CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Aluminium Metal Matrix Composites (AMC’s) are well known for their exceptional properties like low weight to strength ratio, ductility, electrical and thermal conductivities, high specific modulus and wear resistance. These features of AMC’s enable it to use in variety of applications viz., automobile, ship building and aerospace industries (Ashok Kumar & Murugan 2012). Fusion welding is widely used method of joining metals and metallic alloys. However, the fusion welding performance regarding joining of metal matrix composites is trivial. Fusion welding, in general, deals with excessive heats and temperatures which is not suitable for welding AMC’s. The phase transformation (solid to liquid) is not preferable during welding of AMC’s, as there is a greater chance of formation of hazardous compounds due to reactions between matrix metal and reinforcement particles. To avoid such lacunas posed by the phase transformation in fusion welding, solid state welding techniques are considered as an alternative (Toptan et al. 2010).

Common ceramic materials that are used as reinforcement particulates in aluminium matrix are SiC, TiB₂, Al₂O₃, B₄C, ZrB₂, AlB₂, and SiO₂. Boride particulates reinforcement is often chosen because of their excellent properties like low density and high wear resistance over other reinforcement particulates. Combination of these reinforcement particles and
matrix metal properties are benefitted in many of the applications such as marine equipments, melting crucibles, ceramic and metal composites. Also, AMC’s reinforced with boron particles are more feasible to various fabricating techniques (Kerti & Toptan 2008, Kubota & Cizek 2008, Mazahery & Shabani 2012, Ağaoğulları et al. 2012).

Addition of boron particulates in aluminium known to enhance the wear behaviour of the composites and it is essential to have this feature for engineering materials. The present research study on friction stir welding of metal matrix composites demonstrates the weldability of ceramic particle reinforced composites viz., AA6061/AlB₂, AA6061/TiB₂, and AA6061/SiC respectively. Fabrication of composites with different weight percentages of reinforcement particles in aluminium AA6061 alloy are carried out by stir casting process. Further, synthesized composite plates are subjected to friction stir welding process. To analyze the joint quality, mechanical performance, and molecular integrity of the particles in the weld region, several number of destructive and non destructive tests are carried out on the welded specimens.

1.2 COMPOSITES

1.2.1 Basics of Composites

Composites are naturally available viz., wood or man manufactured in most of cases. They can be manufactured by incorporating one or more secondary phase materials into the primary phase metal matrix in order to obtain the enhanced mechanical and metallurgical properties of the resultant composite material. The primary objective of producing composites is to enhance the desired property of the metal, which usually remains to be a flaw of the metal property. Metal based composites consist of two phases, primary metal matrix phase and secondary reinforcement phase. Reinforcement phase
is embedded into the metal matrix phase to create the composites. This process aids in improving the mechanical and thermal properties of the defined metal and establishing it as a potential alternative for conventional engineering material for industrial applications.

Reinforcement is typically in anyone of the forms of ceramics, particles, fibers, or sheets, while matrix phase includes the metals, alloys, or plastics. Berghezan (1966) described composites as compound materials with preserving fundamental characteristics of each individual element to inherit the advantages and thus producing better mechanical properties. Jartiz (1965) defined composites as multifunctional material systems that yield characteristics from varying compositions of the materials, that are not found in materials available. They are produced with physical bonding between two or more elements and made up of cohesive structures.

Kelly (1967) pointed out that the composites reveals the combination of materials properties are expressed either in terms of resistance to heat or strength or other desirable quality, typically better than their constitute elements alone or completely deviating from each other. Van Suchetclan (1972) defined composite materials as heterogeneous materials with two or more solid phases physically bonded with each another on a microscopic scale. Composites may be considered as homogeneous materials since any part of the material exhibits the same mechanical characteristics.

