Friction and Wear Behaviour of Aluminium Silicon Carbide Metal Matrix Composite under Lubricated Condition

Thesis submitted in partial fulfilment of

the requirements for the degree of

Master of Mechanical Engineering

By

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We hereby recommend that the thesis presented under our supervision by **Mr. Samar Mondal** entitled "**Friction and Wear Behaviour of Aluminum Silicon Carbide Metal Matrix Composite under Lubricated Condition**" be accepted in partial fulfillment of the requirements for the degree of Master of Mechanical Engineering.

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ACKNOWLEDGMENT

First and foremost, I would like to express my sincere gratitude to my honorable guide **Prof. Tapan Kumar Barman** for his continuous support in my study and research, for his patience, motivation, enthusiasm and immense knowledge. He has guided me in each and every step for the progression of my research work and writing this thesis. I would also like to thank our respected **Prof. Prasanta Sahoo** f0r enhancing my interest and motivation in the field of tribology. He has also guided me along with **Prof. Tapan Kumar Barman** for the completion of the thesis. I could not have imagined to have better advisors and mentors for my study.

I would also like to convey my sincere gratitude to laboratory in charge of Machine Element laboratory and all other professors who helped me to complete the thesis. A special thank goes to **Arkadeb Mukhopadhyay**, research scholar and **Abhijit Mukherjee**, research scholar for giving me the training to operate the tribotesting machine. A sincere thank goes to **Partha Halder**, who has helped me in the machining operation of alumina disc. I would also like to thank **Engineering Physics laboratory, Jadavpur University, Kolkata** for giving me the permission to take (Field Emission Scanning Electron Microscopy) FESEM micrograph. I would like to thank **Central Glass and Ceramic Research Institute (CGCRI)** for helping me in Vicker's micro hardness test of alumina. Lastly, I would like to thank **Department of Metallurgical Engineering, Jadavpur University, Kolkata**, for helping me to calculate the Vicker's hardness number of Aluminum Silicon Carbide Metal Matrix Composite.

I thank all my friends, specially **Subrat Kumar Maharana** and lab-mates for interactive discussion, support and fun which has always been constructive and refreshing.

In this respect, I would like to grab this opportunity to express my heart-felt gratitude to my father and mother whose constant cooperation, suggestion and helping attitude helped me to write the thesis on time.

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Dedicated to

My Parents

ABSTRACT

Metal matrix composite (MMC) is one of the emerging class of materials for modern days engineering application. Composite materials are used in various engineering applications particularly in aerospace applications, automobile industry, automotive industry, military and sport application etc. Nowadays, brake drums of two wheelers are also being manufactured by aluminium silicon carbide (AlSiC) metal matrix composites. From the literature review it is observed that, there are engineering applications where composite may be subjected to lubricated condition. But, this particular tribological area is unexplored so far. So, keeping these applications in mind, present study investigates the friction and wear behavior of silicon carbide based aluminium metal matrix composite under lubricated condition. The composite reinforced with 2.5 weight % SiCis prepared through stir casting method. The experiments are conducted on a pin on disc type tribotester under lubrication using five levels of load and sliding speed varying from 10 N to 90 N and 0.26 m/s to 0.78 m/s respectively. The experiments are carried out based on the combination available in Taguchi's L_{25} orthogonal array (OA). Then the effect of design factors on wear rate has been investigated. . Then, the variation of coefficient of friction (COF) and Wear rate with respect to load and sliding velocity is analyzed. Experimental results reveal that, with increase in load, wear rate increases and with increase in sliding velocity, wear rate decreases. But, variation of coefficient of friction cannot be explained by any specific rule. Taguchi's method has been implemented to find the optimal parameter combination. Statistical analysis has been made to find out the relative influence of design factors on wear rate. Analysis of variance is also carried out to find the significant design factors. Field emission scanning electron microscopy (FESEM) is carried out for characterization of worn out surface.

CONTENTS

Chapter 1: Introduction

Chapter 3: Results and discussion

Chapter 5: Conclusions and future scope

LIST OF FIGURES

Page No.

.

LIST OF TABLES

Page No.

Chapter 1

Introduction

1.1 Introduction

The contribution of materials and metals for the advancement of human civilization is inevitable. In the ancient time, various metals like iron, copper and bronze have played important role for improving the daily life of human being. In modern civilization, different material like iron, copper, aluminium, silver, diamond, ceramic, polymer etc. have their great impact. So, importance and choice of materials have changed time to time. Most recently, there was a necessity of a material system of high strength to weight ratio for many engineering applications. To have a material system with high strength to weight ratio, composite material was introduced. When two or more insoluble, non-reactive material systems with different mechanical properties are combined to have a new material system, they can be called composite materials. During applications, all the constituent material systems act as a single material which is completely different from its parent constituents. In composite, one of its constituent material systems is present in large proportion which is called matrix phase. The constituent or constituents present in small proportion is called reinforcement. So, composite has two parts- matrix phase and reinforcement phase. When more than two reinforcements are used, then the composite is called hybrid composite. These constituents may or may not differ in geometrical form but they need to be different in chemical composition. The constituent should be insoluble to each other. Engineering applications, where high strength to weight ratio is considered, aluminium based composites have proved to be a potential alternative. Different parts of aerospace and spacecraft, exterior parts of automobile vehicles, wind turbine blades, cylinder blocks etc. are being made from composites. Recently, at least 50% of the exterior part of the spacecraft is being covered with composite structure (Fig 1.1). The popularity of polymer based composite is also increasing in this particular field. Beside high strength to weight ratio, composite materials provide excellent mechanical properties which may not be achieved from monolithic materials. Some of the important mechanical properties are – high tensile strength, high fatigue strength, high torsional strength, good shear modulus, Young modulus etc.

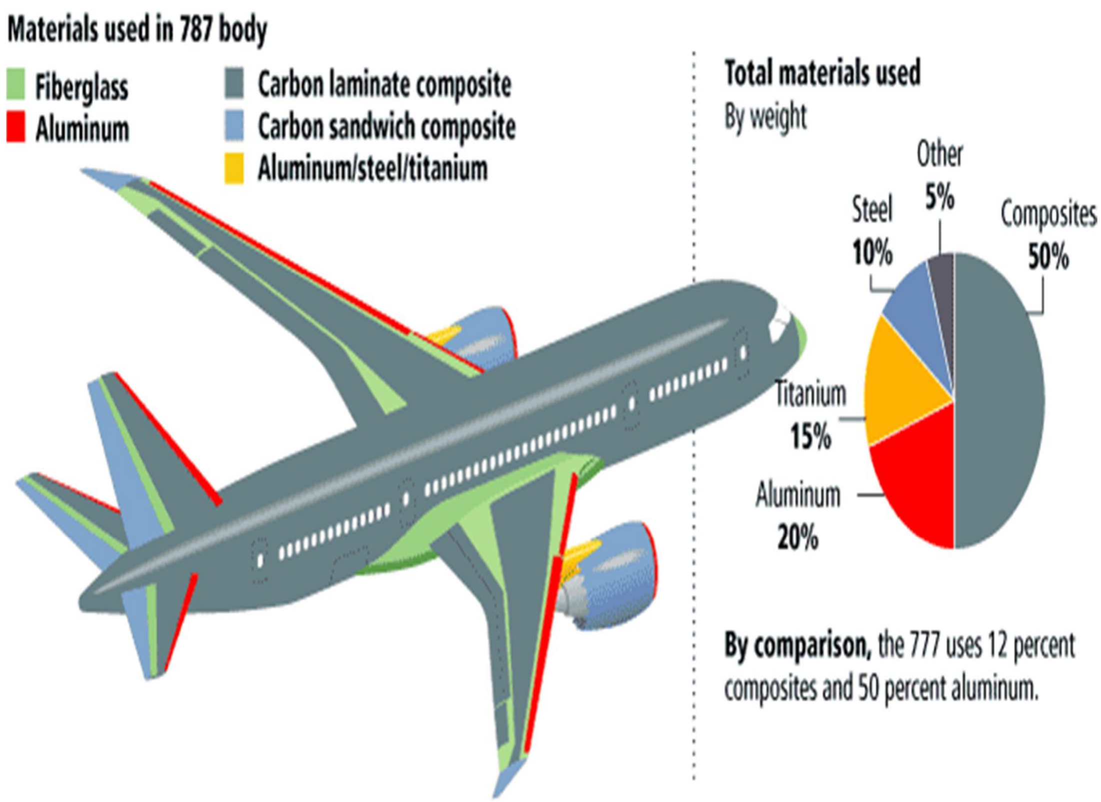


Fig 1.1 Graphical representation of composite materials used in modern spacecraft (Modern airliners boeing 787 specs, Deramliner materials pictorial)

So, the applications of composite materials are versatile. One of the important application areas of composite material are tribological application. Decorative items are also being made from composite materials. Various utensils used in our daily life are also being produced from composites. So, based on different applications, different types of composites materials have been developed. Each of the composite materials has its own application area because of its unique properties. Even choice of a particular material has been changed over time. For example, initially metal matrix composites were being used for aerospace applications. But, polymer metal composite is taking their place in recent days. This has been possible because of the advancement of modern technology. With the help of these technologies, composite material with better mechanical properties is being developed. These composite can be divided in different groups based on their properties, matrix materials, reinforcement materials etc. one way classification of different type of composite materials is discussed in the next section of this chapter.

1.2 Classification of composite materials

1.2.1 Classification based on matrix material

1.2.1.1 Polymer matrix composite

This is one of the significant classes of composite material. Polymer metal composites are drawing the attention of engineers because of its applications in aerospace engineering. Because of the advancement in properties of polymer matrix composites, their application in aerospace engineering is increasing compare to the metal matrix composite. There are some basic advantages to use polymer as a matrix material. Firstly, they are very lightweight which is very important for aerospace application. Secondly, Polymer matrix composites are very easy to machine. Generally, poly ester and vinyl ester are used as a matrix material in polymer composite. Fiber is important reinforcement material for this type of composite. They are cheaper compared to the Metal Matrix Composite (MMCs). This is another reason for popularity of composite material over metal matrix composites. But, this type of composite has some limitations because of their low melting point temperature, high coefficient of thermal expansion and dimensional stability. Their mechanical properties are also inferior compare to the MMCs.

1.2.1.2 Metal matrix composite

Metal matrix composites have very influential effect among all kind of composites. These composites have some inherent advantage of their base material. Ductile material is generally used as a matrix in metal matrix composites. Among them Aluminium, Magnesium, Titanium are most important. Reinforcement used in metal matrix composite is generally hard and brittle in nature. Silicon carbide (SiC), Titanium di-boride (TiB_2), Alumina (Al_2O_3), Titanium Oxide (TiO_2) are important of them. When reinforcement phase added to the composite, these composites gain high strength, high modulus of elasticity and fracture toughness. They are abrasion resistant, creep resistant and resistant to thermal distortion during high temperature application. Most common applications of MMCs are in aerospace and automobile industries. These composite are more expensive compare to the polymer matrix composite (Hull & Clyne, 1996).

1.2.1.3 Ceramic matrix composite

Ceramic materials are very hard and brittle in nature. They generally exhibit very strong ionic bond and in few cases they show covalent bonding. This is why ceramic materials have high melting points. They also show good corrosion resistance, stability at elevated temperatures and high compressive strength. But, limitation of ceramic is that they are subjected to brittle fracture. Reinforcement materials are added to ceramic to decrease their brittleness and to increase the toughness. Ceramic matrix composites (CMCs) are generally used in automobile and aerospace engineering. But it is observed that, applications of ceramic matrix composites are limited to high temperature applications. So, reinforcement materials are also chosen based on their melting temperature (Hull & Clyne, 1996).

1.2.2 Classification based on reinforcement

Based on reinforcements, composite materials can be of four types (Surappa, 2003; Clyne & Withers, 1995) -

1.2.1.1 Fibre reinforced composite

When the aspect ratio of the reinforcement is high, then they are called fibre. Ratio of length to width is called aspect ratio. They generally have aspect ratio more than 5. Now, depending on the aspect ratio, fibre can be divided in two groups – continuous fibre and discontinuous or short fibre. When aspect ratio is comparatively small, then those are called discontinuous or short fibre reinforced composites. When short fibre is made of a single crystal, they are called whiskers. They are produced by powder metallurgy or liquid infiltration process. Discontinuous or short fibres may be oriented in the direction of the applied load, perpendicular to the applied load or in random manner. Mechanical properties of short reinforced composites are better than both particle and short fibre reinforced composites. This type of aluminium composites are used to make pistons. But, health hazards have been detected for using whisker reinforcements. So, feasibility of commercial utilization of short fibre reinforced composite is limited. Whisker reinforced type of composites are used to make track shoes in some advance technology military tanks to reduce the weight of the tanks. Short fibre-reinforced composites are used to make piston and cylinder liner. When aspect ratio of the composite is very high, then they are called continuous fibre reinforced composites. Their typical length is less than 20μm.Alumina, SiC and Carbon fibres are some of these types of reinforcements. Alumina can be reinforced up to 40% volume fraction by squeeze infiltration method. These composites have high tensile strength, elastic stiffness and increased damping capacity. But, the composite retains its strength up to 300 °C and even beyond it. Continuous fibre reinforced composite are used to manufacture piston rods for automobile engines, flywheels, high-speed motor retainer rings, brake calipers etc. This type of composite has four times electrical conductivity than steel. So, recently this type of composite is also used to make core of overhead electrical conductors.

1.2.2.2 Particle reinforced composite

Particle reinforced metal composites are fabricated with ceramic particles with aspect ratio less than 5. Most commonly used ceramic particles are - $Al2O_3$, SiC, TiB_2. These particles may be in triangular, spherical, rectangular or any other geometrical form. Their dimensions are more or less equal in all direction. Stir casting method can be used for fabrication process of particle reinforced composite. In this process, small particles of reinforcement material distribute themselves in the matrix phase. So, homogeneous composite can be produced by this technique. These composites allow secondary forming operations like forming, extrusion, forging, rolling etc. There are two type of particle reinforced composites (William & Callister, 2001)-

i. Large particle reinforced
ii. Dispersion strengthen composite

These composites are mainly used as structural or wear resistance based applications. Sometimes ceramic particle reinforced composites are used as heat sink in electronic applications. Particle reinforced aluminium metal matrix composites are also used to make automotive and aerospace components. Brake disks of automobile are also being manufactured by particle reinforced composites. This type of composites is less expensive than continuous fibre reinforced composites.

1.2.2.3 Laminar composite

They can be described as a series of sandwich structure. In this structure, a layer of reinforcement structure is covered by two layers of matrix material or vice versa. These layers of materials are bonded together. Now, here the composition of matrix and reinforcement material can change as per requirement. The layer of composites and reinforcement may be arranged in a particular direction or may vary layer by layer.

1.2.2.4 Mono filament reinforced composite

Monofilaments are fibres, which have larger diameter than continuous fibres. Diameter of monofilaments is in the range of 100-150 μm. This type of fibre is produced by chemical vapour deposition of SiC or Boron in the core of carbon fibre or tungsten wire. Monofilament reinforced composites are fabricated by diffusion bonding method. In monofilament reinforced aluminium metal matrix composite, the applied load from matrix phase is transferred to the filament reinforcements. The filaments bear a large portion of the load. These composites show directionality of mechanical properties. The strength of the composites is high in the direction of filaments. Lower strength is observed in the direction perpendicular to the filament orientation. Different type of reinforcement is shown in Fig 1.2.

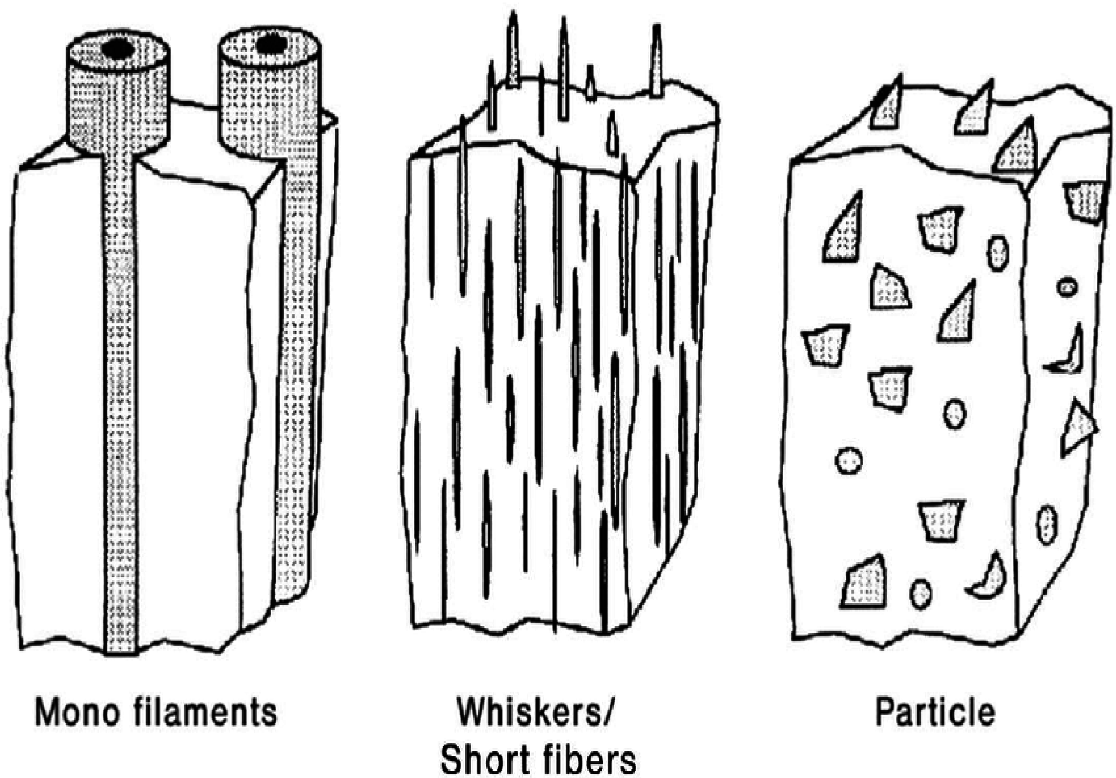


Fig 1.2 Schematic representation of different type of composites (Clyne & Withers, 1993)

1.3 Metal Matrix composites

Metal matrix composites have most influential effect among all kind of composites. Metal matrix composite was introduced as a material system of high strength to weight ratio for aerospace engine applications. Now-a-days, metal matrix composites are one of the most popular class of materials. They are used in aerospace engineering, automobile engineering etc. In metal matrix composites (MMCs) matrix phase is made of metals. Generally, soft and ductile metals are used for matrix phase. Reinforcement phase is generally consists hard particles, while they are introduced in ductile and tough matrix phase, it results unique properties.

1.3.1 Base metal used in metal matrix composite

Metal matrix composites are generally not used for low temperature application. So, normally metals with high melting temperature are used as base metal. Generally, light and ductile metals with low density values are used as matrix material. But strength and stiffness values of these matrix materials are very low. To increase these properties, they are reinforced with hard ceramic reinforcements. Some common base metals which are used to produce MMCs are Aluminium, Magnesium, Copper (Pawar & Utpat, 2014). Nowadays, Aluminium, Titanium and Magnesium based composites are being popular for using aircraft based applications.

1.3.2 Reinforcement used in metal matrix composites

Reinforcement used in metal matrix composite has high hardness value. They are brittle in nature. Most commonly used reinforcements in MMCs are carbides (TiC, SiC, WC) (Amirkhanlou et al., 2014; Gonzalez-Doncel et al., 1988; Christman & Suresh, 1988; Yang et al., 2004; Flom & Arsenault, 1986), Nitrides (Naranjo et al., 2003; Wang et al.; 2009; Imai et al., 1990; Ramesh et al., 2009), oxides (Al_2O_3, TiO_2) (Antolin et al.1992; Kang & Chan, 2004; Prielipp et al., 1995; Breslin et al., 1995; Breval et al., 1993), borides (AlB_2, TiB_2) (Melgarejo et al., 2010; Suresh et al., 2012), Aluminides (Ni_3Al, NiAl) (Wang & Reinforth, 2002; Wang & Reinforth, 2001), Silicides (Torres et al., 2002) etc.

1.4 Fabrication Process of metal matrix composites

There are several standard procedures to fabricate the composite materials (Sahin, 2003; Singh & Lewandowski, 1993; Mishra et al., 2003). Fabrication method is selected based on the type of the composite to be produced, mechanical and tribological properties to be imparted, so that they can be implemented in a particular application. For example, when homogeneous composite structure is required, stir cast may be suitable process to manufacture the composite material. Similarly, to produce continuously reinforced composite, squeeze casting can be utilized. Recently some decorative items are also being produced from the metal matrix composite. So, fabrication method needs to be selected so that machining operation can be performed on composite materials. The expenses to fabricate a composite in different process are different. So, fabrication methodology is selected in such a manner that fabrication charge is minimized. Based on the state of the matrix phase during fabrication, composite material can be broadly categorized in three parts –

i. Liquid state processing
ii. Solid state processing
iii. Vapor state processing

1.4.1 Liquid state processing

In this processes, matrix phase remains in liquid state. As metal is used as matrix phase, this is a high temperature process. Most commonly it is observed that, this process suffers from lower wettability problem. So, a particular temperature is generally maintained to control the wettability of the matrix. Sometimes, temperature of reinforcement phase is also maintained at elevated temperature to control the wettability. Because of high temperature, this method is subjected to chemical reaction which affects the properties of the composites. So, inert gas environment is generally preferred for this fabrication technique.

1.4.1.1 Stir casting

This method is primarily preferred when homogeneous composite structure is desired. Sometimes, this method is preferred because of its low production cost. Now, to get a homogeneous structure matrix and reinforcement phase requires good wettability. As stir casting process suffers from low wettability, matrix and reinforcement are kept at predefined temperature. To control the interactions with environment, generally inert gas chamber is used. Sometimes some additives are utilized to increase the wettability. Application of magnesium (Mg) is most common of them (Singh & Lewandowski, 1993). In stir casting, there are four steps to complete the fabrication process (Karnivas et al., 2016; Mishra et al., 2003).

1.4.1.1.1 Melting of matrix material

Particular amount of commercially available matrix ingots are placed in available melting chamber. Then, the matrix phase is melted to liquid state by heating in the induction furnace to a predefined temperature. A small amount of magnesium is added to the molten metal, which increases the wettability and minimizes the oxidation during the melting process (Casati & Vedani, 2014). This helps to prevent casting defects.

