CHAPTER 2

STATE-OF-THE-ART

2.1 INTRODUCTION

Metal Matrix Composites (MMCs) have excellent combination of mechanical and physical properties such as high stiffness, strength and hardness in addition to lightweight and high abrasive resistance, as compared to the unreinforced alloys (Naher et al 2003). Aluminium is potentially an important material for tribological application because of its low density and high thermal conductivity (Askeland 1996). However, the wear resistance of aluminium is low in dry sliding application. The prediction of wear rate is difficult because it is not an intrinsic property of the material but rather a function of the system (Deuis et al 1997). In order to understand and access the current status of research in wear characteristics of aluminium metal matrix composites with various reinforcements, an extensive literature review has been carried out and selective literature reviews for the present investigations are discussed in this chapter.

2.2 PROCESSING OF METAL MATRIX COMPOSITE

Emergence of newer technologies have made many sophisticated fabrication processes to be adapted with greater control and led to several routes commonly used for production of discontinuously reinforced MMCs.
Metal matrix composites are obtained by incorporating ceramic particles into an aluminium alloy. The favourable combination of technological properties was arising from proper mixing of reinforcement and metal matrix. Nevertheless aluminium-based MMCs have two main problems and they are

1) The high cost of reinforcement and

2) The high cost and low spread of production technologies

The first problem will probably be resolved when larger quantities of reinforcements are produced in response to market requirements and utilizing naturally available reinforcements. The second problem has been faced by many researchers trying to discover ways to produce MMCs at low cost. The lowest cost route for particle-reinforced aluminium composite is produced using liquid metal handling particularly stir-casting. Material produced in this way represents a substantial proportion of the MMCs in commercial use today. Clearly, liquid metallurgy technique is the most economically viable among all the routes for MMC production. In addition, this process also allows very large size components to be fabricated (Surappa 2003).

2.3 STIR CASTING PROCESS

In the present study, the focus is on fabrication of Aluminium Metal Matrix Composites (AlMMCs) using stir casting process. The new stir casting process to produced MMCs of Al-5Si-2Fe alloy reinforced with ceramic oxides and carbides with 10 to 30 wt % (Mehrabian et al 1974). It was noted that the coarser 340 μm size particle settled to the lower extremity of the end-chilled plate because of difference in density.
Pai (1976) has successfully fabricated alumina particle reinforced metal matrix composite by stir casting technique and demonstrated that considerably higher percentage of alumina particles are retained in the castings when mechanical stirring is used compared with the case when manual stirring is used.

In preparing metal matrix composites by the stir casting method (Hashim et al 1999), there are several factors that need considerable attention including,

1. The difficulty of achieving a uniform distribution of the reinforcement material.
2. Wettability between the two main substances.
3. Porosity in the cast metal matrix composites.
4. Chemical reaction between the reinforcement material and the matrix alloy.

### 2.3.1 The Distribution of Reinforcement Materials

One of the problems encountered in metal matrix composites processing is the settling of the reinforcement particles during melt holding (or) during casting. These undesirable phenomena are the more significant because the size of the reinforcing elements is small and the density difference between the liquid metal and the reinforcement is high.

The mechanical stirrer used during stirring, the melt temperature, the amount and nature of particles are some of the main factors to be considered when investigating these phenomenon (Franck et al 1987). Proper dispersion of the particles in a matrix is also affected by pouring rate, pouring temperature and gating system (Hashim et al 1999).
2.3.2 Wettability between the two Main Substances

Wettability is another significant problem that exists in the liquid metallurgy route. Wettability can be defined as the ability of a liquid to spread on a solid surface (Hashim et al 1999). The addition of certain alloying elements can modify the matrix metal alloy by producing a transient layer between the particles and the liquid matrix (Franck et al 1987 and Pai 1976). The composites produced by the liquid metallurgy technique show excellent bonding between the ceramic and metal when reactive elements such as Mg, Ca, Ti, Zr are added to induce wettability (Hashim et al 2001).

2.3.3 Porosity in the Cast Metal Matrix Composites

The porosity in such casting is generally believed to be due to: 1) solidification shrinkage occurring when the pressure gradient is insufficient to overcome the resistance offered by dendrite networks to feed voids 2) precipitation of dissolved gas in the melt and 3) gas entrapment due to vigorous stirring (Srivatsan et al 1995).

