CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

This chapter provides the literature survey carried out to review the research efforts related to composites, reinforcement of particles, study of mechanical properties, wear behavior, thermal effect and corrosion behavior. MMCs have numerous applications from automotive to space applications. It is being proven universally that the composite structure provides savings of about 20% over metal counterparts, registered in operational and maintenance cost (Dhingra et al., 1986). The composite material can provide unique mechanical and physical properties as it combines numerous desirable properties of its constituents (William et al., 2009). The literature survey reveals that most of the engineering applications demand high strength, light weight and high resistance to corrosion and wear for use in the structural elements. The Al-MMCs had gained significant importance in automobile and aerospace industries due to their inherent properties like high strength, stiffness and corrosion resistance in spite of its limited wear resistance. However the wear resistance can be improved by the addition of hard ceramic particles as reinforcement (Prasad et al., 2004).

In Al-MMCs, aluminium has been used as the matrix material and the reinforcement is usually a non-metal such as SiC, B$_4$C and Al$_2$O$_3$ etc. The addition of reinforced-particles in Al-MMCs produces improvement in mechanical properties like, tensile strength, yield strength, wear resistance, specific heat capacity and lower density in comparison with other conventional materials (Miyajima et al., 2003).
New composite development and their applications are expected to increase with cheaper processing methods and the prospects of recycling (Mehrabian et al., 1974). There has been a lot of scope in the field of composites aimed at developing low-cost processing methods and recyclable types of composites, by proper selection of the constituents and the production techniques (Eliasson et al., 1995).

The literature collected from various sources for the present research work is presented briefly under the following captions:

1. Material selection for matrix phase
2. Reinforcement materials
3. Fabrication methods of MMCs
4. Effect of mechanical and physical factors
5. Testing of MMC for its mechanical and physical properties
6. Effect of material factors
7. Wear analysis
8. Heat treatment of MMCs
9. Microstructural studies
10. Corrosion analysis
11. Design of experiments
12. Summary
2.2 MATERIAL SELECTION FOR MATRIX PHASE

Aluminium alloys are the most widely used non-ferrous materials in engineering applications owing to their attractive properties such as high strength-to-weight ratio, good ductility, excellent corrosion resistance, availability and low cost. Today’s researchers have mainly focused on aluminium metals for automotive application because of its unique combination to attain excellent mechanical properties as compared to other metals. The unique thermal properties of aluminium composite such as metallic conductivity with high coefficient expansion that can be tailored down to zero and their prospects in the aerospace and avionics, being assumed to be the most important characteristics (Rohatgi et al., 1992).

Clyne et al. (1993) explained Aluminum as the most abundant metal and the third most abundant chemical element in the earth’s crust, comprising over 8% of its weight. Aluminum alloys are broadly used as a main matrix element in composite materials. Aluminum alloys for its light weight, has been on the net of researchers for enhancing the technology. The broad usage of aluminum alloys is dictated by a very desirable combination of properties, combined with the ease with which they may be produced in a great variety of forms and shapes.

Arsenalt and Taya et al., (1987) studied the oxidation/corrosion resistance and other properties of the matrix play a vital role in the selection of the matrix materials. Generally, Al, Ti, Mg, Ni, Cu, Pb, Ag, Zn and Si are preferred as the matrix materials for making MMCs among which Al, Ti and Mg have been used widely. Along with the basic properties required for a material to behave as a matrix, Mg based systems also possess lower elastic modulus. Mg often results a higher improvement in the properties with reinforcements than that of aluminium, although many of the composite fabrication processes have been common to both Al and Mg based systems.
(Doychak et al., 1992). Mg and its alloys are among the lightest materials for practical use as a matrix phase in MMCs. When compared to other currently available structural materials, Mg is very attractive because of its unique combination of low density (around 35% lower than Al) which makes it competitive in terms of strength and density (Kim et al., 1990). However, it has been reported by Shipway et al., (1998) and Tyagi et al., (2005) that Mg alloys are not good competitors for Al alloys in terms of absolute strength.

The reason for Al being a successful matrix material over Mg is mainly due to the design flexibility, good wettability and strong binding at the interface. Among the enormous varieties of aluminium alloys, A356 is preferred as the better choice for high strength components in automotive, aerospace and military applications due to its excellent castability, weldability, high strength, pressure tightness and corrosion resistance (Jorstad et al., 2001). The alloy is generally heat-treated to provide various combinations of desired mechanical (strength and toughness) and physical properties. The properties of A356 alloy (ASM Handbook) are given in Table 2.1.

**Table 2.1 Properties of A356 (ASM Hand Book)**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>221-232 MPa</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>165-185 MPa</td>
</tr>
<tr>
<td>Elongation</td>
<td>5-6%</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>72.4 GPa</td>
</tr>
<tr>
<td>Hardness</td>
<td>70-80 HB and 58-60HV</td>
</tr>
<tr>
<td>Density</td>
<td>2.685 kg/m³</td>
</tr>
<tr>
<td>Liquidus Temperature</td>
<td>615°C</td>
</tr>
<tr>
<td>Solidus Temperature</td>
<td>577°C</td>
</tr>
<tr>
<td>Linear Coefficient of Thermal Expansion</td>
<td>23.5μm/mºK at 20-300°C</td>
</tr>
<tr>
<td>Thermal Conductivity at 25°C</td>
<td>151-155W/mºK</td>
</tr>
</tbody>
</table>
2.2.1 Aluminium Metal Matrix Composites

In general, the major advantages of AlMMCs compared to unreinforced materials, such as steel and other common metals, are as follows:

- Increased specific strength
- Increased specific stiffness
- Increased elevated temperature strength
- Improved wear resistance
- Lower density
- Improved damping capabilities
- Tailorable thermal expansion coefficients
- Good corrosion resistance

These advantages can be quantified in terms of percentages. For instance, Al-MMCs can offer potential mass savings of up to 60%, and increases in stiffness and strength of up to 200% over the conventional aluminium alloys. Furthermore, Al-MMCs can be produced with near-zero coefficients of thermal expansion.

Tjog et al., (2000) reported that Al-MMCs have been extensively used in many industrial applications due to their favorable properties such as high specific modulus, strength, hardness, low density, excellent wear resistance, low heat expansion coefficient and stability properties at elevated temperatures. Al-MMCs have superior properties as compared with the monolithic alloys and it can be tailored easily to suit specific applications. The presence of hard reinforcement phases (particulates, fibers, whiskers or
flakes form) has endowed these composites with good tribological characteristics.

2.3 **REINFORCEMENT**

Reinforcement is added to matrices of the materials to increase their strength, stiffness and lower the density of MMC (Srivatsan et al., 2003). The addition of hard ceramic particles like SiC, Al₂O₃, B₄C etc., resulted in enhanced wear resistance and strength-to-weight ratio than the conventional alloys (Ramesh et al., 2009). The selection of type of reinforcement, its method of production and compatibility with matrix play a vital role in order to achieve the required properties in the MMCs. The following aspects have to be considered while selecting the reinforcement materials (Adedoyin et al., 1991).

- Size - diameter and aspect ratio
- Shape - chopped fiber, whisker, spherical or irregular particulate, flake, etc.
- Surface morphology - smooth or corrugated and rough
- Poly-or-single crystals
- Structural defects - voids, occluded material, second phases
- Surface chemistry - e.g. SiO₂ or on SiC or other residual films
- Impurities - Si, Na and Ca in sapphire reinforcement
- Inherent properties - strength, modulus and density

The reinforcements can be divided into two major groups, continuous and discontinuous. The MMCs produced by them are called continuously (fiber) reinforced composites and discontinuously reinforced composites. However, they can be subdivided broadly into four major
categories: continuous fibers, short fibers (chopped fibers, not necessarily the same length), whiskers, particulate. The properties like high strength, ease of fabrication, good chemical stability, density distribution and cost depend upon the types of reinforcement, selected to incorporate with matrix materials.

Davis et al., (1993) reported that continuous and discontinuous phases may constitute from 10 to 70 volume percentage of the composite. Continuous fiber or filament reinforcements for aluminium include Graphite, SiC, Boron and Al₂O₃. Discontinuous reinforcements consist mainly of SiC in whisker form, particle (particulate) types of SiC or Al₂O₃ and short and chopped fibers of Al₂O₃ or graphite. Previously, many works have been carried out on Al-MMCs concentrated on continuing fiber types and found that the major disadvantage of continuous fiber is having low strength in the direction perpendicular to the fiber orientation. Therefore, at present, most of the research works are focusing on discontinuously reinforced (particle or whisker) Al-MMCs because of their greater ease of manufacture, low production cost and relatively isotropic properties.

