result showed that the wear rate is increased linearly with applied load. Heat treatment of the composite provided an improvement in wear resistance.

Suresha and Sridhara [2010] presented an experimental study on composites with aluminium LM25 as a matrix and silicon carbide graphite as reinforcement. In a composite composition of SiC and graphite (1.25, 2.50, 3.75, 5 wt. %) of both were same and prepared by stir casting process. Dry sliding wear test was carried out on a pin on disc equipment of which EN31 steel disc with surface roughness R_a =0.1. Wear test specimen were clean with acetone before performed a test. Samples were weighed before and after the test performed on a weighing machine to an accuracy of 0.0001gram to measure the amount of wear loss. The effect of wear on percentage reinforcement, load, sliding velocity and sliding distance factors and their interactions were analyzed with the help of statistical software Minitab14. Results showed that wear was increased with increase of sliding distance. Wear was reduced by increasing a speed due to the effect of graphite, supporting the mechanically mixed tribo layer. Hardness was reduced by increasing an amount of graphite in aluminum alloy and increased by adding the amount of SiC.

Abarghouie and Reihani [2010] investigated the wear and friction behavior of 2024 Al/20 vol. % SiC composite. The composite was prepared by powder metallurgy process. Dry sliding wear tests were conducted on pin on disc apparatus. The parameters of the wear test were fixed, a constant sliding velocity of 0.5 m/s, a sliding distance of 2500m and an applied load of 20 N. composites showed a transition from mild-to-severe wear at high load conditions. It has been found that the wear rate and the coefficient of friction of the composites is decreased as compare to unreinforced alloy. Analysis of wear debris and worn surface were done with the help of optical microscope. Their result showed that a more ploughing and slight adhesion were present on the wear surface of the unreinforced alloy as compare to 2024 Al/20 vol. % SiC composite.

Reddy and Zitoun [2010] studied the mechanical properties of three different metal matrix composites fabricated from Al6061, Al7075 and Al6063 matrix alloys reinforced with silicon carbide particles. The composites were fabricated in oil-fired furnace and well stirred with the help of stirrer. The volume fraction of SiC reinforcement was used 20% in the metal matrix. The sizes of the SiC particulates were 10 μm. The average values of yield strength, ductility in terms of tensile elongation, and ultimate tensile strength, were obtained on universal testing machine. It was found that the Al 6061 matrix alloy has the highest yield strength as compare to other alloys, Al7075 and Al6063. The yield strength, ultimate strength, and ductility of Al/SiC metal matrix composites are in the descending order of Al 6061, Al6063 and Al 7072 matrix alloys.

Kalaiselvan et al. [2011] studied the fabrication and testing of aluminium based metal matrix composite (MMCs) reinforced with B_4C. The composite were fabricated by stir cast method. B_4C particles (of size 10μm) were added to the matrix. The reinforcement added was in steps of 2 wt. % (from 4 wt. % to 12 wt. %). K_2TiF_6 Flux was added in the matrix to improve their wettability. Micro structural studies showed good and uniform bonding between the matrix and the reinforcement. SEM study and XRD analysis showed the presence of reinforcement particles in the composite is dispersed homogeneously. The micro hardness of the composite was increased by the addition of weight percentage of B_4C particles. It has been found that the tensile strength was increased by 185 MPa to 215 MPa with addition of B_4C particles. It was showed that a very small amount of B_4C particles are sufficient to cause a large improvement in mechanical properties.

Gopalakrishnan and Murugan [2011] studied the production and wear behavior of aluminium (AA 6061) based metal matrix composite reinforced with titanium carbide Particulates. The composites were fabricated by indigenously developed enhanced stir casting process. Magnesium 1% was used in the matrix to improve the wettability of TiC. Argon gas was used to prevent the oxidation and atmospheric reaction in the molten metal. A mathematical model was used to analyze the wear behavior of the composite and compare with the physical experiment. Wear test was performed on pin on disc apparatus. The results showed the specific strength of the composite was improved with the addition of TiC. Percentage elongation was maintained even though the specific strength is increased. It has been found that the wear loss in terms of volume is less as compare to earlier studies conducted on in situ process at the same conditions.

Sameezadeh et al. [2011] fabricated and studied the nanocomposites of AA 2024 Aluminium alloy matrix. MoS_2 particles are reinforced with different volume fractions ranging from 0 to 5%. The composite was fabricated by using mechanical alloying technique. The prepared composite powders were bound by hot pressing and then heat treated. The wear behavior and hardness of the composites were investigated on pin on disc apparatus and Brinell hardness machine. The results show that the significant effect of volume fraction, particle size and heat treatment on the hardness and wear property. The results shows that the T6 heat treatment increases the hardness as compare to hot pressed condition. The hardness of the composites was continuously increases with increases the volume fraction of MoS_2 particles up to 3–4% and then decreases further addition. It has been found that the wear resistance of the heat treated composites is less as compare to hot pressed condition and increases with increasing MoS_2 content.

Ravindran et al. [2012] studied the response of wear and sliding behavior of Al2024 metal matrix composite in which the hard ceramic (5 wt.% of SiC) and soft lamellar structure particles which is as a solid lubricant (0, 5, and 10 wt.% of graphite) is reinforced. The composites were fabricated by powder metallurgy process route. The average grain size of SiC (43-53 micron) and graphite (43-60) were used. Wear and coefficient of friction were studied on a pin-on-disk apparatus, on which the test was based on a parameter load, sliding velocity and sliding distance is varied according to the rule of design of experiments. The test results were analyzed with the help of analysis of variance. It has been found that the load and a sliding distance is the major parameter which is mainly affected the wear and coefficient of friction. The wear resistance was found superior containing 5 wt. % SiC and 5 wt. % graphite in hybrid composite as compare to the unreinforced alloy. After addition of graphite, the hardness of a composite was decreased. Further the correlation between the influencing parameter was analyzed with the help of linear regression model and validates the results. SEM analysis was carried out to understand the wear mechanism, and was found that debris size in Al/SiC/Gr composites is small as compare to Al/SiC composite.

Vinoth et al. [2012] analyzed the effects of tribological and mechanical behavior of Al-Si10Mg and self-lubricating Al-Si10Mg/MoS_2 composites. The composites were fabricated by stir casting process. The melting of the composite was carried out under envelop of argon gas at 1073 k to prevent the oxidation. MoS_2 solid lubricant with an average particle size of 1.5 μm and a density of 4600 kg/mm^3 was used. The hardness was measured by using a vicker hardness testing machine at a load of 100 g. The result showed that hardness, % elongation and ultimate tensile strength is decreased with an addition of MoS_2 particles in Al-Si10Mg. However, the densities of the Al-Si10Mg/MoS_2 composites were greater than the base alloy. A pin-on-disc apparatus was used to measure the wear behavior of composites. The disc material was made of EN-32 steel and the hardness of a disc is 65 HRC. It has been found that the wear resistance of Al-Si10Mg/MoS_2 composites is better as compare to the base alloy. The optical micrographs taken for the micro structure analysis of the Al-Si10Mg/MoS_2 composite specimens showed that the MoS_2 particles are uniformly distributed in the matrix.

Kumar and Tirth [2013] investigated the effect of stirring speed on retention of ceramic dispersion in the matrix of A2218 Aluminium Alloy (AA). The composite was prepared by stir casting process. Alumina particles size was mixed in the composite is less than 53 microns. The vortex flow was obtained by the optimum stirrer speed action in the molten metal. The speed of the stirrer was varied in steps 180, 250, 400 and 1400 rpm and weight percentage of particle were also varied 10 to 20 respectively. The results showed that the distribution of particles in a matrix is more uniform with increase in stirrer speed; it is due to the more energy supplied by the stirrer. The hardness, impact strength and ultimate strength are increased with increase of stirrer speed and weight percentage of alumina. Microstructure of the casting showed a homogeneous dispersion of reinforced particle in the matrix alloy at high rpm.

Baradeswaran and Perumal [2014] studied the effect of wear and mechanical behavior of Al 7075/Al_2O_3/5wt.% graphite hybrid composite. Al 7075/Al_2O_3/graphite hybrid composite were consist a 5% graphite and 2, 4, 6 and 8 wt. % of Al_2O_3. The composites were fabricated by liquid metallurgy route. Further the composites were T6 heat treated for a preparation of samples on which various test performed like as hardness, tensile strength, flexural strength and compression strength. It has been found that the hardness, tensile strength, flexural strength and compression strength are increased by increasing the weight percentage of Al_2O_3. The hardness test was performed on Brinell hardness testing machine and followed an ASTM E10-07 standards. The tensile and compression strength were measured as per ASTM E9-09 standards on computerized universal Testing Machine (UTM-Auto instrument). Wear behavior of composites were investigated on pin on disc apparatus. It was found that the wear rate decreases with addition of Al_2O_3 and minimum at 2 wt. % Al_2O_3/5 wt. % graphite, it was almost 36% less as compared to the base metal Al 7075. The results indicated that the presence of graphite also decrease the coefficient of friction. Worn surfaces and wear mechanism were analyzed on SEM.

Rebba and Ramanaiah [2014] studied the mechanical properties of Al2024 based metal matrix composite in which Molybdenum Disulphide (MoS_2) particles of approximately 40 micron were reinforced. Composite samples were fabricated at different weight percentage (1, 2, 3, 4 and 5) through stir casting technique. Magnesium ribbons were added into the molten metal to improve their wettability property of aluminium. Composite samples were subjected to various tests. Hardness was carried out on standard Rockwell hardness testing machine. The hardness of composite samples were gradually increased by increasing the weight percentage up to the 4% and then decreased at 5% weight. The tensile test result showed that the ultimate strength also increases with addition of Molybdenum Disulphide, maximum at 4% weight. Optical micrograph and XRD showed that the MoS_2 particles were well distributed and homogeneously mixed in a matrix.

Krishna and Xavier [2014] were investigated the mechanical properties of a metal matrix hybrid composite in which the matrix is Al6061 alloy and reinforcement is SiC and Graphite. The composites were fabricated by stir casting route, in which reinforcement was varied from 5 to 15% in three steps. The particles size of SiC and graphite were 37 and1 μm respectively. Aluminium alloy was preheated in electric furnace for 2 hours before melting at 450^0 – 800^0 C and graphite particles were preheated at 1100^0 C for the improvement of wetness. Magnesium powder was also added to maintain a good wettability. It has been found that the mechanical properties were gradually improved by addition the weight percentage of reinforcement. The density was increased with increase the weight percentage of SiC and decreases in SiC/Gr. The maximum tensile strength was found that 192.45 MP at 15wt. % of Sic/Gr. SEM was carried out to investigate the morphology of the composite. The microstructure was studied in metallurgical microscope at magnification of 50X, 100 X and 500 X.

Negara et al. [2014] analyzed the wear behavior of Al 6061metal matrix composites reinforced with SiC particles by using TAGUCHI'S techniques. 6-9 wt. % of SiC particulates were varied in three steps. The composites were prepared by using liquid metallurgical route by stir cast process. Before fabrication of every casting SiC particles were preheated up to a 300^0C for improve their wettability and distribution. The dry sliding wear characteristics were studied on Ducom made Pin on disc tribometer. 27 trial experiments were performed according to the L27 standard orthogonal array by using Taguchi Technique. From the experimental details it was revealed that wear rate is decrease with the percentage increase of SiC. It was found that load is the most significant factor which influences an increase of wear rate.

Saravanakumar et al. (2014) synthesis and investigated the behavior of AA 6063-x wt. % Al_2O_3- 1% Gr (x = 3, 6, 9 and 12 wt. %) hybrid composites. AMC was fabricated by different combination of Alumina and graphite by a use of stir casting technique. Further, the composites were hardened by heat treatment. The Alumina (Al_2O_3) and graphite particles of size 20 μm and 80μm respectively were used as the reinforcement particulates for fabrication of the composite. The presence of Al_2O_3 and Gr particulates in the composite were checked by X-ray diffraction (XRD) test. It was observed that the hardness of composite is increased by the addition of up to 6 wt. % and beyond that it started to decrease. The mechanical properties like hardness, compressive strength, flexural strength and impact strength were increased in AA 6063-6 wt. % Al_2O_3-1 wt. % Gr hybrid composite. The effect of agglomeration of reinforcement in the matrix ws examined by SEM.

Kumar and Mishra [2014] presented the mechanical behavior of Al6063/Al_2O_3/MoS_2 hybrid MMCs. In an Al6063/Al_2O_3/MoS_2 hybrid composite the 10 wt. % of aluminium oxide was fixed and weight percentage of Molybdenum disulphide were varied at (i.e. 3%, 5%, 7% & 9%). The hybrid composite was fabricated by stir casting process. It has been found that the density and the Vickers hardness value of the Al6063/Al_2O_3/MoS_2 composite is increased with increase in wt. % of MoS_2. The results revealed that the ultimate tensile strength were decreased with addition of MoS_2 and Al_2O_3 together in the base matrix alloy.

Thomas et al. [2014] studied the development in feeding and stirring mechanisms for stir casting of MMCs. Al LM6/SiC composites were fabricated with the help of an existing stirrer design and a new modified feeding mechanism. New modified design consist a funnel shaped feeder of 83 mm height and a holes with diameter of 3 mm on its body. SiC particles fed through the hole in the feeder and the feeder was attached with the rod which can be rotated at 800 rpm. SiC particles were escaped from the feeder with the help of centrifugal force act on it. The results shows that there is an improvement in percentage elongation in tensile test and BHN value in hardness test with the use of new modified feeding mechanism as compared to the existing design. They contributed it to the better uniform, homogeneous and controlled spraying of SiC in the molten metal.

2.2 Summary of Literature

From the literature review, it has been found that a lot of work has been done in Aluminium metal matrix composite with various types of hard and soft particles as reinforcements (Al_2O_3, SiC, Gr, MoS_2, B_4C, TiC) with different sizes (in micro and nano range), and fabricated by different techniques (Stir cast process, Powder metallurgy process etc.), then heat treated or aged at optimum temperature and time durations to correlate between the microstructure and the mechanical properties. It has been found that alloy composition and its fabrication process factors (temperature, holding time, pouring time, surrounding conditions, stirring time, and stirring speed etc.) influence the mechanical (hardness, tensile strength, impact strength) and tribological properties (wear and friction) of the composite. Based on the literature survey it is observed that the reinforced SiC particles improves the hardness, strength and wear resistance in the aluminium metal matrix composites [Chu and Lin, 2000; Singh et al., 2002; Das et al., 2008]. The lamellar structure soft particles (Gr and MoS_2) were used as a solid lubricant to reduce the wear rate and coefficient of friction of a self-lubricated aluminium metal matrix composites [Baradeswaran and Perumal, 2014; Ravindran et al., 2012; Suresha and Sridhara, 2010]. The wt. % of MoS_2 influences the hardness and strength of the composite [Rebba and Ramanaiah, 2014; Vinoth et al., 2012]. The processing parameters such as stirring speed and stirring time influence the microstructure and hardness of composite [Balasivanandha et al., 2006; Thomas et al., 2014; Kumar and Tirth, 2013]. The worn surfaces, wear debris and wear mechanism were analyzed with the help of SEM and optical microscope [Kumar et al., 2008; Saravanakumar et al., 2014]. The factors (load, sliding velocity, sliding distance and composition of reinforcement) and their interactions which influence the tribological behavior of the composites were analyzed with the help of statistical software [Basavarajappa et al., 2006; Suresha and Sridhara, 2010; Negara et al., 2014].

2.3 Gaps from the Literature Survey

From the above discussion it is evident that hard ceramic particle addition with aluminium alloy improves properties of the base metal/alloy. Most of the research in this regard oriented towards enhancement of mechanical properties of the fabricated composites. Although, a lots of works are reported in the literature regarding the superior wear resistance of MMC over base metal, a very few studies are reported on the tribology study of 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. Some works are found to minimize the friction using graphite as reinforcement in the composites; on the other hand use of MoS_2, another potential solid lubricant is yet to be explored. Also, rarely any work is reported in the literature which dealt with the wet tribology of hybrid composite.

Thus, studies on the tribological behavior of aluminium alloy MMC is still being a research gap and there is a vast potential and opportunities for the researchers 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.

2.4 Scope and Objective of the Present Study

The scope and the requirement for this study could be well explained by understanding the problem of wear and friction in the machine parts like as piston, cylinder liner, bearings etc. The various machine components are failed during their function due to the cause of wear and friction. As the aluminum and ferrous alloys alone are unable to meet these demands, design of Aluminum Matrix Composites (AMCs) to find optimum wear resistance and enhanced friction response are necessary. So now researchers are interested to investigate the new aluminium metal matrix self-lubricating composite material which overcome these problems and helps to increase the life of a machine component. 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 above mentioned applications show that there is a lot of research required in the area of self-lubricating aluminium metal matrix composite which has led to the origin of this study.

2.4.1 Establishment of Objective Function

The main objective of the present study is to investigate the tribological properties (especially dry sliding wear rate and coefficient of friction) of an aluminium based hybrid metal matrix composite. The wear mechanisms, different parameter that influences the wear loss and the role of the reinforcement phases are also presented. It will be seen that it is possible to optimize the tribological properties of aluminium metal matrix composites by using the proper combination and proportion of different ceramic particle as reinforcement.

The key issues taken up during the proposed work are as follows:

- To fabricate the AMMC and AMM hybrid composites by stir casting method.
- To study the microstructure, phase and extent of dispersion of filler (SiC, Gr and MoS_2) in the matrix, density and hardness of the above composites.

- To estimate the effect of various influencing parameters (composition of reinforcement particle, load, sliding distance, sliding velocity) in dry sliding wear and coefficient of friction behavior of the above composites using and their interaction.
- To compare the performance of solid lubricant graphite and MoS_2 in AMMC.
- To study the wear mechanism of a worn surface of a hybrid composite.

CHAPATER 3

Pilot Experiment and Design of the Study

3.1 Introduction

This chapter brings forth the details of design of the proposed study. The chapter describes the Pilot Experiment and Design of the study based on the selection of an input parameters (concentration), selection of material used to fabricate the hybrid composite, the method of fabrication, experimental equipment and facilities used for evaluating the properties of the aluminium alloy metal matrix and hybrid composites, and the process parameters which helped to achieve the objective.

3.2 Pilot Experimentation

The effects of SiC (1%, 3%, and 5% in weight) in Al 6063/SiC composite and its base alloy Al6063 were investigated through the pilot experimentation. After the fabrication of the composites with stir casting method, dry sliding wear resistance and coefficient of friction were calculated. A pin-on-disc apparatus is used to perform the wear experiment. All composites and alloy samples are well prepared, were cleaned using acetone to remove all dirt and foreign particles from the specimens prior to testing. Each sample is weighed using a Digital balance having an accuracy of 0.0001 gm. before and after the wear test. For all experiments, the input parameters during the test on pin on disc apparatus are: load is 9.81 N, sliding speed is 1.5 m/s, sliding distance is 1800 m and time is 1200 seconds are to be set. Table 3.1 shows a data of cumulative weight loss.