On the other hand, it has been observed that reinforcement particles have a tendency to associate themselves with porosity, thereby giving rise to particle porosity clusters (Sylvie Yotte 2001). The porosity formation is due to the solidification rate and metal feeding and this was demonstrated in 359Al/SiC\(_p\) and 359/Al\(_2\)O\(_3\) composites. The process parameters of holding times, stirring speed, and the size and position of the impeller will influence the development of porosity (Hashim et al 1999).

2.4 MECHANICAL PROPERTIES

There have been numerous reports about mechanical properties of particle reinforced aluminium composites. These composites have a high specific modulus and strength but low ductility. Generally fracture of particle
and localization of matrix deformation are considered as the main factors of decreasing ductility (Llorca et al 1995).

2.4.1 Effect of Reinforcement on Hardness of MMCs

The resistance to indentation or scratch is termed as hardness. Among various instruments for measurement of hardness, Brinell’s, Rockwell’s and Vickers’z hardness testers are significant. The micro-hardness is a direct, simple and easy method of measuring the interface bonding strength between the matrix and reinforcement (Prasad et al 1994). Theoretically, the rule of mixture of the type $H_c = V_r H_r + V_m H_m$ (suffixes ‘c’, ‘r’, and ‘m’ stand for composite, reinforcement and matrix respectively and $V$ and $H$ stand for volume fraction and hardness respectively) for composites (Sharma 2001) helps in approximating the hardness values.

The particulate reinforcements such as SiC, Al$_2$O$_3$ and aluminide (Hutching 1987, Husking et al 1982 and Debdas roy et al 2005) are generally preferred to impart higher hardness. The coating of reinforcements with Ni and Cu (Uan et al 2001), also leads to good quality interface characteristics and hence contribute in improving hardness. Mechanical characterization revealed that the presence of zircon sand and garnet particles in aluminium matrix significantly improved the hardness (Das 2006 and Sharma 2001). The increase of hardness value observed on zircon sand reinforced composite (Das et al 2006) and effect of ageing on hardness was tested with different quenching media (Das et al 2008).

Deuis et al (1997) concluded that the increase in the hardness of the composites containing hard ceramic particles not only depends on the size of reinforcement but also on the structure of the composite and good interface bonding. The heat treated alloy and composite exhibits better hardness (Sawla and Das 2004, Song et al 1995 and Das et al 2008), however, the over-aged condition may tend to reduce the hardness significantly (Wang and Rack 1991).
2.4.2 Effect of Reinforcement on Tensile Strength of MMCs

The mechanical properties of the composites are of immense importance for any application (Robi et al 1996 and Satyanarayana et al 2001). Charles and Arunachalam (2003) demonstrated improvement in strength and hardness by adding quartz and silicon carbide. Tensile strength of Al-Cu-Mg (2080) / SiCp-T8 composite with varying volume fraction (at a constant particle size of 5 \( \mu \)m) and varying particle size (at a constant volume fraction of 20 %) has studied by Nikhilesh Chawla and Yu-Lin Shen (2001). With an increase in volume fraction of SiC, higher elastic modulus, macroscopic yield and tensile strengths were observed, coupled with lower ductility. In general, the particle reinforced Al-MMCs are found to have higher elastic modulus, tensile and fatigue strength over monolithic alloys (Singh et al 1993). In case of heat treatable Al-alloys and their composites, the yield strength of composites increase after heat treatment (Rong Chen et al 2000) by reducing the cracking tendency and improving the precipitation hardening (Vencl et al 2008).

2.5 WEAR ON MMCs

Wear is the progressive damage, involving material loss, which occurs on the surface of a component as a result of its motion relative to the adjacent working parts (Peter and Blau 1997). The wear damage may be in the form of micro-cracks or localized plastic deformation (Sanchez-Santana 2006). For a particular dry sliding situation the wear rate depends on the normal load, the relative sliding speed, the temperature, and the thermal, mechanical, and chemical properties of the materials in contact. There are many physical mechanisms that can contribute to wear and certainly no simple and universal model is applicable to all situations. So the wear is a complex phenomenon in which real contact area between two solid surfaces compared with the apparent area of contact is invariably very small, being limiting to the points of contact between surface asperities. The load applied to the surfaces will be transferred through these points of contact and the localized forces can be
very large. Commonly available test apparatus for measuring sliding friction and wear characteristics in which, sample geometry, applied load, sliding velocity, temperature and humidity can be controlled are Pin-on-Disc, Pin-on-Flat, Pin-on-Cylinder, Rectangular Flats and Rotating Cylinder (Veeresh Kumar et al 2011).