2.3.1 Short Fibers

The driving forces behind the development of most of the existing composites have been their capability to be designed to provide needed types of material behavior. Discontinuously reinforced metal matrix composites have virtually isotropic properties and lend themselves to metallic design methodologies. Aigbodion et al., (2007) reported that the reasons for the success of reinforcing short fiber is due to their desirable properties that are low density, high hardness, high compressive strength, wear resistance, etc. Therefore discontinuously reinforced aluminium composites are being recognized as an important class of engineering materials that are producing significant progress.
Axen et al., (1994) investigated the friction and abrasive wear behavior of an Al-Si, Mg-Mn aluminium alloy reinforced with 10, 15 and 30 volume percentages of alumina fibers. The influence of fiber content, matrix hardness, and applied load as well as the hardness and size of the abrasive grits were evaluated and it was found that fiber reinforcement increased the wear resistance. Zongyi et al., (1991) investigated the abrasive wear of discontinuous SiC short fiber reinforced A6061 alloy composites. The results showed that the composites exhibited excellent abrasive resistance compared to the unreinforced matrix alloy. The abrasive resistance of the composites containing SiC fibers is an order of magnitude greater than that of the matrix alloy.

2.3.2 Whiskers

Whiskers are mono-crystalline materials with a high aspect ratio of 50 to 100 by the weight of glass fibers to the weight of the total compositions. Their small size lends them a method into powder metallurgy, known as an MMC production method. Whiskers-reinforced MMCs are mostly used in the form of extrusions, forging and rolled sheet. The fabrication costs are high compared to other types of reinforcement (Graff et al., 1986). Yoshiro Iwai et al., (1995) investigated wear properties of SiC Whiskers-reinforced A2024 aluminum alloys with volume fraction of whiskers ranging from 0 to 16% produced by a powder metallurgy technique. It was concluded that the SiCw reinforcement can improve the wear resistance for both severe and mild wear.

2.3.3 Particulates

Particulates are the most common and cheapest reinforcement materials. These produce the isotropic property of MMCs, which shows a promising application in structural fields. Reinforcing an Al alloy with particles of a second phase can improve the physical, mechanical and
tribological properties of the material, it may also result in material savings with desired properties. This could reduce the cost and weight of energy-intensive metals for potential applications in engineering components for a new generation of vehicles (Kumar et al., 2011).

Kakani et al., (2009) stated that due to particle reinforcement procedure stiffness and strength had received the most attention as tailorable properties. The microstructure of metal and ceramic composites showed the particle of one phase spread into another known as particle reinforcement composite. The particle may be of different shapes like square, triangular and round shapes. The dispersed sizes of particulate reinforcement in composites are of few microns and volume concentrations. Zhang et al., (1993) studied the use of graphite reinforcement in a metal matrix and they revealed that MMC has potential to create material with high thermal conductivity, excellent mechanical properties and attractive damping behavior at elevated temperatures.

Thomas et al., (1992) revealed that the lack of wettability between aluminium and the reinforcement, oxidation of the graphite lead to manufacturing difficulties and cavitation. Alumina and other oxide like TiO$_2$, SiO$_2$ etc., have been used as reinforcing particle in Al-MMCs. Alumina has received more attention as reinforcing phase as it increased hardness, tensile strength and wear resistance in Al-MMCs (Deonath et al., 1980).

Surappa et al., (1981) & Banerji et al., (1983) experimented mica, alumina, silicon carbide, clay, zircon and graphite as reinforcements in the production of composites. Zedalis et al., (1991) used oxides, nitrides, borides and carbides as a reinforcement material for reinforcing into high-temperature discontinuously-reinforced aluminium. It had been found that all these reinforcement materials exhibits good compatibility with aluminium in elevated temperature and produced the highest values of specific stiffness.
2.3.4 Red-mud and its Properties

The ever-increasing demand for low cost reinforcements stimulated the interest towards the production and utilization of by-products from industries as reinforcements, since they are readily available or are naturally renewable at affordable cost. Aigbodion et al., (2010) focused on the refinement of aluminium-based MMCs using low cost industrial waste (byproducts) as the reinforcement particulate Kankara clay (alumino-silicate) in reinforcing Al-Si alloy.

Naresh et al., (2006) worked on the development and characterization of MMC using red-mud, an industrial waste for wear resistant applications. The MMC exhibited improvement in hardness and also the wear behavior of the composite. Bienia et al., (2003) used fly ash in reinforcement of aluminium matrix. They reported good dispersion and the recovery of the particles in the composite castings. Fly ash from coal combustion had been successfully combined with aluminium alloys using the foundry process to produce a class of MMCs called Ash alloys. It was demonstrated by Rohatgi et al., (2007) that Ash alloys offer the advantages of reducing the disposal volumes of electric utility industries, providing a high value-added use for fly ash, and at the same time introduced a class of new materials with improved properties at reduced cost.

It is in the light of foregoing researches, the investigation into the possibility of using maize stalk ash in a metal matrix particulate composite for engineering applications was motivated. Studies have shown that Al-Si-Mg alloys were reinforced with ceramic materials such as SiC, Al₂O₃, and TiB. But recent research had shown that biodegradable agricultural wastes can also be used to reinforce the alloy. Locust bean shell waste particulates were used as reinforcement on Al-Si-Mg alloy and it was observed that the tensile strength and hardness values increase as the
reinforcement increased (Sidiet et al., 2011). Moreover, orange peel ash particulates were used to reinforce Al–Si–Mg alloy and the results showed that there was a slight decrease in the mechanical properties due to poor adhesion of the reinforcement to that of the alloy (Shehu et al., 2011). Carbonized maize’s stalk particulates had been used to reinforce polyester and the results showed an enhancement in the mechanical properties of the developed composites (Hassan et al., 2012).

Liu et al., (2011) studied the economic way of using red-mud in cement production, which is also an efficient method for large-scale recycling of red-mud. Aysegul et al., (2007) investigated the synthesis and characterization of red-mud/polyaniline composites. New types of conducting composites using red-mud as an inorganic substrate and polyaniline as the conducting phase were prepared. It was found that the composites exhibit conductivities in the 0.42–5.2 S cm\(^{-1}\) range, depending on the amount of polyaniline. The thermal stability and the conductivity of RM/PANI composites were studied by ageing at 125 °C, the conductivity being measured in-situ, and found to have increased.

Satapathy et al., (2010) analyzed dry sliding wear behavior of red-mud filled polyester composites using Taguchi methodology. For this, a standard pin-on-disc test set-up and Taguchi’s orthogonal arrays were used. Taguchi’s experimental design method eliminates the need for repeated experiments and thus saves time, materials, and cost. It identifies the significant control factors and their interactions predominantly influencing the wear rate. From the experimental findings, an optimal combination of control factors was obtained on the basis of which a predictive model was proposed.

Patel et al., (2012) reported their study on processing a composite using jute fiber and epoxy resin as matrix and red-mud as a filler material and the degradation of the composite mechanical properties such as flexural
strength had been studied under different environmental conditions. It was found that chemical modification of fibers reduced the overall water uptake of the jute fibers. The flexural strength of the composite with modified fibers increased significantly compared to untreated fibers.

Sandhyarani et al., (2012) investigated a series of bamboo-fiber-reinforced epoxy composites which were fabricated by using red-mud and copper slag particles as filler materials. The effects of these two fillers on the mechanical properties of bamboo-epoxy composites were studied and it was found that the addition of copper slag filler improves the hardness of the bamboo-epoxy composites, whereas the addition of red-mud filler reduced the hardness value of bamboo-epoxy composites.

Mohini et al., (2008) studied the property characterization and utilization of abundantly-available and renewable resources of plant fibers such as jute and sisal. These plant fibers along with industrial wastes like fly ash and red-mud have been used for synthesizing value-added composite materials. The study strongly suggested that the newly developed plant fiber and/or industrial waste reinforced polymer composite materials were quite capable to serve as a potential cost and energy effective, technologically viable, and attractive substitute to the conventionally used wood and other identical materials.

From the detailed literature survey on reinforcements, it has been found out that there has not been much research carried out using red-mud as reinforcement in aluminum alloys. The ever-increasing demand for low cost reinforcement stimulated the interest towards the production and utilization of red-mud that contains major elements like \( \text{Al}_2\text{O}_3 \), \( \text{Fe}_2\text{O}_3 \), \( \text{TiO}_2 \), and \( \text{Na}_2\text{O} \) for the preparation of a MMC for wear resistance applications as it has good compatibility with aluminium even at elevated temperatures.
2.4 FABRICATION TECHNIQUES

A key challenge in the processing of composites is to homogeneously distribute the reinforcement phases to achieve a defect-free microstructure. Based on the shape, the reinforcing phases in the composite can be either particles or fibers. The relatively low material cost and suitability for automatic processing has made the particulate reinforced-composite preferable to the fiber-reinforced composite for automotive applications.