1.4.1.1.2 Preheating of the reinforcement material

As micron-sized reinforcement powder does not mix well with liquid state matrix phase, it must be preheated to a specific temperature. To get a proper wettability of reinforcement, particle size is also important. From the literature review it is observed, particle size generally varied from 5 to 40μm. Then, the particles are preheated to a specified temperature in the preheating chamber available in the setup.

1.4.1.1.3 Mixing of the ingredients

Preheated reinforcement phase is added in the matrix phase. Prior to the addition of reinforcement, molten matrix phase is stirred continuously by the mechanical stirrer. When a vortex is formed in the crucible, placed inside the furnace, preheated reinforcement particles in predefined amount are added to the molten matrix phase. The mechanical stirrer ensures the uniform distribution of reinforcement phase in the matrix.

1.4.1.1.4 Casting of the composites

Finally, the mixture is transferred to a cleaned permanent metallic preformed die mould of desired shape. The molten composite mixture was allowed to solidify at room temperature. The cast composite material is then removed from the mould and used as the input material for the preparation of specimens and further investigations.

1.4.1.2 Squeeze casting

Another liquid state processing used to produce MMC is squeeze casting. This process is generally used to produce aluminium based composite. In this process, matrix phase is melted at a predefined temperature. Then, the molten metal is made to enter in the preformed fibrous or particulate mould. As solidification starts, pressure is applied on the mould which has some inherent advantages. Firstly, problem like gas entrapment, porosity may be eliminated in this technique. Secondly, because of the application of pressure, molten metal always remain in contact with mould. This reduces the solidification time of the casting. So, this process is comparatively faster. This process gives good casting integrity. But, complex specimen cannot be produced by this technique.

1.4.1.3 Investment casting

Another method very commonly used is vacuum assist flask investment casting. This process generally involves 3 steps - preform, mould making and casting (Girot et al., 2013). To make the preform, generally polyvinyl alcohol, SiC and colloidal silica are used. This slurry is converted to perform of the specimen to be made by suitable heat treatment process. To make the mould the pattern wax (melt at 90˚c) and mould slurry is used. After casting and proper heat treatment, mould is heated at 110˚c for de-waxing purpose. Once the mould is made, the MMC slurry is poured in the mould. After the completion of the process, mould is removed and casting of the composite material is separated.

1.4.2 Solid state processing

Powder metallurgy (PM) is most popular among solid state processing. It is widely used for producing metal matrix composites. This usually involves three major stages - blending, pressing or cold compression and sintering. During blending, matrix and reinforcement phases are mixed homogeneously (as much as possible). Then, the mixture is compressed in an iso-static pressing. In this step, composite gets its predefined form. But, at this stage hardness of the composite is very poor. To increase the hardness and to impart better mechanical properties, sintering is done in the next step. Sometimes, compression and sintering may be performed simultaneously. During sintering, temperature of the composite remain high which helps in chemical bonding between matrix and reinforcement phase. Although PM gives good mechanical properties of composites (Ling et al., 1995; Girot et al., 1987), there are some disadvantages associated with conventional powder metallurgy such as porosity and segregation of the reinforcing particles. This often leads to a degradation of the mechanical properties. These problems become more important when the difference in particle size between the reinforcement and the matrix phase is large or when the volume fraction of the reinforcement is high. As this is a high temperature and high pressure process, proper precaution needs to be taken for safety purpose. This becomes crucial when small reinforcement particles with large surface area are handled.

1.4.3 Vapour state processing

Among the process available for vapour state processing, spray forming is most popular. In this process, a spray gun is used to atomize the liquid matrix phase. Then, preheated reinforcement phase is injected in the atomized matrix phase. Homogeneous metal matrix composite can be produced by this technique. Some other techniques have also been developed for vapor state processing. For example, Lanxide process or pressureless molten metal infiltration process (PRIMEX), Martin Marietta process or XD process etc.

1.5 Literature review

1.5.1 Application of composite materials

Emergence of composite materials was the result of the requirement of material with high strength to weight ratio for aircraft engines. But, nowadays the applications of metal matrix composites are versatile. Most important applications of composite materials found in aerospace engineering (Rohatgi, 1993; Das, 2004,). Rotor blade, fin, doors, Rocket motor case, high temperature nozzle of missile and launch vehicle are also made by composite materials. Metal matrix composite has found their application in sports equipment like fishing rods, paddles, racing car with reduced weight (Pawar & Utpat, 2014; Subhramanian & Kumar, 2015). In automotive, accelerating pedals, brake, piston ring, rotor, cylinder block, intake manifolds, fuel tanks are being made from composite (Natarajan et al., 2006; Howell & Ball, 1995). Al-SiC based MMC can be used to produce spur gear (Pawar & Utpat, 2014). In electronics and automotive industry, MMCs are being adopted due to their low coefficient of thermal expansion and high thermal conductivity. In electronics industry, MMCs are also used as heat sink or heat spreader (Schobhel et al., 2011; Bukhari et al., 2011; Hunt & Miracle, 2000).

So, it is observed that metal matrix composites have their versatile applications in various fields. The popularity of metal matrix composite is increasing day by day. New application areas are being introduced with the help of modern technology. For example, generally metal matrix composite is used for exterior part of the spacecraft. But, most recently polymer matrix composites are being competitive to the metal matrix composite. To utilize the composite materials for a particular area, the knowledge of composite materials, its fabrication technology, its mechanical and tribological properties is a must. Since the introduction of composite materials, many researchers have studied the composite materials to understand the various properties of the composites and for the improvement of these properties. Properties of the composite can be broadly divided in two parts – mechanical properties and tribological properties.

Among the mechanical properties, high strength to weight ratio is most important. Besides high strength to weight ratio, composite materials provide excellent mechanical properties which can't be achieved from monolithic materials. Some of these properties are - tensile strength, hardness, fatigue strength and corrosive resistance etc. Generally, incorporation of reinforcement improves the various mechanical properties of composite like tensile strength, hardness, fatigue strength and corrosive resistance, fracture strength, dimensional stability, hardness etc. (Pramanik, 2016; Rees, 1998; Padmanavan et al., 2004; Nam et al., 2008; Bhansali & Mehrabian, 1982). The properties of the composites like Young's modulus, shear modulus, fatigue strength and corrosive resistance, Poisson's ratio, depend on properties and concentration of reinforcements.

Apart from the mechanical behaviour, MMCs also provide good tribological behaviour when reinforcements are added in proper amount in the composite matrix. Most important tribological properties of composite are wear resistance and corrosion resistance. To reduce the engine power loss, piston ring of engine cylinder is made from MMCs. In recent days, brake drum of automobile is being produced from AlSiC MMCs (Kennedy et al., 1970).

1.5.2 Fabrication methods

From the literature survey it is observed that, researchers have utilized several techniques to produce composite materials. Among the fabrication processes, stir casting (Mishra et al., 2003; Radhika et al., 2011), powder metallurgy (Al-Rubaie et al., 1999; Kwak & Lim, 1999; Sahin, 2010) are popular. Some of the researchers have used squeeze casting (Prasad & Asthana, 2004) and investment casting method (Kwak & Lim, 1999) to manufacture composite materials.

1.5.3 Aluminium silicon carbide as MMC

Aluminium is the most popular base material for composite material. It is also known as a malleable material. Because of this property, aluminium can be rolled in thin sheets. But, aluminium has high potential for various engineering application because of its low density. This can be accomplished by improving the mechanical properties of aluminium. This is done by alloying or by adding reinforcement. When reinforcement is added, along with the ductility other mechanical properties like hardness, wear resistance, creep resistance also improve. This gives very high strength to weight ratio. So, AlSiC metal matrix composite can be used in aerospace and automobile application for weight minimization. Piston ring, brake drum, disc brake, speed breaker, household articles, mine instruments are also being made from AlSiC metal matrix composites. Nowadays, AlSiC is also being used in electronics industries as heat sink or heat spreader. For these reasons, aluminium is the most popular matrix material right now.

Most commonly used reinforcement materials are silicon carbide (SiC), alumina (Al_2O_3) Titanium di-boride (TiB_2) nitrides (Si_3N_4) etc. for the improvement the mechanical and tribological properties of composite (Nair et al, 1985; Pramanik, 2016; Lee et al., 1992). Hardness and wear resistance of pure aluminium alloy increase greatly (Pramanik, 2016; Lee et al., 1992). It is observed that, in some operating condition coefficient of friction also decreases. SiC also provides elastic strengthening of the composite (Nair et al., 1985).

When hard SiC reinforcement phase is incorporated within the matrix, the combination of both creates unique mechanical and tribological properties. Generally, incorporation of SiC reinforcement improves the various mechanical properties of AlSiC metal matrix composite like tensile strength, hardness, fatigue strength and corrosive resistance, fracture strength etc. (Pramanik, 2016; Rees, 1998; Padmanavan et al., 2004; Nam et al., 2008; Bhansali, 1982). With the increase of hard SiC reinforcement volume fraction, dimensional stability increases. With increase in SiC reinforcement volume percentage, hardness of AlSiC generally increases and tensile strength first increases and then decreases (Nam et al., 2008). Under combine loading like tension and torsion, torsion and compression, AlSiC composites give better mechanical properties compare to the unreinforced matrix (Rees, 1998; Padmanavan et al., 2004).

1.5.4 Resistance against indentation

Micro-hardness is the measure of a material's resistance to plastic deformation against indentation with an applied load. A standard way to represent the hardness of a material is its hardness number. Hardness number is generally measured by microhardness tester (Rees, 1998). Most commonly micro hardness is expressed as Vickers hardness number (VHN). The VHN of a material is calculated by making an impression on the surface of a specimen by applying a load/pressure with a square-based pyramid-diamond indenter. The diagonal face of the indentation is measured by a microscope. The VHN can be calculated from the diagonal dimension of the impression, the applied load and the apex angle of the pyramid indenter. A material with a higher VHN value has greater resistance against deformation. The effect of inclusion of SiC particles in the composites against indentation can be compared by the Vickers hardness numbers of the specimens. From literature, it is seen that VHN drastically increases with increase in SiC volume percentage (Miyajima & Iwai, 2003; Kumar & Balasubramanian, 2014) as represented in Fig 1.3. Now, improvement of hardness depends on the reinforcement size and shape. Among particulate, whiskers and fibre reinforcement material, particulate reinforcement provides maximum improvement in the hardness value.

The lowest improvement is observed in case of fibre reinforced composite (Hamid et al., 2008; Hamid et al., 2006; Huching, 1994). Wu & Li (2000) have reported that, with decrease in particle size, hardness improvement increases. They have suggested that, smaller particle provides more surface area which is responsible for the higher value of hardness.

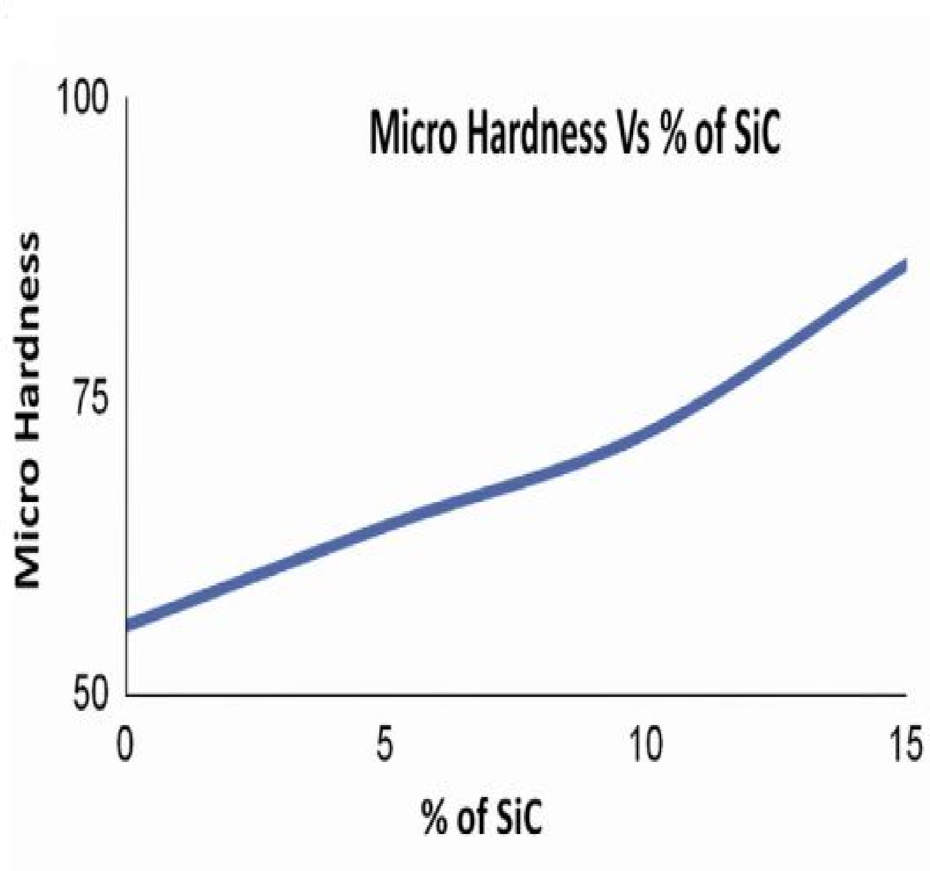


Fig 1.3 Variation of microhardness with increase in SiC volume percentage, (Kumar & Balasubhramanin, 2014)

1.5.5 Impact strength behavior

Impact strength of a material can be measured by its toughness. Now, toughness of the material is basically the amount of energy a body can withstand before catastrophic failure. Generally, ductile materials are tough enough. But, as ductility of a material decreases or hardness increases, its toughness generally decreases. Aluminium is a known ductile material. So, aluminium has very high toughness. When hard particles incorporated within it, it is observed that, up to 2% toughness increases. It has been explained by better bonding of SiC particles with the matrix. But, if the reinforcement quantity is more than 2%, then toughness decreases. This is because of the increase in hardness of composite with the addition of SiC particles. Actually, with increase in volume percentage of reinforcement, large number of bond is formed. When external load is applied, breaking of these bonds leads the composite to failure. So, the energy which previously used to deform the matrix, cannot transmit to the matrix. This may be the possible reason for decreasing the toughness of composite with increase in volume percentage of reinforcement.

1.5.6 Stress – strain behaviour of composite materials

Tensile strength or yield strength is one of the important properties of any mechanical member. Like monolithic materials, composite can't get a standard yield stress value. Yield stress value depends on various factors like reinforcement shape, reinforcement volume percentage, their orientation etc. Experimental tests were performed by several researchers to find the tensile strength behavior of AlSiC MMC. It has been observed that, AlSiC MMC has the ability to support load at much higher tensile and shear stress compare to the pure aluminium (290 MPa) as represented in Fig 1.4 and Fig 1.5 (Padmanavan et al., 2004). It has also been found that under compressive force material fails basically by void nucleation (Jahanmir et al., 1975). The fracture occurs along principal plane under tensile loading and maximum shear stress direction is followed when compressive load is act in AlSiC MMC (Rees, 1998). There are two categories of fracture, namely, brittle fracture and ductile fracture. In brittle fracture, a very limited amount of plastic deformation occurs and promotes a sudden failure without warning. Normally, brittle materials will break sharply and exhibit flat fracture surfaces consisting of trans-granular cleavage facets, which are caused by the fast propagation of the crack penetrating through the grains. On the contrary, in ductile fracture the gross plastic deformation occurs and exhibits necking before failure. Within the necking area, micro-voids are formed, which may expand and join together to create a micro-void of large dimension. Coalescence of micro-void may lead to cracking of composites when the load is greater than its maximum tensile strength (Schobhel et al., 2011). The failure pattern of the specimen, namely, cleavage facets and micro-void coalescence, can be observed in the microscopic images acquired at higher magnification. The effect of reinforcement on resistance against tensile force can be analyzed by their tensile strength values. The mode of fracture can be observed through high-magnification microscopic images of the broken surface of the composite.

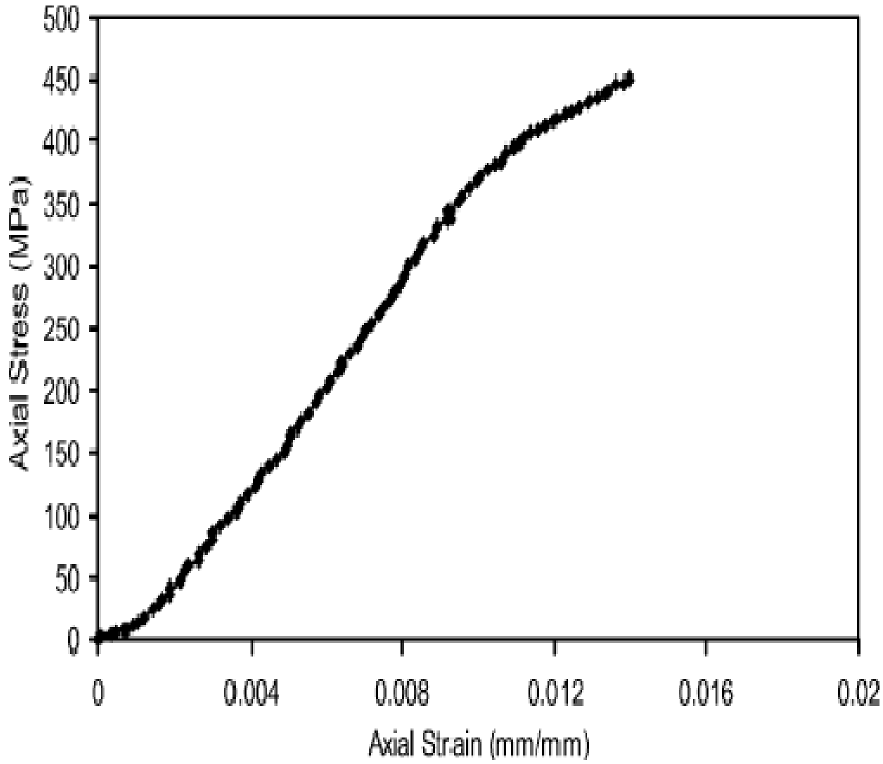


Fig 1.4 Axial stress vs Axial strain curve of AlSiC MMC, (Padmanavan et al., 2004)

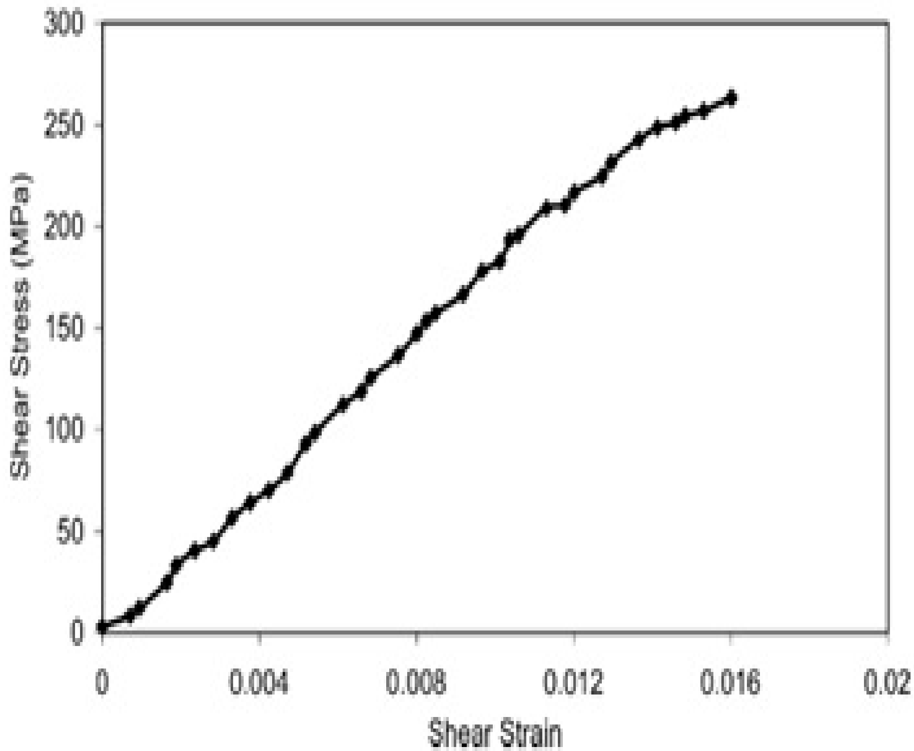


Fig 1.5 Shear stress vs Shear strain curve of AlSiC MMC, (Padmanavhan et al., 2004)

1.5.7 Composite materials under combined loading

It is observed that, composite materials give better mechanical properties under tensile and torsional loading. But, mechanical members are sometimes subjected to combine loading. So, composite material was tested under various combine loading condition to investigate their mechanical behaviour. When composite is loaded under fixed torsional load and varying axial load, it has been reported that, yield stress increases by 10-15% (Jjahanmir et al., 1975). Similarly, when composite is loaded fixed axial load and varying torsional loading shows the increment of yield stress.

1.5.8 Compressive strength of composite

Under compressive load, the composite generally fails by micro-void Coalesce. These voids form in regions of greatest particle density under high internal strains. It is observed that, all the test pieces fail along 45˚ of crack plane under compressive loading (Jahanmir et al., 1975). De-bonding of particles may occur as voids grow around them within a narrow band containing the fracture surface.

1.5.9 Friction behavior of composite materials

Now-a-days, a large number of tribological members are being made from composite materials. Coefficient of friction is one of the important properties of tribological members. So, tests have been carried out under different design factors and different testing environments. Results show that, coefficient of friction is not controlled by any specific mechanism. Mechanism which controls coefficient of friction changes with the change of design factors. A large number of literatures are found where tests have been carried out under low load and low speed condition. It is observed that, the predominant friction mechanism under low load and low speed is adhesion in nature (Alpas & Embury, 1990; Sannino & Rack, 1993). They have explained the phenomena as bonding of two asperities under low load and load speed. When two tribological members come in contact, at first contact occurs between two asperities. Then, adhesion bond is formed between two asperities. Now, if one surface is moved over another, it must break the adhesive bond. The force required to break the bond comes out to be frictional force. Some of the researchers have carried out the tribological test under comparatively higher loading. Rehman et al. (2012) have reported that presence of SiC particles enhance the coefficient of friction. It is reported that, under higher loading condition friction mechanisms are controlled by abrasion, microcutting and microploughing (Huching, 1993; Al-Rubaie et al., 1993; Sasada et al., 1981). At higher loading condition, the Hertzian pressure in the contact area is higher. Now, this contact pressure is sufficient to deform the asperity in contact and to create a deformation zone. This enables the harder component to penetrate within the comparatively softer material. In this case, hardness of alumina is much higher than the composite. So, it may penetrates on the counterpart i.e. AlSiC MMC samples. Now, one surface tries to move, the harder asperity need to deform the material ahead. This is called micro ploughing. After ploughing, the material is attached to the parent surface. If the material is separated from the parent surface, it is called microcutting. This requires more energy to supply compare to the braking of adhesive bond. This may be the possible reason behind high friction coefficient at higher loading condition. Now, Wear debris may be created because of breaking of adhesion bond at lower load or because of microcutting at higher load. Now, these particles may get entrapped in between the surfaces. As one surface moves, these entrapped particles get rotational motion. So, adhesion or microcutting controlled friction behaviour transformed to rolling friction. This gives abrasive controlled friction behaviour a lower frictional coefficient.