2.6 FACTORS AFFECTING THE WEAR BEHAVIOUR OF ALMMCS

The principal tribological parameters that control the friction and wear performance of reinforced Al-MMCs are extrinsic (mechanical and physical) factors such as the effect of load normal to contact surface, sliding velocity, sliding distance, reinforcement orientation, environment, temperature, surface finish of the counterpart and intrinsic (material) factors such as the reinforcement type, size, shape and distribution of the reinforcement, the matrix microstructure and the reinforcement volume fraction (Sannino and Rack 1995). Therefore, it is difficult to select the type of reinforcement and volume fraction that would give optimum wear properties (Miyajima and Iwai 2003). Many investigators carried out experiments on the wear behaviour of MMCs against different counter surfaces with various test conditions (Uyyuru et al 2006). Under the following sections the effect of different parameter on the wear of MMCs are discussed (Veeresh Kumar et al 2011).

2.6.1 Effect of Reinforcements Type

The SiC particles are harder than other reinforcements and will provide a more effective barrier to subsurface shear by the motion of the adjacent steel counter-face (Kassim et al 1999) and this result is likely due to differences in particles size and shape (Garcia Cordovilla et al 1996). An additional drawback of Al-MMCs with reinforcing phases, such as SiC and Al₂O₃ is the tendency of the reinforcement to act as a second-body abrasive against the counter-face increasing its wear rates (Rang Chen et al 1997). In
addition, reinforcement liberated as wear debris acts as a third-body abrasive to both surfaces. The abrasive wear behaviour of 15 vol.% zircon particles of size ranges 44-74 and 74-105 µm were tested on pin on disc test rig and the wear resistance and micro hardness of aluminium alloy were improved by adding the zircon particles (Das et al 2007). Wear characteristics revealed that the presence of zircon sand and garnet particles in aluminium matrix significantly improved the wear resistances (Das et al 2006 and Sharma 2001). An addition of garnet particulate to Al6061 showed that it not only delays the transition wear but also reduces the wear rate and coefficient of friction (Sharma 2001). The wear resistance of the composites improved by incorporating TiB₂ particle reinforcement and the refinement of the matrix grains greatly improved the mechanical properties of the composites (Chaudhury et al 2005). In all such type of investigations, the authors have selected the various ceramic reinforcements, in the current research has been constricted to few reinforcement types such as Al₂O₃, SiC, B₄C, ZrO₂ (Joel hamanth 2009). Limited work has been reported on fabrication and wear characterization of aluminium composites reinforced with zircon and garnet particles.

2.6.2 Effect of Reinforcement Volume Fraction and Size

Uyyuru and Surappa (2006) studied the effect of reinforcement volume fraction and size distribution on the tribological behaviour of Al-Si/SiCp composites against automobile brake pad material using pin-on-disc. When reinforcement in matrix has wide size distributions, wear rate and friction coefficient increases compared to mono size reinforcement. It has been reported that the wear resistance of composite increases with increase in volume fraction of the zircon reinforcement (Das et al 2000). The wear resistance of MMCs can be improved by increasing the volume fraction of the reinforcing ceramic phase by as much as 70% (Ceschini et al 1998). Also the dry sliding wear resistance increases with increase in particle volume fraction. At higher volume fraction, the friction coefficient was found higher and there
was almost no effect of load on friction coefficient (Uyyuru et al 2006). The wear rates of the counter-face material increased with increase of volume fraction of the ceramic particles. This is mainly due to the fact that the hardness and strength of composites are higher and they increased with increase in filler content (Das et al 2008). The volumetric wear rate increased with increasing applied load while it decreased with increasing volume fraction of the filler material (Ferhat Gul and Mehmet Acilar 2004). At any constant load, wear rate decreases with increase in addition of SiCp and improves the load bearing properties of Al-alloy during sliding. Increase in the addition of SiC restricts the flow or deformation of the matrix material with respect to load (Kumar and Balasubramanian 2008).