2.4.1 Two (Solid / Liquid) Phases

Primary processes for manufacturing of Al-MMCs at industrial scale can be classified into two main groups. Liquid and solid state processes: Liquid state processes include stir casting, compo-casting, squeeze casting, spray casting and in situ (reactive) processing, ultrasonic assisted casting.

Solid state processes: Solid state process includes powder blending followed by consolidation (PM processing), high energy ball-milling, friction-stir process, diffusion bonding and vapors deposition techniques. The selection of the processing route depends on many factors including the type and level of reinforcement loading and the degree of microstructural integrity desired.

2.4.2 Selection of Fabrication Method

Stir-casting: In a stir-casting process, the reinforcing phases (usually in powder form) are distributed into molten aluminum by mechanical stirring. The simplest and the most commercially used technique has been known as vortex technique or stir-cast method. The vortex technique
involves the introduction of pre-heated ceramic particles into the vortex of molten alloy created by the impeller. In this process, it is the most important to create good wetting between the particulate reinforcement and the molten metal. The conventional stir-casting method has been attractive processing method for producing Al-MMCS.

Ravi et al., (1993) mentioned that the conventional casting is relatively inexpensive and offers a wide selection of materials and processing conditions. Figure 2.1 (a) represents electric furnace which was used for preparing the A356-RM MMCs. Kerti et al., (2008) found that the stir-cast method offers better matrix particle binding due to stirring action of particles into the melts. The conventional stir-cast technique involves adding ceramic particles into the melt in the crucible which has been kept inside the furnace. The melt has been transferred to the permanent mould after stirring Figure 2.1 (b).
Gopalakrishnan et al., (2011) dealt with the modified stir-casting, which involves direct transfer of the melt into a permanent mould with a bottom pouring arrangement attached to the furnace is shown in Figure 2.1 (c).

![Diagram of modified stir-casting method](image)

**Figure 2.1 (c) Schematic diagram of modified stir-cast method**

Microstructural of heterogeneities can cause notably particle agglomeration and sedimentation in the melt and subsequently during solidification. Heterogeneity in the reinforcement distribution in these cast composites could also be a problem as a result of interaction between suspended ceramic particles and moving solid-liquid interface during solidification. This process has the major advantage that the production costs of MMCs are very low.

### 2.4.3 Stir - Casting Features

Stir-casting has been characterized by the following features.

- Content of dispersed phase has been limited to maximum of 30 wt%
• Distribution of dispersed phase throughout the matrix has not been perfectly homogenous owing to local clusters of the dispersed particles or gravity segregation of the dispersed phase due to a difference in the densities of the dispersed and matrix phase.

• The technology has been relatively simple and low cost.

2.4.4 Process Variables in Stir-casting

The stirring speed in the stir-casting has been very important for the successful production of casting. Rotational speed influences the structure of the casting produced. Pouring temperature exhibits a major role on the mode of solidification and partly in relation to the type of structure required. The pouring temperature must be high to ensure sufficient metal flow and free from cold portions, so that coarse structures can be avoided.

Assar et al., (2013) studied the influence of processing variables on the structure and porosity in stir-casting Al-Cu alloys and recommended the processing variables as follows: stirring speed, \( v \) from 340 to 995 rpm, stirring temperature between liquids and solids from 590° to 620°C, and isothermal stirring time, from 0 to 30 mins. Koket al., (2005) investigated 2024 Al-MMCs reinforced with three different sizes and weight fractions of \( \text{Al}_2\text{O}_3 \) particles up to 30 wt.% fabricated by a vortex method with subsequent application pressure. He had recommended the rotational speed from 500-650 rpm which has been found in most of the literature.

2.5 TESTING OF METAL MATRIX COMPOSITE FOR ITS MECHANICAL AND PHYSICAL PROPERTIES

A metal testing is very important to evaluate the characteristics of MMCs to validate the properties of matrix phase and reinforcement.
Seah et al., (1997) studied the mechanical properties of zinc-aluminium alloy/graphite particles added MMC. Ductility, ultimate tensile strength (UTS), compressive strength and Young’s modulus increased and significant decrease in hardness of the composite material were observed. Lin et al., (2007) reported that increase in graphite content in aluminium matrix material, reduced the UTS, Young’s modulus and elongation of the composite. This was due to cracking of the matrix/particulate interface, reduces the percentage elongation with the addition of graphite content.

Nandipati et al., (2013) investigated Metal Matrix Nano Composites (MMNCs) with the addition of nano-sized ceramic particles can which is significant for automobile, aerospace and numerous other applications. The physical and mechanical characteristics of the light refractory carbides such as SiC, TiC and \( \text{B}_4\text{C} \) make them suitable for being used as reinforcements in aluminium base metal matrix composites. The mechanical properties, including tensile strength and yield strength of the nano-composites were improved significantly, while the ductility of the base metal alloy matrix was retained. The microstructural study was carried out with an optical microscope and SEM which showed a good dispersion of nano-sized \( \text{B}_4\text{Cp} \) in a metal matrix. Mechanical properties of the as-cast MMNCs had been improved significantly even with a low weight fraction of nano-sized \( \text{B}_4\text{C} \).

Prashant et al., (2012) studied the mechanical and wear properties of Al6061-graphite and Al6061-SiC composites. The composites were prepared using stir-casting method in which the amount of reinforcement varied from 6-12% in steps of 3wt\%. The prepared composites of Al6061-Graphite and Al6061-SiC were characterized by microstructural studies and hardness, micro-hardness of the Al6061-SiC composite was found to be increase with increased filler content and whereas Al6061-Graphite composite
found to decrease with increased filler content and found to be 98-151 VHN and 98-76 VHN respectively. The dispersed graphite and SiC in Al6061 alloy contributed in enhancing the tensile strength of the composites. The wear resistance of the Al6061-SiC composite was found to decrease with increased in filler content, whereas the wear resistance of the 6061-graphite composite was found to decrease up to 6wt% but thereafter tended to increase.

Kumar et al., (1994) studied the impact properties of A356-T6 alloys. They reported that the refinement of the silicon structure through the addition of strontium-containing master alloys to the melt improved the impact properties of A356-T6 castings. The impact energy increased with solution treatment time.

Sedat et al., (2007) investigated the impact behavior of Al-based SiC particle reinforced MMCs. Charpy impact tests were performed on extruded and heat-treated specimens at temperatures varying from 176 to 300°C. Composite specimens based on Al alloys of 2124, 5083 and 6063 and reinforced by SiC particles were manufactured. Two different SiC sizes of 157 and 511 μm and two different extrusion ratios of 13.63:1 and 19.63:1 were used. The impact behavior of composites was affected by clustering of particles, particle cracking and weak matrix-reinforcement bonding. Accumulation of particles reduced the impact strength of Al 2124 and 6063 based composites. Al 6063 alloys and composites showed a better impact strength. The impact strength of 6063 composites increased with particle size and extrusion ratio.

Aigbidion et al., (2007) studied the effects of silicon carbide reinforcement on microstructure and properties of cast Al–Si–Fe/SiC particulate composites. In their investigation, a total of 5–25 wt% silicon
carbide particles were added to Al–Si–Fe alloy and the physical and mechanical properties measured include: densities, porosity, ultimate tensile strength, yield strength, hardness values and impact energy. The results revealed that, addition of silicon carbide reinforcement, increased the hardness values and apparent porosity by 75 and 39%, respectively, and decreased the density and impact energy by 1.08 and 15%, respectively, as the weight percent of silicon carbide increased in the alloy. The yield strength and ultimate tensile strength increased by 26.25 and 25% up to a maximum of 20% silicon carbide addition, respectively. These increases in strength and hardness values are attributed to the distribution of hard and brittle ceramic phases.

Rohatgi et al., (2006) studied the compressive characteristics of A356/fly ash cenosphere composites synthesized by pressure infiltration technique. They observed that these MMCs containing different volume fractions of fly ash particles showed that their yield stress, Young’s modulus, and plateau stress increased with an increase in density. The compressive strength of the composites was found to be increasing with the volume percentage addition of the fly ash.

2.5.1 Effect of Applied Wear Load

Archard’s law states that the wear rate varies with normal load which has been significantly lower in the case of composites. Mandal et al., (1998) investigated the two-body abrasive wear behavior of a cast aluminium alloy (ADC12) and ADC-12-10 wt.% Al₂O₃ particle composites studied with different wear loads (1 to 7 N) and abrasive sizes (30 to 80 μm). The effects of load on the wear rate of both the alloys were more severe as compared to that of abrasive size.
Abdulhaqq et al., (2008) investigated the influence of porosity of aluminium composite on wear rate. They reported that the applied normal load increased with the cumulative volume loss and increased with the temperature increases, due to contact of surfaces.