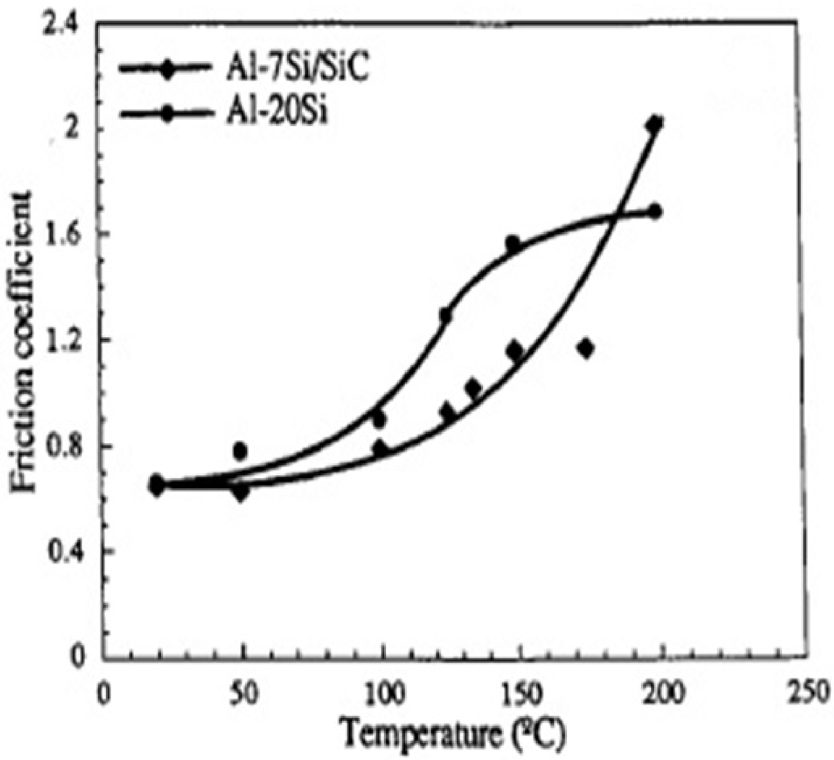


Fig 1.6 Specific wear rate as a function of temperature,

(Martinez et al., 1993)

The effect of temperature is also reported by several scientists. The effect of temperature is much more prominent for chemically active elements like, Al, steel etc. For aluminium, at low sliding speed, aluminium matrix gets sufficient time to get oxidized. Wear mechanism is basically counter surface to aluminium oxide surface. But after a critical temperature, Al present in the matrix does not get sufficient time to oxidize. So, wear mechanism is basically Al to counter surface resulting high increase in friction coefficient as represented in Fig 1.6. But, again after a second critical temperature the material oxidation rate increases resulting gradual increase in friction coefficient (Martinez et al., 1993).

1.5.10 Wear behaviour of composite materials

For tribological applications, wear behaviour of tribological member is the most important. Sufficient number of literature is studied for analysis of wear behaviour. It is observed that, at low load (below 10 N), wear mechanism is generally adhesion controlled. At low load, the Hertzian pressure on the contact area is low, results only a small amount of deformation zone at the contacting surface. So, main wear mechanism is adhesion. When this adhesive bond breaks because of the movement of a tribological member, some debris is created as wear particles. Now as the load increases, Hartzian contact pressure also increases. So, asperity in the contact zone gets deformed. But, it starts at a distance from the surface because of stress tri-axiallity. These deformations accumulate each and every cycle which lead to crack at most heavily stressed point. When this crack propagates, a layer of material removed creating debris or transferred to the counter surface. Vingsbo (1988) have described that wear is a tribo fracture phenomenon. Sometimes it is also observed that, high Hertzian pressure will develop large plastic deformation zone. In this condition, the asperity of the hard surface get embedded to the asperity of the other surface. In this condition, when a tribological member tries to move, wear occurs by microcutting and microploughing. Sometimes, very low wear rate with low coefficient of friction is observed. This generally occurs when wear rate is abrasive in nature. When wear particle is created by rupture of adhesive bond and microcutting mechanism, these particles may get entrapped between two surfaces (Bai et al., 1995; Dewvedi, 2010). When composite samples are under sliding motion, these entrapped particles also move within the contacting surfaces, creating abrasive wear. This is called three body abrasion. When wear occurs between composite and counter surface, it is called two body abrasion. Like coefficient of friction, wear rate may be influenced by chemical reaction. For example, Bai et al. (1995) have reported that, binding energy of AlSiC is 73.8 eV. The binding energy of the Aluminium oxide (Al2O3) is 74.0 eV. So, binding energy both of them is almost equal. So, during operating condition there is high probability to form an oxide and this oxide layer may be present on the composite surface. Now, this oxide has very different properties compare to the base material. Presence of this oxide layer greatly influences the friction and wear behaviour. With the presence of oxide layer, composite shows lower coefficient of friction and wear rate. Some of the researchers have reported the transition of wear rate. They have explained this phenomenon as the result of the change of wear mechanisms. At lower load, wear is adhesion controlled. Sometimes two body and three body abrasion is also observed. At higher load, wear mechanisms are - microploughing and microcutting in nature,which increases the wear volume. This transition wear can also occur by means of increasing sliding speed and temperature. To minimize the wear rate, suitable operating point should be below the critical tribological parameter.

1.5.11 Effect of some extrinsic factors on friction and wear behaviour

1.5.11.1 Normal load

In general, as the load increases wear rate increases. But, after a critical applied load transition of wear rate from mild wear to severe wear is observed. Then, again wear increases in ordinary manner. Below the critical load, unreinforced metal and composite shows almost same wear behavior (Cao et al., 1990). But, it has also been reported that, in the first region composite can be ten times resistant to wear (Alpas & Ghang, 1992). This difference is because of the difference in load bearing capacity of SiC particle. If the applied stress is beyond the fracture stress of SiC particles, then wear volume increases (Jokien & Anderson, 1999). As load increases, adhesion controlled friction and wear mechanism transformed to microcutting (Hosking et al., 1982).

1.5.11.2 Sliding velocity

Generally, with increase in load transition of wear occurs after a critical load. This transition load depends on sliding velocity (Cao et al., 1990). But, there are some situations, where wear is independent of sliding velocity (Hosking et al., 1982). It is interesting to know that, below certain sliding velocity, where the friction mechanism is micro-cracking, sliding velocity does not affect wear behavior (Wang & Rack, 1991). But, after that sliding velocity as the velocity increases more debris is created that changes the wear mechanism from adhesion wear to abrasion wear. Then, finally transition of wear occurs which can be described by micro-cutting controlled debris generation (Wang & Rack, 1991). It has been reported that, various type of reinforcement material like SiC, Alumina, TiC, glass; SiC gives different wear resistance with varying velocity (Lee et al., 1992). So, wear rate is a function of both sliding velocity and normal load. Because of this dependency, a map is generated from where one can predict the wear severity and wear mechanism during dry sliding wear as a function of sliding velocity and normal load (Lim & Ashby, 1987). With increase in speed, friction coefficient generally decreases. This decrease in friction coefficient with increase in sliding speed may be attributed to two factors, i.e. (a) reduced adhesion due to increase oxidation encouraged by high sliding surface temperature caused by localization of the heat and (b) reduced time available for the formation of cold junction at interface which in turn reduces the force required to shear off weld joints at sliding interfaces to maintain the relative motion.

1.5.11.3 Sliding distance

When the specimen is tested, initially friction coefficient also increases up to a particular sliding distance. This zone is called transition zone. This is followed by a steady state friction coefficient (Sannino & Rack, 1993) as represented in Fig 1.7. In transition period, as sliding distance increases friction coefficient also increases. According to some

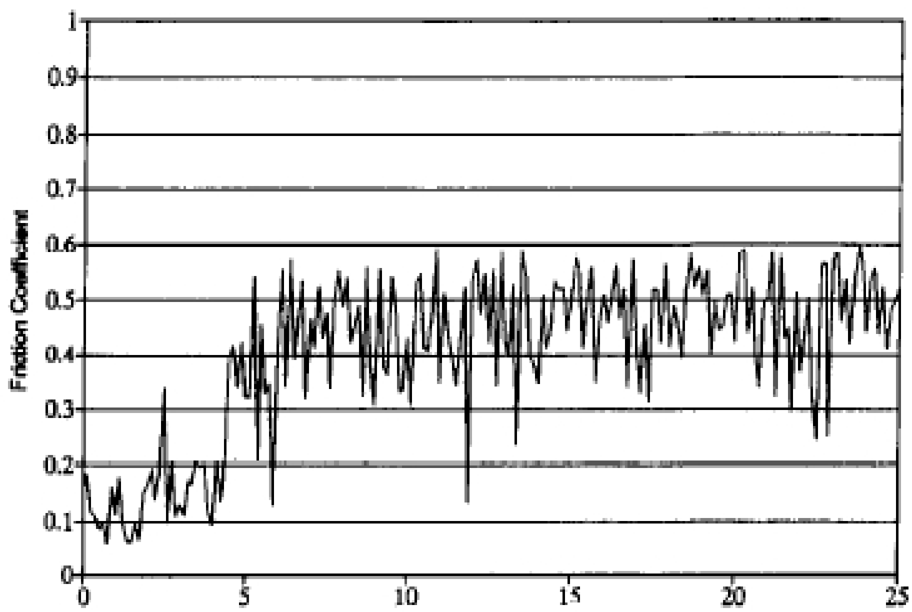


Fig 1.7 Typical frictional coefficient against sliding distance for 9000 AlSiC, (Sannino & Rack, 1993)

investigations, the loose debris present in the track of sliding direction mainly responsible for this change (Alpas & Embury, 1990). The formation of loose debris is generally controlled by delamination of subsurface layers (Alpas & Gheng, 1992). As the composition of the composite changes, run-in distance of transition zone also gets changed (Pan et al., 2008). It has also been reported that as the specimen some residual strain induces in the composite which increases with increase in sliding distance (Jun et al., 2010).

1.5.11.4 External temperature

The temperature at the interface influences wear behavior. Two distinct behaviors may be observed with increase in temperature (Martinez et al., 1993) as represented in Fig 1.8. At lower temperature, wear generally controlled by reinforcement material. But, at higher temperature tribological behavior of metal matrix composite is controlled by Matrix material. At higher temperature, they act as better wear resistant. This is probably because of the thermal stability of entire MMC increases with increase in temperature.

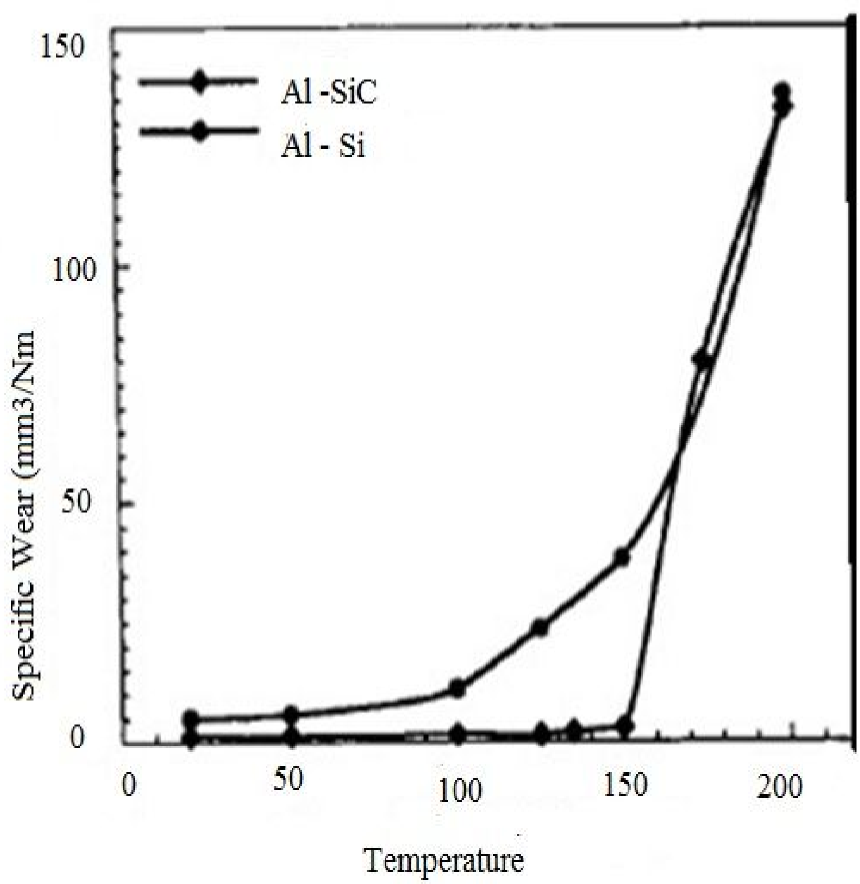


Fig 1.8 Effect of temperature on wear rate, (Martinez et al., 1993)

1.5.11.5 Orientation of reinforcement

The run-in period wear rate of the composites depends upon the reinforcement orientation (Wang & Rack, 1991). The highest rate is being observed with the perpendicularly oriented SiC composite. However, the steady state wear rate is generally independent of the reinforcement geometry (particulates vs. whiskers) and orientation (perpendicular vs. parallel) when load is fixed. At higher normal load, the sliding wear rate of SiC, composite varied by two fold in magnitude depending on orientation. The higher wear rate is found for the perpendicular-oriented SiC, whereas the highest performance is for the parallel orientation (Pan et al, 2008). So, the reinforcement orientation becomes more significant when load increases. In this operating condition, wear resistance of composite depends on both reinforcement geometry and applied load.

1.5.11.6 Surface finish

It has been reported that, the effect of surface finish is observed within few meters of sliding of sliding distance (Sasada et al., 1981). But after that, surface finish has no effect on wear.

1.5.11.7 Heat treatment

It is reported that, over-aged composite gives better resistance against abrasive wear compare to the under-aged composite (Singh & Lewandowski, 1993; Pan et al, 2008). This may be due to the reinforcement-matrix embrittlement. It has also been reported that, sometimes stress relaxation decrease the wear resistance of composite. Therefore, heat treatment and over aging wear performance depend on competition of two mechanisms i.e. stress relaxation and reinforcement- matrix embrittlement. It is also reported that, heat treatment also influence the wear rate. It has been reported that, with increasing aging, crack in the subsurface layer follows the grain boundary while propagating (Prasad & Asthana, 2004). So, this heat treatment process restricts the transgranular fracture. So, to separate a particle from matrix crack has to travel longer distance resulting decrease in wear rate.

1.5.12 Effect of some intrinsic factors on friction and wear behaviour

1.5.12.1 Reinforcement type

Friction and wear behavior closely related to their reinforcement type. With the introduction of reinforcement, wear is generally decreases (Sato & Mehrabian, 1976). SiC reinforced aluminium matrix improves mechanical properties better than any other reinforcement material like Alumina (Hosking et al, 1982). This result may be because of the difference in hardness of alumina and SiC. But, when volume fraction of reinforcement is constant, hybrid composition of Alumina and SiC gives best performance (Long et al., 1988). The crack depth is also dependent on the material used for reinforcement. For Titanium Carbide, higher crack depth is observed but wear resistance is lower (Roy et al., 1992). It has been reported that, if the grains are equiaxed then predominant wear mechanism is delamination (Caracostas et al., 1992). For non-equiaxed grain orientation, surface fracture is the main wear mechanism (Jahanmir et al., 1975).

1.5.12.2 Reinforcement size

At low load, a significant improvement of wear performance is observed in some operating condition when reinforcement size increases. But, these mechanisms are predominant at low load and particle size between 1-42µm (Hosking et al., 1982). But, at higher load, increase in particle size, slight decrease in wear is observed for SiC_p. It is observed that, for particle size 13-29µm wear rate increases. But, for the particle size 1-13µm, drastic reduction in wear is observed. This phenomenon can be explained due to the better protection from large reinforcement against adhesion wear (Jokinen & Anderson, 1999). In contrast, it is also reported a higher wear rate at particle size 46 µm compare to the particle size 20µm for 15 volume % SiC. This may be due to the transition of wear mechanism from micro cutting and micro ploughing, to fracture induced delamination and abrasion (Sannino and Rack, 1993). From these result, it may be concluded that, effect of particle size cannot be determined as a simple rule as in different mechanisms particle size act differently. Mechanism of wear is again related to sliding velocity induced temperature effect and normal load.

1.5.12.3 Reinforcement shape

When a composite is undergoing high strain deformation, either void can nucleate at the interface due to inhomogeneous plastic deformation (Argon et al., 1975) or cylindrical or plate like particles get fractured. Particulate reinforcement generally supports load by undergoing rotation or bearing load (Lee et al., 1992). This provides the region of stress concentration and subsurface delamination (Jahanmir & Suh, 1975). It is observed that, at low velocity whisker gives better performance and the same at higher speed for particulate reinforced. If we find the distribution of SiC in matrix, it is observed that these particles are sharp edged which has a vital role to bind them properly with the matrix. During solidification, they make interfacial bonding with the matrix which changes the properties of entire matrix significantly.

1.5.12.4 Effect of volume % of SiC and spatial distribution

The effect of changes in the constituent weight percent of AlSiC composites can be analyzed by determining the mechanical behavior of specimens subjected to different types of external loading. As volume percentage of SiC increases, the matrix becomes harder and its ductility decreases gradually (Fig 1.9). This also increases the wear performance of composite up to 20% reinforcement. It has also been reported that, after 35% of reinforcement wear behaviour deteriorates. They describe this phenomenon as increase in interfacial area that creates lower cohesive bond and large stress concentration zone. With increase in volume fraction, reinforcement wear rate decreases and unreinforced wear rate increases, these two criteria provide overall tribological performance. So, Archard (1953) law may not give the actual wear prediction. Rana & Stephenscu (1989) have found decrease in friction coefficient with increase in reinforcement volume percentage. However, decrease in wear was found by Wang & Rack (1991) at low velocity. As the speed increases, friction coefficient tends to decrease. They describe this fact as the change in wear mechanism from adhesion to abrasion with increase in reinforcement articulate.

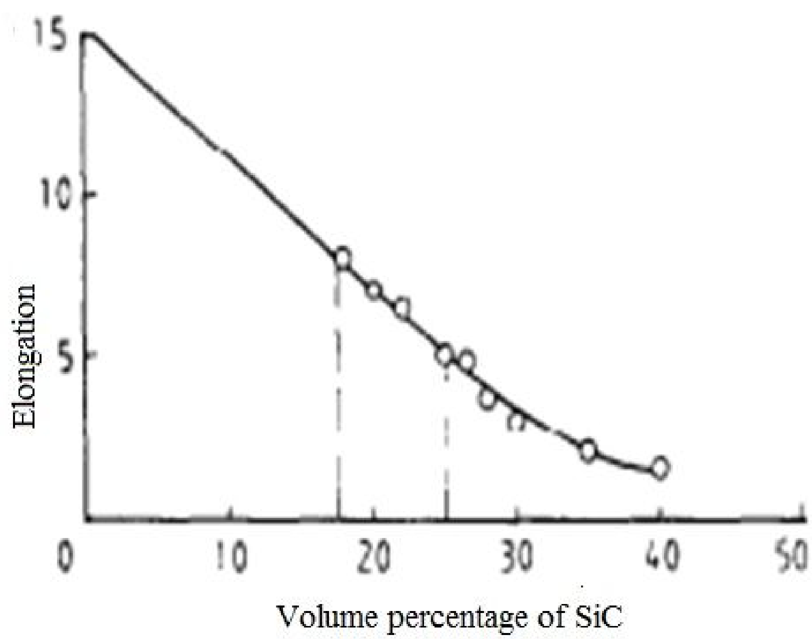


Fig 1.9 Ductile to brittle transformation of AlSiC with increase in volume percent of carbon (Mohanty et al., 2017)

1.5.13 Coefficient of thermal expansion of composite materials

Coefficient of thermal expansion (CTE) is a strong function of temperature. From Fig 1.10 it may be observed that, there are three different zone where three different mechanisms work for CTE. In the first zone, with increase in temperature CTE increases. But, in the second zone decrease in coefficient of thermal expansion is observed. Actually, in all composite material some porosity is always present. Even in equilibrium, void formation can never be avoided. The presence of void strongly influences the wear behavior of MMC. It has been experimentally found that this void is responsible for decreases in CTE after 250˚C (Nam et al., 2008). In this temperature range, that void and porous space get filled up and CTE decreases. But, beyond that CTE again increases as all void space is already been filled up.