Table 3.1: Data of cumulative weight loss

S.No	Sample name	Initial weight (gram)	Final weight (gram)	Weight loss (gram)
1	Base Alloy Al6063	5.5904	5.5722	0.0182
2	Al6063/1wt. % SiC	5.2358	5.2202	0.0156
3	Al6063/3wt. % SiC	5.2827	5.2687	0.0140
4	Al6063/5wt. % SiC	6.1135	6.1009	0.0126

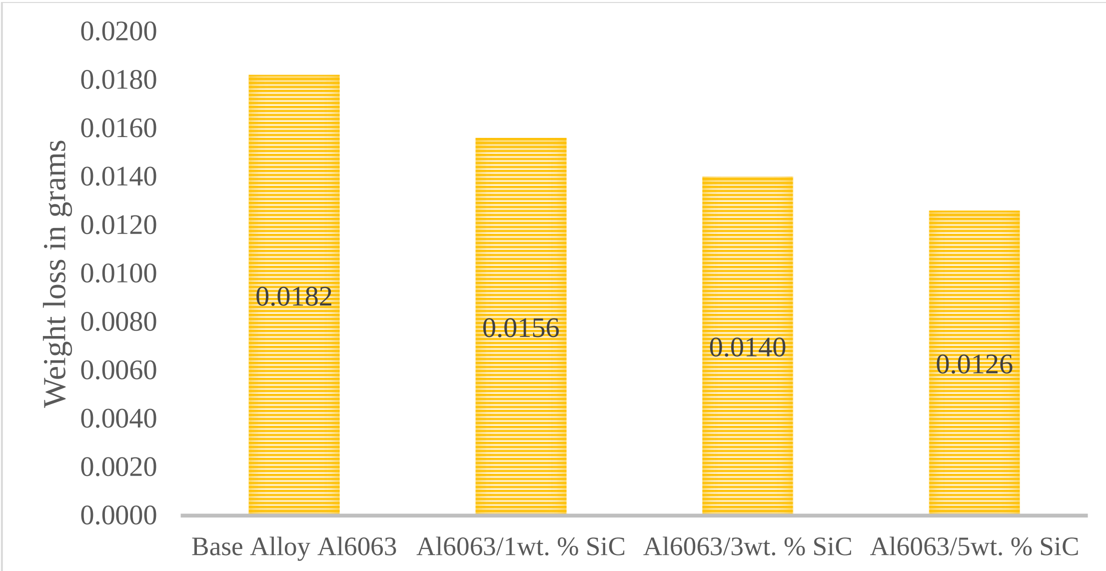

Figure 3.1: Weight loss of Al alloy and Composites

Table 3.2: Hardness and Density of the Al 6063 alloy and composites

S. No.	Composition in wt. %	Density(g/cm^3)	Hardness (HRB)
1	Base Alloy Al6063	2.6800	48
2	Al6063/1wt. % SiC	2.6853	52
3	Al6063/3wt. % SiC	2.6959	57
4	Al6063/5wt. % SiC	2.7065	61

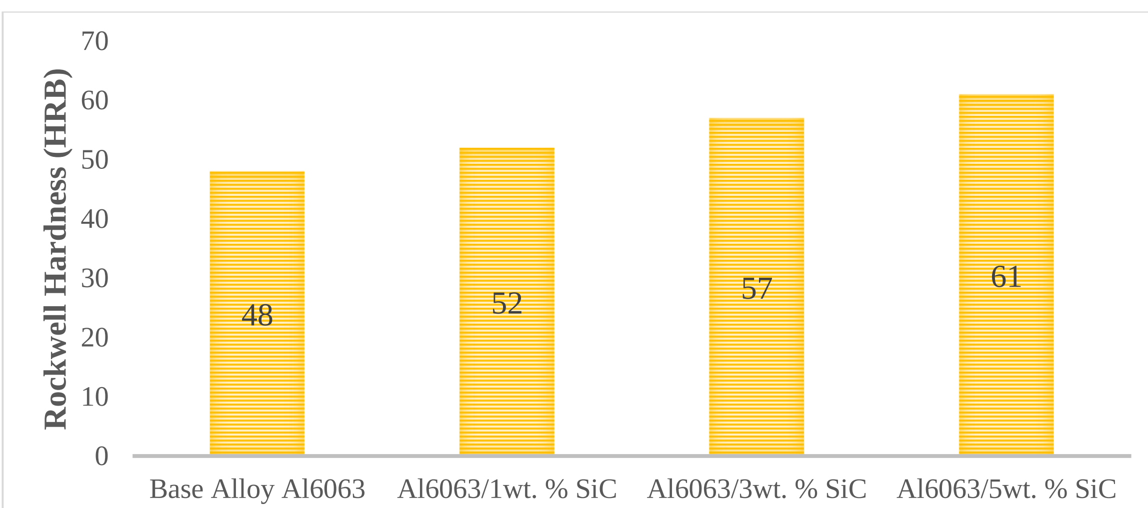

Figure 3.2: Hardness of Al6063 alloy and its Composites

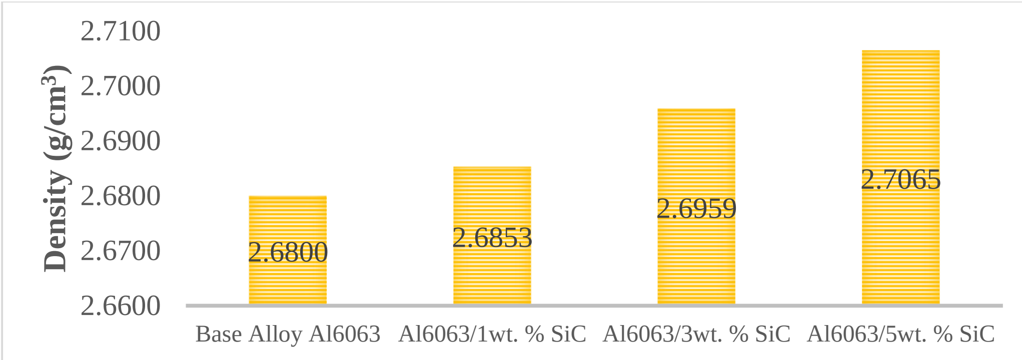

Figure 3.3: Density of Al6063 alloy and its composite

Figure 3.1 shows the cumulative weight loss of base Alloy Al6063 and Al6063/x wt. % SiC (x=1,3,5) composites. After addition of reinforced particles (SiC) in matrix alloy Al6063, the sliding wear decreases significantly or we can say that weight loss is decreasing with increase the weight percent of SiC. Figure 3.2 and Figure 3.3 shows that the hardness and density of composites were increased with increase in the weight percent of SiC.

3.3 Plan of work

The main objective of the present study is to evaluate the Tribological properties (especially dry sliding wear rate and coefficient of friction) of an aluminium based hybrid metal matrix composite. In the present work, SiC, Gr and MoS_2 particles has been reinforced in the Al6063 alloy matrix, then to achieve the goal of study the work plan is made as follows:

- ❖ Once the process parameters and operating parameters are set fabricate the following composites by stir casting method.
  - Al6063 matrix alloy.
  - Al6063/1wt. % Silicon carbide, 3wt. % Silicon carbide and 5wt. % Silicon carbide (hereafter referred to as SiC)
  - Al6063/5wt. % Silicon carbide with 1wt. % and 2wt. % of Graphite (hereafter referred to as Gr)
  - Al6063/5wt. % Silicon carbide with 1wt. % and 2wt. % of Molybdenum disulphide (hereafter referred to as MoS_2)
- ❖ Fabricated composites are used to study the microstructure, density and hardness, determine the phase and extent of dispersion of filler (SiC, Gr and MoS_2) in the matrix.

- Perform friction and wear testing.
- Estimate the effect of various influencing parameters and their interaction (composition of reinforcement particle, load, sliding distance, sliding velocity) in dry sliding wear and coefficient of friction behavior of the above composites using Analysis of Variance (ANOVA).
- Study the wear mechanism of a worn surface of a hybrid composite with the help of SEM, XRD and Optical micrographs.
- To compare the performance of solid lubricant graphite and MoS_2 in MMCs.

3.4 Material Selection

This section describes the constituents (of the composites to be fabricated) with regards to their characteristics, properties, concentration range etc. to be used in the proposed work.

3.4.1 Matrix Material

In this study, Aluminium 6063 alloy in shape of cylindrical rod was used for the purpose of matrix material is shown in Figure 3.4. The density and Rockwell hardness of aluminium 6063 is 2.688 g/cm^3 and 48 HRB respectively. Al6063 alloy exhibits excellent corrosion resistance under ordinary atmospheric conditions along with medium strength and hardness. The details of the composition of used aluminium 6063 alloy are shown in Table 3.3.

Figure 3.4: Aluminium 6063 alloy

Table 3.3: Chemical composition of aluminium alloy used (wt. %)

Element	Symbol	Composition % in Al 6063
Silicon	Si	0.2-0.6
Iron	Fe	0.35 max
Copper	Cu	0.10 max
Manganese	Mn	0.10 max
Magnesium	Mg	0.45-0.9
Chromium	Cr	0.10 max
Zinc	Zn	0.10 max
Titanium	Ti	0.10 max
Aluminium	Al	Remaining

3.4.2 Reinforcements

Generally, the selection of the reinforcement depends upon the following properties of the materials: low density, compatibility with matrix alloy, thermal stability, chemical compatibility and interfacial bonding between the matrix and reinforcement. In MMCs, reinforcement like alumina, boron carbide, silicon carbide etc. provide strengthens to the metal matrix. The enhancing properties of the metal matrix composite mainly depend upon the interaction and interfacial bonding between the reinforcement and the matrix. In hybrid metal matrix composites, a soft reinforcement like graphite and molybdenum disulphide contribute to low wear rate, friction, and anti-seizing properties.

- **Hard Reinforcement:** In the present study, silicon carbide (SiC) particles shown in Figure 3.5(a) were used as hard reinforcement in the hybrid metal matrix composites. The details of SiC is shown in Table 3.4 Silicon carbide particulates possesses very low reactivity in molten metal, relatively cheap and also improves the composite properties such as stiffness and strength though not as high as those of either the alumina or boron carbide reinforcement. With increasing the content of SiC particles in the composite materials, improves hardness, tensile strength, yield strength and elastic modulus can be attained [Zhong et al., 1995]. Pilot study has already proved that the wear resistance is improved by adding the SiC as reinforcement in the matrix.

- **Lamellar structure reinforcement particulates:** In the present study, Graphite and MoS_2 lamellar structure particulates shown in Figure 3.5(b) and Figure 3.5(c) are used as reinforcement (solid lubricant) in metal matrix composite to enhance the Tribological properties of the hybrid metal matrix composite. Though, it is one of the important constituents, but special attention has been given to relative amounts of solid lubricants in the metal matrix composites because its increase amount gives the worse effect on the mechanical and Tribological properties significantly due to its low density, low hardness and agglomeration problems. For the present research work, Gr and MoS_2 amount was varied 1-2 wt. % in the composite system. Details of reinforcement are shown in Table 3.4

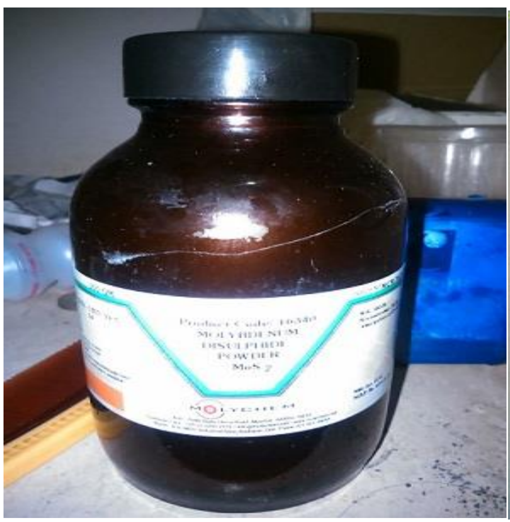

Figure 3.5(a): MoS_2 particulates

Figure 3.5(b): Graphite Particulates

Figure 3.5(c): Silicon carbide Particulates

Table 3.4: Details of reinforcements.

Reinforcement	Grain size (μm)	Density(g/cm^3)
SiC	30-35	3.21
Gr	5-10	2.09-2.23
MoS_2	5-10	5.06

3.5 Experimental Equipment and Facilities

This section provides an overview of the various machines and equipment used in the present study for fabrication, characterization and testing of the composites.

3.5.1 Weighing Balance

The digital weighing balance (Make: Mettler-Toledo, Greifensee, Switzerland) as shown in Figure 3.6 was used for weighing a specimen before and after an experiment. This facility is available in Chemical Engineering Department, Thapar University, Patiala. It is a highly accurate and precise measuring device with least count 0.0001 g

Figure 3.6: Weighing balance
(Photo courtesy: Chemical Engineering Department, Thapar University, Patiala)

3.5.2 Casting Furnace

A Casting furnace is a furnace with a heated chamber; the walls of the furnace are radiated heat due to the electrical resistance heating element. So that the material being heated has no contact with the flame. Casting furnace is used to heat and melts the material to desired temperature by the principle of conduction, radiation and convection. Figure 3.7 is shown a Casting furnace have a maximum temperature range of 1100^0 C.

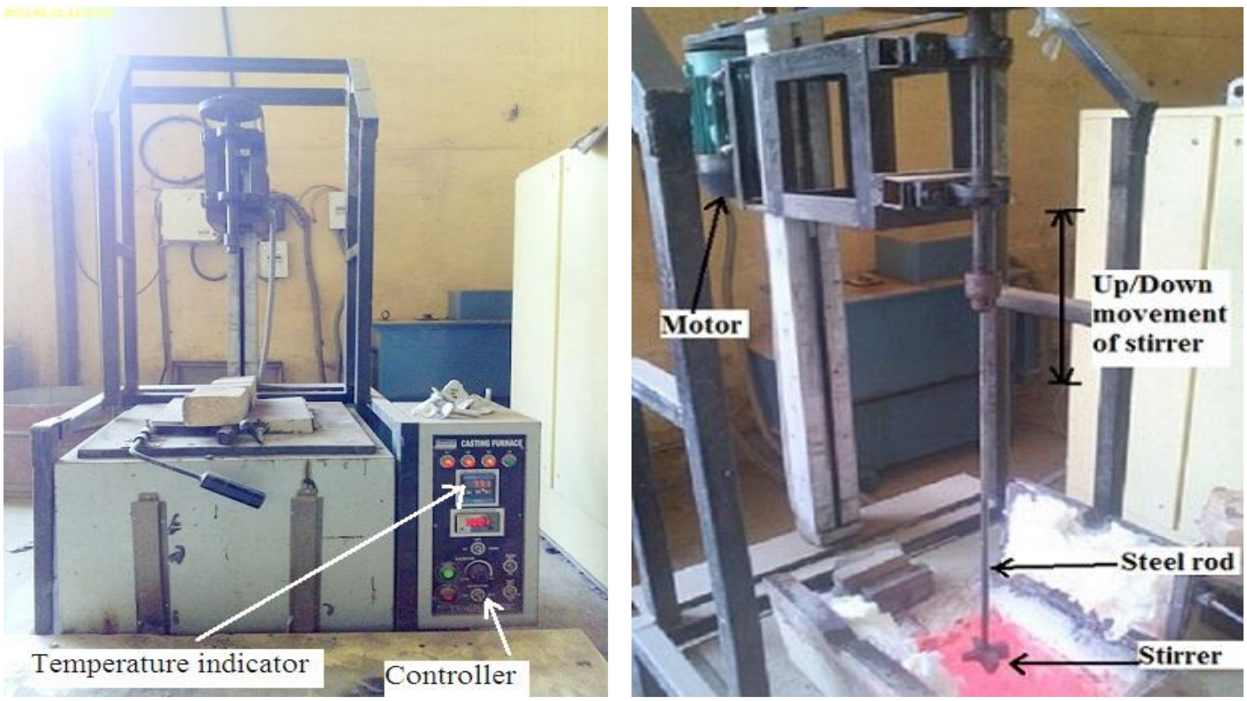

Figure 3.7: Casting furnace
(Courtesy: Central Workshop, Thapar University, Patiala)

3.5.3 Graphite stirrer

The function of a stirrer is to agitate the liquid metal and mix up the reinforcement particulates into the molten metal. Stirrer design plays an important role to maintain a vortex formation for the homogenous dispersion of the particulates. Figure 3.8 is shown a graphite stirrer have a wings bent at 45 degree. In stir casting process stirrer speed is a very critical parameter for consideration to maintain a vortex. During the fabrication of stir casting, stirring speed was 240 rpm used which was effectively producing vortex without any spreading the molten metal.

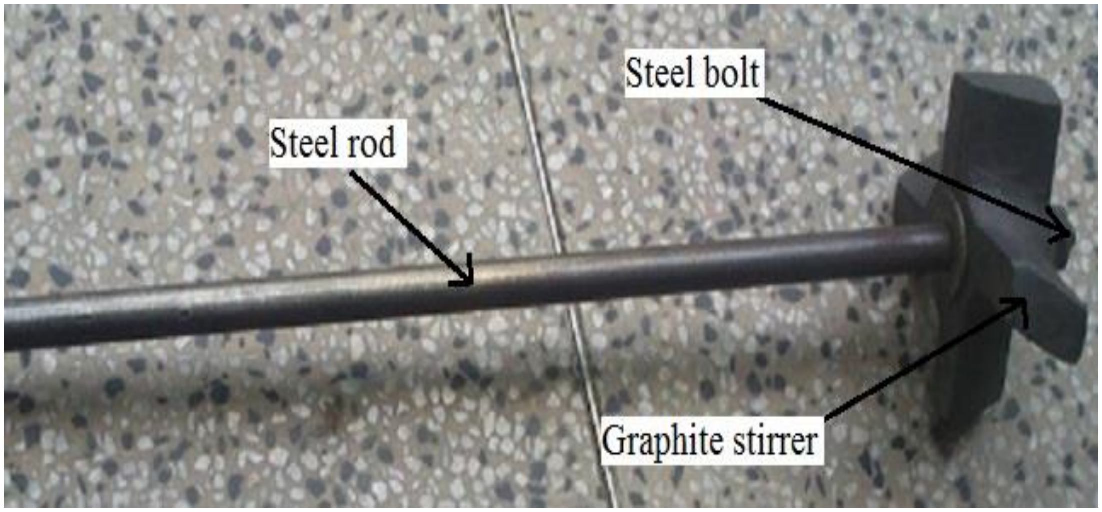

Figure 3.8: Graphite stirrer

3.6 Fabrication of Composites by Stir Casting Process

The various steps involved in the processing and fabrication of composites in the present work are described as follows. The steps are:

1. The relative weight percent of constituents of the composite system (i.e. Aluminium 6063, SiC, Gr/ MoS_2 and Magnesium 1 wt. % of base Alloy) was calculated as follows:

Calculate the weight of constituents by deciding the final weight of the composite. Let the final weight of the composite be 700 g. For example: For a composite containing 1% Graphite and 5% Silicon carbide by weight.

Total weight of the composite = 700 g

Weight of Graphite = 0.01×700 = 7.0 g

Weight of Silicon carbide = 0.05 ×700 = 35 g

Weight of the Aluminium alloy and Magnesium = 700- (7.0+35) = 658 g

Weight of Magnesium = 0.01 × 658 = 6.58 g

Weight of Aluminium alloy = 658- 6.58 = 651.42 g

2. Aluminium alloy was melted in a graphite coating crucible shown in Figure 3.9 by heating it in a casting furnace at above its liquidus temperature i.e. 750^0 C. The graphite crucible is used to keep the molten metal in the casting furnace.