It was reported by Joel et al., (2005) and Kumar et al., (2008) that the unreinforced and reinforced composites eventually seize when the load was increased. This increased the wear rate, thus creating noise and vibration. Ferhat et al., (2004) determined that the wear debris size was in the order of millimeters at higher load while at the lower load, it has the order of few hundred micrometers. Chaudhury et al., (2005) found that as the load increased the proportion of metallic wear debris increased and the size of the delamination also increase for the composites.

2.5.2 The Effect of Sliding Distance and Sliding Velocity

The wear rate and cumulative wear loss increased for the materials with the increase of sliding velocity and sliding distances as reported by Ranganth et al., (2001). Wilson et al., (1997) reported in their investigation that at higher speeds, the micro-thermal softening of matrix takes place, which further lowers the binding effect of the reinforced-particles to that of matrix materials. It was being discussed by Kwok et al., (1999) and Shorowordi et al., (2004) that at higher sliding velocity wear rate was lower for MMCs due to the formation of a compact transfer layer at the region of the worn surfaces. The amount of the constituents of the counter body in the transfer layer increased as the sliding velocity increased, thus the formation of the protective cover of oxides reduced the wear rate.
2.5.3 Effect of Temperature

Radhika et al., (2012) studied the thermal behavior of the Hybrid MMCs (HMMC’s) during wearing process by measuring the temperature rise during the wear process. It was observed that the temperature rise of wear sample increased as the load increased. The rise of temperature increased the friction coefficient and the wear rate. The composite transition temperature was higher than that of the unreinforced alloy, thus the composites gave lower wear volume. The increase in normal pressure decreased to the transition temperature (Poza et al., 2007). Vissutipituk et al., (2005) concluded in their study that higher thermal conductivity of the reinforcement contributed the improvement in wear resistance.

2.5.4 Effect of Material Factors

In the composite system, the fine reinforcement particles are preferred, so as to obtain the stiffness benefits of a composite with lower fracture toughness. Dong et al., (2007) studied the mechanical properties by varying the particle size of SiC reinforcement in Al MMCs and reported that the bonding strength increased as the particle size reduced. It was also observed that larger particle size produces larger flaws with more defects and decreased the strength of the material. Sahin et al., (2004) reported that the hardness and density of the MMC increased with increasing the content of ceramic reinforcement and porosity decreased with increasing particle content.

Saravanan et al., (1997) studied on composites A356-10 vol. % SiCp with excess addition of 0.4% magnesium. The hardness and Young’s modulus of the material increased with the addition of SiC particles. Addition of extra magnesium to the composite slurry increased the wettability.
Akhlaghi et al., (2004) reported that, as the particle size is increased it led to a slight increase in tensile strength over the unreinforced aluminum.

Sudarshan et al., (2008) synthesized A356 Al-fly-ash particle composites. They studied mechanical properties and dry sliding wear and concluded that fly ash with a narrow size range (53-106 µm) showed better properties compared with the wider size range (0.5-400 µm) particles.

Davidson et al., (2000) studied on mechanical behavior of 6061 aluminium alloy reinforced with copper coated and uncoated SiC particles. The copper coated SiC particles, improved the bonding strength with matrix material and the applied load were more effectively transferred from the particles, which enhanced the larger strain failure compared to uncoated SiC particles.

2.5.5 Effect of Reinforcement and Reinforcement Distribution

Iwai et al., (2003) studied the effect of different reinforcement on the properties of MMCs and found that there exist a strong dependence on the kind of reinforcement and its volume fraction in the improvement of the mechanical properties of MMCs.

Ramesh & Safiulla (2007) in their research work improved dry wear resistance of Al6061 based composites with different reinforcements and found that, reinforcement of hard particles in Al matrix protected the matrix surface against the destructive action of the abrasive during the wear process. There is a growing interest at the international level in manufacturing HMMCs, since they exhibit improved mechanical and tribiological properties (Chi et al., 1999).
Ramachandra et al., (2007) studied the effect of reinforcement of fly ash on sliding wear, slurry erosive wear and corrosive behavior of Al-MMCs. Aluminium (12 wt% Si) as matrix material and up to 15 wt% of fly ash particulate composite was fabricated using the stir-casting route and concluded that fly ash improved abrasive wear resistance (20-30%) of aluminium and reduced the coefficient of friction. But the corrosion resistance of reinforced composite decreased with increase in fly-ash content.

Das et al., (2000) reported that the TiC reinforced A356 alloy has been the hardest and exhibits the lowest wear rate. The wear resistance of the composites was improved by incorporating TiB$_2$ particle reinforcement and the refinement of the matrix grains improved the mechanical properties of the composite (Mandal et al., 2007).

The distribution of reinforcements is influenced the mechanical properties like ductility, fracture toughness and strength. Lewadowski et al., (1989) reported that a uniform reinforcement distribution has been essential for effective utilization of the load carrying capacity of the reinforcement. The non-uniform distribution of the reinforcement on the early stages of processing has been observed to persist to the final product in the form of clusters of infiltrated reinforcement with their attendant porosity, all of which lowered ductility, strength and toughness of the materials.

2.5.6 Effect of Volume Fraction

The volumetric wear rate increases with increasing applied load while it decreases with increasing volume fraction of the filler material. This may due to the reason that the addition of ceramic content results in a pronounced drop in ductility (Ferhat et al., 2004). Roy et al., (2005) studied the tribiological properties of Ti-aluminide-Al based MMC, by varying percent volume fraction of 10 to 40% and they had concluded that at 20%
volume fraction reinforcement MMC has five times lower wear volume than the base Al alloy.

Viswanatha et al., (2013) reported their study on microstructure and mechanical properties of Al-MMCs reinforced with SiCp and graphite particles. A356 alloy was used as the matrix material with varying the reinforcement of SiC from 0 to 9 wt% in steps of 3 wt% and fixed quantity of 3 wt% of graphite and it was reported that there was significant improvement in hardness and tensile properties by increasing the weight percentage of SiC particles. Ramachandra et al., (2007) reported that the damping capacity of composite increases with the increase in volume fraction of fly ash. The Fracture surface of composites shows mixed mode (ductile and brittle) fracture. The Addition of 6% of fly ash particles into A356 Al alloy showed low wear rates at low wear loads (10 and 20 N) while 12% of fly-ash reinforced composites showed lower wear rates compared to the unreinforced alloy in the load range 20–80 N.

Ceschini et al., (1998) reported that the wear resistance of MMCs can be improved by increasing the volume fraction of the reinforcing ceramic phase as much as 70 percentage. Nair et al., (1985) and Ibrahim et al., (1991) had reported an increase in hardness which may further increase the wear resistance of the composites. At any constant load, wear rate decreases with an increase in the addition of SiCp and improves the load bearing properties of aluminium alloy during sliding.

Kumar et al., (2008) reported that the increase in the addition of SiC restricted the flow or deformation of the matrix material with respect to load. Leng et al., (2008) investigated the addition of 3-7% volume fraction of graphite particles to the SiCp/Al material and found that improved the machinability and tribiological properties but it decreased the tensile, elastic modulus of the material. Buytoz et al., (2001) studied the effects of volume
fraction of $\text{Al}_2\text{O}_3$, particle size and amount of porosity present on the abrasive wear resistance of Al alloy MMCs under different abrasive conditions. It was observed that the abrasive wear rates of composites decreased more rapidly with increase in $\text{Al}_2\text{O}_3$ volume fraction.

2.5.7 Effect of Damping Characteristics

Wei et al., (2001) investigated the effects of macroscopic graphite (Gr) particulates on the damping behavior of commercially pure aluminum. The damping capacity of the Al/Gr MMCs, with three different volume fractions of macroscopic graphite reinforcements, was compared with that of unreinforced commercially pure aluminum specimen. It was found that the damping capacity of the materials increased with increase in volume fraction of the macroscopic graphite particulates.

Wu et al., (2010) studies the damping capacities and microstructures of magnesium matrix composites reinforced by graphite particles. Magnesium matrix composites reinforced by graphite particles were fabricated using stir-casting with graphite particle size of 50 µm and graphite particle volume fractions of 5, 10, 15 and 20% respectively. A dynamic mechanical analyzer was used to measure the damping capacities of as-cast composites.