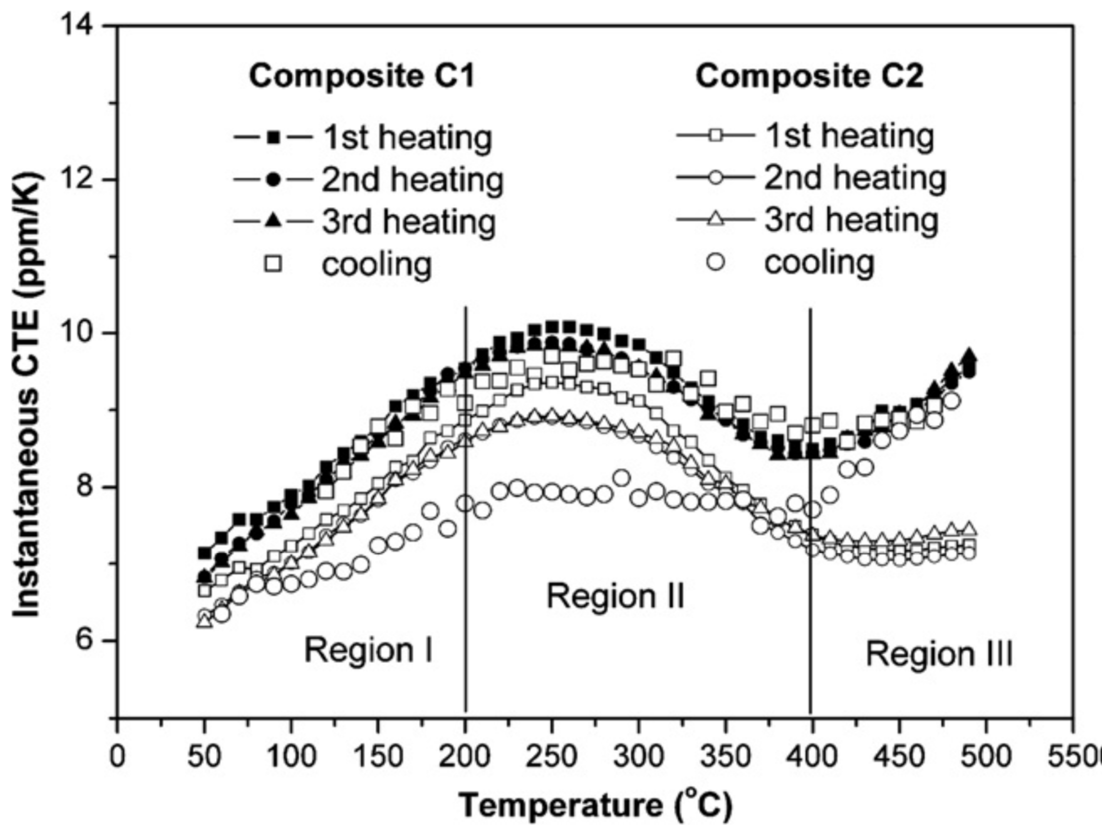


Fig 1.10 Variation of CTE of AlSiC with temperature (Nam et al., 2008)

1.5.14 Interaction with surroundings

To analyze the effect of surrounding medium, experiment has been carried out in acidic, corrosive, alkaline and aqueous medium. The result shows friction and wear rate is a strong function of environment conditions. The humidity is also measured during experiments as it may influence the results. Temperature also may affect the results of the experiments. From the literature it has been noticed that, the test results are different when we perform the experiment in ambient condition and in presence of any other medium. Some researchers (Pradhan et al., 2016; Pradhan et al., 2011; Pradhan et al., 2017; Das et al., 2005) have described the wear and friction behavior under dry, aqueous acidic and alkaline condition. The result shows that, coefficient of friction decreases with increasing in load for all sliding environments. But, under dry condition it is observed that, with increase in load, coefficient of friction increases. They describe this contradiction by the formation of transfer film. Under dry condition, with increase in normal load effect of oxide layer at aluminium surface is destroyed. So, coefficient of friction increases. But, under acidic, aqueous or alkaline medium, a transfer film is produced in the interface of the contacting surface. As this transfer film is stable in nature, they help to reduce the friction coefficient. Highest coefficient of friction of friction is observed in aqueous medium and lowest coefficient of friction is observed in alkaline medium. It is reported that, this may be because of the low viscosity of water. As lower viscosity provide lesser lubrication effect, formation of transfer film is prohibited in this case. It is observed that, wear rate increases with normal load for all sliding condition. The wear rate is maximum at alkaline and lowest at dry condition (Pradhan et al., 2017). So, under dry condition, oxide layer of alumina plays an important role for wear rate to minimize the wear rate. But, in presence of different medium, when oxide layer is removed from the surface, oxygen from surround can't react with aluminium. This increases the wear rate when tests are conducted under different medium.

1.5.15 Wear rate and COF optimization

In most of the engineering applications, the wear minimization is required. Depending upon applications, demand of coefficient of friction may increase or decrease. This friction and wear behaviour depend on various design parameters like normal load, sliding velocity, volume of reinforcement present etc. Now, it is possible to find out optimal operating condition for a particular application. There are various methods to optimize the wear rate or coefficient of friction. Some of the methods are Taguchi's method (Mukhopadhyay et al., 2016; Poria et al. 2014, Radhika et al., 2011) Particle swarm optimization (Mohanty et al., 2017), Genetic algorithm (Aharwal & Krishna, 2018), Fuzzy Logic (Mukhopadhyay et al., 2016) etc. Several researchers have found the optimal operating condition for wear rate and COF.

1.6 Summary of literature review

From the literature review it is observed that, most of the researchers have performed their analysis under dry condition. Some researchers have studied the composite behaviour under solid lubricated condition (Suresha & Sridhara, 2010). Most recently some researchers have performed their analysis under various medium like, acidic environment, aqueous, alkaline environment (Pradhan et al., 2017). But, if we concentrate on the application of aluminium silicon carbide (AlSiC) metal matrix composite, there are engineering applications, where AlSiC MMC can be utilized under lubricated condition. Some of the important application of this particular field is piston ring of automobile engine, brake drum of automobile etc. But, very limited literature is found in this particular field. So, present thesis concentrates on the tribological behaviour of composite under lubricated condition.

1.7 Present work

In this thesis, friction and wear behaviour of aluminium silicon carbide metal matrix composites (AlSiC MMC) is investigated under lubricated condition. At first, AlSiC MMC were fabricated with 2.5 weight percentage of silicon carbide content by volume by stir casting method. When the composites were developed microstructure and hardness study were done. Then, tribological tests were performed. After tribotest the worn surfaces' morphology were analyzed. The microstructure analysis and worn surface analysis were done with a scanning electron microscope (JSM-6360, Hitachi Japan). The hardness analysis was done with a Vickers Microhardness Tester. The tribotest was performed on a pin-on-disk-tribotester (Ducom, India).

1.8 Present thesis

The present thesis has five chapters. The first chapter is an introduction to different types of composite materials, its fabrication technique and extensive literature review. This chapter also gives brief description of present thesis work. The second chapter contains the details of different experimental set up and experimental procedures. The third chapter contains the tribological behaviour of AlSiC under lubricated condition. The fourth chapter deals with the optimization of wear rate. The fifth chapter contains the conclusions of the present work and scope of future work.

1.9 Closure

This chapter deals with the classification of different type of composite materials and their fabrication processes. This chapter also represents the extensive literature review of the metal matrix composite. Finally, brief description of current study and structure of representation of the thesis has been included.

Chapter 2

Experimental work

2.1 Introduction

In the present thesis, tribological behaviour of AlSiC MMC under lubricated condition is considered. AlSiC composite is prepared by stir casting method. After the completion of the stir casting, subsequent machining operation is performed to prepare the samples. A pin-on-disc type tribo-tester has been utilized for this purpose. All the pre requisite tests like roughness measurement, hardness measurement have been performed prior to the tribological tests. After the completion of the tests, experimental data is collected from data acquisition system for further investigations.

2.2 Fabrication of AlSiC samples

AlSiC samples can be produced by various techniques like – powder metallurgy, investment casting, stir casting etc. For present analysis, stir casting method has been selected for sample preparation. It is a very simple method. At the same time, this method is cost effective to for large scale production. But, this process suffers from some disadvantages also. Some of the limitations of this process are –

- It is very difficult to achieve uniform reinforcements distribution inside the matrix material;
- Wettability of the reinforcements is also not good in the liquid matrix material;
- Generation of porosity in the cast metal matrix composites;
- Due to high temperature of the liquid matrix metal there is high chance of chemical reaction between the reinforcement and the matrix material.

Various methods have been proposed to overcome those limitations. In present analysis, vortex method is used to distribute the grain uniformly within the matrix. To improve the wettability, SiC particles are pre-heated. Some amount of Mg is also added to improve the wettability. De-gasifier has been utilized to reduce the porosity which is created by the entrapment of the gas produced during stir casting. De-gasifier is basically chemicals which absorbs the gas produced during stir casting. So, after these precautions we may expect food casting quality from the stir casting. In stir casting, there are four steps to produce composite material.

2.2.1 Melting of the matrix material

In the very first step, particular amount of commercially available aluminum (Al) ingots are placed in the graphite crucible, available in the melting chamber of the stir cast set up represented in Fig 2.1 and Fig 2.2. The ingot is then converted to liquid phase by heating to a temperature greater than 700 ˚C. A small amount of magnesium (about 6%) is added to the molten metal, which increases the wettability and minimizes the oxidation during the melting process. This helps to prevent casting defects. Because of higher wettability, uniform grain distribution is also obtained. So, by adding Mg, homogeneous composite can be produced. The detail composition of aluminum alloy is represented in Table 2.1.

Table 2.1 The composition of aluminium alloy used as matrix material to prepare AlSiC MMC

Element	Cu	Mg	Fe	Mn	Ni	Zn	Al
Wt%	3.2	6.0	0.6	0.4	0.2	0.15	Remaining

2.2.2 Preheating of the reinforcement material

The size of SiC particles, used to produce composite is varied from 4-30 micron. This micron size particle does not mix well with aluminum alloy. Wettability is a great problem in stir casting process. To overcome this, SiC particles is preheated at a temperature of 600°C. After keeping at this temperature for sufficient time, these reinforcement particle are poured on the aluminum alloy vortex.

2.2.3 Mixing of the ingredients

When the aluminum alloy is melted completely, it is stirred by a mechanical stirrer, rotating at 600 rpm for 10–15 min. Because of the rotation of mechanical stirrer, a vortex is formed in the crucible placed inside the furnace. Preheated SiC particles are added to the molten aluminum alloy at the vortex in a predefined amount so that, 2.5 weight percentage of SiC is assured.

2.2.4 Casting of the composite material

The molten slurry is then transferred with a pouring temperature at a range of 650 ˚C to 700 ˚C to a cleaned permanent metallic preformed die mould of desired shape. The molten composite mixture is allowed to solidify for approximately 8 h at room temperature. After solidification, the casting is separated from the mould and subsequent machining operations are performed to produce AlSiC samples for tribological tests. The rectangular casting is firstly divided in small rectangular pieces by parting operation. Then turning and grinding operations are performed to produce the cylindrical samples of dimension Φ6×30 mm. The schematic representation of AlSiC preparation is represented in Fig 2.3

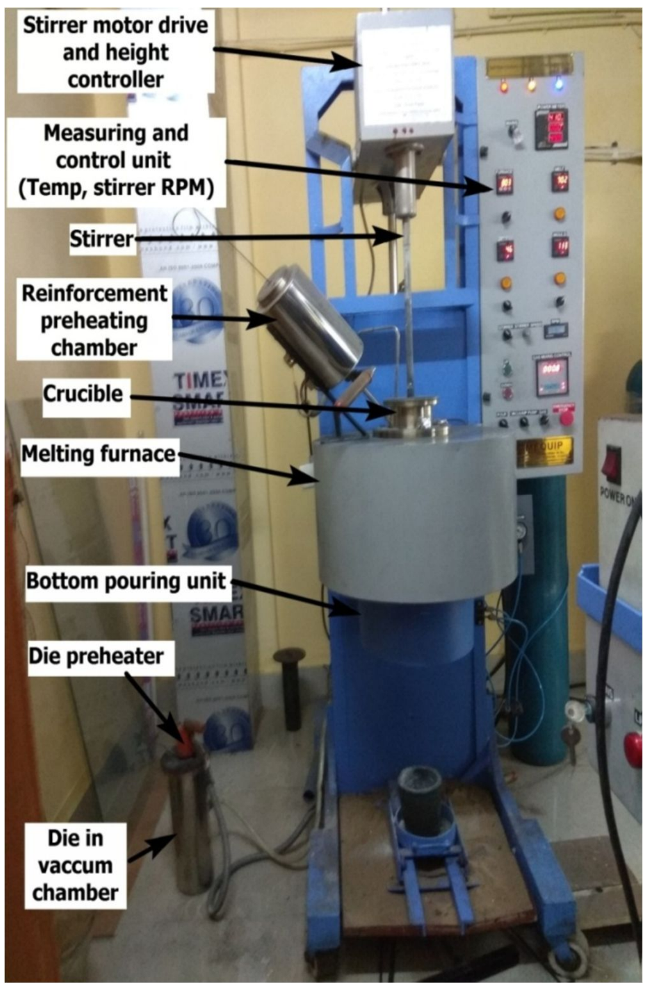


Fig 2.1 Stir casting furnace used to prepare AlSiC composite

Fig 2.2 Ultrasonic vibrator to provide ultrasonic cavitation

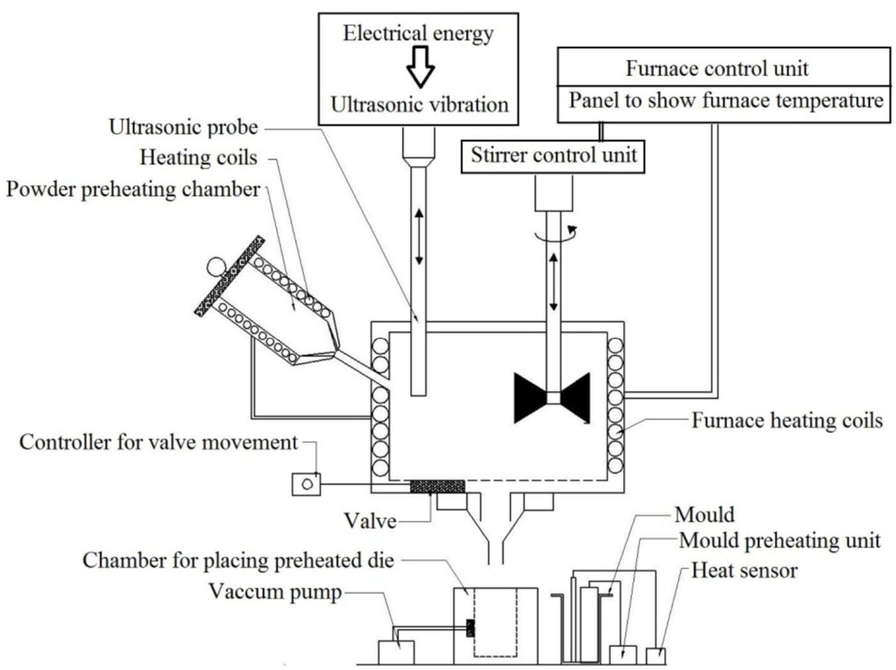


Fig 2.3 Schematic diagram of the stir casting set-up

2.3 Roughness study of AlSiC samples and alumina disc

Roughness study is very important for any tribological analysis. This study tells us that, whether the analysis is independent of surface roughness or not. For present analysis, roughness is measured by Talysurf (Talor Hybson) shown in Fig 2.4. For each and every sample, roughness test is performed over the length of 2.5 mm. Test has been repeated for three times for each samples. Then average roughness value (R_a) has been calculated. After the calculation of roughness value of all the samples, samples with variation of roughness less than 1% is selected for tribilogical tests. This makes the experimental results independent of surface roughness.

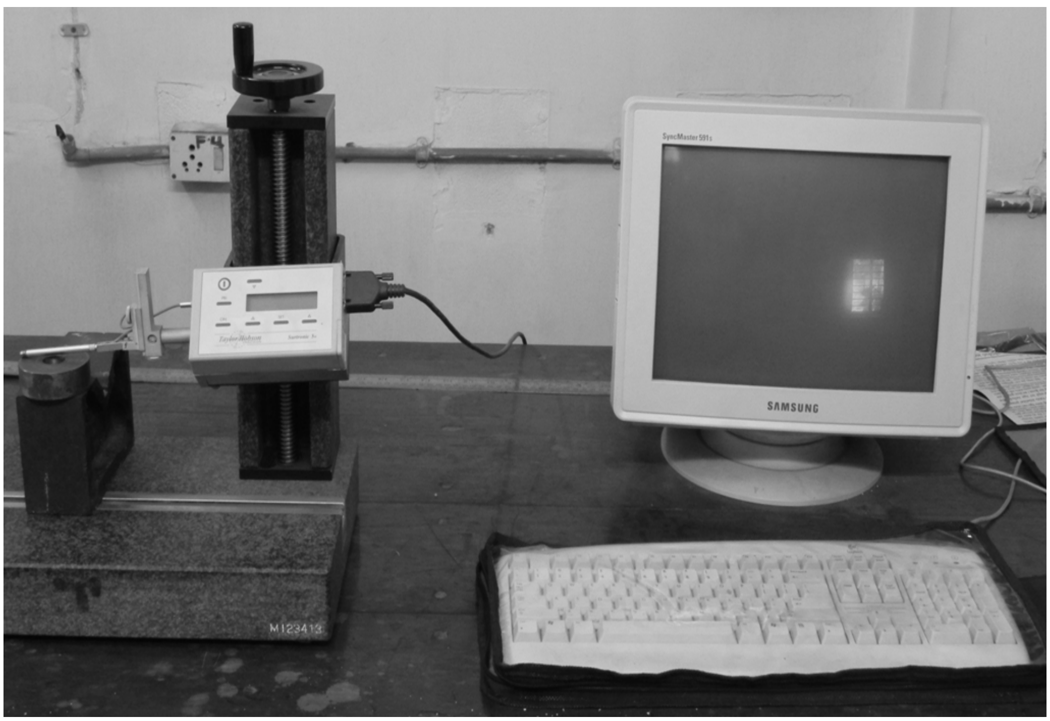


Fig 2.4 Talysurf (Taylor Hybson) for measurement of surface roughness

2.4 Hardness Study

Alumina (Al_2O_3) disc of Φ80 is selected as counter surface material against AlSiC samples. Hardness test has been carried out on Leco Hardness Tester (LV700), U.S.A. It is a Vicker's hardness tester. The indenter used to measure the hardness is square base pyramid shape with apical angle of 136°. The indentation by the indenter in alumina sample is represented in Fig 2.5. It may be observed from Fig 2.5 that, two diagonal has been detected from that indentation of the Vicker's hardness test. Knowing the apical angle, applied load and mean diagonal length of the indentation, Vicker's hardness number can be calculated. If the mean diagonal length is d (in mm), the area of indentation is given by

$$A = \frac{d^2}{2Sin(\frac{136}{2})} = \frac{d^2}{1.8544} \quad (2.1)$$

If the applied load is F, Vicker's Hardness Number can be calculated by

$$\text{VHN} = \frac{F}{A} = \frac{1.8544F}{d^2} \quad (2.2)$$

Vicker's hardness test is carried out for AlSiC sample on vicker's microhardness tester. To measure the hardness, 50 gmf normal load is applied with a dowel time of 15 seconds. The mean hardness value comes out to be 68.7. Now, from the literature it is observed that, hardness of single crystal alunina is 2720. Hardness value of alumina prepared by different process is generally varied for 1600 to 2000. So, it may be interpreted that, hardness value of alumina is considerably higher than AlSiC MMCs. So, when AlSiC samples and alumina disc makes tribological contact, most of the wear occurs from AlSiC samples and wear from alumina disc may be neglected.

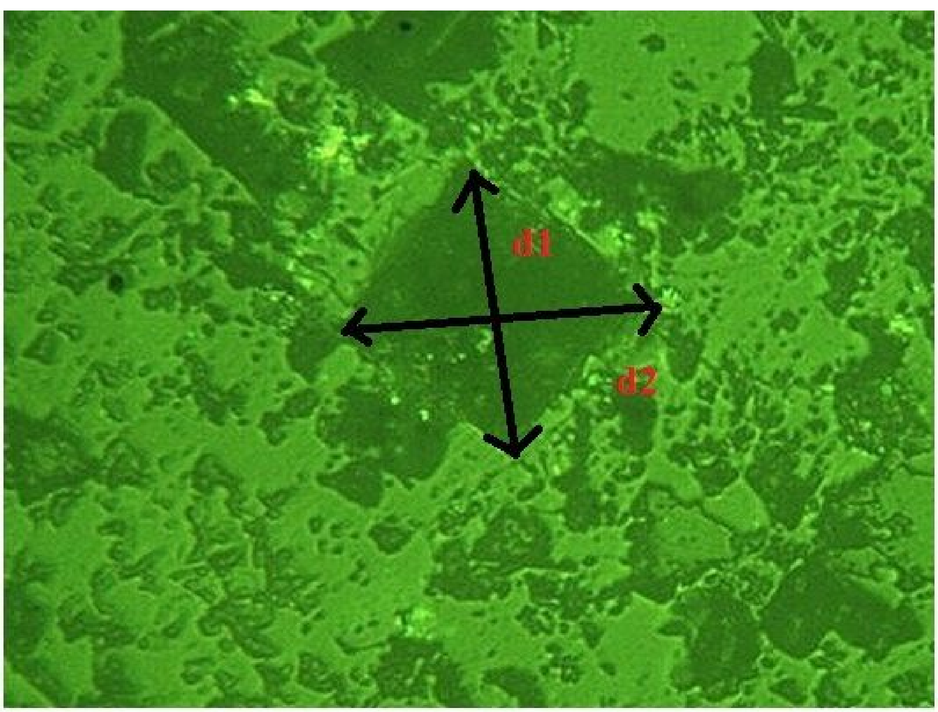


Fig 2.5 Indentation of Vicker's Indentor in Alumina sample

2.5 Tribological study

For present investigation, a pin-on-disc type tribotester (Ducom, India) represented in Fig 2.6, is used. Here, AlSiC samples of Φ6×30 mm is kept stationary by means of a clamping arrangement. The clamping arrangement is mounted at one end of the loading lever. Alumina disc of Φ80×5 mm is rotated against the AlSiC sample. So, in present investigation, alumina behave as counter surface material. Counter surface material is selected based on engineering applications. In piston ring and cylinder, tribological pair is formed between AlSiC MMCs and steel. So, steel can be selected as counter surface materials. But nowadays, automobile brake drum is made from AlSiC MMCs to minimize the weight and the contacting surface of brake caliper is made from alumina. So, during real life applications, they form a tribological pair. So, keeping those applications in mind, alumina (Al_2O_3) is selected as counter surface materials for present study.Now, this alumina disc is connected to the recess of a steel disc by means of adhesive (Araldite + Hardener, 3:1). This forms a permanent joint between alumina disc and the steel plate. This steel plate is mounted on the spindle which is connected to the AC motor installed in theexperimentalsetup.Thismotoris connectedtothespindle by means of timer belt. This belt also provides positive drive with low vibration. The

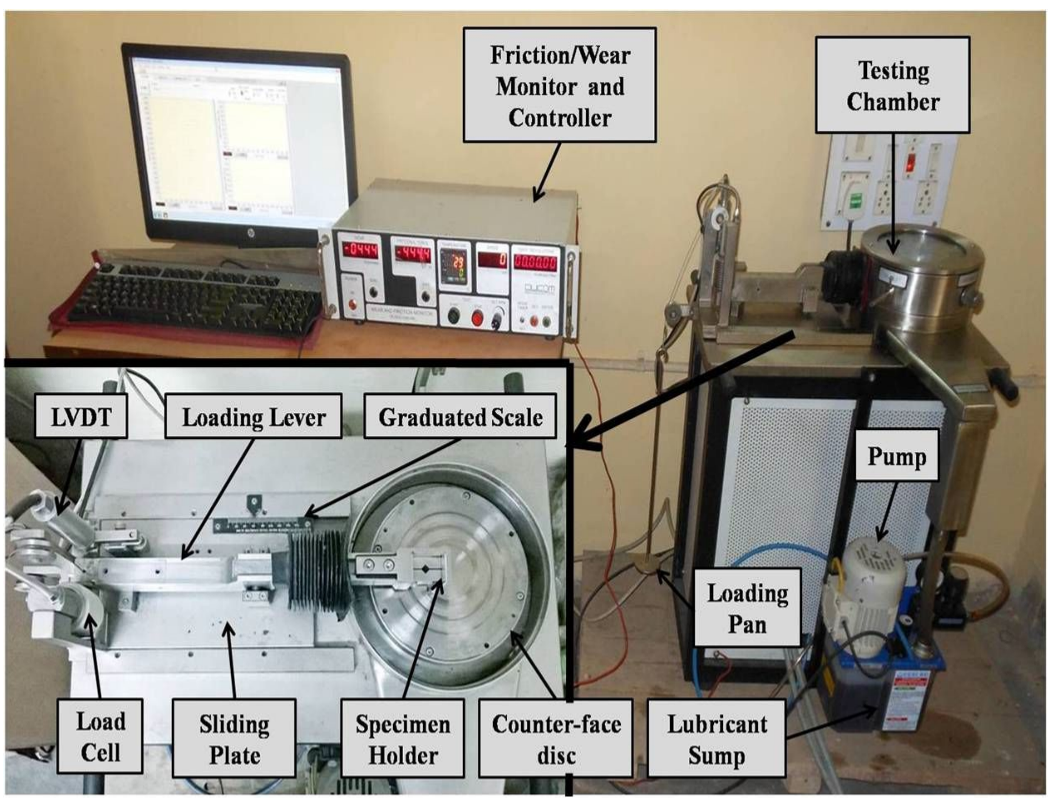


Fig 2.6 Pictorial representation of experimental set up

AC motor can be operated from the control unit to start the experiment. Before starting the experiment, design factor of the experiments like rotational speed, duration of the experiment can be set to a predefined value. One end of the loading lever is connected to the wire in which loading pan is connected. During experiment, dead weight can be put on the loading pan, which transfers the normal load on the specimen by means of loading lever. The pump connected to the experimental set up can be operated to feed the lubricating oil on the experimental set up. A data acquisition system is connected in the experimental set up. In this system, we can provide a sample identity for a particular test. The pre-defined factors like track diameter, experiment duration can be added in the same sample ID. We may have three graphs from this data acquisition system which plot wear depth, coefficient of friction (COF) and temperature against the entire experiment duration. After the completion of the experiments, experimental data for coefficient of friction and wear rate can be collected from the data acquisition system.