Figure 1.1 shows the schematic explanation of production of composites with the basic two phases (matrix phase and reinforcement phase).
1.2.2 Need and Characteristics of Composites

Some of the prominent features that exhibit by the composites are high strength to weight ratio, high stiffness, and low weight. The high strength to weight ratio makes it to use in many of the sensitive applications like in critical components of aircraft applications where the primary goal is to have less weight and high strength. The other main advantage of the composites is load sharing i.e., load subjected on the composites is transferred to the reinforcement particles evenly and mitigates the propagation of cracks. The other positive feature is its adaptability and flexibility of complex design methods and can be easily moulded to any given shape.

By choosing optimal volume percentage of reinforcement and matrix phases and a viable fabrication technique leads to greater corrosion resistance and enhances material working temperature range. Owing to these feasible properties composites are emerging rapidly and are started replacing conventional engineering metals in many of the industrial applications. However, manufacturing cost for some types of composites is quite expensive with posing challenges.
1.2.3 Classification of Composites

Figure 1.2 shows the different types and classification of composite materials.

The composite materials are mainly classified into two types:

a) Based on Matrix Material
   - Metal Matrix Composites
   - Ceramic Matrix Composites
   - Polymer Matrix Composites

b) Based on Material Structure
   - Particulate Composites
   - Fibrous Composites
   - Laminate Composites
   - Flake Composite
   - Filled Composite

1.3 METAL MATRIX COMPOSITES

Metal Matrix Composites (MMCs) are the combination of two or more elements or alloys. The primary phase consists of a metal or its alloy known as matrix. The secondary phase known as reinforcement phase consists of ceramic or metallic particles distributed and embedded in the primary matrix metal. The objective of metal matrix composites is to enhance the particular single or multiple properties of the metal, the properties which matrix does not possess.
Figure 1.2 Composites: types and structures

Depends on the size, dimension and quantity of the reinforcement phase material, the properties of composites are defined. Most commonly available composites that are particulate reinforced composites are often
described as discontinuously reinforced metal matrix composites. These particulate based composites typically constitute of 5-25% of recent advanced materials. The microstructures of these particulates in the composites play a vital role in determining the mechanical properties of the composites. In general, most of mechanical properties hold a direct relationship with the reinforcement particles. For example, increasing the weight percentage of the reinforcement phase in the metal matrix leads to an increased ultimate tensile strength, yield strength, and stiffness. However, the ductility of the particulate reinforced MMCs is in contrast with the other mechanical properties and remains to be a major drawback of the composites.

Aluminium oxide, titanium boride, and silicon carbide, either in the form of fibers or particulates, are often used as reinforcement particles in the aluminium matrix. Addition of these particles in the aluminium alloys and their mechanical and metallurgical behaviour for both as-synthesized and welded configurations has been emerged as a potential topic of research. Recently, aluminium composites that are reinforced with aluminium oxide and silicon carbide finds in many of automotive and aerospace applications as cylinder heads and engine pistons. The above said composites are generally exhibits good mechanical properties, but the wear behaviour of the materials proves to be enhanced. Therefore, the studies pertaining to the improvement of wear behaviour of the composites is receiving considerable importance in meeting the standards of various industries.

The incorporation of hard second phase ceramic reinforcement particles in the aluminium alloy matrix to produce AMC’s, has also been reported to be more beneficial and economical, due to its high specific strength and corrosion resistance properties. The enhancement in properties helps these materials to find usage in variety of applications in the following areas.
Metal Matrix Composites (MMC’s) are an agglomeration of ceramic reinforcing materials and a base metal termed as the matrix. The widely available metal matrix composites are often fabricated by conventional stir casting processes and contain a matrix phase and ceramic particles as the reinforcement phase. The commonly synthesized MMC’s are

1. Metal composites
2. Reinforced metals
3. Reinforcement + metals
4. Fiber reinforced Metals
5. Filament reinforced metals
6. Whisker reinforced metal
7. Aluminium metal matrix composites
8. Titanium metal matrix composites
9. Aluminium + Silicon Carbide
10. Aluminium + Boron Carbide
11. Titanium + Silicon Carbide
12. Magnesium metal matrix composites
13. Copper metal matrix composites