The experimental results revealed that the graphite particles play an important role on the damping capacities of as-cast composites. The strain amplitude independent damping of as-cast composites increases significantly as the graphite particle volume fraction increases from 0 to 15%, but decreased when the volume fraction exceeded 15%.

particle composites were fabricated using stir-cast technique and hot extrusion. Composites containing 6 and 12% vol. fly ash particles were processed. Narrow size range (53–106 μm) and wide size range (0.5–400 μm) fly-ash particles were used. Hardness, tensile strength, compressive strength and damping characteristics of the unreinforced alloy and composites were measured. Bulk hardness, matrix micro-hardness, 0.2% proof stress of A356 Al–fly-ash composites were higher compared to that of the unreinforced alloy. Additions of fly-ash led to increase in hardness, elastic modulus and 0.2% proof-stress. Composites reinforced with narrow size range fly-ash particle exhibited superior mechanical properties compared to composites with wide size range particles. A356 Al–fly-ash MMCs were found to exhibit improved damping capacity when compared to unreinforced alloy at ambient temperature.

Shanta et al., (2001) investigated the damping behavior and dynamic Young’s modulus of base alloy and the particulate-reinforced composites over a temperature range of 30–300°C using a dynamic mechanical analyzer. The damping capacity of the materials was observed to increase with the increase in temperature, whereas the dynamic modulus was found to decrease with the increase in temperature. The damping capacity at higher temperature may be attributed to the matrix-reinforcement interface and thermo-elastic damping.

2.5.8 Effect of Thermal Conductivity

Recep et al., (2012) studied the effect of reinforcement volume ratio on porosity and thermal conductivity in Al-MgO composites. In the production of composites, EN AW 1050A Al alloy was used as the matrix material and MgO powders as reinforced metal matrix composites. It was reported that the increase in the reinforcement volume ratio increased
porosity. Effective thermal conductivity of Al-MgO composites increased with the decrease in reinforcement volume ratio.

Cem et al., (2012) studied the thermal expansion and thermal conductivity behaviors of Al-Si/SiC/graphite HMMCs. The thermal expansion and thermal conductivity behaviors of hybrid composites with various graphite contents (5.0, 7.5, 10% wt.) and different silicon-carbide particle sizes (45 and 53 µm) were investigated. Results indicated that by increasing the graphite content the dimensional stability improved, and there was no obvious variation between the thermal expansion behaviors of the 45 µm and the 53 µm silicon carbide reinforced composites. The thermal conductivity of hybrid composites was reduced due to the enrichment of the graphite component.

El-Sayed et al., (2011) investigated the electrical and thermal conductivities of cast A356/Al₂O₃ Metal Matrix Nano-composites (MMNCs). The A356/ Al₂O₃ metal matrix nano-composites (MMNCs) were fabricated using a combination of rheo-casting and squeeze casting techniques. Two different sizes of Al₂O₃ nano-particles were dispersed into the A356 Al alloy, typically, 60 and 200 nm with volume fractions up to 5%. The effect of the nano-particles size and volume fraction on the electrical and thermal conductivities was evaluated. The results revealed that the A356 monolithic alloy exhibited better electrical and thermal conductivities than the MMNCs. Increasing the nano-particles size and/or the volume fraction reduced both the thermal and electrical conductivities of the MMNCs.

2.6 THEORY OF WEAR

Wear is a process of gradual removal of a material from the surfaces of solids subject to contact and sliding. Damages of contact surfaces are results of wear. Wear can have various patterns (abrasion, fatigue,
ploughing, corrugation, erosion and cavitation). Wear is the most commonly encountered industrial problem leading to the replacement of components and assemblies in engineering. The wear of materials is the result of many mechanical, physical and chemical phenomena. Several types of wear have being recognized, e.g., abrasive, adhesive, fatigue, fretting, erosion, oxidation, corrosion. Wear of solids is usually treated as the mechanical process (Kato 2002).

Ashby et al., (1990) have stated that wear is not an intrinsic material property, but characteristics of the Engineering system which depend on load, speed, temperature, hardness, the presence of foreign material and the environmental condition. The wear of aluminium based MMCs depends on several factors such as volume fraction, morphology, and size of reinforcing phase as well as the strength of the interface.

Lee et al., (1992) studied the effect of sintered porosity, volume fraction and particle size of SiC on abrasive wear resistance of SiC reinforced Al6061 alloy. Their results show that the beneficial effect of the hard SiC addition on wear resistance, the wear rates decreased when the amount of SiC increased. Further, it was observed that for the composite containing the same amount of SiC, the wear rates decreased with increasing particle size.

In most basic, wear studies, where the problems of wear have been a primary concern, the so-called dry friction has been investigated to avoid the influences of fluid lubricants. Wear may be of following distinct types.

2.6.1 Abrasion Wear

Abrasive wear removes the protective oxidized metal and polarized coatings to expose oxidized metal, in addition to removing metal particles. It also forms microscopic grooves and dents for concentration cell corrosion.
Also, it increases the microscopic surface area exposed to corrosion. It removes strain-hardened surface layers. It cracks brittle metal constituents forming sites for impact hydraulic splitting. Plastic deformation of high-stress metal-mineral contact causes strain hardening and susceptibility to chemical attack.

### 2.6.2 Corrosion Wear

Corrosion wear produces pits that induce micro-cracking. Micro-cracks at pits invite hydraulic splitting during impact. It roughens surface, reducing energy needed to abrade away metal. It may produce hydrogen with subsequent absorption and cracking in steel. It selectively attacks grain boundaries and less noble phases of multiphase microstructures, weakening the adjacent metal.

Plastic deformation makes some constituents more susceptible to corrosion. It cracks brittle constituents, tears apart ductile constituents to form sites for crevice corrosion, hydraulic splitting. It also supplies kinetic energy to drive abrasion mechanism and pressurizes mill water to cause splitting, cavitation, and jet erosion of metal and forms protective oxidized material.

The measures of wear have been formulated with respect to changes of the following quantities: (a) mass of the removed material from the solid, (b) volume of the removed material, (c) reduced dimensions of the body. The measures of wear have non-zero values as long as an observable amount of the material is removed. Due to this, usually, but not always, a significant period of the sliding time (or a great number of cycles) must be taken into account. Symptoms and appearance of different types of wear are shown in the Table 2.2, to understand types of wear (Kok et al., 1987).
Table 2.2 Symptoms and appearance of different types of wear

<table>
<thead>
<tr>
<th>Types of wear</th>
<th>Symptoms</th>
<th>Appearance of the worn-out surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasive</td>
<td>Presence of clean furrows cut out by abrasive particles</td>
<td>Grooves</td>
</tr>
<tr>
<td>Adhesive</td>
<td>Metal transfer is the prime symptoms</td>
<td>Seizure, catering rough and worn-out surfaces.</td>
</tr>
<tr>
<td>Erosion</td>
<td>Presence of abrasives in the fast moving fluid and short abrasion furrows</td>
<td>Waves and troughs.</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Presence of metal corrosion products.</td>
<td>Rough pits or depressions.</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Presence of surface or subsurface cracks accompanied by pits and spalls</td>
<td>Sharp and angular edges around pits.</td>
</tr>
<tr>
<td>Impacts</td>
<td>Surface fatigue, small sub-micron particles or formation of spalls</td>
<td>Fragmentation, peeling and pitting</td>
</tr>
<tr>
<td>Delamination</td>
<td>Presence of subsurface cracks parallel to the surface with semi-dislodged or loose flakes</td>
<td>Loose, long and thin sheet like particles</td>
</tr>
<tr>
<td>Fretting</td>
<td>Production of voluminous amount of loose debris</td>
<td>Roughening, seizure and development of oxide ridges</td>
</tr>
<tr>
<td>Electric attack</td>
<td>Presence of micro craters or a track with evidence of smooth molten metal</td>
<td>Smooth holes</td>
</tr>
</tbody>
</table>

Barber et al., (1989) suggested that the wear rate is a prescribed function of the normal pressure, sliding velocity and temperature. The form of the function of a given material could be determined by laboratory wear tests. Galin et al., (1980) recognized that besides elastic deformations of the body
contacting with the rigid foundation, irreversible changes in the shape of the body take place in the wear process. In the case of abrasive wear, the amount of the removed material is proportional to the work of the frictional force.

Haque et al., (2001) studied the wear behavior of both as-cast and heat-treated specimens were studied under dry sliding conditions at room temperature using a pin-on-disc type wear testing apparatus. The parameters for this test were sliding distance and load. Wear increased with increase in load and time for both as-cast and heat-treated specimens, and found that for as-cast specimen wear was more pronounced. For heat-treated specimens a mild wear was observed at the wear surface, and for as-cast specimen an adhesive wear with plastic deformation was observed. The overall investigation showed that the heat-treated aluminium-silicon piston alloy had higher strength, hardness and wear resistance properties. However, they concluded that in order to obtain the best combination of the structure and properties in such material, further investigation was needed.