2.5.1 Design Factors and design of the experiments

From the literature review it is observed that normal load and sliding velocity are two important parameters for wear study under dry condition. For present study, these two parameters are taken as design factors. Five levels of load and sliding velocity have been used for investigation of wear rate under lubricated condition. Normal load is varied from 10N to 90N and the sliding velocity is varied from 100 rpm to 300 rpm. Table 2.2 represents design factors along with their different levels. Design of experiments is carried out based on L_{25} Orthogonal array. The same has been used to carry out the experiments.

Table 2.2 Tribotesting parameter with their different levels

Level	Load (N)	Speed (RPM)	Sliding distance (m)
1	10	100	706.58
2	30	150	
3	50	200	
4	70	250	
5	90	300	

2.5.2 Testing Environment

All the tests are performed under lubricated condition at 30°C. Commercially available heavy duty engine oil Servo Pride – 40, prepared by Indian Oil is chosen for lubrication of contacting surfaces. The oil of high viscosity index also provides safety from health hazards. Separate lubrication circuit has been implemented to the experimental set up for lubrication purpose. A pump is installed to feed the oil to the contacting surface at desired flow rate. The detailed characteristic of Servo Pride – 40 is represented in Table 2.3.

Table 2.3 Properties of engine oil Servo Pride-40

Property	Value
Kin. Vis. cSt @100°C	13-15
Viscosity Index, Min.	90
Flash Point, (COC),°C, Min.	220
Pour Point, °C Max	(-) 6
TBN mg KOH/gm	9.5-12.5

2.5.3 Measurement of COF

Friction force between AlSiC samples is measured by means of a strain gauge type load cell. This load cell in mounted on a bracket. Distance of the bracket from the pivot is equal to that of the sample. The load cell is fixed in a sliding plate. This sliding plate can be moved to change the track diameter of the test as per experimental requirement. When load acts on the load cell, its deformation is sensed by foil type strain gauge. The strain gauge initially is connected to the balanced wheat stone bridge. So, because of the deformation, an electrical signal is generated. This electrical signal is proportional to the load acting on the load cell. This frictional force is also displayed on the control unit of the experimental set up. Dividing the frictional force by applied normal load, coefficient of friction may be calculated which is displayed in the display of data acquisition system. From this data file, coefficient of friction can be calculated.

2.5.4 Measurement of wear rate

A linear variable differential transducer (LDVT) is used to measure the wear rate between AlSiC sample and alumina disc. A sensor is placed at the same distance from the pivot as compare to the specimen. This sensor is placed on the hardened pin projection from the lever. Now, during experiment as material get eroded, loading lever try to move upward. This movement is an indication of wear. As loading lever moves, sensor also moves upward direction. This displacement of sensor is measured by LDVT. This displacement is also a measure of wear depth which is displayed on the control unit. The detail of load cell and wear sensor is represented in Fig 2.7.

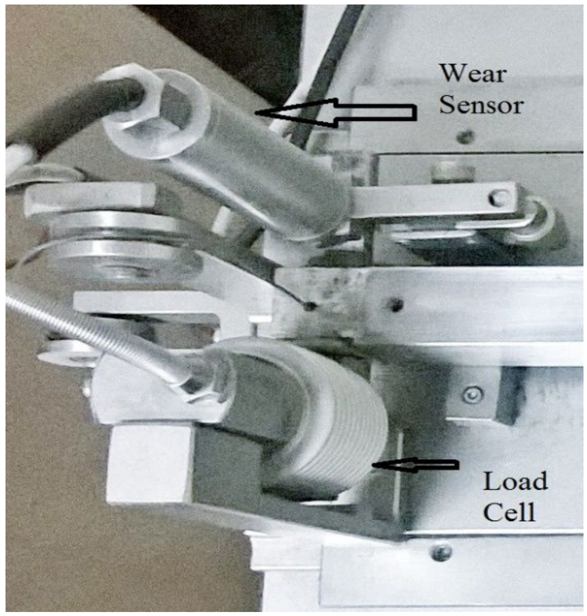


Fig2.7 The load cell and wear sensor used in tribological test

But for current analysis, wear rate has been calculated by measuring the weight loss for better reliability. A digital weight balance, represented in Fig 2.8 is used for this purpose.

Fig 2.8 Digital weight balance

To calculate the specific wear rate following equation has been used –

$$Wear\ rate = \frac{\Delta m}{\rho * v * t * F} \frac{mm^3}{Nm} \quad (2.3)$$

Where, ρ = density of AlSiC; v= sliding velocity (m/s); t= experiment duration; F= normal load.

Sliding velocity, v is calculated from the equation $v = \frac{\pi DN}{60}$; where D is track diameter and N is rotational speed in rpm.

2.5.5 Microstructural study

Microstructure characterization is an useful technique to find out the mechanisms associated for a particular tribological output. In present study, variation of coefficient of friction and wear rate with respect to load and sliding velocity is analyzed from the experimental data. Then, FESEM is carried out to find out the possible mechanisms associated with COF and wear. For present study, Supra PV35, (Carl Zeiss, Germany), represented in Fig 2.9 is utilized for microstructure study.

Fig 2.9 Field emission scanning electron microscope (FESEM),Supra PV35 (Carl Zeiss, Germany)

2.6 Closure

This chapter basically deals withal the necessary steps needs to be followed prior to the tribological test. Here, the importance of hardness study, surface roughness measurement and parameter selection are discussed. Analysis of lubricant properties is also done, as experiments will be performed under lubricated condition. Detail of experimental set up and mechanism of various instrument connected to it is also covered. Finally, experimental procedure and data acquisition system is considered. Also attempts are made to see the microstructure of the samples.

CHAPTER 3

Results and Discussion

3.1 Introduction

In the present study, tribological behaviour of aluminium silicon carbide (AlSiC) metal matrix composites (MMCs) under lubricated condition is investigated. AlSiC samples with 2.5 weight percentage are prepared by stir casting method. Subsequent machining operation is also performed to produce the cylindrical samples of AlSiC of Φ6×30 mm. A pin-on-disc type tribotester is used to perform the tribological tests. An alumina disc of Φ80×5 mm is attached to the experimental set up which rotate against the AlSiC samples to create a tribological contact. Prior to the tests, all the prerequisite tests like hardness study, roughness study is also performed. Lubricating oil Servo pride – 40 is used to have a lubricated contact zone during the experiments. The effect of two design factors i.e. normal load and sliding velocity is considered in the present study. After the completion of all the experiments, variation of coefficient of friction (COF) and wear rate with the design factors is discussed.

3.2 Experimental details

The tribological tests are conducted on pin-on-disc type tribotester (Ducom, India). Two design factors i.e. normal load and sliding velocity are selected based on literature survey for present investigations. During the experiments normal load is varied from 10 N to 90 N and the sliding velocity is varied from 100 rpm to 300 rpm. The design of experiment has been carried out based on the L_{25} Orthogonal Array (OA). The same is utilized to carry out the experiments. All the experiments are carried out for a constant sliding distance of 706.58 meters. Track diameter for AlSiC rotation is selected as 50 mm for all experiments. Before starting the experiments, lubricating oil is feed to the contact zone by a lubricating pump attached to the experimental set up to ensure fully lubricated tribological contact during experiment.

3.3 Results and discussion

3.3.1 Hardness study

Hardness tests are a prerequisite of tribological test. These tests confirm which tribological member will suffer more wear. For present investigation, hardness tests are carried out for AlSiC samples. It is observed that, Vicker's hardness number for AlSiC samples is 68.7. The load used for the test is 50gmf and the dowel time is 15 seconds. When hardness of alumina is measured at the same scale of AlSiC with the help of standard chart, it is observed that, hardness of alumina is much higher compared to the AlSiC MMC. So, wear of alumina disc may be neglected during tribological tests.

3.3.2 Roughness study

Roughness test is generally performed to eliminate the surface roughness effect of experimental results. For present study, roughness tests of AlSiC samples and alumina are conducted on Talysurf (Taylor Hobson). Samples with less than 2% surface roughness variation are selected for tribological tests. It is seen that the average roughness of the samples is 1.59 µm. Roughness test of alumina disc was also performed on the same machine. It was observed that, roughness of alumina was much lesser (0.89µm) compare to the AlSiC samples.

3.3.3 Tribological behaviour of AlSiC under lubricated condition

Tribological tests are conducted on a pin-on- disc type tribotester. Two design factors i.e. normal load and sliding velocity is selected as design factors. Design of experiments is carried out on L_{25} Orthogonal Array (OA). The experiments are conducted based on the design of experiments. In the present study, variation of wear rate and coefficient of friction is considered. Experimental results are discussed in the subsequent sections of this chapter.

3.3.3.1 Results of wear

3.3.3.1.1 Wear rate measurement

Wear depth of AlSiC MMC samples can be calculated from the display of data acquisition system. But, for current analysis, wear rate has been calculated by measuring the weight loss for better reliability. The weight of the sample is measured before the experiments. A digital weight balance is used for this purpose. The weight of the same sample is measured after the experiments. The difference in the weight before and after the test gives the weight loss. As wear rate is generally expressed in volume, density value of 2.5 weight percentage AlSiC is taken as 1.543 gm/cc to measure the wear rate. Once weight loss is calculated, Equation 2.3 can be utilized to calculate the wear rate. Experimental data corresponding to the current analysis is represented in Table 3.1

Table 3.1 Experimental results of weight loss, wear rate and average COF

Load (N)	Sliding Speed (RPM)	Weight Loss (gm)	Wear Rate (mm^3/Nm)	Average COF
10	100	0.00369	3.3832	0.096
10	150	0.00342	3.1357	0.108
10	200	0.00325	2.9798	0.039
10	250	0.00217	1.9896	0.035
10	300	0.00113	1.0360	0.021
30	100	0.01801	5.5042	0.095
30	150	0.01277	3.9028	0.042
30	200	0.01202	3.6735	0.007
30	250	0.00792	2.4205	0.038
30	300	0.00653	1.9957	0.068
50	100	0.0294	5.3911	0.015
50	150	0.02441	4.4761	0.037
50	200	0.02227	4.0837	0.011
50	250	0.01936	3.5501	0.042
50	300	0.01732	3.1760	0.070
70	100	0.04094	5.3623	0.116
70	150	0.03684	4.8253	0.027
70	200	0.03391	4.4415	0.004
70	250	0.03125	4.0931	0.050
70	300	0.02942	3.8534	0.112
90	100	0.05732	5.8394	0.143
90	150	0.05602	5.7069	0.131
90	200	0.0543	5.5317	0.081
90	250	0.04798	4.8879	0.071
90	300	0.04402	4.4845	0.160

3.3.3.1.2 Wear behaviour analysis

The variation of wear rate of AlSiC MMC under different load and speed combination have been represented in Fig 3.1. It may be observed that, there are three distinct region of wear rate at 100 rpm. Initially, with increase in load wear rate increases, after that wear rate gets stabilized. The stability of transfer film thickness or the abrasion controlled wear mechanism may be responsible for this result. Further increament in normal load increases the wear rate. But, at higher speed, with increase in load wear rate increases monotonically. At lower load, adhesion controlled wear mechanism may be responsible for low rate of wear (Alpas and Embury, 1990). After that wear rate increases gradually up to a normal load of 70 N. This may be the result of stability of the transfer film (Natarajan et al, 2006; Pradhan et al., 2017). As load increases further, wear rate increases sharply. At level 4 or level 5, initially low wear rate is seen. This may be the result of minimum time available for adhesive wear (Cao et al., 1990; Lee et al., 1992). After that, wear rate increases sharply. This may be because of high Hertzian contact pressure, resulting wear mechanism delamination, microcutting and microploughing controlled (Hosking et al., 1982).

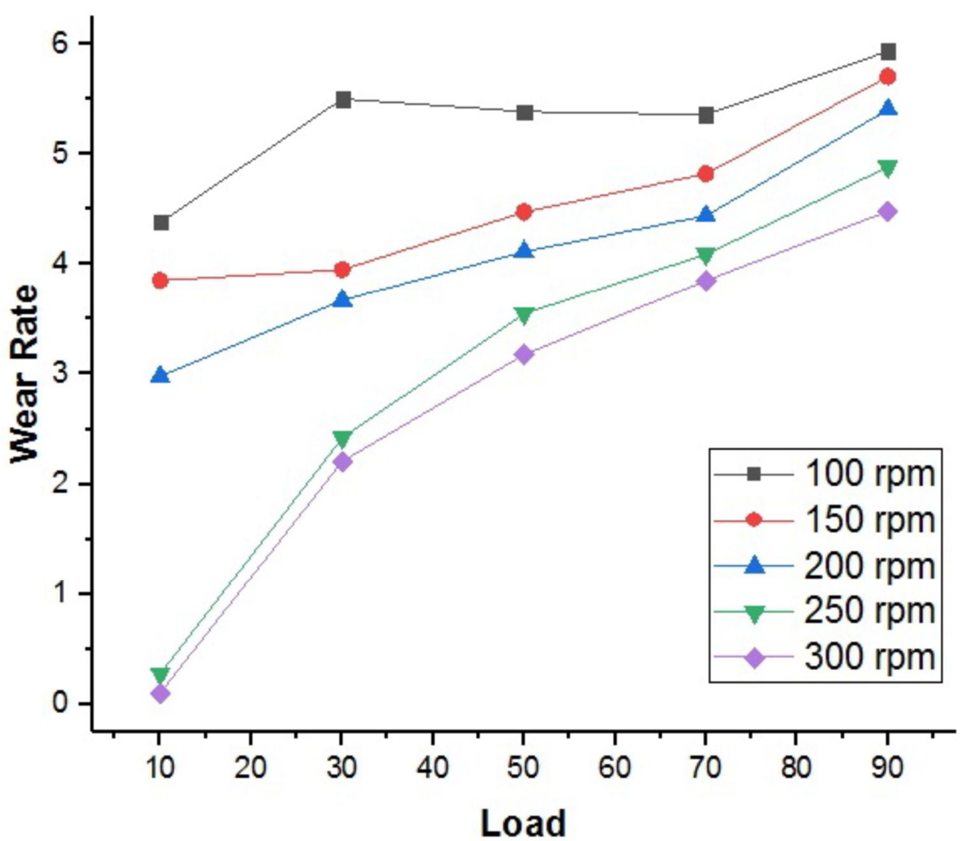


Fig 3.1 Variation of wear rate with normal load

It may also be observed from Fig 3.1 that, with increase in sliding speed wear rate decreases. At low loading condition, as wear is adhesion controlled, increase in speed provides insufficient time for adhesive wear to occur. Presence of transfer film may also restrict the tribological members to make adhesive bond. For higher loading condition, effect of abrasive wear, delamination wear, micro-cutting and micro ploughing are more prominent.

3.3.3.1.3 Optimization of wear rate

Wear of mechanical component is a major concern in many engineering applications. Minimization of wear rate reduces frequent replacement of mechanical parts. As we always want to minimize the wear rate of mechanical components, we may find out the optimal operating condition for minimum wear rate. So, basically it forms a minimization problem where wear rate is the objective function. In this study, optimization of wear rate is also performed by Taguchi's S/N ratio method.

3.3.3.1.4 Optimal Parameter Combination

In present investigation, the objective is to fine the parameter combination for which wear rate is the minimum. So, this is a minimization problem. As it is a minimization problem, Lower-the-Better type function is to be used for statistical analysis which can be written as-

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y^2\right) \quad (3.1)$$

where n represents number of observation and y is the corresponding observed data. Parameter combination based on Taguchi's L_{25} design of experiment along with the wear rate and S/N ratio is represented in Table 3.2.

The relative influence of each design parameter in wear rate can be investigated in Taguchi's S/N ratio method by means of main effect plot and interaction plot. The main effect plot gives some key information which can also be utilized to find the best operating condition and best parameter combination. If a line, representing the effect of design factor has highest inclination with respect to the horizontal line, it will have highest influence in output. The highest point in the main effect plot represents the best operating condition. Main effect plot for S/N ratio based on present investigation is presented in Fig 3.2. It is clear from Fig 3.2 that normal load and sliding velocity both of the design factor are significant for wear rate under lubrication. With increase in normal load wear rate increases and with increase in sliding velocity wear rate decreases. For normal load level 1 (10 N) and for sliding velocity level 5

(300 RPM) comes out to be the best level for wear rate minimization. But the most dominant design factor can be detected by analyzing the response table represented in Table 3.3.

Table 3.2 S/N ratio table for wear rate (smaller is better)

No of Exp.	Parameter combination		Wear rate ($\frac{mm^3}{Nm}$)	S/N ratio
	Load	Speed		
1	10	100	3.3832	-10.5866
2	10	150	4.0525	-12.1545
3	10	200	2.9798	-9.4837
4	10	250	2.5506	-8.1328
5	10	300	2.1009	-6.4479
6	30	100	5.5042	-14.8139
7	30	150	3.9028	-11.8274
8	30	200	3.6735	-11.3017
9	30	250	2.4205	-7.6781
10	30	300	2.6069	-8.3226
11	50	100	5.3911	-14.6336
12	50	150	4.4761	-13.0180
13	50	200	4.8172	-13.6558
14	50	250	3.5501	-11.0047
15	50	300	3.1760	-10.0376
16	70	100	5.3623	-14.5870
17	70	150	4.8253	-13.6705
18	70	200	4.4415	-12.9506
19	70	250	4.0931	-12.2411
20	70	300	3.8534	-11.7169
21	90	100	5.8394	-15.3273
22	90	150	5.7069	-15.1280
23	90	200	5.7079	-15.1296
24	90	250	4.8879	-13.7824
25	90	300	4.4845	-13.0342

3.3.3.1.5 Significant design factor for wear rate

Relative significance of each design factor on wear rate can also be calculated from the response table. Response table can be generated during analysis by Taguchi's approach. Response table corresponding to the current analysis is represented in Table 3.3. This table consists of S/N ratio of each level of design factor and their variation when the level is changed. The delta value can be calculated by making the difference of highest to lowest S/N ratios. Design factor showing highest delta value will have highest impact to the wear rate. The rank of this design factor will be assigned as 1. The rank to the other design factor will be assigned subsequently based on their impact on wear rate. It is clear from Table 3.3, that normal load has greater impact in wear rate compare to the sliding velocity. Optimal parameter combination is found to be level 1 (1o N) for normal load and level 5 (300 rpm) for sliding velocity.

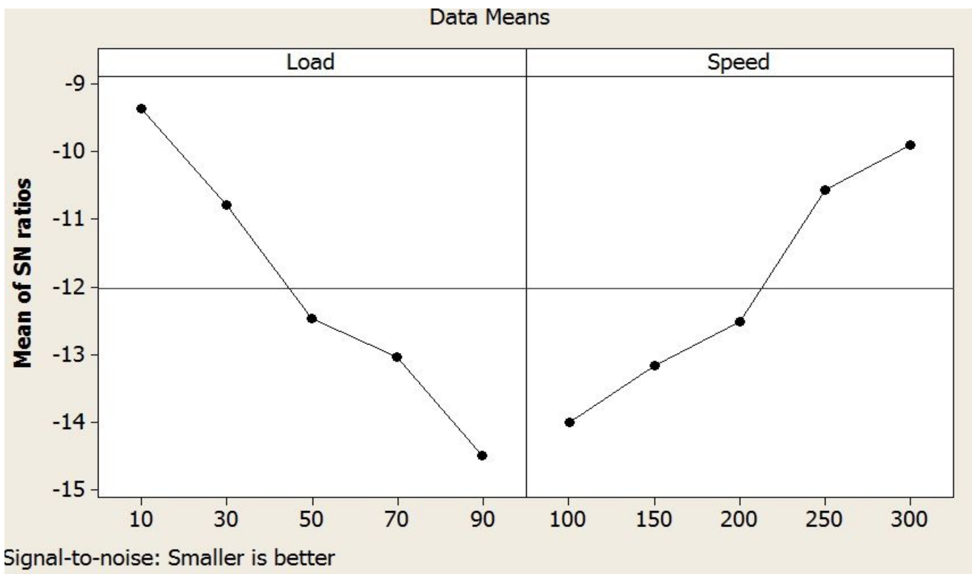


Fig 3.2 Main effect plot of S/N ratio for wear rate

Table 3.3 Response table for signal to noise ratios (smaller is better)

Level	Load	Speed
1	3.013	5.096
2	6.622	4.593
3	4.282	4.324
4	4.515	3.500
5	5.325	3.244
Delta	2.312	1.852
Rank	1	2

ANOVA or analysis of variance is another important method to find the significance of design parameter and their interaction in a particular output, wear rate for present investigation. ANOVA table for wear rate taken directly from MINITAB is represented in Table 3.4 based on the result obtained from current analysis. ANOVA table gives some key information which can be used for statistical analysis. Higher F and lower P value of a design factor signify better control in output. On the other hand, lower F and higher p value indicate that design factor do not have significant effect in output of the experiments. From Table 3.4, it can be interpreted that normal load and sliding velocity both are significant for wear rate under lubricated condition.