Figure 3.9: Graphite coated crucible

3. The silicon carbide, graphite and MoS_2 particulates were preheated at 500 to 600^0C respectively for two to three hours in an electric oven, to remove the adsorbed artificial hydroxide layer and other gases on the surface.
4. When the metal is totally melted and temperature reaches above the liquidus temperature 750^0C, then the melt is cooled down between the liquidus and solidus points and kept in a semi solid state.
5. Before addition of reinforcement, Magnesium ribbon was added into the melt to improve the wettability. Magnesium ribbon is shown in Figure 3.10

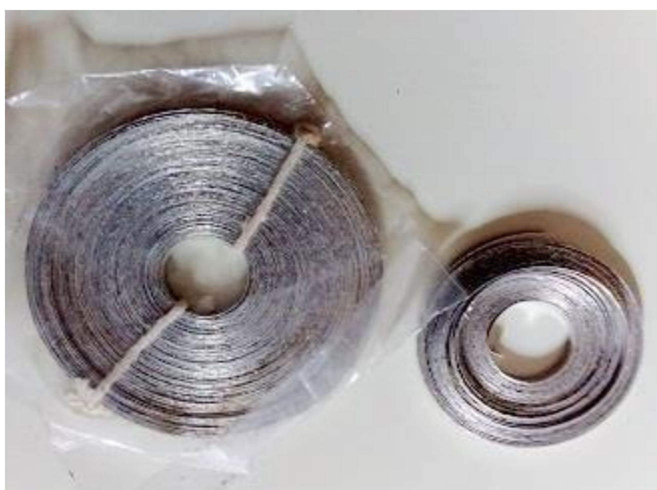

Figure 3.10: Magnesium ribbon

6. Calculated amount of reinforcement is being fed into the melt three to four times rather than introducing all at once, and mixed for 10 min in the vortex with the help of stirrer. Then the slurry is again heated to a fully liquid state. The furnace temperature was controlled at 760 ± 100^0C.

7. After stirring process the melt was poured into the sand casting mold as shown in Figure 3.11 and get a desired shape of casting as shown in Figure 3.12

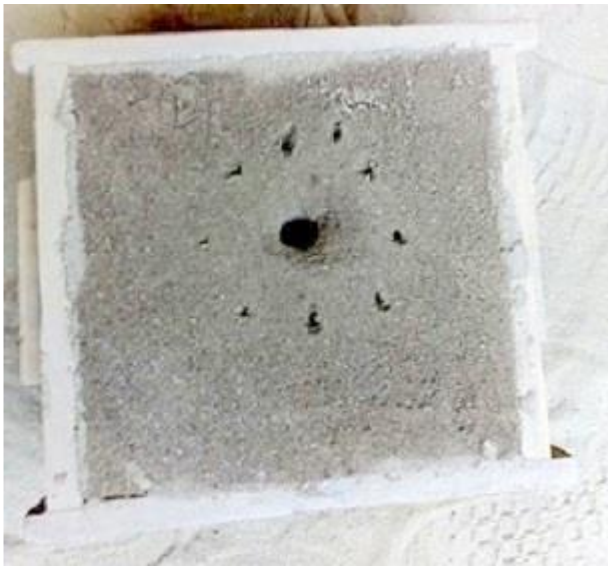

Figure 3.11: Sand casting mold

Figure 3.12: Composite casting of desired shape

8. After solidification the casting were taken out from the mold and then cut the samples according to desired test specimen.

3.7 Characterization of composite material

In the present study, the main purpose of characterization is to determine the effectiveness of the hybrid metal matrix composites in the wear resistance and friction behavior. The characterization methods used here are: Rockwell hardness testing, Metallographic analysis, (metallurgical microscope, XRD, SEM), density measurement, pin -on- disk wear testing and coefficient of friction measurement. They are discussed below in details.

3.7.1 Density Measurement

The densities of a stir cast hybrid aluminium metal matrix composites were measured by Archimedes principle, which provides an easy and accurate method for determining the density of several irregular solids. Due to the irregular shape of the composites sample, it is difficult to calculate their volume directly by using their dimensions. So the volume of composite sample is determined by using water displacement. The mass of composite was measured on a highly accurate digital weighing balance with an accuracy of 0.0001g.

Procedure:

a) Record the mass of a composite sample using a balance.
b) Add approximately 20 ml of water in a graduated cylinder and record the initial volume.
c) Add the metal piece carefully in to the graduated cylinder and record the final volume.
d) The volume of the composite is equal to the volume change in the graduated cylinder.
e) Then we can use the equation below to determine the density of specimen.

ρ =Mass of composite sample/ volume displaced by sample

(According to the Archimedes principle, volume of object is equal to volume displaced by it in liquid.)

3.7.2 Hardness Measurement

Surface properties of a composite play a main role in wear and friction behavior. Hardness represents the mechanical property of the material. Hardness is a quick and very simple method to obtain the mechanical property of the material. The basic principle of the hardness test is to provide a force through the indenter on a specimen surface and measured the dimensions of the indentation. The Rockwell scale is a hardness scale which is categorized according to the hardness of a material. The Rockwell testing machine measures the hardness on the basis of depth of penetration of an indenter as compared to the penetration made by preload. The result is a dimensionless number like as HRA, HRB, HRC, etc. The last alphabetical letter represents the Rockwell scale. Rockwell hardness testing machine is shown in Figure 3.13

In the present study, the hardness of a stir cast hybrid MMCs was performed on a B scale with ball diameter 1.588mm and a load of 100kgf. Hardness was measured at five different locations on both sides of a sample and sample is cut between the centers of the composite material. The average reading of the five different locations was reported.

Figure 3.13: Rockwell hardness testing machine
(Courtesy: Strength of Material Lab, Thapar University, Patiala)

3.8 Metallographic Analysis

Metallographic analysis is a powerful quality tool (Metallurgical microscope, X-ray diffractometer, SEM, etc) to investigate the microstructural examination and primary characteristics of a hybrid metal matrix composite. These are discussed below:

3.8.1 Metallurgical Microscope

Metallurgical microscope shown in Figure 3.14 is an optical microscope which uses a visible light and a system of lenses is to magnify the images of small samples. The images are captured by the high pixel light sensitive camera which generates the micrograph of the material surface. It has different lenses like 10x, 20x, 50x, 100x. Optical microscope is used to observe the internal structure of the metals at different scale and provide a qualitative and quantitative description. In the present study metallurgical microscope is used to analyses the shape, size and dispersion of the reinforcement particles in the matrix alloy. Before examining the structure of hybrid metal matrix composite, samples are well polished with the help of fine grade emery paper and then etched with a Keller etching solution for 20- to 40 seconds.

Figure 3.14: Metallurgical Microscope
(Courtesy: Advanced metallurgical lab, Thapar University, Patiala)

3.8.2 Scanning Electron Microscope (SEM)

A scanning electron microscope (SEM) shown in Figure 3.15 is a type of electron microscope which produces an images of a specimen by scanning it with a highly focused beam of high energy electrons. The electrons are interacting with the atoms of the specimen and generate a various types of signals at the surface of the solid specimen that can be detected and produce the information about the sample's surface topography and morphology. The high energy electron beam is mainly scanned a raster scan pattern, and the beam's position is combined with the detected signal to produce an image. SEM as shown in Fig. 3.15 (Make: JSM-6510LV, JEOL Ltd, Tokyo, Japan) is a highly accurate and precise instrument 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). The SEM testing was used to study the worn surfaces and wear mechanism. This facility is available at SAI Lab, Thapar University, Patiala.

Figure 3.15: Scanning electron microscope
(Photo courtesy: SAI Labs, Thapar University Campus, Patiala)

3.8.3 X-Ray Diffractometer

X-ray diffraction (XRD) shown in Figure 3.16 is a non-destructive rapid analytical technique. It is generally used for identification of an unknown crystalline material, study of crystal structure, and atomic spacing. X-ray diffraction is working of the principle of Bragg's law. The X-rays are generated by the cathode tube which is passed through the collimated lens and to focus on the material sample. The samples and X- rays interact with each other and produce a diffracted ray. These diffracted X-rays are then detected, processed and counted. When the incident X-rays fall on the sample and it satisfies the Bragg Equation, constructive interference and a peak intensity occurs. A detector records and processes this X-ray signals then it converts the signal to a count rate which is then output to a device such as computer monitor .The 2θ range is varied from 2 -80 degree.

Figure 3.16: X-ray diffractometer
(Photo courtesy: SAI Labs, Thapar University Campus, Patiala)

3.9 Wear testing on Pin-on-Disk Apparatus

3.9.1 Sample Preparations for Wear tests

The wear pin samples were cut from the stir cast hybrid metal matrix composite material with a height 40mm and 6mm diameter hemispherical tip are shown in Figure 3.17. The Pin samples were polished with a fine emery paper of grades 600, 800, 1000 and 2000 on a polishing machine shown in Figure 3.18 before conducting the dry sliding wear tests. Dry sliding wear test were performed according to the ASTM G99-95a standards. The material of counter disc was EN32. The disc had a diameter of up to 80 mm and thickness of 8 mm. The pin and disc are cleaned by acetone before and after performing the wear test.

Figure 3.17: Pin samples

Figure 3.18: Polishing machine

3.9.2 Experimental Setup

The pin-on-disk apparatus (DUCOM make), shown in Figure 3. 19 was used to examine the dry sliding wear characteristics and the coefficient of friction of the hybrid metal matrix composites. A pin which is made up of composite material is rest on a rotating disc under the effect of a dead weight. Influencing parameters such as normal load, sliding velocity, wear track diameter and sliding distance is to be set according to the design of experiment

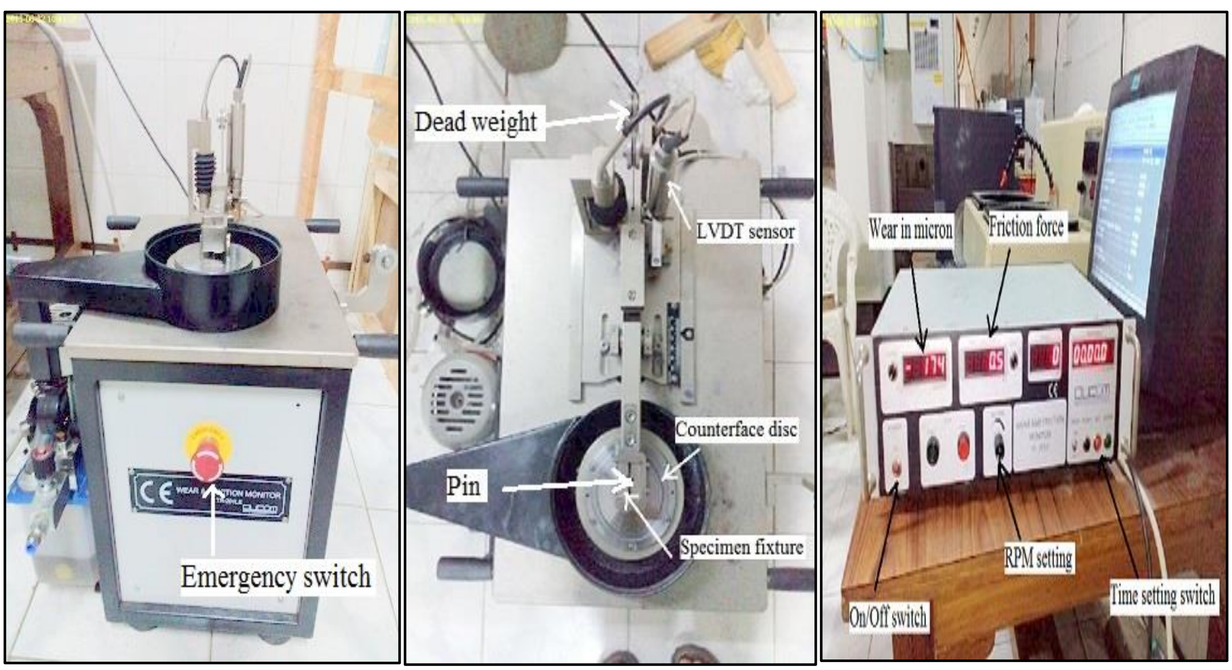

Figure 3.19: Components of pin-on-disk test apparatus

3.9.3 Experimental Procedure

Different composite samples are tested on pin on disk apparatus with applied normal load ranges from 5 -25 N. A varying sliding distance of 700, 1100 and 1500 m was employed, with sliding speed of 0.75, 1.25 and 1.75 m/s. Wear test condition are shown in Table 3.5. Samples were tested at each trial condition according to the L27 orthogonal array shown in Table 3.7 and calculated a dry sliding wear and coefficient of friction. After completed each trial, sample and counter disc were cleaned with acetone to remove dust and worn debris. The sample pin was weighed before and after the trial test with an accuracy of 0.0001 g to calculate the amount of wear loss. The friction forces were directly obtained from the automatic digital reading and then calculate coefficient of friction in terms of dividing the friction force by normal applied load.

Table 3.5: Wear test condition

Pin material	Al hybrid composites
Disc material	EN31 steel disc
Sliding speeds	0.75m/s to 1.75m/s
Track diameter	50 mm to 80mm
Loads	5-25 N
Temperature	Room temperature (not constant)
Sliding distance	700 m to 1500m

3.10 Experimental Design

In the present study Taguchi method was used to investigate the Tribological behavior of a hybrid metal matrix composite. Further the analysis of variance (ANOVA) is used to determine the most significant factor and their interactions.

3.10.1 Taguchi Method

When the number of process parameters and their levels are more, it is too difficult to perform a large number of experiments, according to the full factorial design. To overcome this problem the Taguchi method gives a special design of standard orthogonal arrays which helps to investigate the entire parameter space with only a limited number of experiments. Taguchi's techniques [Roy, 1990] consist of an experimental plan to obtain information about the behavior of a process. Further the responses are analyzed by analysis of variance.

3.10.2 Analysis of Variance

ANOVA was first described by Sir Ronald Fisher a British Statistician. ANOVA is a method to find the significant factor and measure its variability into identifiable sources of variation. The F-test is a ratio of sample variances. Comparing the F-ratio of a source with the tabulated F-ratio is called the F-test. When Analysis of Variance has been performed on a set of data and the respective sums of squares have been calculated, it is possible to use this information to distribute the corrected sums of squares to the appropriate factors. Comparing this value with the total sum of squares gives the percent of contribution of each factor. The percent contribution due to error provides an estimate of the adequacy of the experiment. Since 'error' refers to unknown and that cannot be controlled factors, the percent contribution due to error suggests that if the sufficiency due to error is low (15% or less), then it can be assumed that no important factors have been omitted from the experiment.

SST = SSF + SSE

SST = $\sum (Y_j - Y_m)^2$

Where, SST = Total sum of squared deviations about the mean.

Y_j= Mean response for jth experiment.

Y_m= Grand mean of the response.

SSF = Sum of squared deviations due to each factor.

SSE = Sum of squared deviations due to error.

In the ANOVA table mean square deviation is defined as:

MS = Mean Square

$$\text{MS} = \frac{\text{SS(sum of squared division)}}{\text{DOF (Degree of Freedom)}}$$

F-value of Fisher's F ratio (Variance ratio) is defined as:

$$\text{F} = \frac{\text{MS for a term}}{\text{MS for the error term}}$$

Depending on F value, P-value (probability of significance) is then calculated. If P-value for a term appears less than 0.05 (For 95% confidence level) then it can be concluded that the effect of the factors / interaction of factors is significant on the selected response.

3.10.3 Design of Experiment

The selection of independent factors to investigate the dry sliding wear and coefficient of friction of the hybrid composite is based upon the understanding of process and literature survey. In the present study four factors such as composition, normal load, sliding distance and sliding velocity at three levels are predominantly govern the tribological parameters like wear rate and coefficient of friction. The level of these factors are selected for the experiment shown in Table 3.6. Wear volume loss and the coefficient of friction are the response variables to be studied. The experimental plan consist of 27 trial tests are shown in Table 3.7. The selected orthogonal array was the L27 (3^{13}), with 27 rows and 13 columns at three levels. The four factors composition, load, sliding distance and sliding velocity are assigned in a 1,2,5,9 column respectively and remaining columns are assigned in their interactions.

Table 3.6: Levels for various control factors

Control factors	Units	Level I	Level II	Level III
A: Gr/MoS_2 Reinforcement	wt.%	0	1	2
B: Load	N	5	15	25
C: Sliding distance	m	700	1100	1500
D: Sliding speed	m/s	0.75	1.25	1.75

3.10.4 Degree of Freedom (DOF)

According to the rule that degree of freedom for an orthogonal array should be greater than or equal to sum of those wear parameters. In L27 orthogonal array, it consist a 26 degree of freedom. The number of factors, levels and their interactions determine the total required degree of freedom for the entire experiment. The degree of freedom for each factor is given by the number of levels minus one.

DOF for each factor: L-1

Table 3.7: L27 Orthogonal array with design factors.

	1	2	3	4	5	6	7	8	9	10	11	12	13
Trial No.	A	B	AXB	AXB	C	AXC	AXC	BXC	D	--	BXC	--	--
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Where L is the number of level for each factor

DOF for interactions between factors: $(L_A-1) \times (L_B-1)$

Where L_A and L_B are number of level for factor A and B

3.11 Summary of the Chapter

This chapter puts forward the design of the present study. The chapter mentions the work plan and the key issues that to be adopted to fulfill the objective of the work. This chapter discussed about the materials selection, machine and equipment's used to process and fabricate the hybrid metal matrix composite. It describes the characterization procedure of composite material and their Design of experiment.

CHAPATER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter deals with the detailed discussion of the results of mechanical, metallurgical properties and tribological behavior of the hybrid MMCs. The effect of various influencing parameters of dry sliding wear and coefficient of friction on metal matrix composites and hybrid metal matrix composites were optimized using ANOVA with Taguchi method. Also, structure of composites, SEM micrographs of worn surfaces and the XRD analysis results are presented.

4.2 Density of the Composites

Density of the composites was measured with the help of the Archimedes Principle. The densities of the aluminium alloy and hybrid composites, according to the weight percentage of the silicon carbide, graphite and molybdenum disulphide particles in composites are shown in Figure. 4.1 The Density of silicon carbide particulates (3.21 g/cm^3) is higher than the aluminium 6063 alloy (2.68 g/cm$^{3)}$) and hence the increase in silicon carbide content in Al matrix will increase the density of the composite. The density of the graphite (2.16 g/cm^3) is less than both the SiC and Al6063 and due to this it is observed that there is a slightly reduction in density of the hybrid Al6063/ 5wt. % SiC/x wt. % Gr (x=1 and 2) MMCs as compared to Al6063/5wt. % SiC composite, but it is still more than the base alloy Al6063.