In the past two decades, numerous studies of wear properties of aluminium based MMCs with different type reinforcements have been studied. Natarajan et al., (2006) investigated the wear behavior of Al-MMCs with 25% SiCp by sliding against automobile friction material and it compared to the gray cast-iron. It was observed that the MMCs had considerable higher wear resistance than the gray cast-iron and the friction coefficient of Al MMC was 25% more than the cast-iron. Shivamurthy & Surappa (2011) studied dry sliding wear and friction behavior of A356 alloy and its composites SiCp using a pin-on-disc setup. The authors observed that the increase in reinforcement material reduced wear rates.

Singh et al., (2007) studied the dry sliding wear behavior of Cu-15Ni-8Sn bronze alloy using a pin-on-disc wear tester under argon atmosphere and normal atmosphere on the surface of a steel series 440C. By
using the X-ray diffraction and SEM, the microstructure of the debris, the worn surface and the subsurface of the pin was characterized. Fe$_2$O$_3$ and CuO phases were found in the debris in addition to bronze particles.

Kerti et al., (2008) studied the abrasive wear resistance of Al-MMCs containing Al$_2$O$_3$ and SiC using a dry rubber wheel abrasion wear tester. Their results showed that composites containing Al$_2$O$_3$ are found to be superior to those containing SiC. Wang et al., (1989) had investigated the response of wear by two body abrasion Al-MMCs reinforced with alumina fiber. Their result showed that wear resistance of the composite was found to be in the range from almost two to six times that of the matrix alloy. Alpas et al., (1994) studied the dry sliding wear of Al-MMCs and determined how the micro-structural parameters such as volume of particulate and particulate size affected the wear resistance of these materials.

Uyyuru et al., (2007) investigated the tribological behavior of Al–Si–SiCp composites/automobile brake pad system under dry sliding conditions. It has been found that both wear rate and friction coefficient vary with both applied normal load and sliding speed. With the increase in the applied normal load, the wear rate was observed to increase whereas the friction coefficient decreased. However, both the wear rate and friction coefficients were observed to vary proportionally with the sliding speed. During the wear tests, formation of a tribo-layer was observed, the presence of which could affect on the wear behavior, apart from acting as a source of wear debris. Tribo-layer formed over the worn disc surfaces was found to be heterogeneous in nature.

Prasad et al., (2013) had experimentally investigated the effect of fillers like RM on the dry sliding wear behavior of pure aluminium. Pure Aluminium of IE-07 grades from National Aluminium Company (NALCO), Angul of Odisha, India, was collected with fillers in 10, 15, 20 and 30%
respectively based on weight and prepared MMC using a stir-casting technique. The results revealed that incorporation of RM fillers led to significant improvement in wear resistance of aluminium. The effect is the increase in the interfacial area between aluminium matrix and RM particles leading to the increase in strength appreciably.

Peter et al., (2003) studied specially designed, sub-scale disc-brake testing system. A series of experiments was conducted to study the friction, wear, and frictional heating characteristics of both conventional and unconventional candidate disc brake materials. The selected sliding speed (11.0 m/s) was comparable to that experienced by a commercial disc brake surface on a truck travelling 60 miles/h (96.6 km/h) and found that the surface roughness of the cast iron and ceramic composite disc was reduced after sliding, but that of the MMC remained about the same, and that of the intermetallic alloy increased due to abrasive wear, due to chip-like particles.

Ravikiran et al., (1997) examined the effect of sliding velocity on the wear behavior of Al-30% SiCp MMC and concluded that the wear rate of pin material (MMC) decreased with increasing speed and also the wear rate of the composite decreased with increasing fraction of SiC particles. Yoshiro et al., (1995) explored the wear properties of SiC whisker reinforced Aluminium 2024 alloy with the volume fraction of whiskers ranging from 0 to 16% produced by powder metallurgy technique. Their result confirmed that SiC whiskers reinforcement can improve the wear resistance of aluminium alloy for both severe and mild wear. Sannino et al., (1995) investigated the effect of the shape of the reinforcement depends on the sliding velocity. The effect of sliding velocity and volume fraction on the frictional wear behavior of aluminium MMCs sliding against the counterpart have been studied by a number of researchers (Sato et al., 1976; Lee et al., 1992; Tjong et al., 1998;
Kwok et al., 1999) revealed that the frictional and wear characteristics of aluminium MMCs depends on the sliding velocity.

From literature survey, it is evident that the wear properties are improved remarkably by introducing a hard inter-metallic compound into the aluminium matrix. It was also found that as the binding strength between intermetallic compound and matrix is very strong pulling out has been presented even at high loads. The wear of aluminium based MMCs depends on several factors such as volume fraction, morphology and size of the reinforcing phase as well as the strength of the interface. Most of the in researches were carried out mainly using SiC, Al₂O₃ and B₄C particles in Al alloy matrix. There are also relatively few discussions on the wear behavior of aluminum MMCs reinforced with alumina fibers and natural minerals. A very few research work was carried out with RM as reinforcement and pure Aluminium as a matrix. But no work has been carried out with A356 as a matrix and RM as reinforcement. Therefore the present investigation is aimed at the preparation of a metal matrix Composite using red-mud as reinforcing material and A356 as matrix material to study the effect of RM on wear behavior and mechanical properties with T6 heat treatment condition.

2.7 HEAT TREATMENT OF METAL MATRIX COMPOSITES

In order to obtain improved mechanical properties, aluminum alloys are often subjected to different heat treatments. During heat treatment, the alloys are exposed to high-temperature corresponding to the maximum safe limits relative to the lowest melting point for each specific composition. By doing so, the soluble phases formed during solidification can be re-dissolved in the matrix. The A356-RM MMCs can be strengthened by precipitation of several metastable phases, which are produced by an artificial ageing (Wang et al., 2008).
2.7.1 Sequences of Heat Treatment

There are many different sequences of heat treatment which improves the properties of aluminium alloys. Its designation consists of one letter T which means ‘heat-treated’ and a number showing how the sequence looks like. The most common sequences are given in Table 2.3 (Polmear et al., 1995).

Table 2.3 Common sequences of heat treatment process

<table>
<thead>
<tr>
<th>Heat treatment designation</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 heat treatment</td>
<td>• Cooled after casting or hot working</td>
</tr>
<tr>
<td></td>
<td>• Naturally-aged</td>
</tr>
<tr>
<td>T2 heat treatment</td>
<td>• Cooled after casting or hot working</td>
</tr>
<tr>
<td></td>
<td>• Cold-worked</td>
</tr>
<tr>
<td></td>
<td>• Annealed</td>
</tr>
<tr>
<td>T3 heat treatment</td>
<td>• Solution heat-treated</td>
</tr>
<tr>
<td></td>
<td>• Cold-worked</td>
</tr>
<tr>
<td>T4 heat treatment</td>
<td>• Solution heat-treated</td>
</tr>
<tr>
<td></td>
<td>• Naturally-aged</td>
</tr>
<tr>
<td>T5 heat treatment</td>
<td>• Cooled after casting or hot working</td>
</tr>
<tr>
<td></td>
<td>• Artificially-aged</td>
</tr>
<tr>
<td>T6 heat treatment</td>
<td>• Solution heat-treated</td>
</tr>
<tr>
<td></td>
<td>• Quenched</td>
</tr>
<tr>
<td></td>
<td>• Naturally-aged</td>
</tr>
<tr>
<td></td>
<td>• Artificially-aged</td>
</tr>
<tr>
<td>T7 heat treatment</td>
<td>• Solution heat-treated</td>
</tr>
<tr>
<td></td>
<td>• Quenched</td>
</tr>
<tr>
<td></td>
<td>• Naturally-aged</td>
</tr>
<tr>
<td></td>
<td>• Overaged</td>
</tr>
<tr>
<td>T8 heat treatment</td>
<td>• Solution heat-treated</td>
</tr>
<tr>
<td></td>
<td>• Cold-worked</td>
</tr>
<tr>
<td></td>
<td>• Artificially-aged</td>
</tr>
<tr>
<td>T9 heat treatment</td>
<td>• Solution heat-treated</td>
</tr>
<tr>
<td></td>
<td>• Artificially-aged</td>
</tr>
<tr>
<td></td>
<td>• Cold-worked</td>
</tr>
</tbody>
</table>
Most common sequences of heat treatment of aluminium alloys are T5 and T6. To specify heat treatment more precisely one or more digits could be added to T1-T9 (ASTM standards).

Tiryakiog et al., (2008) investigated the effect of artificial ageing on tensile work Hardening characteristics of a cast Al-7% Si-0.55% Mg (A357) alloy. The specimens excised from continuous cast bars were solution treated at 540°C for 22 hours, quenched, and finally aged artificially at 155, 175 and 205°C respectively for various times. The results of the current analysis indicated that the shearing-bypassing transition in precipitates took place at peak strength. The elongation-to-fracture was determined by work hardening.