Table 3.4 Analysis of variance (ANOVA) table of wear rate

Source	DF	Seq SS	Adj SS	Seq SS	F	P
Load	4	79.339	79.339	19.853	19.16	0.000
Speed	4	59.830	14.957	14.957	14.45	0.000
Error	16	16.562	16.526	1.035		
Total	24	155.732				

3.3.3.1.5 Interaction of design factors

Interaction of design parameter on output can be found by plotting interaction plot of S/N ratios. For present analysis, interaction plot of S/N ratios for two design factors normal load and sliding speed has been represented in Fig 3.3. Nonparallel lines in this diagram represent the interaction of parameters and when lines cut each other then it represents strong interaction effect. Comparatively horizontal line represents very small interaction. From the plot it is seen that normal load and sliding velocity both design factors have strong interaction effect to the wear rate.

3.3.3.1.7 Regression analysis

General regression analysis has been performed to find out the relationship between design factors (Normal load, sliding speed) and the response variable i.e. wear rate. The relationship between load speed and wear rate can be represented by equation 3.2.

$$\text{Wear rate} = 5.15067 + 0.0183823{*}\text{Load} - 0.0118926{*}\text{Speed} + 4.6023{*}e^{-5}{*}\text{Load}{*}\text{Speed} \qquad (3.2)$$

The coefficient of determination is given by R square value which is found to be 89.53 percent. So, it can be interpreted that 89.53 percent of the variation is explained by the design factor included in the model. Now, the feasibility of the model can be justified by residual plot represented in Fig 3.4. Residual is basically the difference between actual value and the predicted value. From the plot it can be noticed that the residual is normally distributed. Residual shows random variation against fitted value but some mathematical relation can be generated for data points near zero residual value and rest of the data can't be explained. Residual is randomly distributed when it is plotted against observation order as represented in Fig 3.4. 3D surface plot is generated using MATLAB and shown in Fig 3.5. It may be observed that optimal parameter combination is found to be 10N normal load and 300 rpm rotational speed. It may also be noticed that with increase in normal load wear rate increases and the same decreases with respect to the sliding speed.

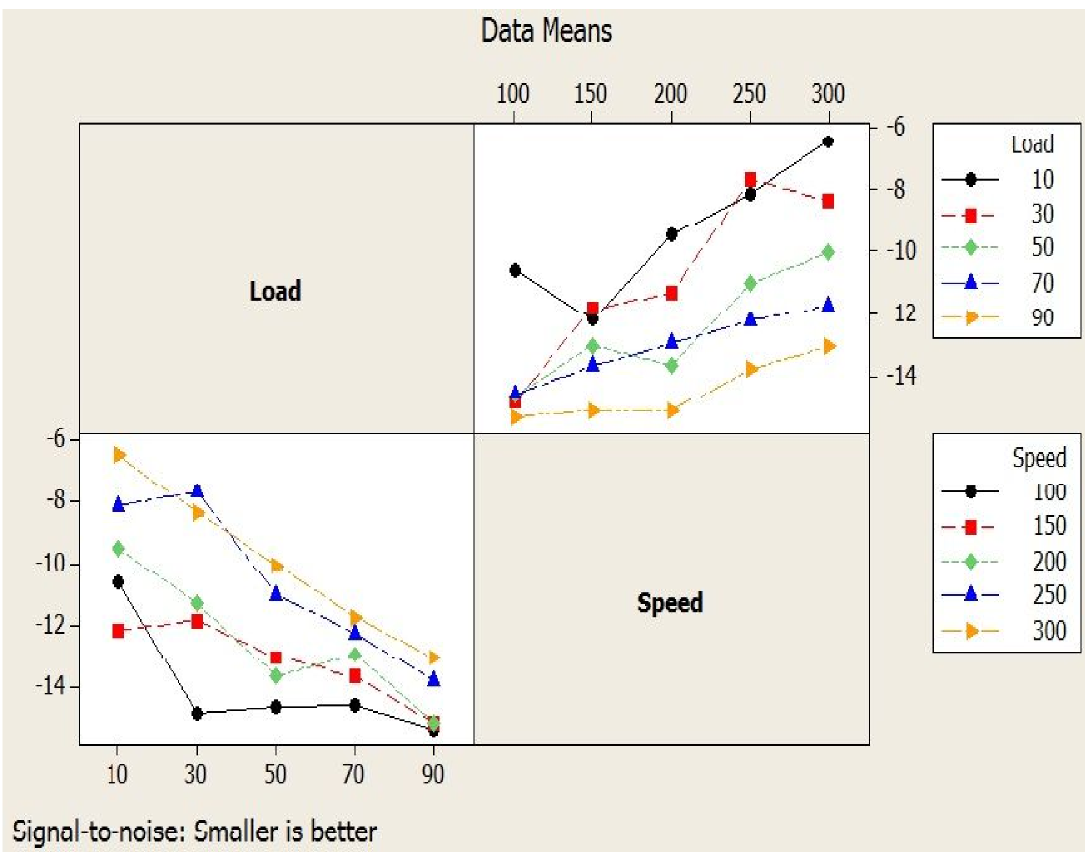


Fig 3.3 Interaction plot of wear rate

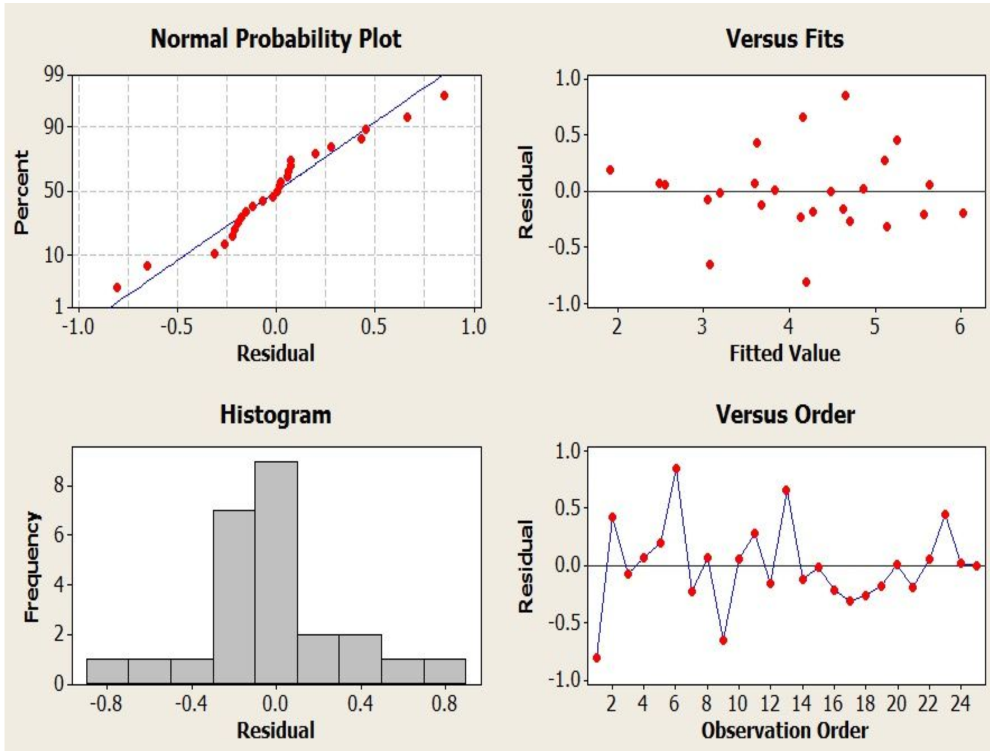


Fig 3.4 Residual plots for wear rate

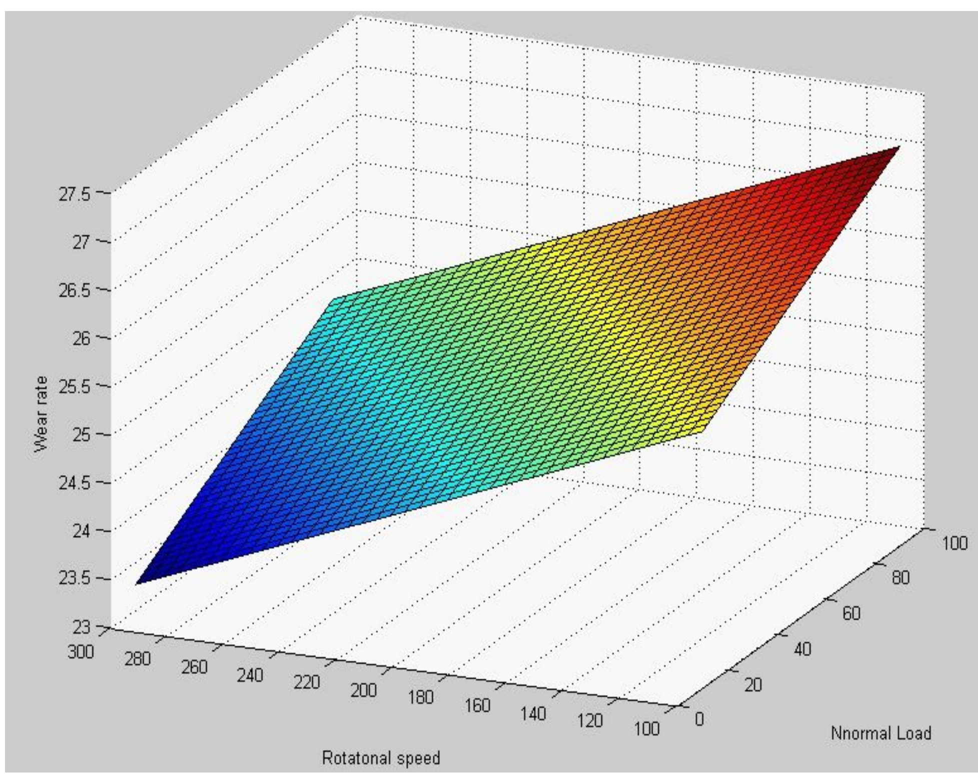


Fig 3.5 Wear rate distribution based on model generated by regression analysis

3.3.3.1.8 Microstructural Characterization

FESEM of worn out AlSiC MMC sample under lubrication is shown in Fig 3.6. The FESEM micrographs are taken at optimal operating condition i.e. 10 N normal load and rotational speed 300 rpm. From the FESEM micrograph, it may be seen from that large number of silicon carbide (SiC) particles of different sizes are present on the worn out surface of AlSiC sample. So, it may be concluded that optimal wear behaviour of AlSiC under lubrication is mainly abrasive in nature.

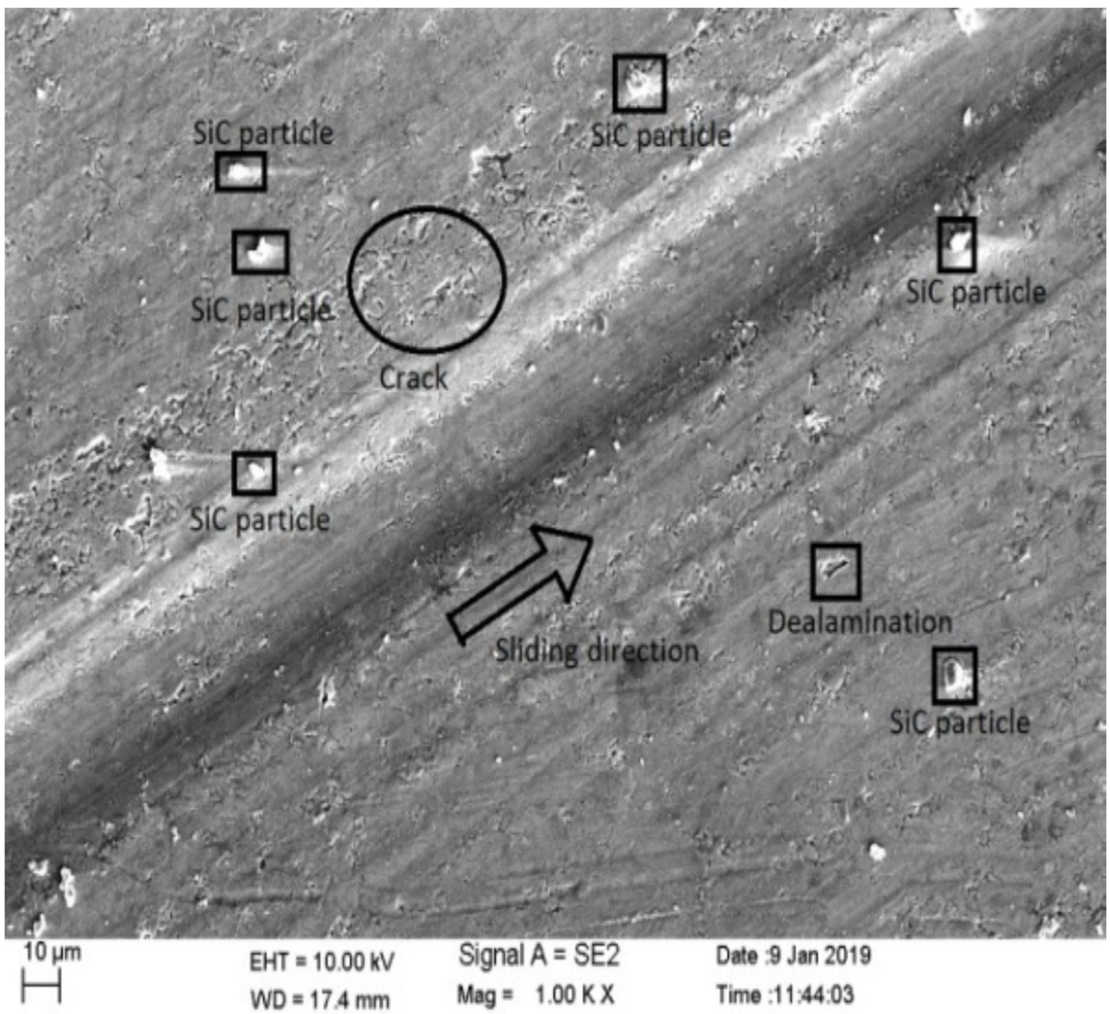


Fig 3.6 FESEM of worn out surface under lubricated condition at optimal operating point (30 N, 300 rpm)

3.3.3.2 Results of coefficient of friction

3.3.3.2.1 Measurement of coefficient of friction

A data acquisition system is attached to the experimental set up discussed in Chapter 2. In this system, we can provide a sample identity for a particular test. The pre-defined factors like track diameter, experiment duration can be added in the same sample ID. Variation of COF is displayed and stored in the data acquisition system as represented in Fig 3.7. Post processing of this data is performed to analyze further. For current analysis, COF vs Time graph is post processed to generate a excel data file. This excel data file gives us instantaneous COF for entire experimental duration. From which, average COF for a particular set of experiment can be calculated. This process is followed for all 25 set of experiment to calculate the average coefficient of friction. The experimental results corresponding to the all 25 test is represented in Table 3.1.

3.3.3.2.2 Variation of coefficient of friction

The variation of coefficient of friction of Aluminium Silicon Carbide Metal Matrix Composite (AlSiC MMC) against Alumina under different load and speed combination has been represented in Fig 3.8. Under lower speed (100-200 rpm), it is observed that, with increase in load coefficient of friction (COF) initially decreases then increases. This indicates that, initially friction mechanism may be adhesive in nature (Rehman et al., 2012;), resulting high coefficient of friction. With increase in load, Hertzian contact pressure increases. This may result subsurface fracture in the contacting surface. Wear particle created from subsurface fracture may get entrapped in the contact zone, transforming the wear mechanism from adhesion to abrasion and delamination which results lower coefficient of friction (Huchung, 1994, Vingsbo, 1988). In this domain, presence of transfer film also may be responsible for the lower coefficient of friction. But, if the load is increased further, asperity of the contacting surface may penetrate the transfer film. Under high load, high Hertzian contact pressure may create large deformation zone (Jokien and Anderson, 1990). Abrasive particles may penetrate in the contacting surface resulting friction mechanism to be micro-ploughing and micro-cutting which shows high value of COF (Sasada et al., 1981). It may be observed that, from Fig 3.8, this transformation of COF depends on sliding velocity. At higher speed (250-300 rpm), initially very low coefficient of friction is observed.

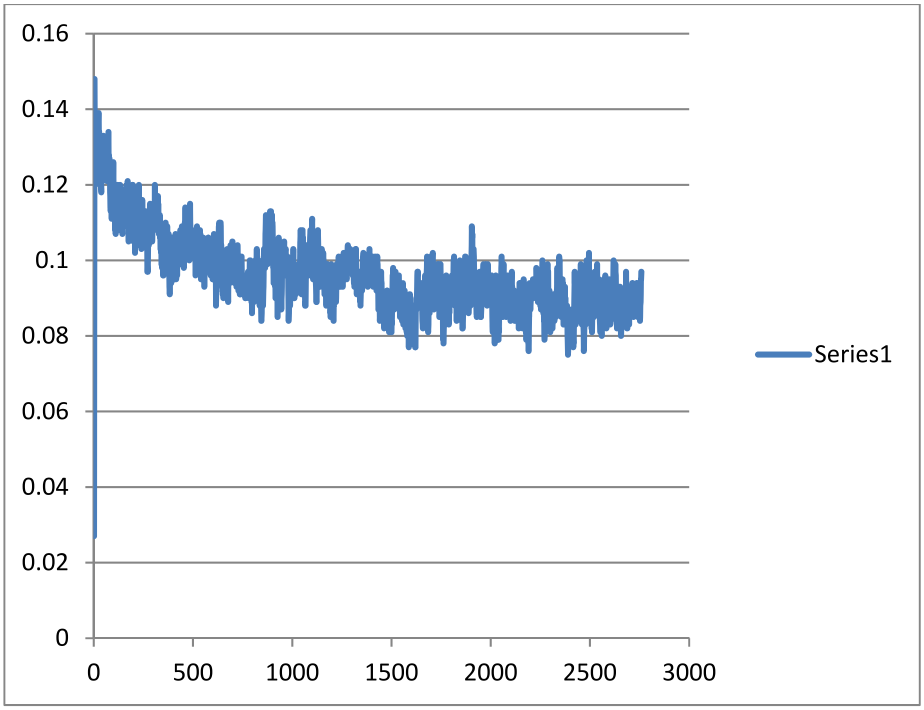


Fig 3.7 Typical variation of coefficient of friction against the duration of experiments

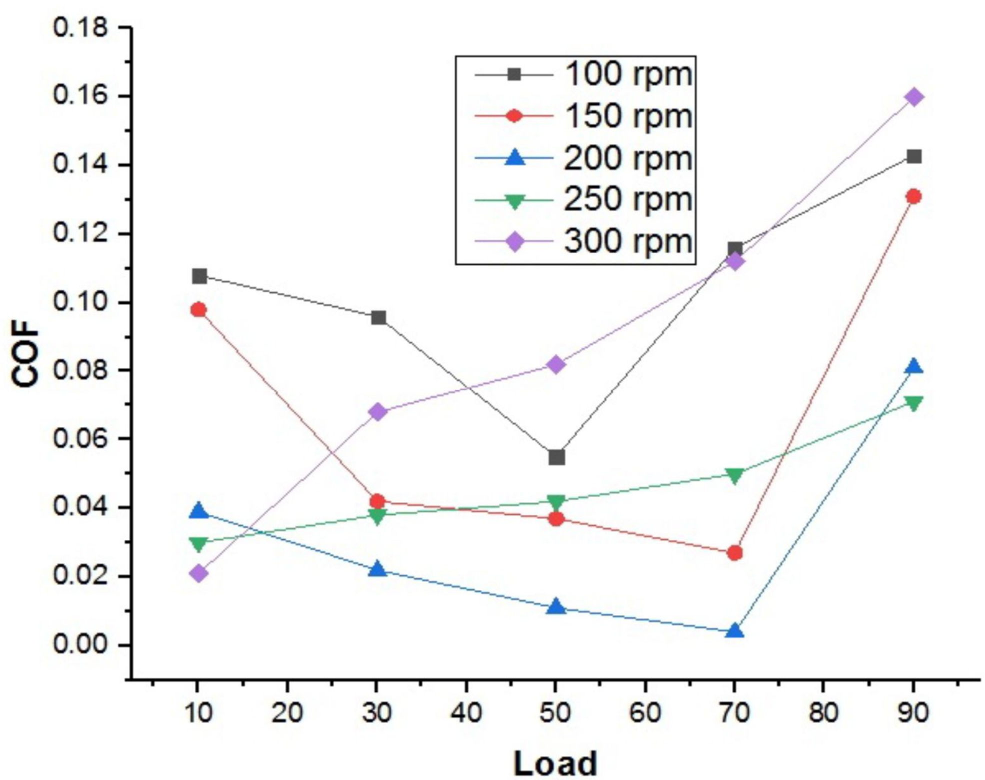


Fig 3.8 Variation of coefficient of friction with normal load

3.3.3.2.3 Optimization of COF

From the literature review it is observed that, AlSiC metal matrix composites have their applications where coefficient of friction is important. So far friction coefficient is concerned, two most important applications are piston ring and brake drum of automobiles. In these applications, minimization the coefficient of friction (COF) is required to have minimum power loss. So, attempt is made to optimize COF.