The wear resistance of the composites is improved significantly by controlling the particle size (Heguo Zhu et al 2008). The predominant friction mechanism at particulate sizes below 13 μm involved adhesion and micro plucking, these being augmented by hard third body SiC abrasion with increasing particulate size. Adhesion and micro cutting were the predominant wear mechanisms for smaller reinforcements, the higher wear rates observed in the larger particulate reinforced composite (Sannino and Rack 1996). The particle–matrix interfacial area is larger for fine particles so the chance for the small particles to pull out from the matrix increases. But in the case of coarse particles, SiC is expected to remain embedded with the matrix until they break down into smaller particles (Kumar and Balasubramanian 2008). Hence, there is a need to reduce the cost component by optimizing its volume fraction and avoiding/minimizing the use of finer particles (Uyyuru et al 2006).

2.6.3 Effect of Applied Load

Applied load affects the wear rate of alloy and composites significantly and is the most dominating factor controlling the wear behaviour (Mondal 1998). Uyyuru et al (2007) studied the tribological behaviour of Al-Si/SiCp composites against automobile brake pad material using pin-on-disc a
tribo-tester. They found that wear rate and friction coefficient vary with applied normal load. With increase in applied load, the wear rate increases whereas friction coefficient decreases. Further, with increased applied load the contact surface temperature increases. If the load is further increased, then the unreinforced and reinforced composites eventually seize. This type of seizure has been referred to as “galling seizure” (Daoud et al 2004). As the wear rate increases with increased applied load, the wear mechanism reported was oxidation at lower loads and adhesion and delamination at higher loads (Ferhat Gul and Mehmet Acilar 2004). At low loads, as particles act as load bearing constituents, the direct involvement of Al-alloy in the wear process is prevented (Rang Chen et al 1997). The wear debris size is of the order of millimeters at higher load while at the lower load, it is of the order of a few hundred micrometers (Chaudhury et al 2005). As the load increased, the proportion of metallic wear debris increased and the size of the delamination increased for the composite (Das et al 2000).

2.6.4 Effect of Sliding Speed and Distance

With the increase of sliding distance, the wear rate and cumulative wear loss increases for all the materials (Kumar and Balasubramanian 2008) and the curve trend was linear (Chaudhury et al 2005). The sliding distance influences the wear mechanism strongly and at minimum sliding distance, the wear rate of the composites is lower. This may happen because at longer distance or duration, the micro thermal softening (Qin et al 2008) of matrix material may take place, which further, lowers the bonding effect of the reinforced particles with that of matrix material (Wilson and Alpas 1997). Uyyuru et al (2006) are found that wear rate and friction coefficient vary with sliding speed. It was observed that the heterogeneous tribo layer was formed on the worn out surface. The formation of tribo layer has two effects, which acts as lubricant and also act as source of wear debris. At higher sliding speed, wear rate is lower for MMCs and is due to the formation of a compact transfer layer at the region of the worn out surfaces (Ibrahim et al 1991). The amount of the
constituents of the counter-body in the transfer layer is seen to increase as sliding speed increases thus forming a protective cover which tends to reduce wear rate (Shorowordi and Haseeb 2004).

2.6.5 **Effect of Sliding Surface Characteristics**

Surface roughness affects the wear rate. The higher the roughness, the higher will be the wear rate (Sanchez-Santana et al 2006). The counter-face hardness is inversely proportional to the wear rate thus the counter material with a lower hardness reduces the wear resistance due to the mutual abrasion between the counter material and the wear surface of the specimen (Kumar and Balasubramanian 2008). Increasing the volume fraction of particles in the composite reduces its wear rate but increases the wear rate in counter-face. Thus both counter-face and composite wear are considered and an optimum volume fraction of particles exists at which wear is lowest (Shipway 1998).