Table 4.1: Density of the hybrid composites

S. No.	Composition in wt. %	Density (g/cm^3)
1	Base Alloy Al6063	2.6800
2	Al6063/5wt. % SiC	2.7065
3	Al6063/ 5wt. % SiC/1wt. % Gr	2.7013
5	Al6063/ 5wt. % SiC/2wt. % Gr	2.6961
4	Al6063/5wt. % SiC/1 wt.% MoS_2	2.7303
6	Al6063/5wt. % SiC/2 wt.% MoS_2	2.7505

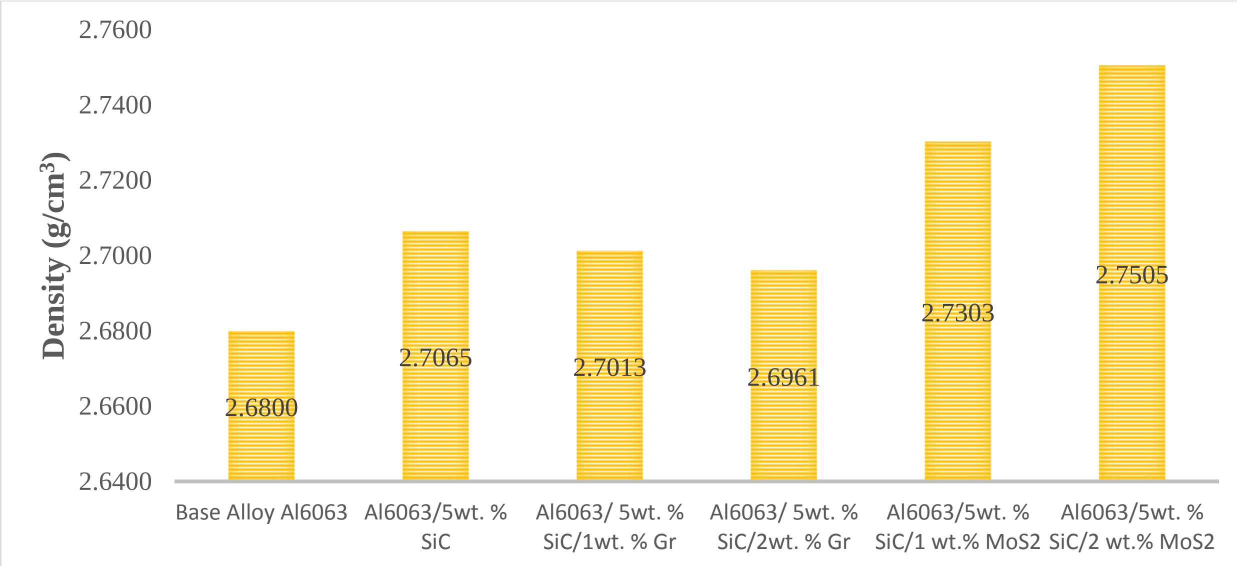

Figure 4.1: Variation of density in Al 6063 and hybrid composites with different weight percentage of SiC, Gr and MoS_2

Density of silicon carbide particulates (3.21 g/cm^3) and molybdenum disulphide particulates (5.06 g/cm^3) is higher than the aluminium alloy; and due to this, the increase in reinforcement (SiC and MoS_2) weight percentage will increase the density of the hybrid composites and was found maximum at 2% wt % of MoS_2 in hybrid composite. It is observed that density of MoS_2 hybrid composite is more than the Gr hybrid composite at the same composition.

4.3 Hardness of the Composites

Hardness of the composites was measured by the Rockwell hardness testing machine. The hardness of the aluminium alloy and hybrid composites, according to the weight percentage of the reinforcement (silicon carbide, graphite and molybdenum disulphide) particles is shown in Table 4.2.

It can be understood from the Figure 4.2 that the hardness of the composites was improved with the increase in weight percent of SiC but due to the soft nature of graphite, hardness is slightly decreased with the addition of graphite in Al6063/ 5wt. % SiC/x wt. % Gr (x=1 and 2) hybrid composite.

It is observed that the hardness is increased with the increase content of MoS_2 reinforcement in hybrid composite and found maximum at 2 wt. percentage. The enhancement in hardness of the hybrid composite is due to the hard SiC reinforcement particles, uniform distribution of SiC in the hybrid composites and the increased density of the composites.

Table 4.2: Hardness of the hybrid composites

S. No.	Composition in wt. %	Avg. Hardness (HRB)
1	Base Alloy Al6063	48
2	Al6063/5wt. % SiC	61
3	Al6063/ 5wt. % SiC/1wt. % Gr	60
5	Al6063/ 5wt. % SiC/2wt. % Gr	58
4	Al6063/5wt. % SiC/1 wt.% MoS_2	64
6	Al6063/5wt. % SiC/2 wt.% MoS_2	66

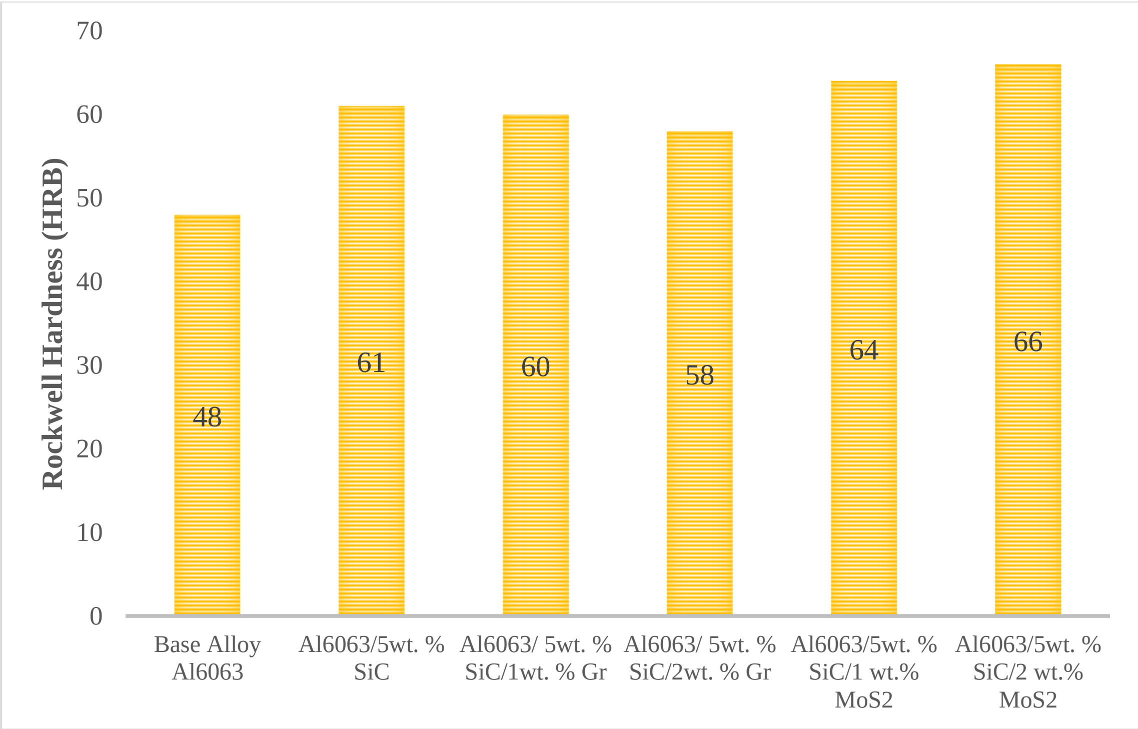

Figure 4.2: Variation of hardness in Al 6063 and hybrid composites with different weight percentage of SiC, Gr and MoS_2

4.4 Microstructure Analysis

The optical micrographs of Al 6063 alloy and hybrid metal matrix composite fabricated by stir casting are shown in Figure 4.3 (a)-(d). All samples are polished with the help of fine grade of emery paper. The polished specimens were cleaned with acetone and etched with etching (30% HCL in water) solution. It is observed from the figure that all reinforcement particles (SiC, Gr, MoS_2) are uniformly dispersed in the matrix which may be due to the effective stirring action and the use of appropriate process parameters. Figure 4.3 (a) shows the microstructure of stir cast AA 6063 matrix. The micrographs reveal the dumb bell shape structure of the graphite particles and grain shape structure of the SiC particles. It is clearly observed in micrographs there is no cracks and agglomeration found in the matrix.

Figure 4.3 (a): Optical micrograph of Al 6063 at 20X

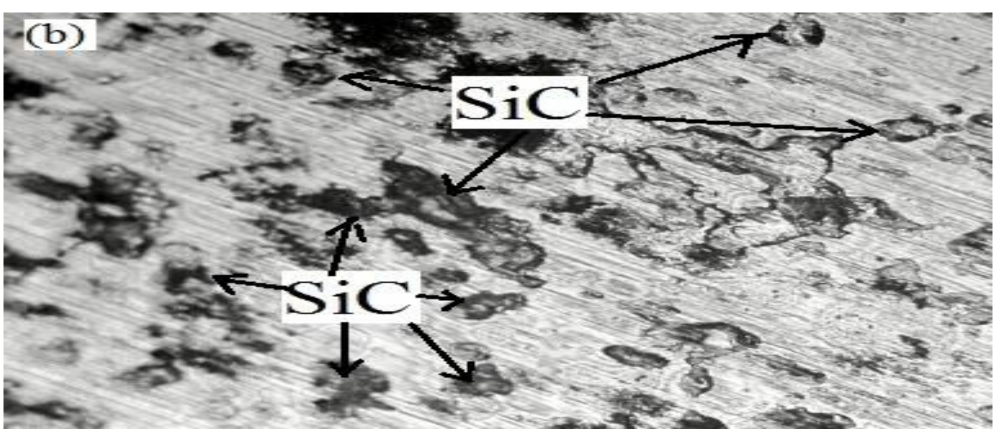

Figure 4.3 (b): Optical micrograph of Al6063/5wt. %SiC composite at 20X

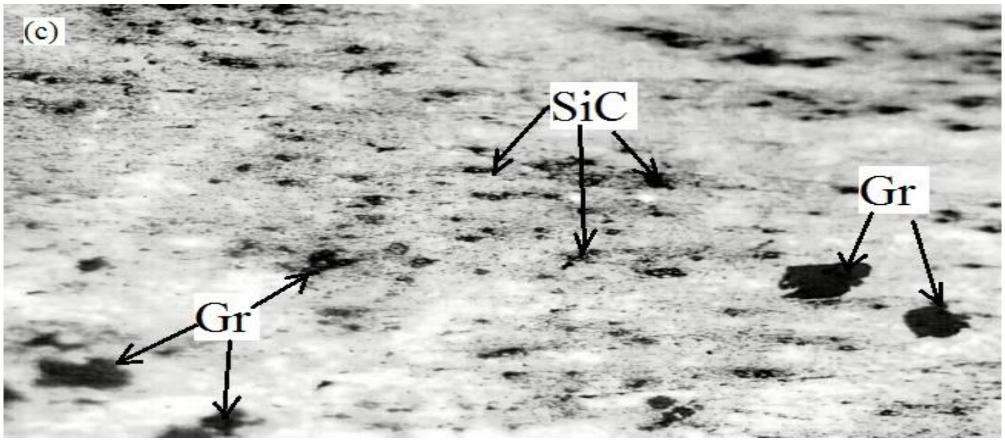

Figure 4.3 (c): Optical micrograph of Al6063/5wt. %SiC/2wt. %Gr hybrid composite at 20X

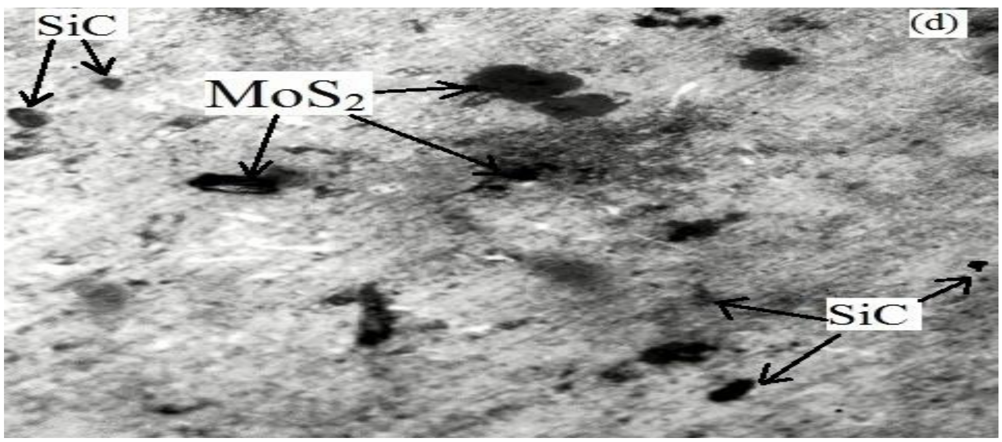

Figure 4.3 (d): Optical micrograph of Al6063/5wt. %SiC/2wt. %MoS_2 hybrid composite at 20X

4.5 X-ray Diffraction Analysis

The X-ray diffraction results of the aluminium alloy and its hybrid metal matrix composites are shown in Figure 4.4(a) (b) (c). XRD gives the details information about the elements and compounds present in the fabricated composites. The results of XRD reveals that the presence of aluminium (in the largest peaks), the presence of silicon carbide particles (second largest peak), MoS_2 and graphite (carbon) indicated by minor peaks. A sharp visible carbon peak is observed in the hybrid composites. Results show that there is no oxygen reaction in the samples during the casting process because compounds of aluminium oxide are not found. It was found that the crystallinity percentage of the hybrid composites is more than 40%. The XRD spectrum patterns indicated that the reinforcement particles are well distributed in the aluminium matrix. The XRD pattern confirmed the presence of aluminium, SiC, Gr (Carbon) and MoS_2 particles in the hybrid composite.

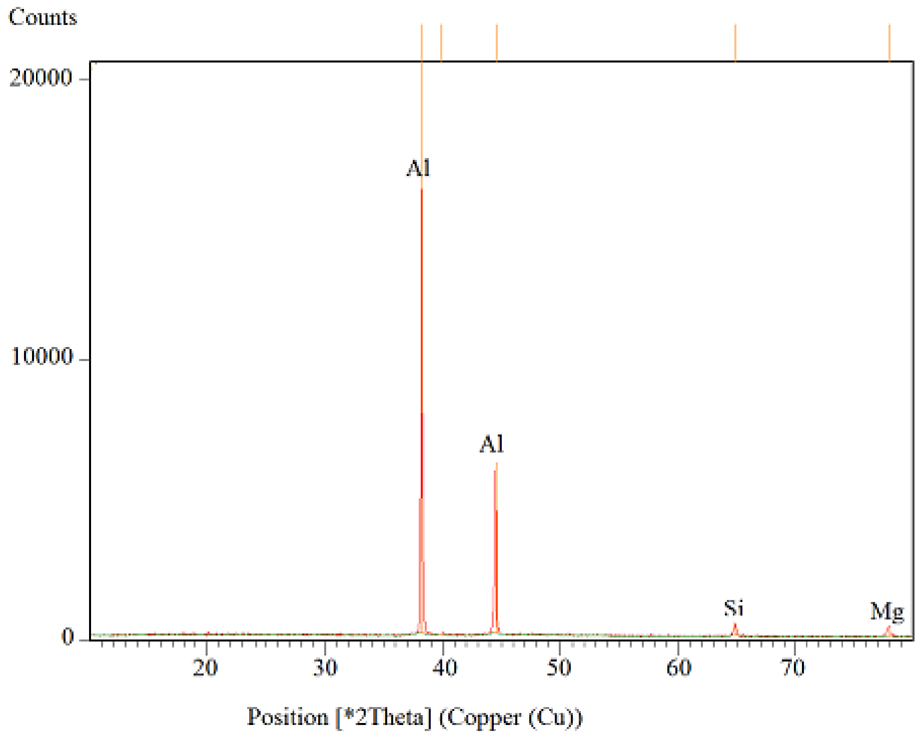

Figure 4.4(a): X-ray diffraction pattern of Al 6063 alloy

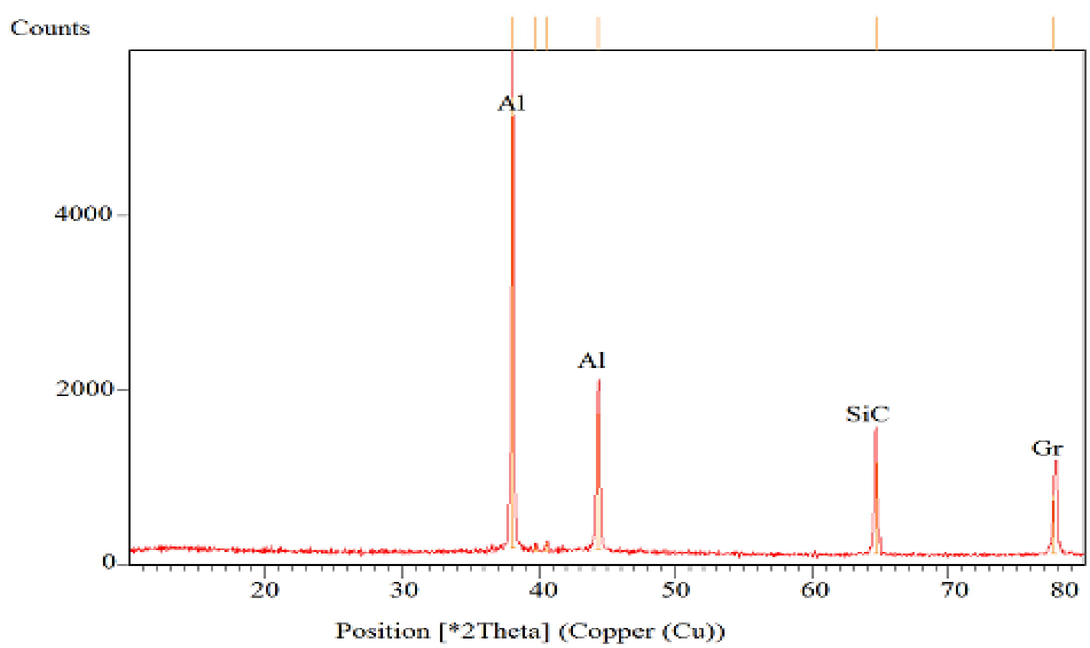

Figure 4.4(b): X-ray diffraction pattern of Al6063/ 5wt. % SiC/2wt. % Gr

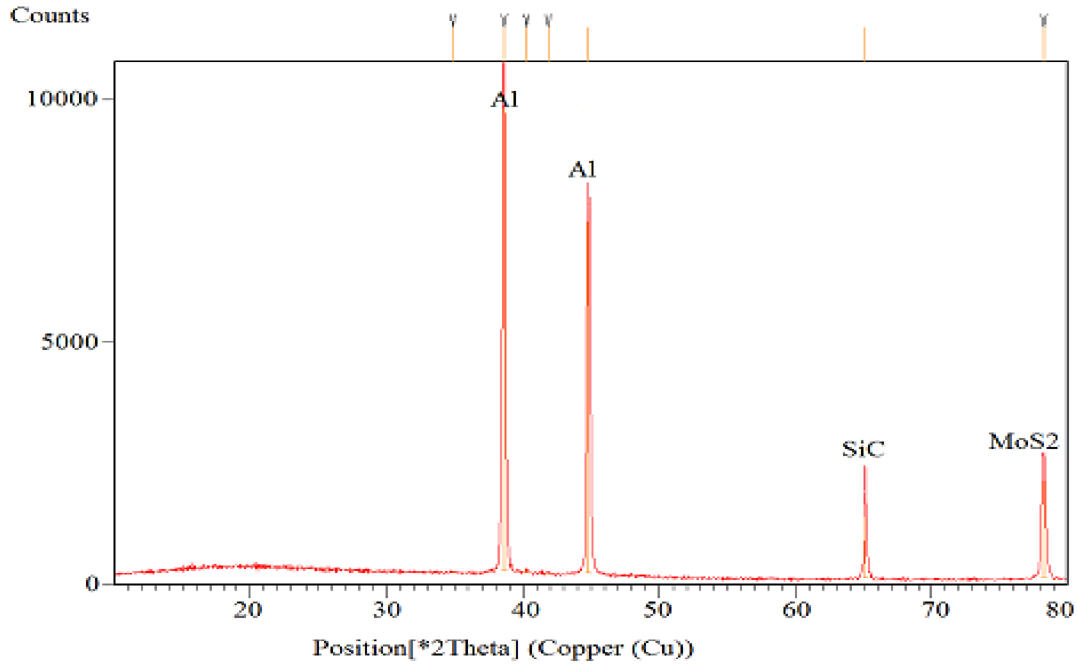

Figure 4.4(c): X-ray diffraction pattern of Al6063/ 5wt. % SiC/2wt. % MoS_2

4.6 Wear Mechanism

The SEM images of the worn surface of Al 6063 alloy and the hybrid composite specimens are tested on pin on disc apparatus at a load of 25 N are shown in Figures 4.5–4.7 The wear pattern, mechanism and worn surface morphology of Al 6063 alloy are shown in figure 4.5 The worn surface of the Al 6063 matrix clearly shows that the deep grooves, presence of large debris on the worn surface, micro cutting, large burrs size at the edge, plastic deformation at high loads and fracture of oxide have caused an increase wear rate. It is observed that in Al 6063 alloy there is a large severe plastic deformation as compare to other hybrid composites (Fig 4.6-4.7). 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 ductile behavior of Al.