Kolar et al., (2012) studied the effect of pre-deformation followed by or together with artificial ageing on the mechanical properties such as strength and ductility of AA6060 aluminium alloy. It was found that precipitation kinetics and associated mechanical response, in terms of hardness and tensile properties were strongly affected by pre-deformations. In terms of ageing behavior, kinetics was accelerated and the peak strength generally increased. Comparing sequential mode and simultaneous mode, the latter seems to give overall better mechanical properties and after considerably shorter ageing times. The result of the two modes of pre-deformation were compared and discussed in view of differences in processing conditions and microstructure characteristics.

Shueiwan et al., (2008) preformed experimental analysis of A356 alloys with thixotropic structure (designated SSM-A356) and systematically studied on mechanical properties in order to establish the database for further investigations in forming and heat treatment. It was found that because of the specific microstructure and characteristics, the heat treatment conditions of SSM-A356 were explored through the observations of microstructure and the
measurement of micro-hardness. The mechanical testing results showed that the yield and ultimate tensile strength of SSM-A356 were respectively around 115 and 34% greater than those of conventional A356, and the elongation was also 2-3 times larger.

El-Sayed et al., (2011) studied the tensile properties of A356/Al₂O₃ at both ambient and elevated temperatures. The A356/Al₂O₃ was fabricated using a combination of the rheo-casting and squeeze-casting techniques. The A356 matrix alloy was reinforced with Al₂O₃ nano-particulates having average sizes of 60 and 200 nm with different volume fractions up to 5% vol. The results revealed that the A356/Al₂O₃ nano-composites exhibited better mechanical properties than the A356 monolithic alloy. Such improvement in the mechanical properties was observed at both room and elevated temperatures up to 300°C. Increasing the volume fraction and/or reducing the size of Al₂O₃ nano-particulates increased both the tensile and yield strengths of nano-composites.

Diana et al., (2011) investigated solution treatment effects on microstructure and mechanical properties of Al-(1 to 13 pct) Si-Mg Cast alloys. Five alloys, with Si levels ranging from 1 to 13 %, were tested in as-cast, T4, and T61 conditions. The eutectic Si was both unmodified and modified. Results showed that the microstructures were affected significantly by alloy composition, eutectic Si morphology, and solution treatment time. Si content had significant effects on Ultimate Tensile Strength (UTS), Yield Strength (YS), and elongation as well as a strong influence on solution treatment response. In T61 treatment with different solutionizing times, UTS and YS reach their maximum values in 1 hour of solutionizing followed by a decrease, then a slight increase, and finally, a plateau close to the maximum level.
Hossain et al., (2013) studied the effect of artificial ageing temperature on the mechanical properties of Al-6Si-0.5Mg alloy containing 0.5 - 4 wt% Cu. The solution treated alloys containing different amounts of Cu were aged isochronally for 1 hour at temperatures up to 300°C. The result showed that during artificial ageing, the yield and ultimate tensile strengths were found to increase with ageing temperature; the maximum being attained at peak aged condition. Ductility and impact toughness of the alloys, on the other hand, decreased with ageing temperature reaching the minimum at the highest hardness. The addition of Cu resulted in an increase in hardness and tensile strength and substantial reduction of ductility and fracture toughness.

One of the most versatile of 300 series (Al-Si-Mg) casting alloys is the A356 alloy. The A356 casting alloy is widely used for the casting of high strength components in automotive, aerospace and military applications due to its excellent castability, weldability, high strength, pressure tightness and corrosion resistance (Jorstad et al., 2001). The alloy is generally heat-treated to provide various combinations of desired mechanical (strength and toughness) and physical properties. The most common heat treatment is T6 treatment, wherein the component is solution heat-treated at around 540°C for about 10 to 12 hours immediately followed by quenching in water maintained at 80°C. The component was then left to natural ageing at room temperature for about 4 to 12 hours, followed by artificial ageing at around 155°C for about 2 to 12 hours (ASTM Standard B917/B917M 2008). In as-cast state the Mg and Si atoms were segregated in the primary Al phase, which is mostly dendritic due to the solidification process. The solutionizing treatment dissolves the Mg and Si elements in the primary Al phase. The quenching after solutionizing is to arrest any precipitation reaction during cooling, which improves the vacancy fraction to aid mobility of the atoms in the ageing process and minimize residual stresses in the component (water at 80°C) to improve fatigue life. The only disadvantage of the quenching process is the
distortion in the part due to the uncontrolled high rate of quenching (Thompson et al., 1971).

The ASTM standard B-917 (B917/B917M2001, 2001) defines the heat treatment of Aluminium casting alloys and the standard specifies that during quenching after solution treatment, it is critical that the cooling proceeds rapidly through the 400°C to 260°C temperature range in order to avoid the premature precipitation which is detrimental to the properties, such as tensile and corrosion resistance. Further, for casting alloys, the quenching delay is recommended to not exceed 45 seconds. In the case of A356.2 alloy, cast by sand casting or permanent mould, it is recommended to reduce the quench delay time of less than 10 seconds as prescribed by ASTM standard B-597 (ASTM1998).

The natural ageing process was adopted wherein the Mg and Si atoms were found to organize in specific clusters and affect the precipitation mechanism in the artificial ageing stage (Jeyakumar et al., 2009). The artificial ageing is carried out to result in the precipitation of Mg_2Si phase in the primary Al phase matrix to provide higher strength and toughness to the component (Maruyama et al., 1997).

In A356 alloy reinforced with RM there has been found, no research study to methodically the mechanisms of atom redistribution in the artificial ageing process and the effect of various ageing times and temperatures on the mechanical properties. This study aims to carry out such an investigation and quantify the effect of artificial ageing process on the resultant mechanical properties of the A356-RM MMCs. The sequence of a precipitation reaction in the primary Al phase during natural ageing would be studied by micro-hardness measurements of the primary Al phase, which will reflect any changes to the atom distribution in the phase.
2.8 MICROSTRUCTURE STUDIES

Phase transformations in alloys can generate particles or “precipitates” of a second phase, which may differ from the matrix by their composition or by their structure. Important parameters of precipitation-hardened alloys are: strength of the precipitate phase, its volume fraction, and the dispersion of the particles - their mean size and the typical distance between them (Lorimer et al., 1978). Figure 2.2 represents isothermal sections of the phase diagram.

![Figure 2.2 Isothermal section of the Al-Si-Mg phase diagram at 340°C](image)

Figure 2.3  Equilibrium solubility versus temperature for Mg$_2$Si in Al (American Society of Metals, editor. Aluminum and Aluminum Alloys. ASM International, Metals Park1993).

Figure 2.3 displays the solubility versus temperature for Mg and Si in solid Al in equilibrium with Mg$_2$Si and Si. After the common thermal treatments, these alloys contain three phases: (i) the Al matrix, (ii) Si (large particles, coarse dispersion), and Mg$_2$Si (small particles, fine dispersion). The precipitation sequence of the alloys with an atomic ratio of Mg : Si is 2:1.

Supersaturated $\alpha$ G-P.zones$\beta \rightarrow \beta$(Mg$_2$Si).

American Society of Metals. Metallography and microstructures of aluminum alloys (1990) and American Society of Metals, editor. Aluminum and Aluminum Alloys (1993) have explained the precipitation of hardening of Al-S-Mg Alloys as “G–P zones” is an abbreviation for Guinier-Preston zones; an early stage of precipitates characterized by an enrichment of solute atoms (Si, Mg) on the lattice sites of the matrix (Al). In case of Al-7%Si-0.3% Mg alloys, these first particles have the shape of needles, oriented along the direction of the Al matrix.

The particles that form in the next stage of the decomposition process, $\beta''$ particles, already have the composition Mg$_2$Al. The crystal
structure is face-centered cubic with a lattice parameter. The particles are rod-shaped, again with the long axis parallel to the directions of the Al matrix. They nucleate heterogeneously, preferentially at dislocations in the Al matrix. The equilibrium phase, β (Mg$_2$Si), finally, has a face centered cubic crystal structure of the CaF$_2$ type with a lattice parameter. It is generally believed that the transformation β to β” is diffusion-less with only minor atomic re-arrangements and some change in the degree of coherency between the precipitate and the matrix. If the alloy contains excess Si, large Si particles form in addition to the Mg$_2$Si particles from the precipitation sequence.

Merlin et al., (2009) studied the mechanical and microstructural characterization of A356 castings released with full and empty cores and they reported that the secondary dendrite arm spacing was comparable in corresponding positions for the two kinds of castings. The distribution of eutectic silicon particles was generally uniform and globular. A finer microstructure always corresponds to higher UTS. From there it can understand that YS did not seem to be well-correlated with the scale of the dendritic structure.