2.6.6 **Effect of Lubrication**

Concerning wear mechanisms under lubricated conditions, the degree of direct contact between the surfaces is minimal and the wear progresses via layers of debris (Bermudez et al 2001). However, for lubricated conditions, AlMMCs with higher hardness show higher wear resistance. Scuffing and seizure problems may be addressed by incorporating solid lubricants, namely, Graphite in Al–Si alloys reinforced with SiC or Al₂O₃ particles (Das et al 1989). It was shown that the addition of graphite flakes or particles in Al-alloys increased the loads and velocities at which seizure took place under the boundary lubricated (Das et al 1991) and dry sliding conditions. The high seizure resistance of graphitic Al-matrix composites has been attributed to the formation of graphite layers on the contact surfaces that act as solid lubricants, which reduce metal to metal contact between the sliding pairs (Rohatgi et al 1992). One more important
factor is that the lubricant used will act as a coolant between the two sliding surfaces avoiding the consequences of increasing temperature of the metals in contact (Rohatgi et al 1992).

### 2.6.7 Effect of Heat Treatment

The alloy and composites exhibit minimum wear rate after heat treatment due to improved hardness (Das et al 2008). During the wear process, the cracks are mainly nucleated at the matrix and reinforcement interfaces. Heat-treated alloy and composite showed better strength and hardness that resulted in fewer propensities for crack nucleation and showed enhancement in wear resistance (Ashutosh Sharma and Sanjeev das 2009).

In case of heat-treated alloy, the effective stress applied on the composite surface during wear process is less due to higher strength and ductility of the Al matrix. This resulted in less cracking tendency of the composite surface as compared to the cast alloy (Sawla and Das 2004). The heat treatment did not radically change the morphology but hardening of the matrix by precipitation hardening took place, which led to higher hardness and strength (Vencl et al 2008). The highest wear resistance was obtained for T6 thermal treatment condition. The studies have determined that the maximum hardening of the matrix was obtained when the composite material was maintained at a temperature of 490-560°C for 3 hours, quenched in ice water at 0°C and ageing done at a temperature of 175°C for 7 hours. It was found that the heat treatment T6 for 7 hours was the one that provided the matrix greater hardness and therefore it was the one, which gave the MMC the higher wear resistance (Gomez de Salazar and Barrena 2004).

### 2.7 MODELS FOR PREDICTION OF WEAR PROPERTIES

Extensive research has been carried out on the study of tribological behaviour of AlMMCs (Veeresh Kumar et al 2008). The most important reason for the damage and consequent failure of machine parts is wear. A lot
of experiments must be conducted in order to study the tribological behaviour. This results in wastage of both man power and money (Hulya Kaçar Durmuş et al 2006). Hence the prediction of wear rate is of utmost importance in the present industrial scenario to assess the life of sliding components in advance to avoid massive financial losses that are incurred due to wear.

### 2.7.1 Theoretical Models in MMCs

The mathematical model to predict the wear rate of Al7075-SiC composites by incorporating the effects of volume fraction, reinforcement size, applied load, sliding speed and hardness of the counter-face material was developed (Kumar and Balasubramanian 2008). The developed model can be effectively used to predict the wear rate of Al7075-SiC composites at 95% confidence level. Sharma (2001) developed a theoretical model for estimating the sliding wear rate considering the effect of frictional heat on the wear properties at contact surfaces, the effect of reinforcement, mechanical load, sliding distance, sliding velocities on wear rates, coefficient of friction and transition wear. This theoretical model was proposed for estimating the sliding wear rate of both alloy and composites.

Bayhan and Onel (2010) found that the Response Surface Models (RSM) are one of the best suited methods to deal with the engineering related problems. They tested the effects of friction load, sliding distance and reinforcement content on the wear rate and weight loss of AlSi7 Mg/SiCp composites were evaluated by using RSM optimisation procedure. Through this research the RSM optimisation procedure was found to be effective to optimise the reinforcement content and sliding distance for the minimization of wear rate and weight loss of tested composites. Jen Fin Lin and Chau Chang Chou (2002) used RSM to depict a disk’s wear rate. They observed that by means of a central composite design (CCD) technique, fewer operating conditions were tested to establish expressions for the wear rate parameter, the contact temperature and the friction coefficient as a function of
sliding speed and applied load. They observed that designs of resolution fine or more are of particular value as main building blocks of CCD which allows estimation of all the terms in a second degree polynomial approximation.