3.3.3.2.4 Optimal Parameter Combination for COF

In present investigation, our objective is to find the parameter combination for which coefficient of friction is the minimum. So, this is a minimization problem like wear rate. So, again Lower-the-Better type function, represented by Equation 3.1 is used. Parameter combination based on Taguchi's L25 design of experiment along with the wear rate and S/N ratio is represented in Table 3.5. Taguchi analysis can be carried out to generate the S/N ratio of COF. Once the S/N ratio is generated, it can be used for main effect plot of S/N ratio. Best operating condition can be found from this diagram. Main effect plot for S/N ratio of coefficient of friction is represented in Fig 3.9. From the diagram it if observed that, 70 N is best operating point for normal load as it is the highest point for normal load. For sliding speed, best operating point is 200 rpm. So, it is observed that, AlSiC metal matrix composite gives lower COF comparatively higher normal load and sliding velocity.

3.3.3.2.5 Significant design factor for COF

Response table, represented in Table 3.6 gives us some key information in the form of rank to find the most significant parameter for a particular output. The design factor with Rank 1, is most significant. So, it may be observed that, most significant design parameter for COF is sliding speed.

The most significant parameter can also be found from analysis of variance (ANOVA) table. ANOVA table for COF is generated by using MINITAB 17.0, represented by Table 3.7. It may be observed from the table that, sliding velocity is the most significant design parameter as it is the parameter with lower P value compare to the normal load.

Table 3.5 S/N ratio table for wear rate (smaller is better)

No of Exp.	Parameter combination		Coefficient Of Friction (COF)	S/N ratio
	Load	Speed		
1	10	100	0.096	20.3546
2	10	150	0.088	21.1103
3	10	200	0.039	28.1787
4	10	250	0.030	30.4576
5	10	300	0.021	33.5556
6	30	100	0.090	20.9151
7	30	150	0.042	27.5350
8	30	200	0.022	33.1515
9	30	250	0.038	28.4043
10	30	300	0.068	23.3498
11	50	100	0.055	25.1927
12	50	150	0.037	28.6360
13	50	200	0.011	39.1721
14	50	250	0.042	27.5350
15	50	300	0.088	21.1103
16	70	100	0.116	18.7108
17	70	150	0.027	31.3727
18	70	200	0.004	47.9588
19	70	250	0.050	26.0206
20	70	300	0.112	19.0156
21	90	100	0.143	16.8933
22	90	150	0.131	17.6546
23	90	200	0.081	21.8303
24	90	250	0.071	22.9748
25	90	300	0.160	15.9176

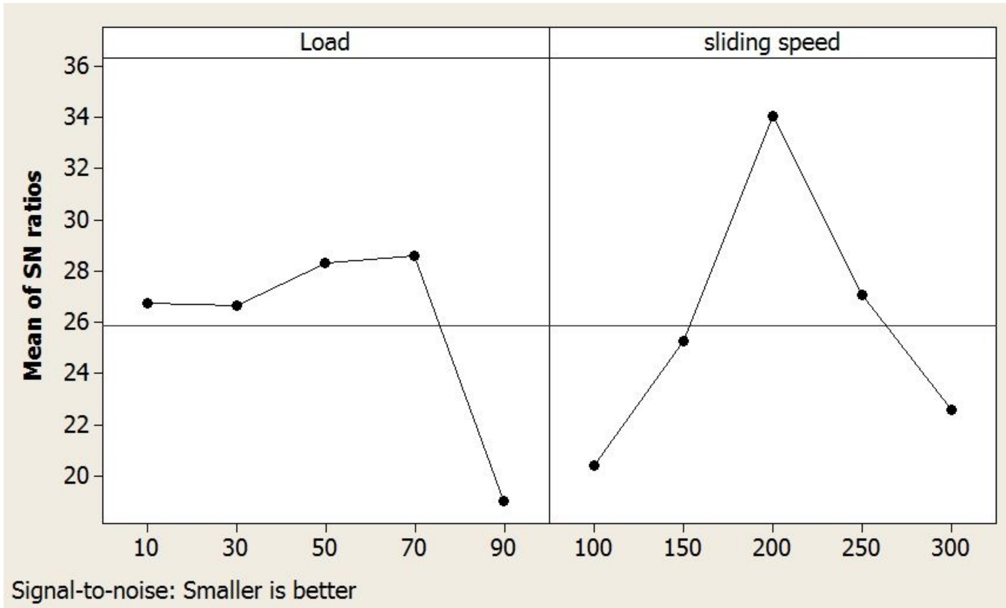


Fig 3.9 Main effect plot of S/N ratio of coefficient of friction

Table 3.6 Response table for signal to noise ratios (smaller is better)

Level	Load	Sliding Speed
1	26.73	20.41
2	26.67	25.26
3	28.33	34.06
4	28.62	27.08
5	19.05	22.59
Delta	9.56	13.64
Rank	2	1

Table 3.7 Analysis of variance (ANOVA) table of wear rate for Normal load and Sliding velocity

Source	DF	Seq SS	Adj SS	Seq SS	F	P
Load	4	307.13	307.13	76.78	2.58	0.077
Speed	4	547.07	547.07	136.77	4.60	0.012
Error	16	476.20	476.20	29.76		
Total	24	1330.40				

3.3.3.2.7 Interaction of design factors

Interaction of design factors represents the dependence of a design factor to the other to generate an output. Interaction plot of S/N ratio can be used for this purpose. Interaction plot of S/N ratio corresponding to the COF is represented in Fig 3.10. It may be observed that, design parameters i.e. normal load and sliding speed have very strong interaction effect.

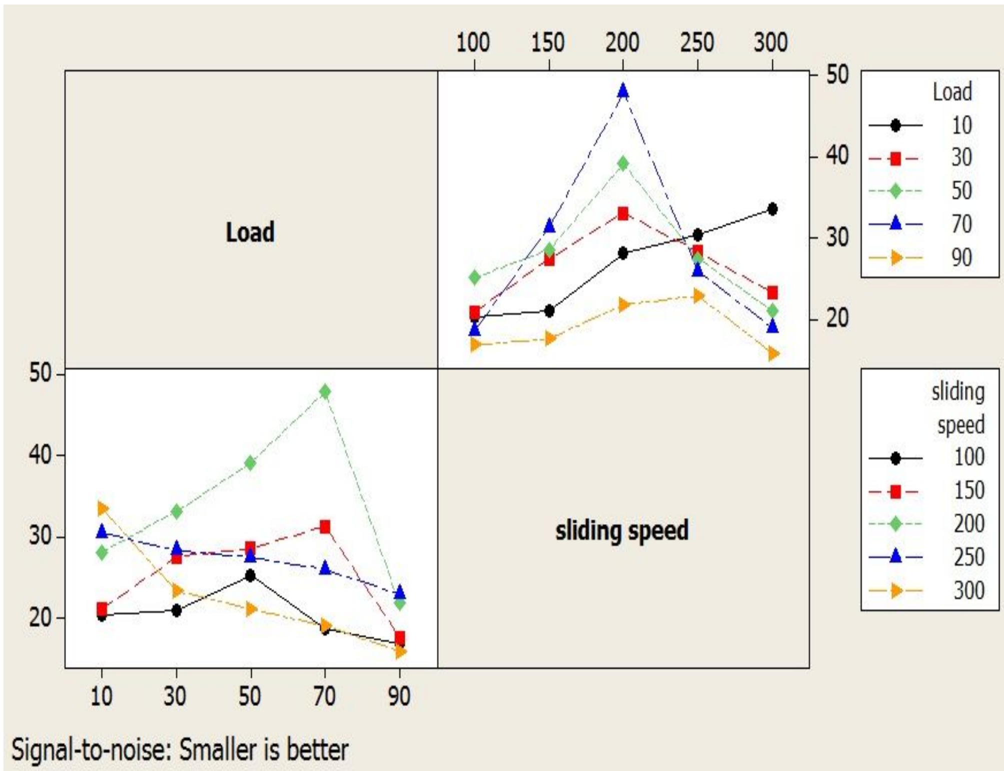


Fig 3.10 Interaction plot of COF

3.3.3.2.7 Regression analysis

General regression analysis has been performed to find out the relationship between design factors (Normal load, sliding speed) and COF. The relationship between load speed and wear rate can be represented by equation 3.3.

$$\text{Wear rate} = 0.09121 - 0.000181 * \text{Normal load} - 0.0002919 * \text{sliding velocity} + 4.07 * e^{-6} * \text{Normal load} * \text{Sliding speed} \quad (3.2)$$

The coefficient of determination is given by R square value which is found to be 26.58 percent. So, 26.58 percent of the variation can be explained by the design factor included in the model. Now, the feasibility of the model can be justified by residual plot represented in Fig 3.11. From the plot it can be noticed that the residual is normally distributed. Residual shows random variation against fitted value Residual is randomly distributed when it is plotted against observation order as represented in Fig 3.11.

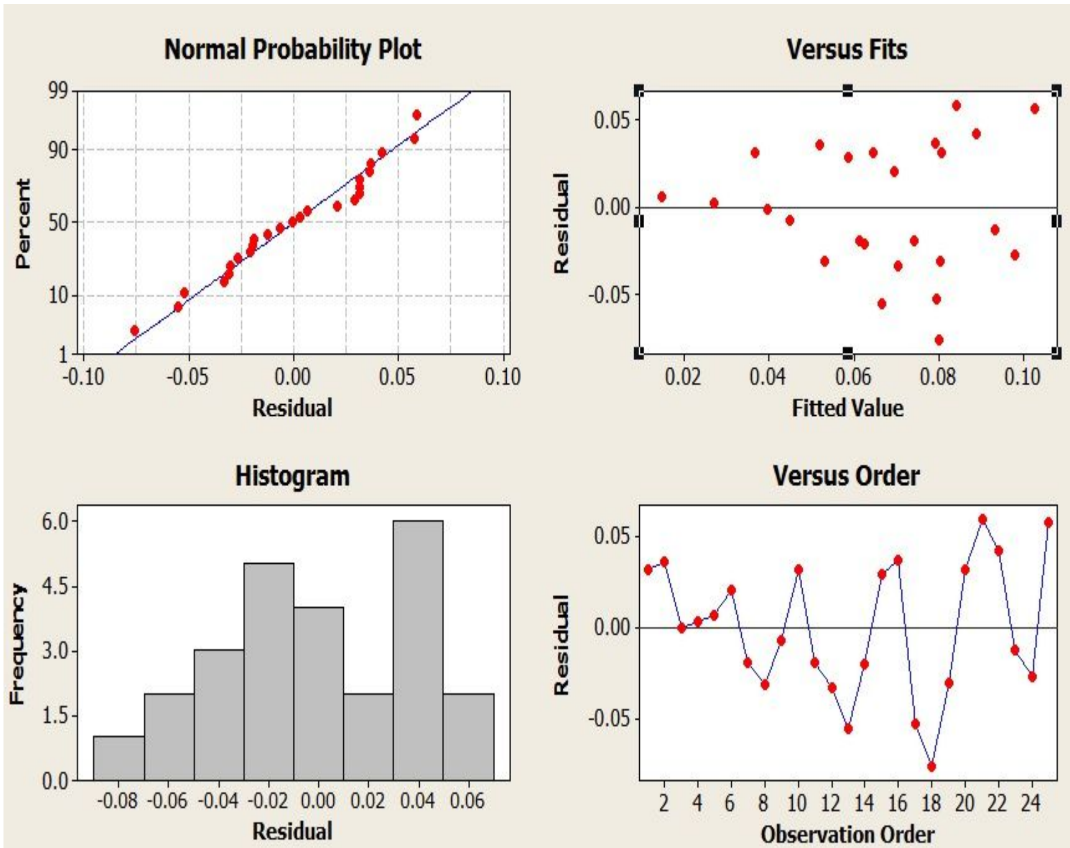


Fig 3.11 Residual plot of coefficient of friction.

3.3.3.2.8 3D plot of Variation of COF

A three dimensional surface plot of coefficient of friction variation is represented in Fig 3.11. This diagram is drawn with the help of MINITAB 17.0. From Fig 3.11, it may be observed that, there is no specific variation of coefficient of friction with respect to the normal load and sliding speed. Optimal operating condition comes at 70 N normal load 200 rpm sliding speed condition. So, when COF is concerned, AlSiC metal matrix composite may give better performance under moderate load and moderate speed condition.

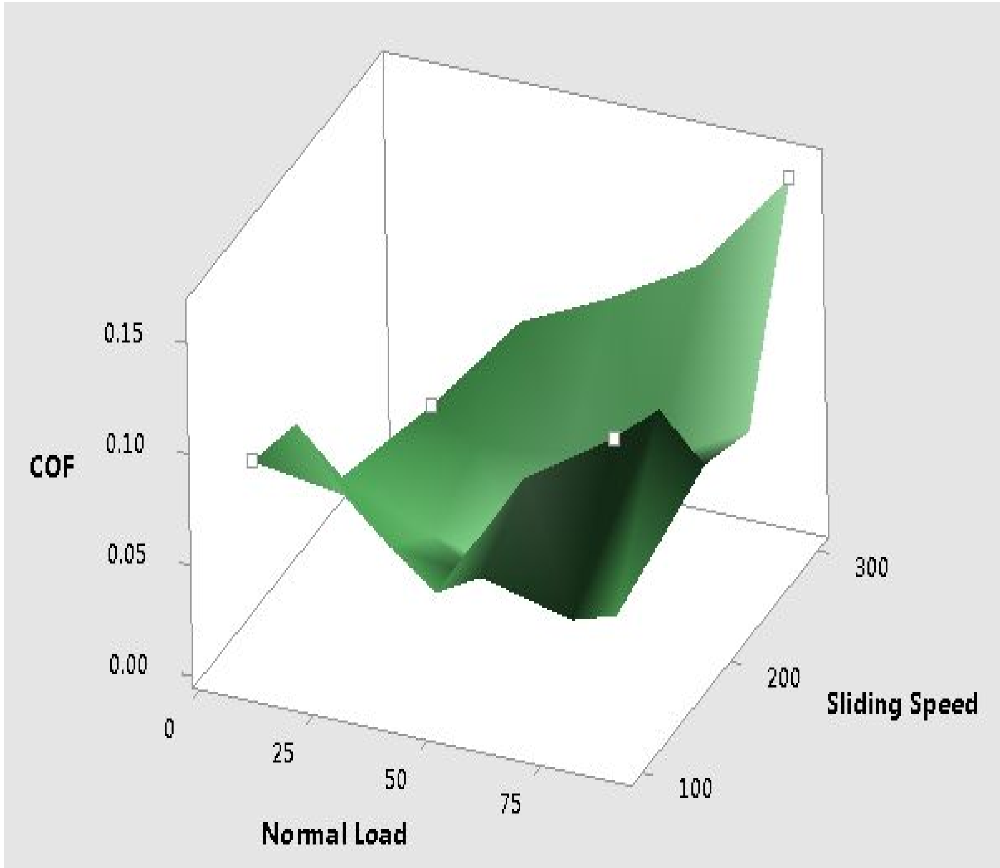
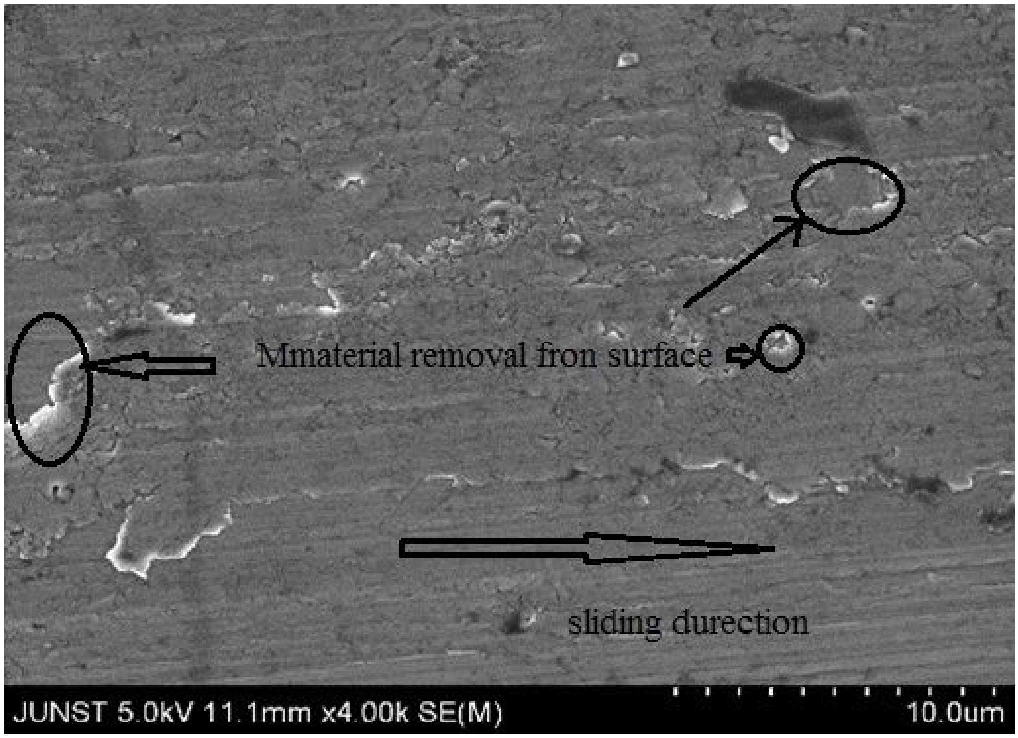


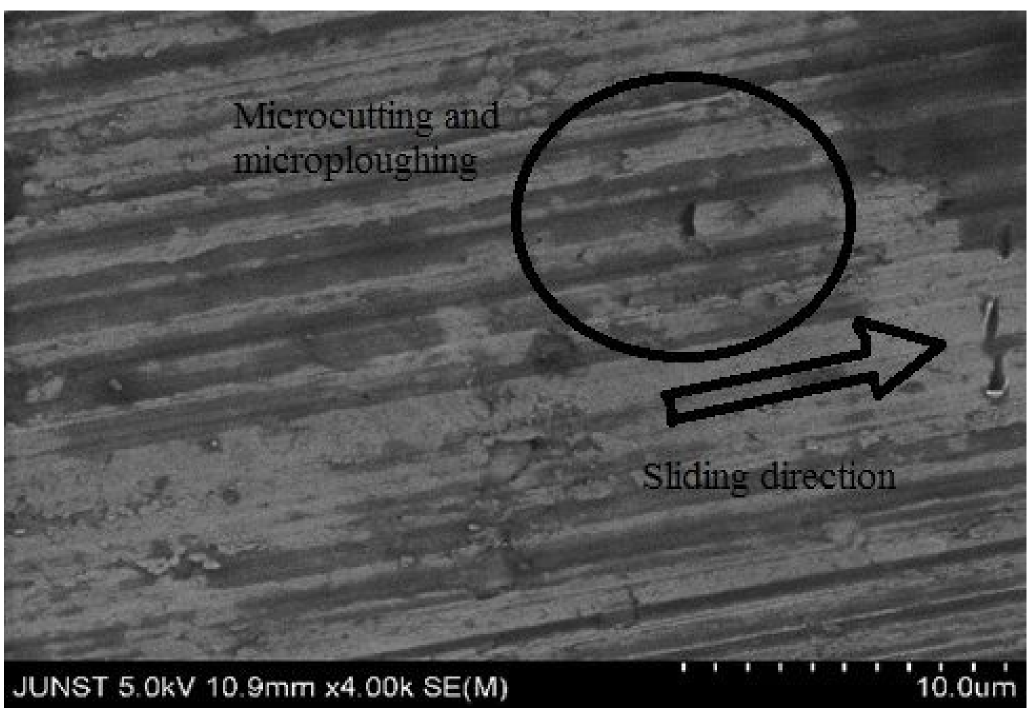
Fig 3.11 Variation of coefficient of friction (COF)

3.3.4 Micro structural Characterization

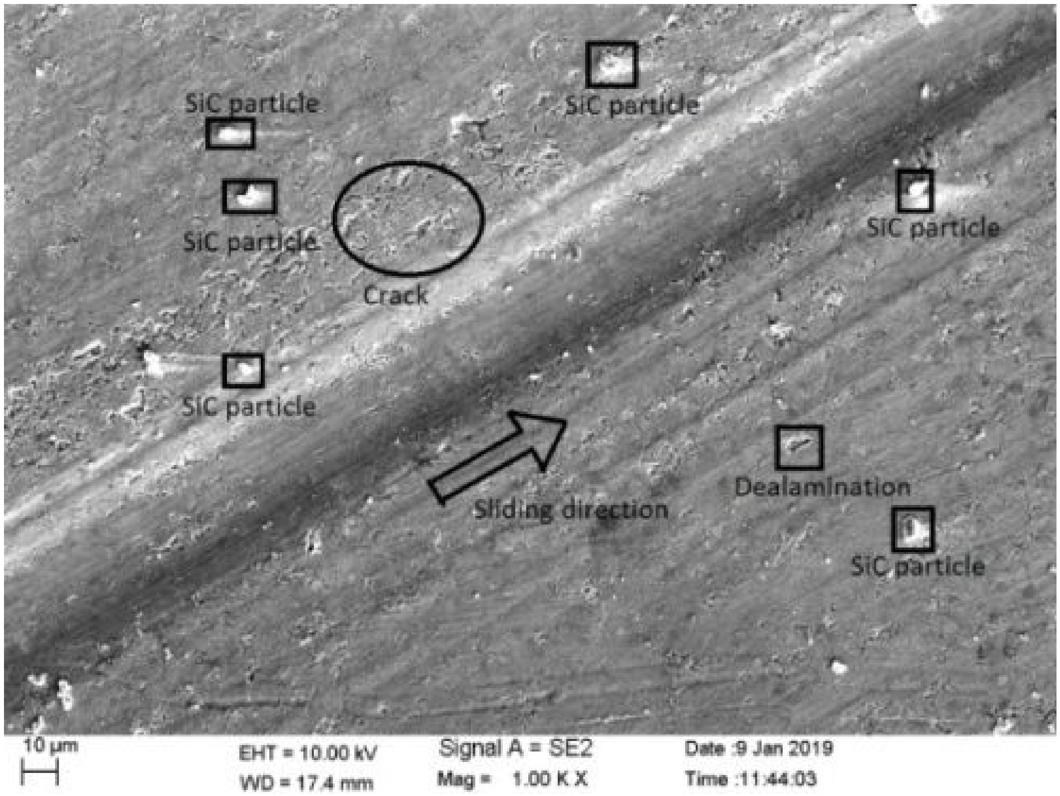
Scanning Electron Microscope (SEM) of worn out AlSiC sample under different load is shown in Fig 3.12. Fig 3.12(a) is taken at 10 N normal load and 100 RPM sliding velocity. A number of regions have been detected from where material has been removed. So, the wear mechanism may be adhesion controlled. Large number of SiC particles of different sizes appears on the worn out surface when FESEM micrograph is taken at 10 N load and 300 rpm rotational speed, represented in Fig 3.12 (b). So, under low load and high speed condition the friction and wear mechanism may be abrasion controlled. The principal friction and wear mechanism comes out to be micro cutting and micro ploughing. At lower load and higher speed condition (Fig 3.12 (c)), friction and wear mechanism is abrasive in nature. At high load and high speed condition various friction and wear mechanisms like microcutting, microploughing, abrasion is observed (Fig 3.12(c)).