1.3.1 Al based Metal Matrix Composites and its Fabrication Methods

Aluminium is sought be most preferable option for matrix metal in manufacturing MMC’s due to the facts that they are ease in handling, lower density and weight, attain strength with precipitation, superior thermal and electrical conductivities, damping capacity and greater corrosion resistance. From 100 years, continuous investigations and developments have been
observed for aluminium based metal matrix composites and efficient performance has been showed in diverse applications such as automotive and aircraft industries, electronic packaging, and structural components. Depends on the chemical composition of the constituents of Al matrix, versatile properties can be yielded for any given specific application. Aluminium metal matrix composites can be synthesized from any of the following techniques:

- Squeeze casting
- Powder metallurgy
- Stir casting

1.3.1.1 Stir casting

The present research study focuses on stir casting process for manufacturing composites owing to its inherent advantages. It is comes under liquid state fabrication method, in which addiction of reinforcement phase takes place in molten state of matrix. To ensure homogenous dispersion of the reinforcement particles in matrix, a mechanical stirrer is used (Figure 1.3). This technique does not involve complex processing steps and it is economically feasible. Molten form of composite is subsequently processed by traditional metal forming methods. Composites are prone to formation of reinforcement particle agglomerations when higher stirring rates are opted. Caution must be taken to restrict the encapsulation of gases in molten state by using proper shielding mechanism which may result in formation of voids or pores.
Stir casting is known to have the following important characteristics:

- Dispersion of phase constituent is limited
- Precautions must be taken to ensure homogeneous distribution of reinforcement phase in matrix which is not observed in some particular samples. There is a less probability of formation of clusters of disbursed particles. Dispersion of distributed phase must be increased for semi-solid matrix metals. This technique is called as rheo-casting.
- If there is a large variations in densities of matrix and reinforcement phases, gravity segregation is observed for reinforcement phase.
- Economical technology
### 1.4 APPLICATIONS OF AMC’s

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<tr>
<th>Application</th>
<th>Components</th>
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<tr>
<td>Aircraft industry</td>
<td>• Cabin and cargo hold finishing</td>
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<td>1. Civil aircrafts</td>
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<td>2. Military aircrafts</td>
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<td>3. General aviation applications</td>
<td>• Thrust reverser</td>
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<td>• Panels and sheets</td>
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<td>• Bricks and blocks for walling</td>
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<td>• Roofing sheets</td>
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<td>• Sanitary ware</td>
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<td>• Kitchen sinks</td>
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<td>Medical applications</td>
<td>• Artificial limbs</td>
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![Image of artificial limbs]
### Application | Components
--- | ---
Power system applications | - Power distribution and lighting  
- Repair, Retrofit and Rebars  
- Insulators  
- Transmission towers  
- Composite modular acoustic enclosure for diesel generator

Automobile industry | - Engine pistons  
- Cylindrical heads  
- Engine compressor  
- Engine blocks  
- Brake rotors  
- Calipers  
- Connecting rods  
- Drive shafts

#### 1.5 FUSION WELDING OF MMC’s

The most widely used fusion welding process is found to be ineffective for welding of metal matrix composites because of long lasting heats applied to the reinforcement and matrix metals. The fusion welding process tends to form compounds that are weak and brittle, due to the
reactions between the matrix metal and reinforcement particles. There are many complexities revolve around the weld joint quality that arise from the solidification phase due to huge differences of melting points of reinforcement particles and aluminium alloy matrix. All these are considered as significant hindrances in producing effective and efficient weld joints. Further, the application range of the composites becomes limited in established industrial processes and areas that are more relevant to conventional engineering materials.