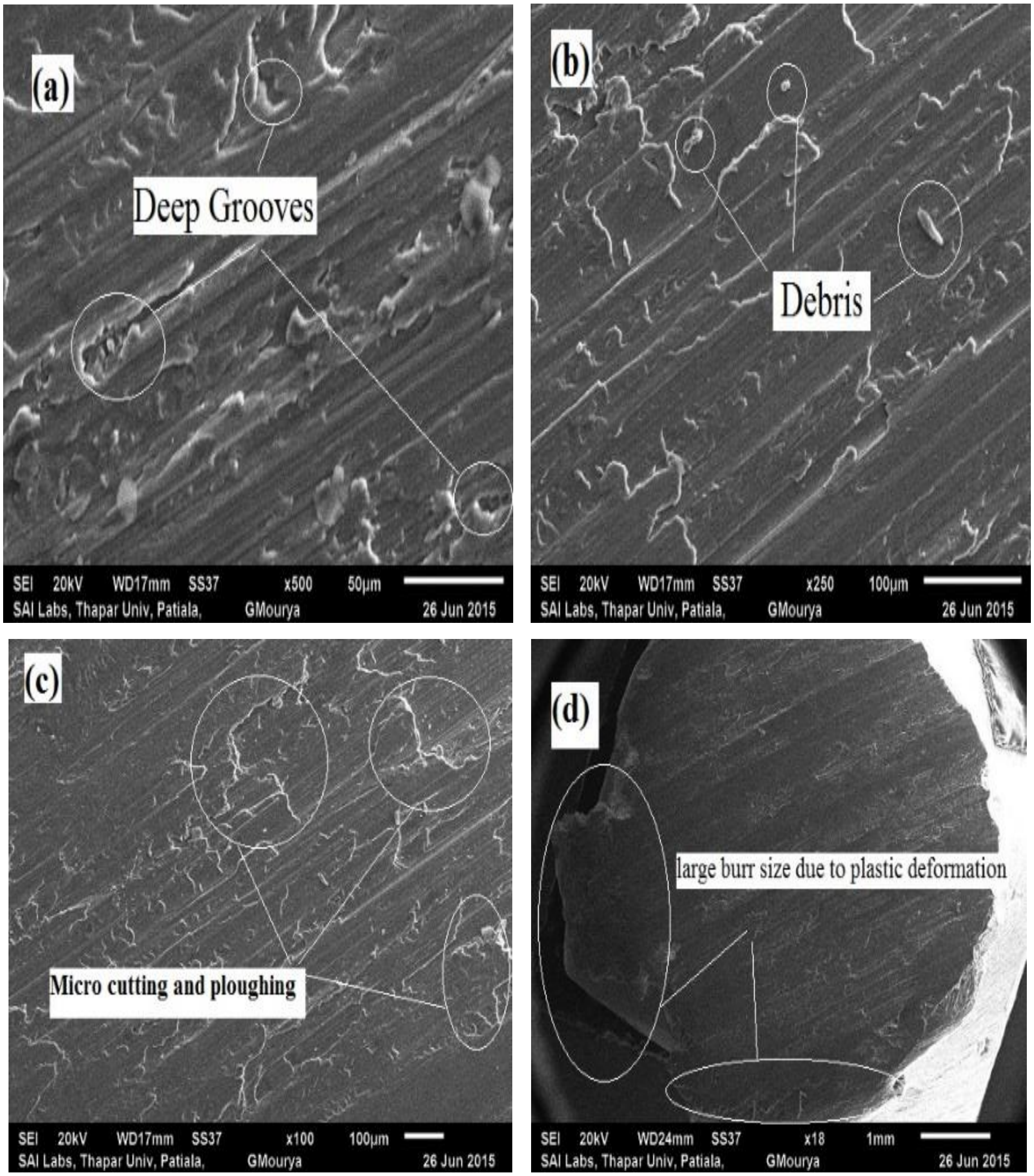

Figure 4.5: SEM morphologies of the worn surface of Al 6063 matrix at applied load of 25 N.

The worn surface morphology of the Al6063/ 5wt. % SiC/2wt. % Gr composite is shown in Figure 4.5. The worn surface of a hybrid Al6063/ 5wt. % SiC/2wt. % Gr composites is changed due to the reinforcement of SiC and Gr lubricant. It is observed that the surface of composite was smooth with small grooves and fine debris. The burr size at the edge of the worn surface is very small as compare to Al 6063 matrix. The material is mainly wear out on the surface of the pin due to the ploughing and fracture of oxide particles.

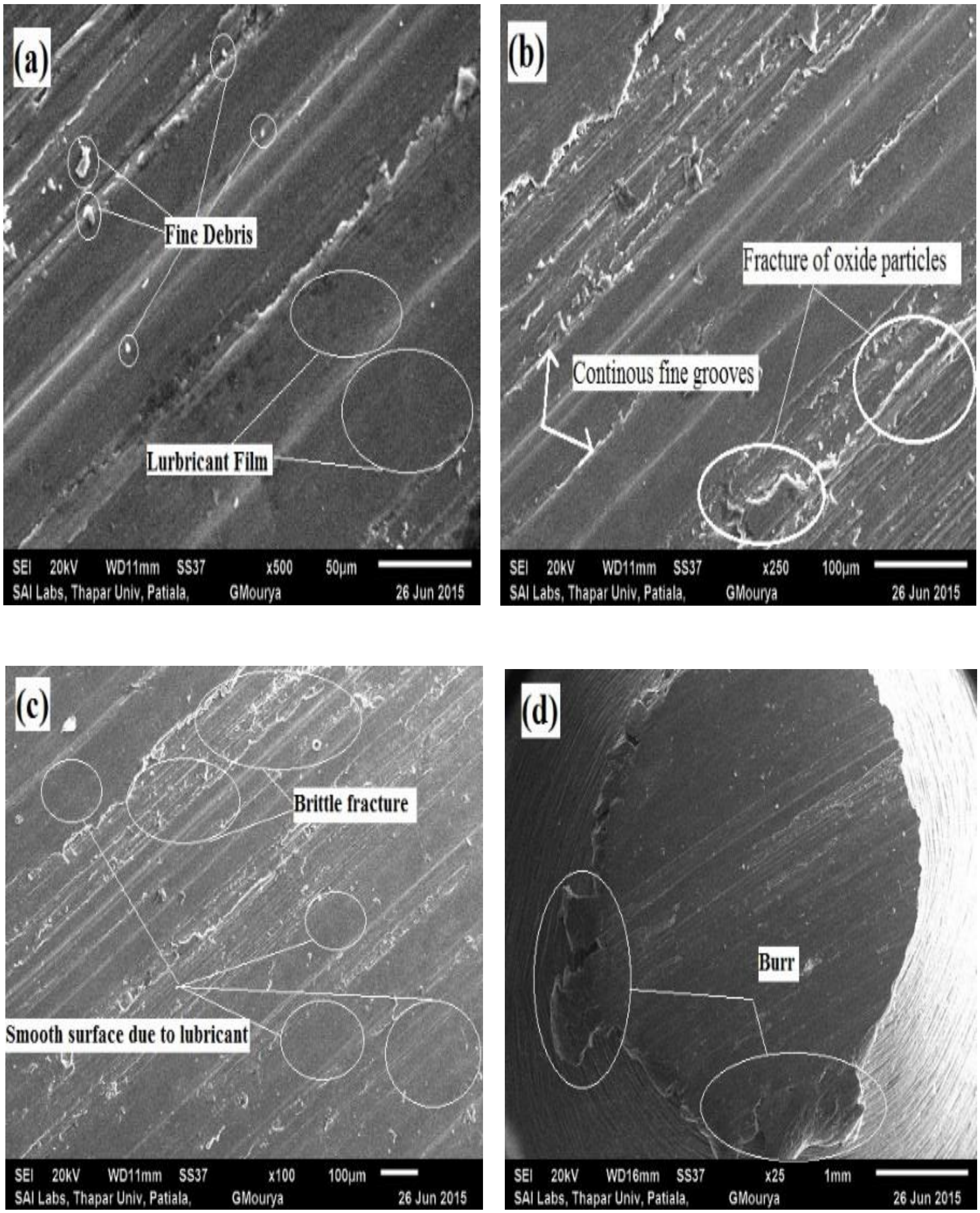

Figure 4.6: SEM morphologies of the worn surface of Al6063/ 5wt. % SiC/2wt. % Gr matrix at applied load of 25 N.

The worn surface morphology of the Al6063/ 5wt. % SiC/2wt. % MoS_2 composite is shown in Figure 4.7. The surface clearly show that the smooth wear pattern, very fine debris and burr at the edge of the surface. It is due to the MoS_2 tribo layer between the contacting pairs. MoS_2 forms an adherent film between the contact surface so due to this it leads to decrease the plastic deformation on the pin sample. A sharp delaminated layer is observed on the worn surface which separates the contacting pair and due to this reduction in a wear rate.

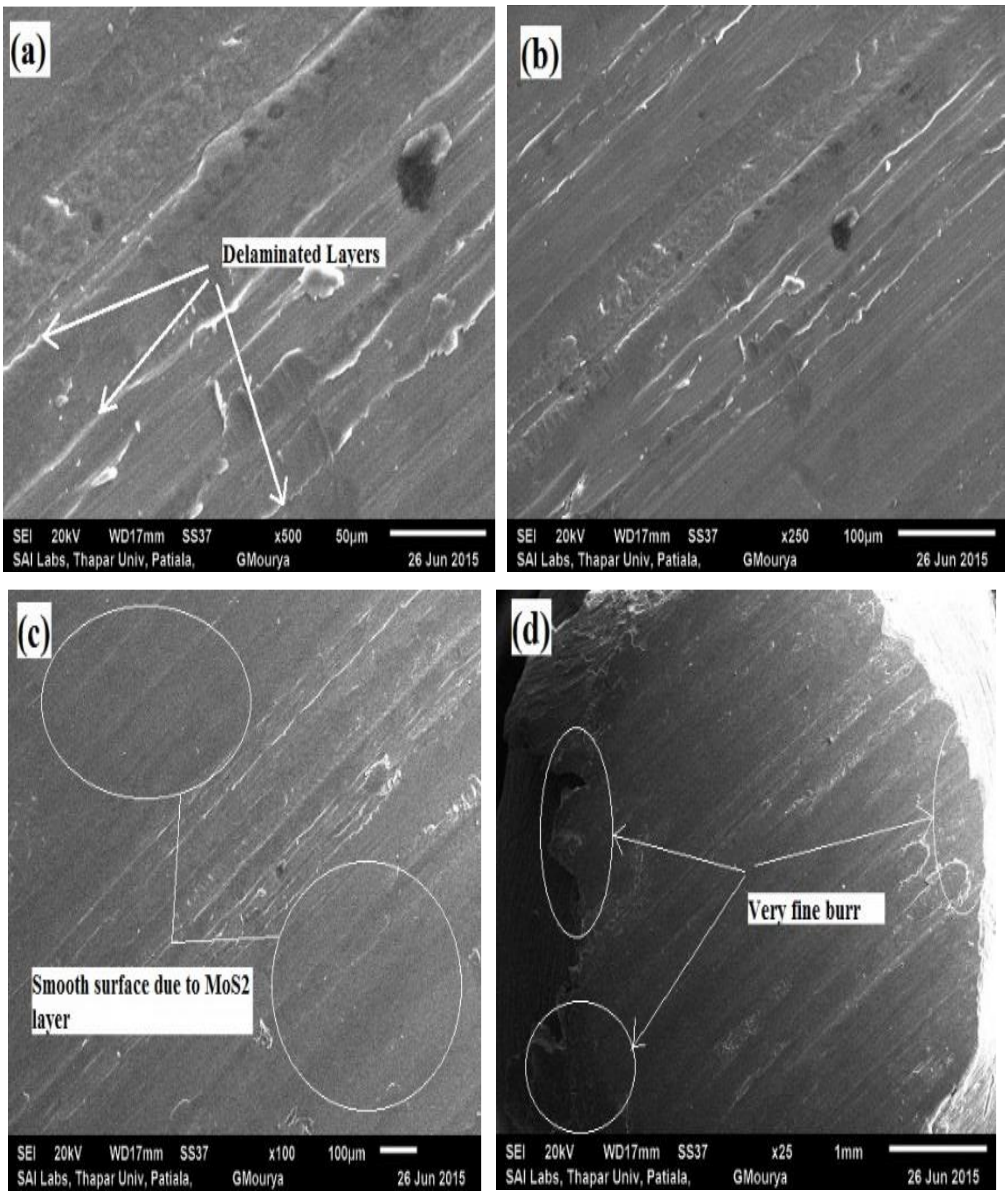

Figure 4.7: SEM morphologies of the worn surface of Al6063/ 5wt. % SiC/2wt. % MoS_2 matrix at applied load of 25 N.

4.7 Statistical Analysis of dry sliding test

In a present study the four main parameters were studied at three levels which influence a loss of wear volume and coefficient of friction. The experiments were performed according to the L27 (2^{13}) orthogonal array. Mean-response graphs of individual factors and their interactions were plotted using Minitab-16 software and the percentage of contribution of various factors was determined by ANOVA analysis.

4.8 Dry Sliding test of Al6063/SiC/Gr Hybrid Composites

In this section dry sliding wear behavior of Al6063/5wt. %SiC and Al6063/5wt.%SiC/x wt. % of Gr (x=1, 2) hybrid composites has been studied and their effect of parameters are discussed. All the factors and their levels which are considered for analyses a wear behavior and coefficient of friction are shown in Table 4.3. Experimental design using L27 (3^{13}) orthogonal array and their corresponding experimental results (wear rate in mm^3/m and coefficient of friction) are shown in Table 4.4

Table 4.3: Designed experimental factors and their levels (Gr)

Control factors	Units	Level I	Level II	Level III
A: Gr Reinforcement	wt.%	0	1	2
B: Load	N	5	15	25
C: Sliding distance	m	700	1100	1500
D: Sliding velocity	m/s	0.75	1.25	1.75

Table 4.4: Experimental design using L27 (3^{13}) orthogonal array and corresponding experimental results (Gr)

L27 (3^{13})	A	B	C	D	Wear loss (gram)	Wear volume (mm^3)	Wear rate (mm^3/m) x 10^{-3}	Specific wear rate (mm^3/N-m) x 10^{-3}	Coefficient of friction
1	0	5	700	0.75	0.0035	1.2932	1.8474	0.3695	0.238
2	0	5	1100	1.25	0.0047	1.7366	1.5787	0.3157	0.320
3	0	5	1500	1.75	0.0057	2.1060	1.4040	0.2808	0.318
4	0	15	700	1.25	0.0036	1.3301	1.9001	0.1267	0.323
5	0	15	1100	1.75	0.0045	1.6627	1.5115	0.1008	0.324
6	0	15	1500	0.75	0.0105	3.8795	2.5863	0.1724	0.313
7	0	25	700	1.75	0.0054	1.9952	2.8503	0.1140	0.334
8	0	25	1100	0.75	0.0086	3.1775	2.8866	0.1155	0.335
9	0	25	1500	1.25	0.0109	4.0273	2.6849	0.1074	0.331
10	1	5	700	1.25	0.0023	0.8514	1.2163	0.2433	0.122
11	1	5	1100	1.75	0.0031	1.1476	1.0433	0.2087	0.149
12	1	5	1500	0.75	0.0063	2.3322	1.5548	0.3110	0.270
13	1	15	700	1.75	0.0028	1.0365	1.4807	0.0987	0.216
14	1	15	1100	0.75	0.0055	2.0361	1.8510	0.1234	0.208
15	1	15	1500	1.25	0.0067	2.4803	1.6535	0.1102	0.207
16	1	25	700	0.75	0.0041	1.5178	2.1683	0.0867	0.206
17	1	25	1100	1.25	0.0056	2.0731	1.8846	0.0754	0.184
18	1	25	1500	1.75	0.0099	3.6649	2.4433	0.0977	0.186
19	2	5	700	1.75	0.0018	0.6676	0.9537	0.1907	0.159
20	2	5	1100	0.75	0.0031	1.1498	1.0453	0.2091	0.229
21	2	5	1500	1.25	0.0038	1.4094	0.9396	0.1879	0.107
22	2	15	700	0.75	0.0032	1.1869	1.6956	0.1130	0.268
23	2	15	1100	1.25	0.0033	1.2240	1.1127	0.0742	0.179
24	2	15	1500	1.75	0.0041	1.5207	1.0138	0.0676	0.155
25	2	25	700	1.25	0.0025	0.9273	1.3247	0.0530	0.293
26	2	25	1100	1.75	0.0034	1.2611	1.1465	0.0459	0.173
27	2	25	1500	0.75	0.0077	2.8560	1.9040	0.0762	0.163

4.8.1 ANOVA and the Effects of Factors (Gr)

To get an influence of selected factors such as Gr wt. %, load, sliding distance, sliding velocity and their interactions, an ANOVA table is developed to find the sequential order of significant factors and their interactions. The results were analyzed for identifying the significant factors at 95% confidence interval.

Table 4.5: ANOVA (mean) for wear rate (Gr)

Source	DOF	SS	Variance (V_e)	F-ratio	F (5%)	SS`	C (%)	
A	2	3.66028	1.83014	32.02	5.14	3.537706	38.77	S
B	2	3.33395	1.66698	29.17	5.14	3.211376	35.20	S
C	2	0.25744	0.12872	2.25	5.14			N.S
D	2	0.90317	0.45159	7.90	5.14	0.780596	8.55	S
A*B	4	0.46147	0.11537	2.02	4.53			N.S
A*C	4	0.07910	0.01977	0.35	4.53			N.S
B*C	4	0.08481	0.02120	0.37	4.53			N.S
Error	6	0.34292	0.05715					
Total	26	9.12315						
e-pooled	20	1.22574	0.061287					

Table 4.6: ANOVA (mean) for coefficient of friction (Gr)

Source	DOF	SS	Variance (V_e)	F-ratio	F (5%)	SS`	C (%)	
A	2	0.089494	0.044747	43.87	5.14	0.08535	61.33	S
B	2	0.006109	0.003055	2.99	5.14			N.S
C	2	0.000661	0.000330	0.32	5.14			N.S
D	2	0.002824	0.001412	1.38	5.14			N.S
A*B	4	0.001281	0.000320	0.31	4.53			N.S
A*C	4	0.018402	0.004601	4.51	4.53			N.S
B*C	4	0.014272	0.003568	3.50	4.53			N.S
Error	6	0.006120	0.001020					
Total	26	0.139164						
e-pooled	24	0.049669	0.00207					

Table 4.7: Response table for mean (Gr)

Level	Wear response				Friction coefficient response			
	A	B	C	D	A	B	C	D
1	2.139	1.287	1.715	1.949	0.3151	0.2124	0.2399	0.2478
2	1.700	1.645	1.562	1.588	0.1942	0.2437	0.2334	0.2296
3	1.237	2.144	1.798	1.539	0.1918	0.2450	0.2278	0.2238
Delta	0.902	0.857	0.236	0.410	0.1233	0.0326	0.0121	0.0240
Rank	1	2	4	3	1	2	4	3

The effect of the main factors on both wear rate and coefficient of friction are shown independently in Figures 4.8(a) and 4.8(b) graphically. In a graph, if the line of the particular influencing parameter is approximately horizontal about the mean line means parameter has not significant effect on the response. On the other hand, a parameter for which the line has the highest inclination, it shows a most significant effect on the response. Table 4.5 shows that the wt. % of graphite (C=38.77%) and load (C=35.20%) has the more influence as compared to other factors on a wear rate. Sliding velocity (C = 8.55%) showed less significant contributions to the wear rate. Sliding distance has no effect on a wear rate. It is observed that in Fig 4.9 (a) the selected interactions had no significant contribution to the wear rate.