Gwozdz et al., (2008) have investigated the influence of ageing process on the microstructure and mechanical properties of aluminium-silicon cast alloys. They reported that the solidification rate and secondary dendrite arm spacing mostly affects properties of alloy in the as-cast state. After solution heat treatment and artificial ageing the properties like UTS, YS and Young’s modulus were worse for the specimens with coarser structure, but they were improved in fine structure.

Diana et al., (2011) has studied the solution treatment effects on microstructure and mechanical properties of Al-(1 to 13 %) Si-Mg cast alloys. They reported that fragmentation of Si particles strengthens the alloys, and in
the alloys with a higher Si content, the fragmentation produced more small particles and induces higher strengthening effects.

Jang et al., (2013) studied the effect of solution treatment and artificial ageing on microstructure and mechanical properties of Al-Cu alloy and reported that the results of solution treatment indicated that the mechanical properties of Al-Cu alloy increased and then decreased with the increase of solution temperature due to the fact that residual phases dissolve gradually into the matrix, and the fraction of the precipitation and increase in the size of the re-crystallized grain. Compared to the solution temperature, the solution holding time had less effect on the microstructure and the mechanical properties of Al-Cu alloy.

Jang et al., (2010) studied the microstructures and wear properties of graphite and Al$_2$O$_3$ reinforced AZ91D-Cex composites. They concluded that the Al$_3$Ce phase improved the thermal stability of the matrix, so the graphite particles can be kept intact, which could still work as a lubricant. At low load, the wear mechanism was abrasive wear and oxidation wear. At high load, the wear mechanism changed to delamination of wear for all the composites.

Karthigeyan et al., (2012) investigated studied the mechanical properties and microstructure of aluminium (7075) alloy matrix composite reinforced with short basalt fibre. They concluded that microstructural characterizations of composite samples revealed the presence and homogeneous distribution of basalt fibres and the second phase precipitates in the Al matrix. The strength value comparisons with various theoretical studies suggested that the experimentally found values best suits the theoretical studies considering the random distribution of basalt fibres in the Al (7075) matrix.
Sunny et al., (1994) studied the wear behavior of SiCp/Al composites and in their analysis they had reported, as the microstructural examinations showed, that neither pulling out nor brittle fracturing of SiC particles occurred to a significant degree in the wear tests. Instead, the main mechanism for the removal of SiC particles was that SiC particles were buried in layers of Al matrix and carried away while the latter detached from the sample surface. Agglomerations of fine wear debris resulted in large wear particles which caused significant abrasion in the subsequent wearing process.

2.9 CORROSION ANALYSIS

Alaneme et al., (2011) studied the influence of Al₂O₃ volume percent and solution heat-treatment of the corrosion behavior of Al6063 composites and its monolithic alloy in salt water, basic and acidic environments. In the investigation Al6063-Al₂O₃ particulate composites containing 6, 9, 15, and 18 volume percent alumina were produced by adopting two steps, stir-casting. The mass loss and corrosion rate measurements were utilized as criteria for evaluating the corrosion behavior of the composites. The author reported that Al6063-Al₂O₃ composites exhibited excellent corrosion resistance in NaCl medium than in NaOH and H₂SO₄ media. The unreinforced alloy exhibited slightly superior corrosion resistance than the composites in NaCl and NaOH media, but the composites had better corrosion resistance in H₂SO₄ medium. Furthermore, solution heat-treatment resulted in improved corrosion resistance for both the composites and the unreinforced alloy while the effect of volume percent Al₂O₃ on corrosion resistance did not follow a consistent trend.

Fernando et al., (2011) evaluated the corrosion resistance of 6101 aluminum alloy after different precipitation heat treatments by corrosion tests of weight loss method and they had concluded that the alloy S23 showed the highest resistance to pitting corrosion of all alloys in both solutions. This is a consequence of complete solubilization and precipitation of fine and coherent
phases, which decreased the effect of micro galvanic couple created between the precipitate and the matrix of aluminium.

Ribeiro et al. (2012) studied the effect of RM addition to the corrosion parameters of reinforced concrete evaluated by electrochemical methods. They have stated that, due to the higher concrete resistivity the penetration of chloride ions became low, therefore there was a decrease in the probability of corrosion and also the degree of humidity of the concrete samples containing RM appeared to exert a considerable influence on the concrete's corrosion resistivity.

Adeosun et al (2011) have investigated the corrosion behavior of heat-treated aluminum-magnesium alloy in chloride and EXCO environments. They concluded that the substantial inducement of Mg$_2$Si precipitates at a relatively higher magnesium addition, increased corrosion because the nature of the Mg$_2$Si crystals being anodic relative to the alloy matrix which easily dissolved under attack by chemical constituents. Formation of Mg$_2$Si intermetallic without corresponding appropriate oxides like SiO$_2$ and MgO, protected the precipitates from galvanic coupling with the matrix, accentuates susceptibility to corrosion.

Oluwayomi et al. (2014) have studied the corrosion behavior of $\alpha$-phase Al bronze alloy in selected environments. They have suggested that aluminium bronze was more susceptible to corrosion attack in acidic environments as compared to marine and alkaline environments and the corrosion rates decreased slightly with time and remained constant for all concentrations in marine and alkaline media, while it increased in acidic media (HCl, H$_2$SO$_4$) and also the aluminium bronze alloy experienced corrosion rate with an increase in concentrations in acidic media but was lower in marine and alkaline media.
2.10 DESIGN OF EXPERIMENTS

An experiment has been designed to evaluate simultaneously two or more factors which possess their ability to affect the resultant average or variability of a particular product or process characteristics. The design of experiments should focus on the preferred level of influencing factors. The results of the particular test combinations have been observed and the complete sets of results have been analyzed by Phillip et al., (1996) to determine the preferred level (optimum) of the various influencing factors. The Taguchi technique has been an optimization tool for solving the design problems as reported by Taguchi & Konishi (1987), Phillip (1990) and Taguchi et al., (1993). This method significantly reduced the number of experiments that have been required to model the response function compared to the full-factorial design of experiments.

Moreover, it has been a systematic and easy approach to optimize the design parameters, such as quality and cost as reported by Ranji et al., (1990). It is a multi-step process technique and has been used to find the possible interaction between the parameters. This approach reported by Paulo Davim et al., (2000) used factorial design approach and created a standard orthogonal array. Based on the Taguchi technique an orthogonal array can be used to reduce the number of experiments for finding out optimum test parameters as established by Ross et al., (1998). Investigation of the experimental outcomes by Siddhatha et al., (2011) uses SN curves to support the determination of the finest process design and has effectively been used for the study the dry sliding wear behavior of composite materials. The identified influencing parameters on the wear rate and friction co-efficient were applied load, sliding velocity sliding time and percentage of reinforcement.
Prasat et al., (2011) studied the influence of parameters such as sliding distance, sliding speed, load and fly ash content on dry sliding wear loss and coefficient of friction (COF) of AlSi10Mg-fly-ash-graphite hybrid composites using Taguchi method. The author has concluded that sliding distance was the most significant parameter having the highest statistical influence on the wear and COF of composites, followed by a load, sliding speed and fly-ash content. The influence of interactions between sliding distance and load on wear loss was found to be significant, whereas the other interactions exhibited only minor influence.

Sandhyarani et al., (2009) investigated the Tribo-performance analysis of red-mud filled glass-epoxy composites using Taguchi experimental design. They concluded that hybrid composites suitable for applications in highly erosive environments can be prepared by reinforcement of glass fibres and filling of micro-sized RM particles in epoxy resin. The erosion wear performance of these composites improved quite significantly by the addition of red-mud filler.

2.11 SUMMARY

A detailed investigation has been carried out to understand the existing literature on development of aluminium alloy based MMCs for automotive applications and an effort have been put to understand the needs of the growing composite industries. This literature survey also revealed the investigation carried out on various aspects like characterization, fabrication, testing, correlation between microstructure and tribological properties of Al-MMC. The effects of heat treatment on the mechanical properties were also investigated. From the basic knowledge obtained from the above literature survey, it can be concluded that the Al alloy composites were selected as a matrix material for the present research work due to their wide range of application, heat treatment capability and processing flexibility.
The literature survey also revealed that many researchers focused the use of reinforcing materials like SiC, Al₂O₃ and TiB₂ etc., either as a particulate form or fiber form. These reinforcing materials are generally costly. Hence, the present research objective is to explore the use of red mud as a reinforcing material which has Al₂O₃, SiO₂, Fe₂O₃, etc. and it is also a low cost option compared to other reinforcement materials. Therefore, the priority of work is to prepare Al-MMCs using A356 as matrix material and red mud as reinforcement and to study its mechanical and tribological characteristics under normal condition and T6 heat treatment condition. The effect of artificial ageing conditions (temperature and time) will also be studied.

The next chapter presents the motivation, aim, objectives and methodology of the current research work.