Mmaterial removal fron surface
sliding durection
JUNST 5.0kV 11.1mm x4.00k SE(M)
10.0um

(a)


Microcutting and
microploughing
Sliding direction
JUNST 5.0kV 10.9mm x4.00k SE(M)
10.0um

(b)



(c)

Fig 3.12 Microstructure of worn out surface (a) 10 N and 100 rpm (b) 90 N and 300 rpm

(b) 10 N and 300 rpm

3.4 Closure

The present chapter deals with the trobological behaviour of AlSiC under lubricated environment. Among tribological behaviour, variation of COF and wear rate are considered. Optimizations of wear rate and COF are also performed by Taguchi's S/N ratio method. Finally microstructural characterization is performed by Scanning Electron Microscope.

Chapter 5

Conclusion and future scope

5.1 Introduction

Composite materials have versatile applications in recent days. Various type of composites are developed based on these application. A number of composite materials is under study. Several researchers are investigating various properties of these composite materials for modern day applications. In this thesis work, friction and wear behaviour of AlSiC metal matrix composites is considered. AlSiC samples are prepared by stir casting method. A pin on disc type tribotester is used for tribological tests. Finally, FESEM is carried out to investigate the friction and wear mechanisms.

5.2 Conclusion

For present investigation, friction and wear behaviour of AlSiC metal matrix composite has been studied under lubricated environment. AlSiC metal matrix composite samples for tribological tests, is prepared by stir casting process with 2.5% by weight of SiC as reinforcement in the matrix. From the literature survey, Normal load and sliding velocity is selected as design factor for their prominent effect on tribological behaviour. These two design factors are varied with their five levels. Design of experiment is carried out based on Taguchi's L_{25} orthogonal array (OA). Tests are conducted on a pin on disc type tribotester following the same design of experiments. Track diameter of the experiments is fixed at 50 mm. each tests is carried out for constant sliding distance of 706.58 meters.

Experimental results reveal that, with increase in normal load wear rate of AlSiC metal matrix composite increases but with increase in sliding speed wear rate of the same decreases. But, variation of coefficient of friction cannot be explained by any single specific pattern. The value of coefficient of friction fluctuates with different level of normal load and sliding velocity combination. Different friction and wear mechanism like adhesion, delamination, abrasion, microcutting and microploughing controls the coefficient of friction and wear results.

The Optimal parameter combination has been determined for wear rate and coefficient of friction minimization. Taguchi's S/N ratio approach has been utilized for this purpose. MINITAB software package has been utilized for statistical analysis. For wear rate minimization, optimal point is found to be 100 rpm sliding velocity and 10N normal load. It is observed that, both normal load and sliding velocity are significant for wear rate minimization. But, between these two design factors, normal load is more significant than sliding velocity. So, these results reveal that, for wear rate minimization operating condition should be low load and low sliding speed condition. After that, optimization of coefficient of friction is performed. It is observed that, minimum coefficient of friction is observed at high load and high speed condition (70 N and 200 rpm). Results show that, both the design factors are significant to the coefficient of friction. But in this case sliding speed comes out to be more significant compared to the normal load. For lower coefficient of friction, AlSiC can be applicable under high load and high sliding speed condition.

Finally, field emission scanning electron microscopy (FESEM) is carried out to determine the friction and wear mechanisms. FESEM micrographs reveal that, adhesion, abrasion, micro-ploughing and micro-cutting are most dominant mechanisms for friction and wear of AlSiC MMCs under lubricated environment under different normal load and sliding speed combination. At optimal operating condition of wear rate, wear mechanism comes out to be abrasive in nature.

5.3 Future scope of study

- Present investigation is focused on friction and wear behaviour under lubricated condition. The same experiment can be performed under dry condition. The result of both the experiment can be compared for friction and wear behaviour.

- The experiment can also be performed under other variations of lubrication. Optimization of wear rate and COF can be performed by optimization tool like genetic algorithm, Particle Swarm Optimization etc.

- It is observed that, adhesion controlled friction and wear behaviour has significant effect on friction and wear. So, reinforcement particle size can be considered in future study.

References:

Aharwal, KR. Krishna, CM.: Optimization of material removal rate surface roughness in EDM machining of metal matrix composite using genetic algorithm. Materials Today, Proceedings 5, 5391-5397 (2018).

Alpas, AT. Gheng, J.: Wear rate transition in cast silicon alloys reinforced with Sic particles. Scr. Metall. 26, 505-509 (1992).

Alpas, AT. Embury, JD.: Sliding and abrasive wear beaviour of an aluminum- SiC reinforced composite. Abrasive wear, 24(5), 931-935 (1990).

Alpas, T. Gheng, J.: Wear rate transition in cast silicon alloys reinforced with Sic particles Scr. Metall. 26505-509 (1992).

Al-Rubaie, KS. Yoshimura, HN. de Mello, JDB.: Two body abrasive wear of Al-SiC composites. Wear 233, 444-454 (1999).

Amirkhanlou, S. Ketabchi, M. Parvin, N. &Drummen, GPC.: Structural evaluation and mechanical properties of aluminum/tungsten carbide composites fabricated by continual annealing and press bonding (CAPB) process. Metallurgical and Materials Transactions B, 45(6), 1992- 1999 (2014).

Antolin, S. Nagelberg, AS. Creber, DK.: Formation of Al2O3/Metal Composites by the directed oxidation of molten aluminum-magnesium-silicon alloys: Part I, Microstructural Development. Journal of the American Ceramic Society, 75(2), 447-454 (1992).

Archard, JF.: Contact and rubbing of flat surfaces. Journal of Applied Physics 24 pp 981–988(1953).

Argon, AS. Im, J. Safoglu, R.: Cavity formation from inclusions in ductile fracture. Merall. Trans. 6A 825-837 (1975).

Bai, M, Wang, Xue, Q. Wan, Y, Wang, X. Liu, W.: Wear Mechanism of whisker reinforced 2024 aluminium alloy matrix composite in oscillating sliding wear tests. Wear 185197-202 (1995).

Bhansali, KJ. Mehrabian, R.: Abrasive wear of aluminum matrix composite. Journal of Metals, 30-31 (1982).

Breslin, MC. Ringnalda, J. Xu, L. Fuller, M. Seeger, J. Daehn, GS. Fraser, HL.: Processing, microstructure, and properties of co-continuous alumina-aluminum composites. Materials Science and Engineering: A, 195, 113-119 (1995).

Breval, E. Aghajanian, MK. Biel, JP. Antolin, S.: Structure of aluminum nitride/aluminum and aluminum oxide/aluminum composites produced by the directed oxidation of aluminum. Journal of the American Ceramic Society, 76(7), 1865-1868 (1993).

Bukhari, MZ. Brabazon, D. Hashmi, MSJ.: Application of Metal Matrix Composite of CuSiC and AlSiC as electronic packaging material. School of Mechanical and Manufacturing Engineering, Dublin City University (DCU), Dublin 9, Republic of Ireland, (2011).

Cao, L. Wang, Y. Yao, CK.: The wear properties of an SiC whiskers reinforced alumunium composite. wear 140, 273-277 (1990).

Caracostas, CA. Chiou, WA. Fine, ME. Cheng, HS.: Tribological properties of aluminium alloy matrix TiB_2 composite prepared by in situ processing. Metallurgical and material transactions Vol 28(A), 491-502 (1997)

Casati, R. Vedani, M.: Metal matrix composites reinforced by nano-particles—a review. Metals, 4(1), 65-83 (2014).

Christman, T. & Suresh, S.: Microstructural development in an aluminum alloy-SiC whisker composite. Acta Metallurgica, 36(7), 1691- 1704 (1988).

Clyne, TW. Withers, PJ.: An introduction to metal matrix composites. Cambridge university press. (1995).

Das, S. Saraswathi, YL. Mondal, DP.: Errosive Corrosive wear of aluminium alloy composites: influence of slurry composition and speed. Wear. 261(2), 180-190 (2006).

Das, S.: Development of aluminium alloy composites for engineering applications. Ttransactions of the Indian Institute of Metals, 57(4), 325-334 (2004).

Dewvedi, DK.: Adhesive wear behaviour of cast aluminium-silicom alloy: verview. Mmaterials and Design, 31, 2517-2531 (2010)

Flom, Y. Arsenault, RJ.: Interfacial bond strength in an aluminium alloy 6061—SiC composite. Materials Science and Engineering, 77, 191-197 (1986).

Girot, FA. Quenisset, JM. Naslain, R.: Discontiniously reinforced aluminium reinforcement composites. Composites Science and Technology, 30(3), 155-184 (1987).

Gonzalez-Doncel, G. Sherby, OD.: High temperature creep behavior of metal matrix Aluminum SiC composites. Acta metallurgica et materialia, 41(10), 2797-2805. 70 (1993).

Hamid, AA. Ghosh, PK. Jain, SC. Ray, S.: The influence of particle content and porosity on the wear behaviour of cast in situ Al (Mn)– Al2O3 (MnO2) composite. Wear, 260(4-5), 368-378 (2006).

Hamid, AA. Ghosh, PK. Jain, SC. Ray, S.: The influence of porosity and particles content on dry sliding wear of cast in situ Al (Ti) - Al2O3 (TiO2) composite. Wear, 265(1-2), 14-26 (2008).

Hosking, FM. Portillo, FF. Wunderlin, R. Mehrabian, R.: Composite of Aluminium alloys: fabrication and wear behavior. Journal of Material Science 17, 487-498 (1982)

Howell, GJ. Ball, A.: Dry sliding wear of particulate reinforced aluminium alloys against automobile friction material. Wear 181–183 pp 379–390 (1995).

Huching, LM.: Mechanism of wear in powder technology: A Review. Powder Technol. 76, 3-13 (1993).

Hull, D. Clyne, TW.: An introduction to composite materials. Cambridge University press (1996).

Hunt, WH. Miracle, DB.: Automotive application of metal matrix composites. Composites, 21, 1029-1032 (2000).

Hutchings, IM.: Tribological properties of metal matrix composites. Materials Science and Technology, 10(6), 513-517 (1994).

Ibrahim, IA. Mohamed, FA. Lavernia, EJ.: Particulate reinforced metal matrix composites—a review. Journal of materials science, 26(5), 1137-1156 (1991).

Imai, T. Mabuchi, M. Tozawa, Y. Yamada, M.: Superplasticity in β-silicon nitride whisker-reinforced 2124 aluminium composite. Journal of Materials Science Letters, 9(3), 255-257 (1990).

Jahanmir, S. Abrahamson, EP. Suh, NP.: The effect of secondary particle on sliding wear of metals. Proc. 3rd North American Metal Working Research Conf., Varnegie Press, Pittsburg, PA, 854-864 (1975).

Jokinen, A. Anderson, P.: Tribological properties of PM aluminium alloy matrix composite. Powder Metallurgy Confference Proc. Princeton, NJ, 517-530 (1990).

Jun, TS. Rotundo, F. Ceschini, L. Korsunsky, AM.: Residual strain in AA2024/SiC_pcomposite linear friction weld. Material and Design, 117-120 (2010).

Kang, YC. Chan, SLI.: Tensile properties of nanometric Al2O3 particulate-reinforced aluminum matrix composites. Materials chemistry and physics, 85(2-3), 438-443 (2004).

Karvanis, K. Fasnakis, D. Maropoulos, A. Papanikolaou, S.: Production and mechanical properties of Al-SiC metal matrix composite. Materials Science and Engineering, 161, doi. 10.1088/1757-899X/161/1/012070(2016)

Kennedy, FE. Balbahadur, AC. Lashmore, DS.: The friction and wear of Cu based silicon carbide particulate based metal matrix composites for brake application. Wear 203-204, 715-721 (1997).

Kumar, S. Balasubramanian, V.: effect of reinforcement size and volume fractionon the abrasive wearbehaviour of AA7075 Al/SiC $_P$ P/M composites-A statistical analysis. Tribology Internationals, 43(1), 414-422 (2010).

Kwak, JKM. Lim, SC.: high speed tribological properties of some Al/SiC_p composites: Friction and wear rate characteristics. Composite science and Technology, 59(1), 55-63 (1999).

Lee, HL. Lu, WH. Chan, SL.: Abrasive wear of powder metallurgy Al alloy 6061-SiC particle compostes. Wear 159, 223-231 (1992).

Lim, SC. Ashby, MF.: Wear mechanism map. Acra Metall., 35(1), 1-24 (1987)

Ling, CP. Bush, MB. Perara, DS.: The effect of fabrication techniques on the properties of AlSiC composites. Journal of Material Processing Technology, 48(1-4), 325-331 (1995).

Long, TT. Nishimura, T. Aisaka, T. Ose, M. Morita, M.: Mechanical property and wear resistance of 6061 alloy reinforced with a hybride of Al_2O_3 fibre and SiC whisker. Trans. Jpn. Inst. Met. 29 920-927 (1988).

Martinez, MA. Martin, A. LLorca, J.: Wear of Al-Si alloy and Al-Si/SiC composites at ambient and elevated temperatures. Wear of Al-Si and Al-Si/SiC, 28(2), 207-212 (1993).

Melgarejo, ZH. Resto, PJ. Stone, DS. Suarez, OM.: Study of particle–matrix interaction in Al/AlB2 composite via nanoindentation. Materials Characterization, 61(2), 135-140 (2010).

Mishra, RS. Ma, ZY. Charit, I.: Friction stir processing: a novel technique for fabrication of surface composite. Materials Science and Engineering, A, 341(1), 307-310 (2003).

Miyajima, T. Iwai, Y.: Effects of reinforcements on sliding wear behavior of aluminum matrix composites. Wear, 255(1-6), 606-616 (2003).

Mohanty, S. Mishra, A. Nanda, BK. Routara, BC.: Multi-objective parametric optimization of nano powder mixed electrical discharge machining of AlSiCp using response surface methodology and particle swarm optimization. Alexandria engineering Journal, doi.org /10.2016/j,aeg.2017.02.006 (2017).

Mukhopadhyay, A. Duari, S. Barman, TK. Sahoo, P.: Wear behaviour of electroless Ni-P-W coating under lubricated condition - a taguchi based approach. IOP Conf. Series: Materials Science and Engineering 149012004 doi:10.1088/1757-899X/149/1/012004 (2016).

Mukhopadhyay, A. Duari, S. Barman, TK. Sahoo, P.:Tribological Performance Optimization of Electroless Ni–B Coating under Lubricated Condition using Hybrid Grey Fuzzy Logic. J. Inst. India Ser D, 97(2), 215-231 (2016).

Nair, SV. Tien, JK. Bates, RC.: SiC-reinforced metal matrix composites. International Metals Reviews 30(6), 275-290 (1985).

Nam, TH. Requina, G. Peter, D.: Thermal expansion behaviour of aluminum matrix composites with densely packed SiC particles. Composites, Part A 39, 856-865 (2008).

Naranjo, M. Rodrıguez, JA., Herrera, EJ.: Sintering of Al/AlN composite powder obtained by gas–solid reaction milling. Scripta materialia, 49(1), 65-69 (2003).

Natarajan, N. Vijayaranjan, S. Rajendran, I.: Wear behaviour of A356/25SiC $_p$ aluminium metal composites sliding against automobile friction material. Wear, 261(7) 812-822 (2006).

Padmanavan, R. MacDonald, BJ. Hashmi, MSJ.: Mechanical behaviour of SiC reinforced Aluminium thin walled tube under combined axial and torsional loading. Journal of Material Processing Technology 155-156, 1260-1763 (2004).

Pan, YM. Fine, ME. Gheng, HS.: Sliding wear of an alloy SiC whisker composite. Tribon Trans. 35, 482-490 (2008).

Pawar, PB. Utpat, A.: Development of Al base silicon carbide particulate metal matrix composite for spur gear. Procedia Materials Science 6, 1150-1156 (2014).

Poria, S. Sahoo, P.: Tribological characterization of Stir – cast aluminum TiB_2 metal matrix composites. Silicon, 8, 591-599 (2016).

Pradhan, S. Ghosh, S. Barman, TK. Sahoo, P.: Wear behavior of metal matrix composite under various corrosive environments. IOP Conf. Ser. Mat. Sci. Engg. 149 012088 (2016).

Pradhan, S. Sutradhar, G. Sahoo, P.:Wear performance Ghosh of Al-5 %SiC metal matrix composites using Taguchi method. J Tribol Res 2(1):33–40 (2011).

Pradhan, S. Ghosh, S. Barman, TK. Sahoo, P. Tribological behavior of AlSiC composite under dry aqueous alkaline medium. Silicon 9, 923-931 (2017).

Pramanik, A.: Effects of reinforcement on wear resistance of Aluminium metal composite. Trans. Nonferrous Mat. Soc., China 26, 348-316 (2015).

Prasad, SV. Asthana, R.: Aluminium metal matrix composite for automotive applications: Tribological consideration. Tribology Letters, 17(3)445-453 (2004).

Prielipp, H. Knechtel, M. Claussen, N. Streiffer, SK. Mulejans, H. Ruhle, M. Rodel, J.: Strength and fracture toughness of aluminum/alumina composites with interpenetrating networks. Materials Science and Engineering: A, 197(1), 19-30 (1995).

Radhika, N. Subramanium, R. Prasat, SV.: Ttribological behaviour of aluminium/alumina/graphite hybrid metal matrix composite using Taguchi's techniques. Journal of minerals and materials characterization and engineering, 10(05), 427 (2011).

Ramesh, CS. Keshavamurthy, R. Channabasappa, BH. Ahmed, A.: Microstructure and mechanical properties of Ni–P coated Si3N4 reinforced Al6061 composites. Materials Science and Engineering: A, 502(1-2), 99-106 (2009).

Rana, F. Stefanescu, DM.: Friction properties of Al-l .5 Pct Mg/ SIC particulate metal- matrix composites. Merall. Trans. 20A, 1564-1566 (1989).

Rees, DWA.: Deformation and fracture of matal matrix composites under combine loading. Composite, Part A, 29 A, 171-182 (1998).

Rehman, A. Das, S. Dixit, G.: Analysis of stir die cast Al-SiC composite brake drum based on coefficient of friction. Tribol Int 51, 36-41(2012).

Rohatgi, PK.: Metal matrix composites. Defence Science Journal, 43(4), 323 (1993).

Roy, M. Venkataraman. B. Bhanuprasad. VV. Mahajan, Y.R. Sudararajan, G.: The effect of particulate reinforcement on the sliding wear behavior of aluminum matrix composite. Metall. Trans. 23A,2833-2847 (1992).

Sahin, Y.: Preparation and some properties of SiC particle reinforced aluminium alloy composites. Materials and Design, 24(8), 671-679 (2003).

Sannino, AP. Rack, HJ.: Dry sliding wear of discontinuously reinforced aluminum composites: review and discussion. Wear 189, 1-19 (1993).

Sasada, T. Norose, S. Mishina, H.: The behaviour of adhered fragment interposed between sliding surfaces and the formation process of wear particles. Journal of lubrication technology 103, 195-202 (1981).

Sato, A. Mehrabian, R.: Aluminum matrix composites: Fabrication and properties. Material transaction 7B, 443-450 (1976).

Schobhel, M. Altendorfer, W. Degischer, HP. Vaucher, S. Buslaps, T. Michiel, MD. Hofmann, M.: Internal stress and void in SiC reinforced alumina composite heat sink applications. Composite science and technology, 71, 724-733 (2011).

Singh, PM. Lewandowski, JJ.: Effect of heat treatment and reinforcementsize. Metallurgical Transactions A, (24) 11, 2531-2543 (1993).

Subhramanian, I. Maheswaran, R.: Effect of inclusion of SiC particle on the mechanical behaviour of stir cast Al6063 SiC composite. Materials and Design 65, 511-520 (2015).

Surappa, MK.: Aluminium matrix composites: Challenges and opportunities. Sadhana, 28(1-2), 319-334, (2003).

Suresh, S. Shenbaga, N. Moorthi, V.: Aluminium-titanium diboride (Al-TiB2) metal matrix composites: challenges and opportunities. Procedia engineering, 38, 89-97, (2012).

Suresha, S. Sridhara, BK.: Wear characteristics of hybrid aluminium matrix composites reinforced with graphite and silicon carbide particulates. Composite science and technology 70 (11), 1652-1659 (2010).

Torres, B. Lieblich, M. Ibanez, J. Garcıa-Escorial, A.: Mechanical properties of some PM aluminide and silicide reinforced 2124 aluminium matrix composites. ScriptaMaterialia, 47(1), 45-49 (2002).

Vingsbo, O.: Fundamental of friction and wear, in FA Smith and P JBlow (eds). Engineering material for advance friction and wear application ASM International, MD, 1-19 (1988).

Wang, A. Rack, HJ.: Dry sliding wear in AlSiC 2124/17-4 PH stainless steel system. Wear 147, 305-374 (1991).

Wang, J. Yi, D. Su, X. Yin, F. Li, H.: Properties of submicron AlN particulate reinforced aluminum matrix composite. Materials & Design, 30(1), 78-81. 71 (2009).

Wang, Y. Rainforth, MW. Jones, H. Lieblich, M.: Sliding wear behaviour ofAA2124 aluminium alloy/Ni3Al composites. Materials Science, 396, 1473-1478 (2002).

Wang, Y. Rainforth, WM. Jones, H. Lieblich, M.: Dry wear behaviour and its relation to microstructure of novel 6092 aluminium alloy–Ni3Al powder metallurgy composite. Wear, 251(1-12), 1421-1432 (2001).

William, D. Callister, Jr.: Materials science and engineering – An Introduction. Asia, John Wiley and Sons

William, D. Callister, Jr.: Materials Science and Engineering- Materials Science and Engineering-An Introduction. Asia. John Wiley & Sons, (2001).

Wu, JM. Li, ZZ.: Contributions of the particulate reinforcement to dry sliding wear resistance of rapidly solidified Al-Ti alloys. Wear, 244(1-2), 147-153 (2000).

Yong, Y. Lan, J. Li, X.: Study on bulk aluminum matrix nano-composite fabricated by ultrasonic dispersion of nano-sized SiC particles in molten aluminum alloy. Materials Science and Engineering: A, 380(1-2), 378-383 (2004).