Similarly, it can be observed from Table 4.6 the wt. % of Gr reinforcement (C = 61.33%) is the only factor which is effected a coefficient of friction of the hybrid composites. In Fig 4.9 (b) show that all the selected interactions between the factors had no significant effect on coefficient of friction.

4.8.2 Effect of parameters on Wear rate (Gr)

Figure 4.8 (a) shows main effect plot for means of wear rate. The graphs are plotted between controlling parameters and wear rate of hybrid composite. The load is the most significant factor in increasing wear rate. The wear rate is significantly increased with increase of normal load because at higher loads attributed to the more plastic deformation due to cracks in the oxide layer and delamination wear. Reinforced particle (SiC) are not able to support in a matrix material against a higher load so mildly brittle fracture will be occur and due to this wear rate is increased.

The wear rate is decreased with the addition of graphite particles in the composite. Graphite particles act as a lubricant between the contacting surfaces. During wear process, graphite particles are released from the composite material and stick on the track of the disc to form a rich tribolayer and prevent the contact between them. Unreinforced graphite composite shows a maximum wear rate because of direct contact between the surfaces as compare to graphite reinforced composite. Wear loss is decreased mildly with increase the sliding speed due to the formation and survival of the rich layer between the contacting surfaces of the pair.

4.8.3 Optimal Design for wear rate (Gr)

Wear rate is preferred to be lower the best. Weight percentage of Gr, load and sliding velocity are the significant parameters. A3B1D3 from Table 4.7 is the optimal condition for wear rate of hybrid composite.

Optimal value for wear rate is calculated as:

$\eta_{opt} = \bar{m} + (m_{A3} - \bar{m}) + (m_{B1} - \bar{m}) + (m_{D3} - \bar{m})$

$= 1.69 + (1.237 – 1.69) + (1.287 – 1.69) + (1.539 – 1.69)$

$= 1.69 – 0.453 – 0.403 – 0.151$

$= 0.683$

Confidence Interval (C.I.) for optimum value is

$$\text{C.I.} = \sqrt{\frac{f\ \alpha{:}v1{:}v2\ X\ Ve}{neff}}$$

α = risk (0.05) confidence = 1-α

v1 = DOF for mean (which is always 1)

v2 = DOF for error = 20

Where $f\ \alpha{:}v1{:}v2 = f\ 0.05{:}1{:}20$ = F ratio = 4.35

Variance (Ve) = $\frac{\text{Sum of square of error pooled}}{\text{Degree of freedom error pooled}} = \frac{1.22574}{20}$ = 0.061287

n_{eff} = number of tests performed using participating factors

$$n_{eff} = \frac{27}{1+\text{DOF of } significant\ factors} = \frac{27}{7} = 3.85$$

C.I. = 0.263

So, confidence interval of wear rate is $(0.683 \pm 0.263) \times 10^{-3}$ mm^3/m

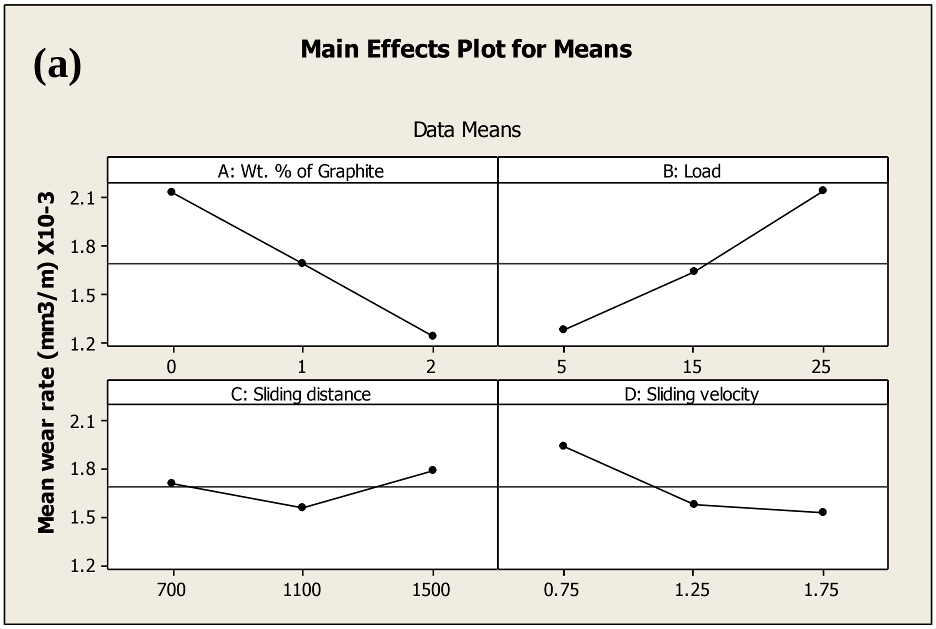

Figure 4.8 (a): Main effects plot for wear rate $(mm^3/m) \times 10^{-3}$ (Gr)

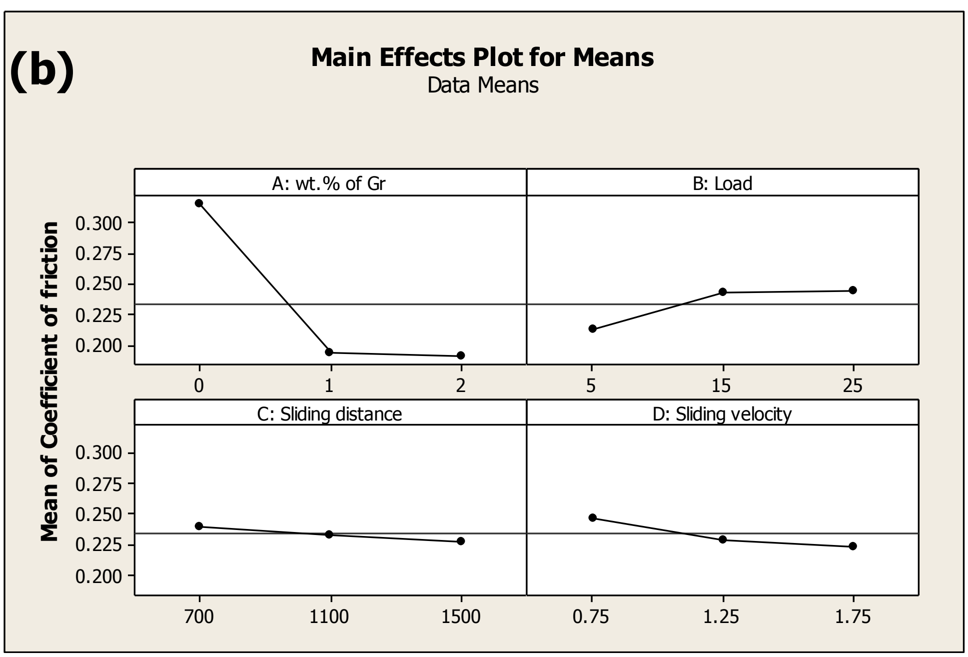

Figure 4.8 (b): Main effects plot for Coefficient of friction (Gr)

4.8.4 Effect of Parameters on Coefficient of friction (Gr)

Figure 4.8(b) shows the main effect plot for coefficient of friction. It is clearly observed in graph the wt. % of Gr is the main significant factor which effects the hybrid composite due to their high inclination. The coefficient of friction decreases with the addition of a graphite. It is minimum at the 2 wt. %. The reduction in coefficient of friction is due to the formation of graphite layer between the contact pair. During wear process graphite particles behave as a lubricant, graphite particles fill the asperities of the worn surface of the pin and also stick on the disc and to prevent the direct contact between the pin and a disc is the main cause of reduce the coefficient of friction.

Load, sliding distance and sliding velocity has an insignificant factor on coefficient of friction because a thin layer of graphite is almost stably maintained between the contact surfaces at all selected loads and speeds.

Coefficient of friction is found higher in unreinforced graphite composite. The high degree of metal to metal contact between surfaces increases the plastic deformation and due to this hard SiC particles are detached from the composite. These hard particles works as an abrasive between the contact surfaces and to form irregular contact surface to cause a high coefficient of friction.

4.8.5 Optimal Design for Coefficient of friction (Gr)

Coefficient of friction is preferred to be lower the best. Weight percentage of Gr is the only significant parameter. A3 from Table 4.7 is the optimal condition for COF of hybrid composite. Optimal value for coefficient of friction is calculated as:

$\eta_{opt} = \bar{m} + (m_{A3} - \bar{m})$

$= 0.23 + (0.1918 – 0.23)$

$= 0.23 – 0.0382$

$= 0.1918$

Confidence Interval (C.I.) for optimum value is

$$C.I. = \sqrt{\frac{f\ \alpha{:}v1{:}v2\ X\ Ve}{neff}}$$

α = risk (0.05)   confidence = 1-α

v1 = DOF for mean (which is always 1)

v2 = DOF for error = 24

Where $f\,\alpha{:}v1{:}v2 = f\,0.05{:}1{:}24$ = F ratio = 4.26

$$\text{Variance (Ve)} = \frac{\text{Sum of square of error pooled}}{\text{Degree of freedom error pooled}}$$

$$\text{(Ve)} = \frac{0.049669}{24}$$

$$= 0.00207$$

n_{eff} = number of tests performed using participating factors

$$n_{eff} = \frac{27}{1+\text{DOF of } significant\ factors} = \frac{27}{3} = 9$$

C.I. = 0.031

So, confidence interval of coefficient of friction is 0.1918 ± 0.031

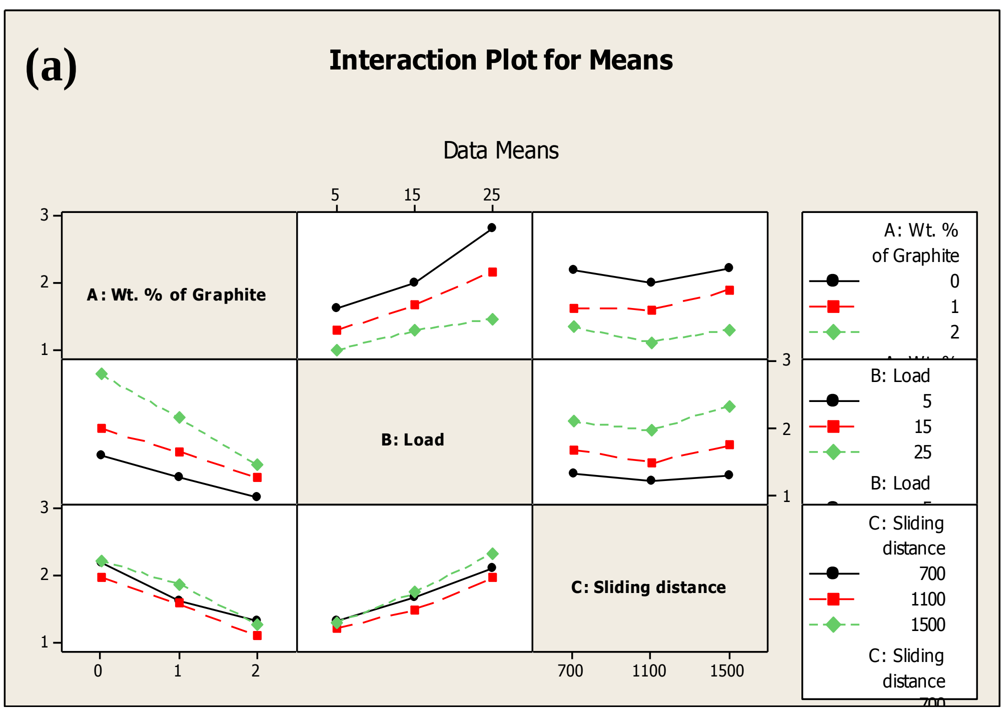

Figure 4.9 (a): Interaction plots for means of wear rate $(mm^3/m) \times 10^{-3}$ (Gr)

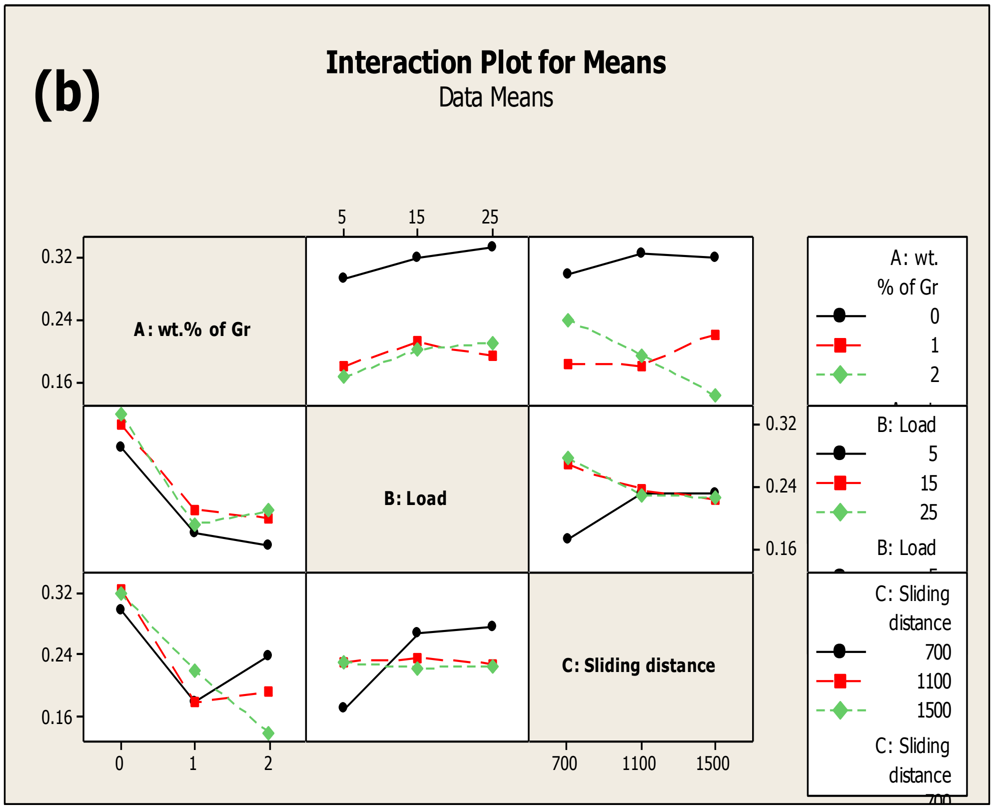

Figure 4.9 (b): Interaction plots for means of Coefficient of friction (Gr)

4.8.6 ANOVA and effect of parameters on Specific Wear rate (Gr)

According to Archard wear model, specific wear rate is the more convenient form of wear characterization parameter, which should be used while comparing the wear behavior of different materials at the same operating condition. Figure 4.10 shows main effect plot for means of specific wear rate. Table 4.9 shows that the load (C=76.44%) and wt. % of graphite (C=12.32%) has the more influence as compare to other factors on a specific wear rate. sliding velocity (C = 3.56%) show less significant contributions to the specific wear rate. Sliding distance has no effect on a specific wear rate.

From Figure 4.10 specific wear rate is decrease with increase a wt. % of Gr, sliding speed and the normal load due to the formation of lubricant layer in between the contacting pairs. Specific wear rate is preferred to be lower the best. A3B3D3 from Table 4.7 is the optimal condition for specific wear rate of hybrid composite (Gr)

Table 4.8: Response table for mean (Gr)

Level	Wear response			
	A	B	C	D
1	0.18921	0.25740	0.15507	0.17520
2	0.15056	0.10967	0.14096	0.14375
3	0.11306	0.08576	0.15680	0.13387
Delta	0.07615	0.17165	0.01585	0.04133
Rank	2	1	4	3

Table 4.9: ANOVA (mean) for specific wear rate (Gr)

Source	DOF	SS	Variance (V_e)	F-ratio	F (5%)	SS`	C (%)	
A	2	0.026094	0.013047	32.98	5.14	0.024902	12.32	S
B	2	0.155578	0.077789	196.94	5.14	0.154386	76.44	S
C	2	0.001360	0.000680	1.72	5.14			N.S
D	2	0.008383	0.004191	10.60	5.14	0.007191	3.56	S
A*B	4	0.005690	0.001422	3.60	4.53			N.S
A*C	4	0.002173	0.000543	1.37	4.53			N.S
B*C	4	0.000315	0.000079	0.20	4.53			N.S
Error	6	0.002374	0.000396					
Total	26	0.201966						
e-pooled	20	0.011912	0.000596					

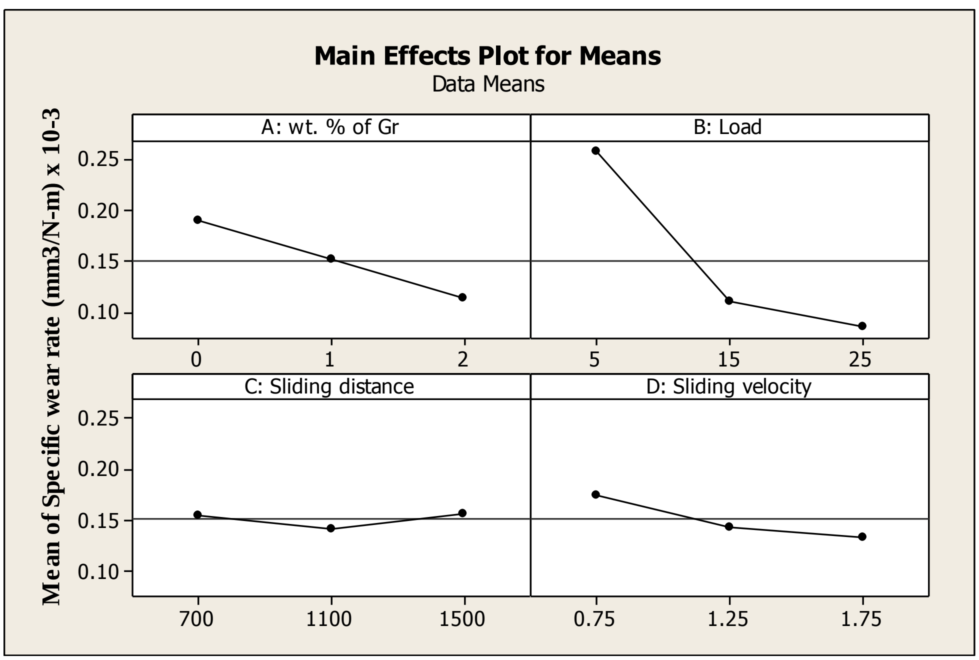

Figure 4.10: Main effects plot for specific wear rate (mm^3/N-m) x 10^{-3} (Gr)

4.9 Dry sliding test of Al6063/Sic/MoS_2 Hybrid composites

In this section dry sliding wear behavior of Al6063/5wt. %SiC and Al6063/5wt.%SiC/x wt. % of MoS_2 (x=1, 2) hybrid composites has been studied and their effect of parameters are discussed. All the factors and their levels which are considered for analyses of wear behavior and coefficient of friction are shown in Table 4.10. Experimental design using L27 (3^{13}) orthogonal array and their corresponding experimental results (wear rate in mm^3/m and coefficient of friction) are shown in Table 4.11

Table 4.10: Designed experimental factors and their levels (MoS_2)