The wear resistance model for the MMCs based on the Taguchi method was developed. The orthogonal array, Signal-to-Noise (S/N) ratio and analysis of variance were employed to find the optimal testing parameters. The results showed that the abrasive grain size was the most powerful factor on the abrasive wear, followed by weight fraction of reinforcement. Optimal wear testing conditions were verified with an experiment. It was observed that there was a good agreement between the predicted and actual wear resistance for a 95% confidence level (Sahin 2005). Factorial design of experiment can be successfully employed to describe the high stress abrasive wear behaviour of Al-alloys and composites and to develop empirical linear regression equations for predicting wear rate within a selected experimental domain (Mondal et al 1998).

2.7.2 Soft Computing Models in MMCs

The Artificial Neural Network (ANN) model was used for the prediction of mechanical properties of particulate reinforced MMCs and concluded that the ANN model with three layer feed forward structure with the Levenberg Marquardt (LM) training algorithm gave better and faster results than other algorithms (Rasit Koker et al 2007). A 3 layered Back Propagation (BP) network which is an effective tool to predict parameters with non-linear relationships could predict density, porosity, hardness, tensile strength, flexural strength, toughness, roughness of machined surface, flow stress and solid particle erosion with a reasonable accuracy (Mehmet Sirac Ozerdem and Sedat Kolukisa 2009). The ANN technique is applied to study the effect of size and weight percent of SiC particulates, applied pressure and test temperature on the wear resistance of Al356-SiC MMCs and have shown that ANN is an effective tool in the prediction of the properties of MMCs and is found more
useful compared with time-consuming experimental processes (Rashed and Mahmoud 2009). The new soft computing technique ANFIS model has been made to compare porosity and density of MMCs (Nrip Jit et al 2011). A well trained ANN model can be used to predict any new data from the same knowledge domain thus avoiding repetition of long-term experiments, wastage of manpower and money (Veeresh Kumar et al 2011).

2.8 SUMMARY

More than hundred research papers, published in leading international journals, related to fabrication, mechanical and wear characterization of AlMMCs were collected and the important findings were critically reviewed. Several techniques were followed by researchers for the processing of particulate reinforced MMCs. It has been reviewed that, the hardness of the composites was increased with increasing reinforcement contents in the matrix material. The mechanical properties were reviewed with respect to strength.

The wear performance of hard ceramic reinforced aluminum matrix composites was reviewed with particular emphasis on the mechanical and physical factors and material factors also with the effect of lubrication and heat treatment etc. From the literature it can be concluded that the ceramic reinforced AlMMCs will have better wear resistance than the unreinforced alloys. Further, the techniques used by the researchers to predict the wear coefficient were also discussed. Finally there is an immense potential, scope and opportunities for the researchers, in fabrication of AlMMCs with natural, low cost reinforcements and prediction of mechanical and wear properties by using soft computing techniques (veeresh kumar et al 2010).
2.9 SCOPE AND OBJECTIVE OF THE PRESENT RESEARCH WORK

The review of the work presented above confirms that fabrication and wear behaviour of AlMMCs needs an in-depth study in order to produce good quality of composites with SiC, zircon and garnet particles. However, to best of my knowledge no comprehensive analysis has been carried out in the fabrication of AlMMCs and their wear behaviour. Hence, there is a need for carrying out fabrication and wear studies on SiC, zircon and garnet reinforced AlMMCs. Thus, the present research problem is formulated as an experimental fabrication and modeling the wear rate of AlMMCs. The scope and objective of the present research work is listed below:

- To fabricate AlMMCs on stir casting process with the variable reinforcement particles, volume fraction and particle size.
- To study parametric influence and interaction effects of various wear parameters on the wear behaviour of composites by analysis of variance.
- To develop a model for predicting wear rate and coefficient frictional using RSM and ANFIS.
- To investigate the influence of different wear parameters (including extrinsic and intrinsic factors) on wear mechanism of AlMMCs.
- To identify the importance of reinforcement materials in the dry and abrasive sliding wear by comparative performance study analysis.
The scheme of the present research work is shown in Figure 2.1

Figure 2.1 Scheme of research