Control factors	Units	Level I	Level II	Level III
W: MoS_2 Reinforcement	wt.%	0	1	2
X: Load	N	5	15	25
Y: Sliding distance	m	700	1100	1500
Z: Sliding velocity	m/s	0.75	1.25	1.75

Table 4.11: Experimental design using L27 (2^{13}) orthogonal array and corresponding experimental results (MoS_2)

L27 (3^{13})	W	X	Y	Z	Wear loss (gm)	Wear volume (mm^3)	Wear rate (mm^3/m) x10^{-3}	Specific wear rate (mm^3/Nm)x10^{-3}	Coefficient of friction
1	0	5	700	0.75	0.0035	1.2932	1.8474	0.3695	0.238
2	0	5	1100	1.25	0.0047	1.7366	1.5787	0.3157	0.320
3	0	5	1500	1.75	0.0057	2.1060	1.4040	0.2808	0.318
4	0	15	700	1.25	0.0036	1.3301	1.9001	0.1267	0.323
5	0	15	1100	1.75	0.0045	1.6627	1.5115	0.1008	0.324
6	0	15	1500	0.75	0.0105	3.8795	2.5863	0.1724	0.313
7	0	25	700	1.75	0.0054	1.9952	2.8503	0.1140	0.334
8	0	25	1100	0.75	0.0086	3.1775	2.8866	0.1155	0.335
9	0	25	1500	1.25	0.0109	4.0273	2.6849	0.1074	0.331
10	1	5	700	1.25	0.0021	0.7691	1.0987	0.2197	0.121
11	1	5	1100	1.75	0.0029	1.0622	0.9656	0.1931	0.209
12	1	5	1500	0.75	0.0062	2.2708	1.5139	0.3028	0.220
13	1	15	700	1.75	0.0026	0.9523	1.3604	0.0907	0.128
14	1	15	1100	0.75	0.0051	1.8679	1.6981	0.1132	0.106

15	1	15	1500	1.25	0.0062	2.2708	1.5139	0.1009	0.181
16	1	25	700	0.75	0.0042	1.5236	2.1766	0.0871	0.259
17	1	25	1100	1.25	0.0056	2.0511	1.8646	0.0746	0.172
18	1	25	1500	1.75	0.0093	3.4062	2.2708	0.0908	0.177
19	2	5	700	1.75	0.0015	0.5454	0.7791	0.1558	0.124
20	2	5	1100	0.75	0.0029	1.0544	0.9585	0.1917	0.121
21	2	5	1500	1.25	0.0038	1.3816	0.9211	0.1842	0.183
22	2	15	700	0.75	0.0031	1.1271	1.6101	0.1073	0.145
23	2	15	1100	1.25	0.0029	1.0544	0.9585	0.0639	0.176
24	2	15	1500	1.75	0.0039	1.4179	0.9453	0.0630	0.151
25	2	25	700	1.25	0.0025	0.9089	1.2984	0.0519	0.183
26	2	25	1100	1.75	0.0032	1.1634	1.0576	0.0423	0.163
27	2	25	1500	0.75	0.0072	2.6177	1.7451	0.0698	0.196

4.9.1 ANOVA and the Effects of factors

Table 4.12 shows that the wt. % of MoS_2 (C=44.08) and load (C=33.25%) has the more influence as compare to other factors on a wear rate. Sliding velocity (C = 8.53%) showed less significant contributions to the wear rate. Sliding distance has no effect on a wear rate.

Table 4.12: ANOVA (mean) for wear rate (MoS_2)

Source	DOF	SS	Variance (V_e)	F-ratio	F (5%)	SS`	C (%)	
W	2	4.48477	2.24238	50.35	5.14	4.37680	44.08	S
X	2	3.40971	1.70485	38.28	5.14	3.30174	33.25	S
Y	2	0.25688	0.12844	2.88	5.14			N.S
Z	2	0.95503	0.47752	10.72	5.14	0.84706	8.53	S
W*X	4	0.45780	0.11445	2.57	4.53			N.S
W*Y	4	0.05840	0.01460	0.33	4.53			N.S
X*Y	4	0.03940	0.00985	0.22	4.53			N.S
Error	6	0.26720	0.04453					
Total	26	9.92919						
e-pooled	20	1.07968	0.053984					

Table 4.13: ANOVA (mean) for coefficient of friction (MoS_2)

Source	DOF	SS	Variance(V_e)	F-ratio	F (5%)	SS`	C (%)	
W	2	0.131688	0.065844	51.81	5.14	0.128934	78.26	S
X	2	0.006647	0.003324	2.62	5.14			N.S
Y	2	0.002667	0.001333	1.05	5.14			N.S
Z	2	0.000264	0.000132	0.10	5.14			N.S
W*X	4	0.004764	0.001191	0.94	4.53			N.S
W*Y	4	0.001389	0.000347	0.27	4.53			N.S
X*Y	4	0.009686	0.002421	0.91	4.53			N.S
Error	6	0.007625	0.001271					
Total	26	0.164730						
e-pooled	24	0.033042	0.001377					

Table 4.14: Response table for mean (MoS_2)

Level	Wear response				Friction coefficient response			
	W	X	Y	Z	W	X	Y	Z
1	2.139	1.230	1.658	1.892	0.3151	0.2060	0.2061	0.2148
2	1.607	1.565	1.498	1.535	0.1748	0.2052	0.2140	0.2211
3	1.142	2.093	1.732	1.461	0.1602	0.2389	0.2300	0.2142
Delta	0.998	0.863	0.234	0.431	0.1549	0.0337	0.0239	0.0069
Rank	1	2	4	3	1	2	3	4

It is observed that in Fig 4.12 (a) the selected interactions had no significant contribution to the wear rate. Similarly, it can be observed from Table 4.12 the wt. % of MoS_2 reinforcement (C = 78.26%) is the only factor which is effected a coefficient of friction of the hybrid composites. In Fig 4.12 (b) show that all the selected interactions between the factors had no significant effect on coefficient of friction.

4.9.2 Effect of Parameters on Wear rate

Figure 4.11 (a) shows main effect plot for means of wear rate. The graphs are plotted between controlling parameters and wear rate of hybrid composite. The load is the most significant factor in increasing a wear rate. The wear rate is significantly increased with increase of normal load because at higher loads attributed to the more plastic deformation due to cracks in the oxide layer and delamination wear. Reinforced particle (SiC) are not able to support in a matrix material against a higher load so mildly brittle fracture will be occur and due to this wear rate is increased.

The wear rate is decreased with the addition of MoS_2 particles in the composite. MoS_2 particles act as a lubricant between the contacting surfaces and prevent the contact between them. During wear process, MoS_2 particles are released from the composite material and stick on the track of the disc to form a rich tribolayer. Unreinforced MoS_2 composite shows a maximum wear rate because of direct contact between the surfaces as compare to MoS_2 reinforced composite. Wear loss is decrease mildly with increase the sliding speed due to the formation of rich layer between the contacting surfaces of the pair.

The smooth surface of Al6063/ 5wt. % SiC/2wt. % MoS_2 matrix at applied load of 25 N with very fine size debris are shown in Fig 4.7 SEM micrographs are an evidence of making a thin tribo layer between the pin and the disc. A fine burr at the edge of the surface shows a less wear rate and sharp delaminated layer is observed on the worn surface which separates the contacting pair and due to this reduction in a wear rate.

4.9.3 Optimal Design for wear rate of MoS_2

Wear rate is preferred to be lower the best. Weight percentage of MoS_2, load and sliding velocity are the significant parameters. W3X1Z3 from Table 4.14 is the optimal condition for wear rate of hybrid composite. Optimal value for wear rate is calculated as:

$\eta_{opt} = \bar{m} + (m_{W3} - \bar{m}) + (m_{X1} - \bar{m}) + (m_{Z3} - \bar{m})$

$= 1.62 + (1.142 – 1.62) + (1.230 – 1.62) + (1.461 – 1.62)$

$= 1.62 – 0.478 – 0.39 – 0.159$

$= 0.593$

Confidence Interval (C.I.) for optimum value is

$$C.I. = \sqrt{\frac{f\ \alpha{:}v1{:}v2\ X\ Ve}{neff}}$$

α = risk (0.05)   confidence = 1-α

v1 = DOF for mean (which is always 1)

v2 = DOF for error = 20

Where $f\,\alpha{:}v1{:}v2 = f\,0.05{:}1{:}20$ = F ratio = 4.35

$$\text{Variance (Ve)} = \frac{\text{Sum of square of error pooled}}{\text{Degree of freedom error pooled}} = \frac{1.07968}{20} = 0.053984$$

n_{eff} = number of tests performed using participating factors

$$n_{eff} = \frac{27}{1+\text{DOF of } significant\ factors} = \frac{27}{7} = 3.85$$

C.I. = 0.246

So, confidence interval of wear rate is 0.593 ± 0.246 x 10^{-3} mm^3/m

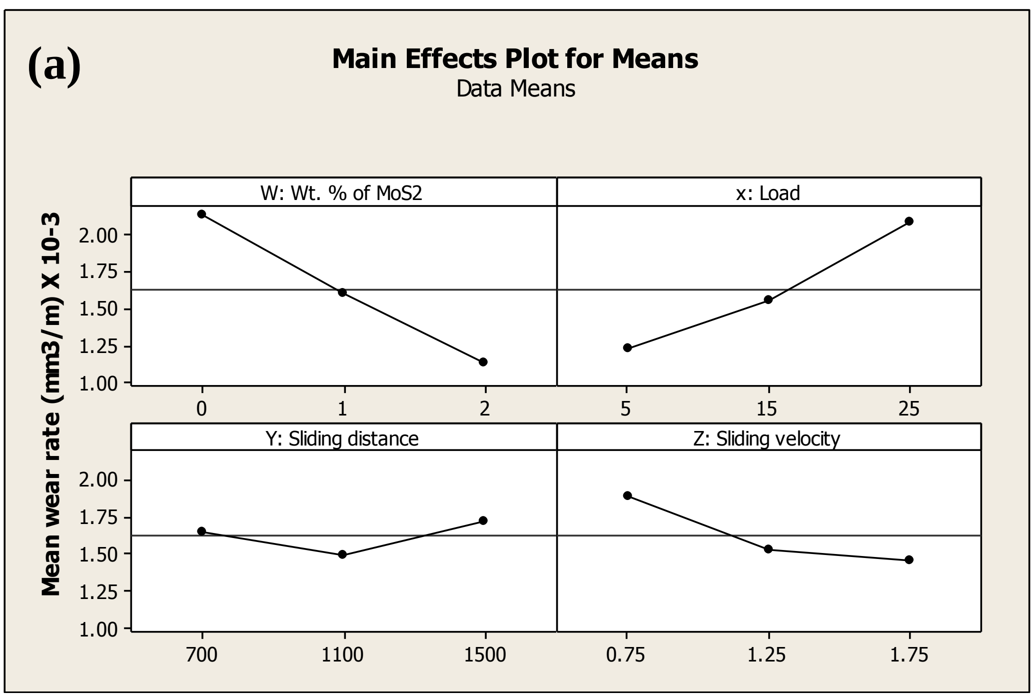

Figure 4.11 (a): Main effects plot for wear rate (mm^3/m) x 10^{-3} (MoS_2)

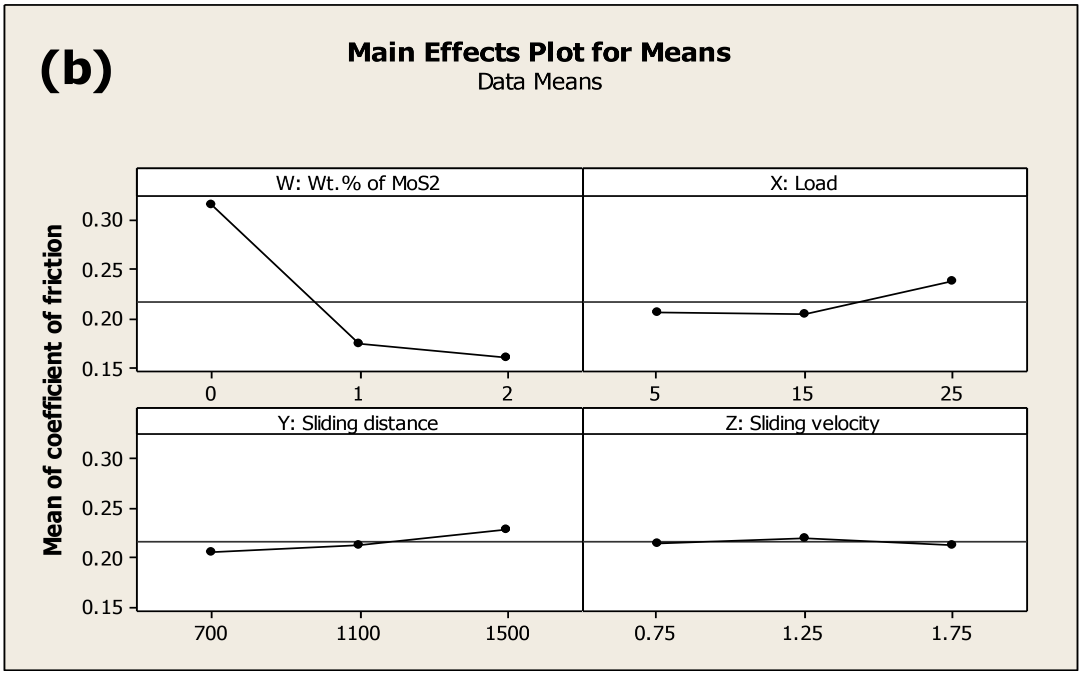

Figure 4.11(b): Main effects plots for Coefficient of friction (MoS_2)

4.9.4 Effect of Parameters on Coefficient of friction (MoS_2)

Figure 4.11(b) show the main effect plot for coefficient of friction. It is clearly observed in graph the wt. % of MoS_2 is the main significant factor which effects the hybrid composite due to their high inclination. The coefficient of friction is decrease with the addition of a MoS_2. It is minimum at the 2 wt. %. The reduction in coefficient of friction is due to the formation of MoS_2 layer between the contact pair. During wear process MoS_2 particles behave as a lubricant, MoS_2 particles fill the asperities of the worn surface of the pin and also stick on the disc and to prevent the direct contact between the pin and a disc is the main cause of reduce the coefficient of friction.

Load, sliding distance and sliding velocity has an insignificant factor on coefficient of friction because a thin layer of MoS_2 is almost maintained stable between the contact surfaces at all selected loads and speeds.

Coefficient of friction is found higher in unreinforced MoS_2 composite. The high degree of metal to metal contact between surfaces increases the plastic deformation and due to this hard SiC particles are detached from the composite. These hard particles works as an abrasive between the contact surfaces and to form irregular contact surface to cause a high coefficient of friction.

The SEM morphology of the worn surface of Al6063/ 5wt. % SiC/2wt. % MoS_2 matrix at applied load of 25 N shown in Fig 4.7 shows a smooth surface pattern and very fine debris like a sand grains. It is evident of maintain a rich tribo layer between the disc and contact surface of pin. The tribo layer is almost stable at every selected speed and loads level and due to this a reduction in coefficient of friction is maintained.

4.9.5 Optimal Design for Coefficient of friction

Coefficient of friction is preferred to be lower the best. Weight percentage of MoS_2 is the only significant parameter. W3 from Table 4.13 is the optimal condition for COF of hybrid composite. Optimal value for coefficient of friction is calculated as:

$\eta_{opt} = \bar{m} + (m_{A3} - \bar{m})$

$= 0.216 + (0.1602 – 0.216)$

$= 0.216 – 0.055$

$= 0.161$

Confidence Interval (C.I.) for optimum value is

$$C.I. = \sqrt{\frac{f\ \alpha{:}v1{:}v2\ X\ Ve}{neff}}$$

α = risk (0.05)   confidence = 1-α

v1 = DOF for mean (which is always 1)

v2 = DOF for error = 24

Where $f\ \alpha{:}v1{:}v2 = f\ 0.05{:}1{:}24$ = F ratio = 4.26

$$\text{Variance (Ve)} = \frac{\text{Sum of square of error pooled}}{\text{Degree of freedom error pooled}}$$

$$(Ve) = \frac{0.033042}{24}$$

$$= 0.001377$$

n_{eff} = number of tests performed using participating factors

$$n_{eff} = \frac{27}{1+\text{DOF of } significant\ factors}$$

$$= \frac{27}{3}$$

$$= 9$$

C.I. = 0.025

So, confidence interval of coefficient of friction is 0.161 ± 0.025

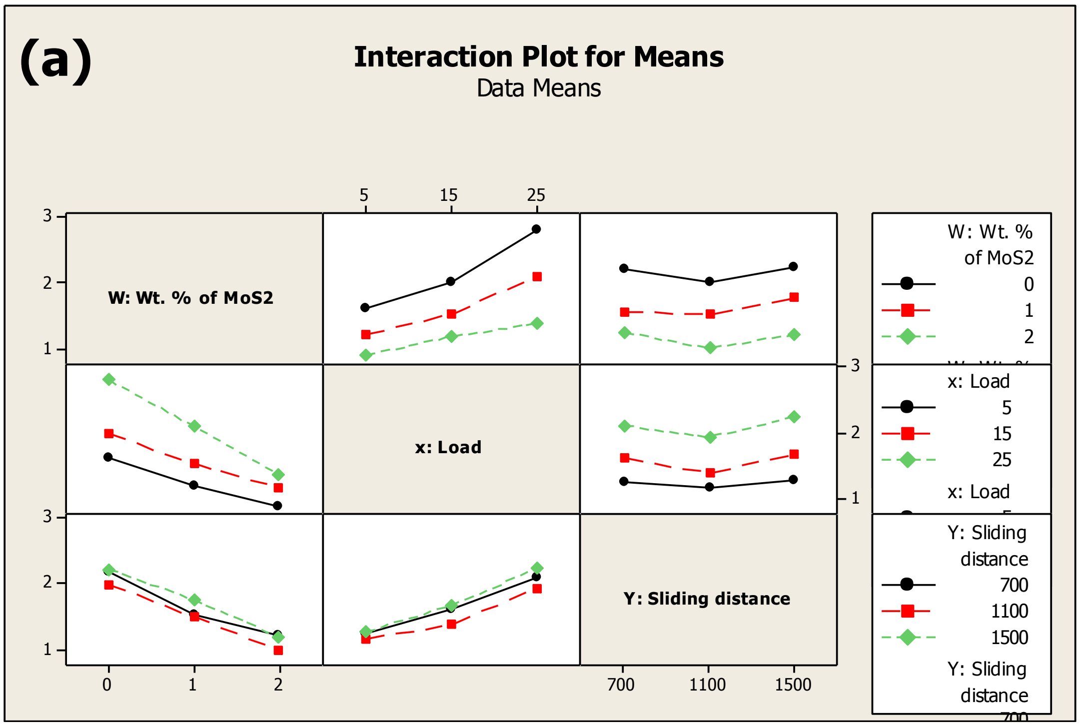

Figure 4.12(a): Interaction plots for means of wear rate (mm^3/m) x 10^{-3} (MoS_2)

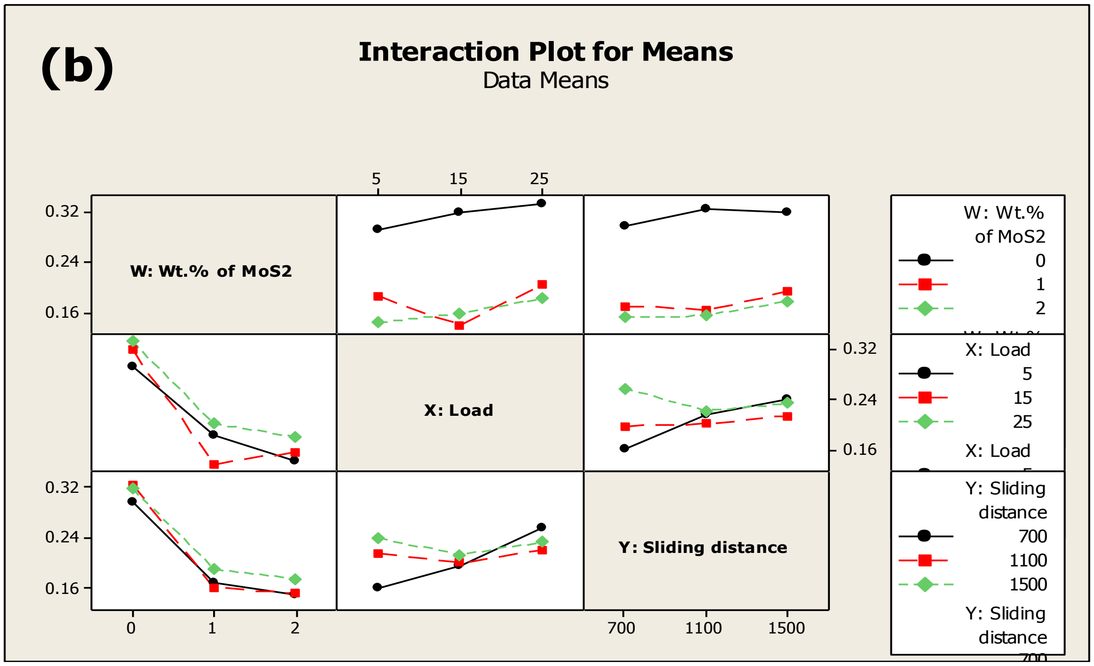

Figure 4.12(b): Interaction plots for means of coefficient of friction (MoS_2)

4.9.6 ANOVA and effect of parameters on Specific Wear rate (MoS_2)

Similar to Gr in this case also specific wear rate is investigated. Figure 4.13 shows main effect plot for means of specific wear rate. Table 4.15 shows that the load (C=70.28%) and wt. % of MoS_2 (C=16.11%) has the more influence as compare to other factors on a specific wear rate. sliding velocity (C = 3.98%) show less significant contributions to the specific wear rate. Sliding distance has no effect on a specific wear rate.

Table 4.15: ANOVA (mean) for specific wear rate (MoS_2)

Source	DOF	SS	Variance (V_e)	F-ratio	F (5%)	SS`	C (%)	
W	2	0.033318	0.016659	34.28	5.14	0.031858	16.11	S
X	2	0.140375	0.070187	144.44	5.14	0.138915	70.28	S
Y	2	0.001517	0.000759	1.56	5.14			N.S
Z	2	0.009337	0.004669	9.61	5.14	0.007877	3.98	S
W*X	4	0.007948	0.001987	4.09	4.53			N.S
W*Y	4	0.002109	0.000527	1.08	4.53			N.S
X*Y	4	0.000113	0.000028	0.06	4.53			N.S
Error	6	0.002916	0.000486					
Total	26	0.197633						
e-pooled	20	0.014603	0.000730					

The specific wear rate is decrease with increase a wt. % of MoS_2, sliding speed and the normal load due to the formation of lubricant layer in between the contacting pairs. Specific wear rate is preferred to be lower the best. A3B3D3 from Table 4.16 is the optimal condition for specific wear rate of hybrid composite (MoS_2)

Table 4.16: Response table for mean (MoS_2)

Level	Wear response			
	W	X	Y	Z
1	0.18921	0.24594	0.14698	0.16993
2	0.14144	0.10433	0.13454	0.13835
3	0.10334	0.08372	0.15246	0.12571
Delta	0.08587	0.16222	0.01792	0.04422
Rank	2	1	4	3

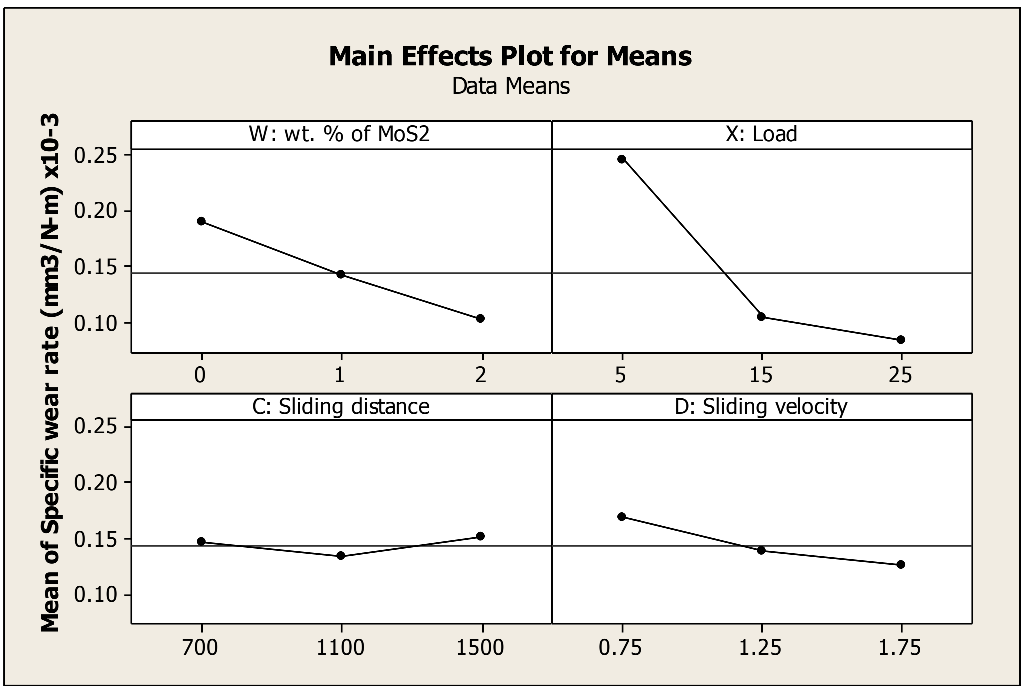

Figure 4.13: Main effects plot for specific wear rate (mm^3/N-m) x 10^{-3} (MoS_2)

CHAPTER 5

Conclusions

5.1 Introduction

This chapter discusses the conclusion of the present experimental study on microstructure analysis, density, hardness, dry sliding wear and coefficient of friction of hybrid metal matrix composites. It also discusses the recommendations and scope of the future study.

5.2 Results and conclusions

Al 6063, Al/SiC, Al/SiC/Gr and Al/SiC/MoS2 composites have been successfully fabricated by Stir Casting Process. Conclusions drawn from the present study are summarized below.

- The hardness and density of the composites are increased with an increase in content of Silicon carbide particulates.
- After addition of Graphite in the hybrid composites, the hardness and density are decreased with an increase content of Graphite. The hardness and density of a hybrid composites are increased with an increase content of MoS_2
- The hardness and density of Al6063/5wt. % SiC/2 wt. % Mos2 composites are more than the Al6063/ 5wt. % SiC/2wt. % Gr. So it is concluded that MoS_2 particulates are better to enhance the hardness property of the composites as compared to graphite.
- The microstructure analysis of the hybrid composites indicates that the Al-SiC-Gr/MoS_2 particulates are homogeneously mixed in the matrix alloy without any defect like porosity, cluster/agglomeration etc.
- The XRD results indicates that the presence of aluminium (in the largest peak), the presence of SiC (in the second largest peak) and MoS_2 and Gr in the smallest peak in the hybrid metal composites.
- Analysis on worn surface was examined by SEM micrographs to investigate the possible wear mechanisms. Worn surface of Al alloy clearly shows that the deep grooves, presence of large debris on worn surface, micro cutting, and large burr size at the edge of the pin

due to the ploughing action on the soft surface. MoS_2 and Gr hybrid composites shows smooth worn surface after performing the wear test due to the formation of thin lubricating layer between the contact pair.

- Also, in MoS_2 composites, very fine debris are found as compare to other composites.
- ANOVA was used to analyze the wear rate and coefficient of friction of hybrid composite.

- Statistical analysis of dry Sliding test of Al6063/SiC/Gr Hybrid composites revealed the following facts
  - The weight percentage of graphite (38.77%), normal load (35.20%) and sliding speed (8.55%) shows a significant contribution to the wear rate whereas sliding distance is the insignificant factor in the wear rate.
  - The addition of graphite reinforcement in Al6063/SiC composite increase the wear resistance of the composite. Wear rate of composite is found minimum at 2 wt. % of graphite. Formation of Gr layer between the contact surfaces seems to be a key aspect to control the wear behavior of the hybrid composite.
  - The wear rate is significantly increased with increase of normal load because at higher loads attributed to the more plastic deformation due to cracks in the oxide layer and delamination wear.
  - Wear rate decreases with increase the sliding velocity due to the formation of stable lubricant layer between the contact surfaces.
  - The specific wear rate is decrease with increase a wt. % of Gr, sliding speed and the normal load due to the formation of lubricant layer in between the contacting pairs.
  - The selected interactions had no significant contribution on the wear rate.
  - The optimal condition for wear rate of hybrid composite is at 2 wt % of Gr, 5 N load and 1.75 m/s of sliding distance.
  - The coefficient of friction is decrease with the addition of a graphite. It is minimum at the 2 wt. %. The reduction in coefficient of friction is due to the formation of graphite layer between the contact pair.
  - Normal load, sliding distance, sliding velocity and selected interactions are the insignificant factors of a coefficient of friction.

- Coefficient of friction is found maximum in Al/SiC composite due to the high degree of metal to metal contact between surfaces and to form an irregular surface cause more coefficient of friction.

Dry Sliding test of Al6063/Sic/MoS_2 Hybrid Composites

- Statistical analysis of dry Sliding test of Al6063/SiC/MoS_2 Hybrid composites revealed the following facts:
- It shows the most significant variables affecting the wear rate of the hybrid composites in term of their individual percentage contribution where the weight percentage of MoS_2 (44.08%), normal load (33.25%) and sliding speed (8.53%) shows a significant contribution to the wear rate. Sliding distance is the insignificant factor in the wear rate.
- The addition of MoS_2 reinforcement in Al6063/SiC composite increase the wear resistance of the composite. Wear rate of composite is found minimum at 2 wt. % of MoS_2. Formation of MoS_2 layer between the contact surfaces seems to be a key aspect to control the wear behavior of the hybrid composite.
- The wear rate is significantly increased with increase of normal load because at higher loads attributed to the more plastic deformation due to cracks in the oxide layer and delamination wear. Wear rate is decrease with increase the sliding velocity due to the formation of stable lubricant layer between the contact surfaces.
- The specific wear rate is decrease with increase a wt. % of MoS_2, sliding speed and the normal load due to the formation of lubricant layer in between the contacting pairs.
- The coefficient of friction decreased with the addition of a MoS_2. It is minimum at the 2 wt. %. The reduction in coefficient of friction is due to the formation of MoS_2 layer between the contact pair.
- Normal load, sliding distance, sliding velocity and selected interactions are the insignificant factors of a coefficient of friction.

Thus, Gr and MoS_2 solid lubricants almost shows the similar characteristics in the composite in terms of wear rate and coefficient of friction. Both show a good lubricant property against wear resistance and coefficient of friction. According to the present study, it is found that the MoS_2 shows a superior tribological characteristics due to their better wear resistance and reduced coefficient of friction.

5.3 Future Scope

The scope of present work can be expanded by including the following areas for future research work.

- Investigate the effect of nano size solid lubricant particulates of Gr and MoS_2 in hybrid metal matrix composite.
- Investigate the environmental effect on hybrid metal matrix composite material.
- Study the effect of both MoS_2 and Gr concentration on wear and friction behavior at elevated temperature.
- The fabricated composites to be heat treated to enhance their mechanical properties and tested at different heat treatment conditions.
- Machinability study could be conducted to determine cutting forces are required to machining the composite material.

References

- Balasivanandha, S.; Karunamoorthy, L.; Kathiresan, S.; Mohan, B. (2005) Influence of stirring speed and stirring time on distribution of particles in cast metal matrix composites. *Journal of Matererials Processing Technology*, 171: 268-273.
- Baradeswaran, A.; Perumal, A.E. (2013) Study on mechanical and wear properties of Al 7075/Al2O3/graphite hybrid composites. *Composites: Part B*, 56: 464–471.
- Basavarajappa, S.; Chandramohan, G.; Davim, J.P. (2006) Application of Taguchi techniques to study dry sliding wear behavior of metal matrix composites. *Materials and Design*, 28: 1393–1398.
- Bhushan, B.; Gupta, B. K. (1991) Handbook of Tribology: Materials, Coatings and SurfaceTreatments (McGraw−Hill, New York)
- Callister, W.D. (2007) Materials Science and Engineering: An introduction. John Wiley and Sons, Inc., New York.
- Chu, H.Y.; Lin, J.F. (2000) Experimental analysis of the Tribological behavior of electroless nickel-coated graphite particles in aluminum matrix composites under reciprocating motion. *Wear*, 239 pp. 126-142.
- Das, S.; Mondal, D.P.; Sawla, S.; Ramakrishnan, N. (2008) Synergic effect of reinforcement and heat treatment on the two body abrasive wear of an Al–Si alloy under varying loads and abrasive sizes. *Wear*, 264: 47-59.
  Education Private Limited, New Delhi.
- Elmadagli, M.; Perry, T.; Alpas, A.T. (2006) A parametric study of the relationship between microstructure and wear resistance of Al–Si alloys. *Wear*, 262: 79–92.
- Gopalakrishnan, S.; Murugan, N. (2012) Production and wear characterisation of AA 6061 matrix titanium carbide particulate reinforced composite by enhanced stir casting method. *Composites: Part B*, 43: 302–308.
- Goto, H.; Uchijo, K. (2007) Effects of environment on friction and wear of Al-Si alloy impregnated graphite composite. *Tribology Transactions*, 48: 548-557.

- Guo, T.M.L.; Tsao, C.Y. (2000) Tribological behavior of self-lubricating aluminium/SiC/graphite hybrid composites synthesized by the semisolid powder-densification method. *Composites Science and Technology*, 60(1): 65-74.
- Hunt, M. (1990) Form and function in metal matrix composites. *Composites*, 6:27-31.
  Kalaiselvan, K.; Murugan, N.; Parameswaran.S. (2011) Production and characterization of AA6061–B_4C stir cast composite. *Materials and Design,* 32: 4004–4009.
- Krishna, M.V.; Xavior, A.M. (2014) An investigation on the mechanical properties of hybrid metal matrix composites. *Procedia Engineering*, 97: 918 – 924.
- Kumar, M.; Mishra, A.K. (2014) Mechanical behavior of Al6063/MoS_2/Al_2O_3 hybrid metal matrix composites. *International Journal of Scientific and Research Publications,* 4(12): 1-4.
- Kumar, P.; Tirth, V. (2013) Effect of stirring speed on retention of particles in AA2218-Al_2O_3 MMCs processed by stir casting. *MIT International Journal of Mechanical Engineering,* 3(2): 123–128.
- Kumar, S.; Chakraborty, M.; Sarma, V.H.; Murty, B.S. (2008) Tensile and wear behaviour of in situ Al–7Si/TiB_2 particulate composites. *Wear*, 265:134–142.
- Nagaral, N.; Shivananda, B.K.; Shambhuling, V.S.; Auradi, V. (2014) Wear behavior of SiC reinforced Al6061 alloy metal matrix composites by using Taguchi's techniques.
- Prabu, S.B.; Karunamoorthy, L. (2008) Microstructure- based finite element analysis of failure prediction in particle-reinforced metal-matrix composite. *Journal of Materials Processing Technology,* 207:53-62.
- Ravindran, P.; Manisekar, K.; Narayanasamy, P.; Selvakumar, N.; Narayanasamy, R. (2012) Application of factorial techniques to study the wear of Al hybrid composites with graphite addition. *Materials and Design,* 39: 42–54.
- Rebba, B.; Ramanaiah, N. (2014) Evaluation of mechanical properties of aluminium alloy (Al-2024) reinforced with molybdenum disulphide (MoS_2) metal matrix composites. *Procedia Materials Science,* 6: 1161–1169.
- Reddy, A.C.; Zitoun, E. (2010) Matrix Al-alloys for silicon carbide particle reinforced metal matrix composites. *Indian Journal of Science and Technology*, 3(12):1184-1187.
- Riahi, A.R.; Alpas, A.T.; (2001) The role of tribo-layers on the sliding wear behavior of graphitic aluminum matrix composites. *Wear,* 251:1396-1407.

- Rohatgi, P.K.; Ray, S. and Liu, Y. (1992) Tribological properties of metal matrix graphite particle composites. *Journal of Materials Processing Technology,* 37(3):129-135.
- Roy R.K. (1990) A primer on the Taguchi method *Van Nostrand Reinhold,* New York.
- Sameezadeh, M.; Emamy, M.; Farhangi, H.; (2011) Effects of particulate reinforcement and heat treatment on the hardness and wear properties of AA 2024-MoS2 nanocomposites. *Wear,* 32(4): 2157–2164.
- Saravanakumar, A.; Sasikumar, P.; Sivasankaran.S. (2014) Synthesis and mechanical behavior of AA 6063-x wt. % Al_2O_3- 1% Gr (x = 3, 6, 9 and 12 wt. %) hybrid composites. *Procedia Engineering,* 97: 951 – 960.
- Singh, M. M.; Modi, D.P.; Jha, A.K. (2002) Two-body abrasive wear behaviour of aluminium alloy–sillimanite particle reinforced composite. *Wear,* 253 pp. 357-368.
- Smith, W.F. (1993) Structure and properties of Engineering Alloys. *Materials Science and Engineering Series,* 2 pp.176-229.
- Smith, W.F.; Hashemi, J. (2008) Materials Science and Engineering, Tata McGraw Hill
- Suresha, S.; Sridhara, B.K. (2010) Wear characteristics of hybrid aluminium matrix composites reinforced with graphite and silicon carbide particulates. *Composites Science and Technology,* 70: 1652–1659.
- Thomas, A.T.; Parameshwarn, R.; Muthukrishnan, A.; Kumaran, M.A. (2014) Development of feeding and stirring mechanisms for stir casting of aluminium matrix composites. *Procedia Materials Science,* 5: 1182 – 1191.
- Vinoth, K.S.; Subramanian, R.; Dharmalingam, S.; Anandavel, B. (2012) Mechanical and tribological characteristics of stir-cast Al-Si10Mg and self-lubricating Al- Si10Mg/MoS_2 composites. *Materials and technology,* 46(5): 497-501.
- Zhong, W.M.; Esperance, G.J.; Suer, M. (1995) Interfacial reaction in Al- Mg (5083)/SiC composite-a fabrication and remelting. *Metallurgical and Materials Transactions,* 26A:2637-2649.

Web References

- https://www.google.co.in/search?q=stir+casting+image&biw=1242&bih=606&tbm=isch&imgil=GFpfeTEcx3uwRM%253A%253BQfEmSs5sknY6oM%253 (accessed on 25th December, 2014)

- https://www.google.co.in/search?q=graphite+structure&biw=1242&bih=566&tbm=isch&tbo=u&source=univ&sa=X&ei=hRqUVfrcH4OjuQTkgYmgDg&sqi=2&ved=0CBwQsAQ#imgrc=xMbdpfJEXG22SM%3A (accessed on 26th December, 2014)

- http://www.substech.com/dokuwiki/lib/exe/detail.php?id=mechanisms_of_wear&cache=cache&media (accessed on 26th December, 2014)