There are fusion welding processes like Gas Metal Arc Welding (GMAW) and gas tungsten Arc Welding Process (GTAW) are effective in welding of some composite materials. However, the process parametric effects on the weld joint performance are limited and the same has to be chosen carefully in the above said processes. The weldment properties can be controlled and enhanced by altering the machine and system parameters. Complete analysis of the composite welds produced by the above processes aid in enhancing the mechanical and metallurgical properties of the weldments. It also helps in improving structural integrity and the secondary material properties like fatigue strength and stress corrosion resistance. Another major drawback associated with joining of metal matrix composites with other MMC’s or unreinforced metallic structures limits the use of fusion welding processes.

1.6 PROBLEMS ASSOCIATED WITH WELDING OF AMC’s

Aluminium based metal matrix composites are generally exhibits poor ductility property which may be affiliated to brittle intermetallic compounds, de-bonding or reactions between reinforcement and matrix phases, formation of particle segregations, presence of voids and pores, and poor wettability (Sukumaran et al. 2008, Yadav & Bauri 2011). Since now, many metallurgists and technologists find difficult in exposition the problems
of joining of aluminium and its alloys due to its complex nature of reactivity. It requires much skill to produce good Al bonds using conventional welding techniques (Aydin et al. 2010). Fusion welding processes possess with the following challenges and making it difficult to be deployed for welding of aluminium metal matrix composites.

- Excessive heats and incompatible filler materials
- Formation of voids and pores
- Formation of eutectic phases
- Deleterious compounds formation
- Oxides formation

To elude the above stated problems, solid state welding techniques are opted for welding AMC’s. In solid state welding process, joining takes place at the temperatures below melting points of the reinforcement and matrix metals. Friction stir welding is well established process for joining of materials at low temperatures. By considering its advantages over other solid state welding techniques, it is adopted for welding AMC’s. Friction stir welding was invented at The Welding Institute (UK) in Thomas et al. (1991). Since that time, it has been introduced into commercial practice in a number of applications. Although aluminium alloys may be joined using conventional fusion welding techniques, Joining of aluminium alloys for industrial applications with fusion welding processes has the major disadvantage of intermetallic layers formation which makes weldment crack sensitive.

So, solid state welding process like Friction Stir Welding (FSW) welding which makes welding of aluminium alloys ease and gives exceptionally better results only if the welding process is controlled from external factors. The strength of weldment is directly depends on the
generated temperature during welding. Other than temperature, factors like lack of penetration and fusion, width of Heat Affected Zone (HAZ) and residual stresses created during the solidification and phase transformation also plays an important role in defining weldment strength. The schematic of construction and working of friction stir welding is shown in Figure 1.4.

Figure 1.4  Schematic of basic friction stir welding (Minak et al. 2010)

The reinforcement particulates clearly affect the welding process in many aspects: reducing plasticity with respect to the pure alloys, leading to a narrower range of the welding parameters; inducing severe wear of the tool and also complicating the microstructural modifications in the welded zone (Minak et al. 2010). Several recent studies have been made on friction stir welding of metal matrix composites consists of base metals like aluminium, silicon and titanium with different reinforcement composites such as SiC, B₄C, Al₂O₃ (Marzoli et al. 2002, Nakata et al. 2003, Wert 2003, Fernandez & Murr 2004).
During FSW of metal matrix composites, the reinforcement particles undergo severe plastic deformation in the base material and leads to reduction in plasticity behaviour. Further, problems like deteriorating of wear behaviour of tool and non uniformity of the microstructures in the welded zone.

1.7 NEED FOR THIS RESEARCH

The applications of MMC’s are confined to sophisticated industries due to the lack of investigation reports associated with their forming and joining. Except for GMAW and GTAW process, other fusion welding techniques for joining MMC’s are found to be ineffective and it is very difficult to form defect free weldments. In fusion welding process, the weldments are more susceptible to deleterious reactions between matrix metal and reinforcement particles along with non homogenous distribution of reinforcement particles during solidification. These implications limit the join-ability of metal matrix composites.

This paves way for adopting solid state welding techniques, particularly FSW process as an alternative to overcome the challenges posed during joining. The joint quality is mainly dependent on the machine and system process parameters: welding speed, rotational speed, axial force etc (Mahoney et al. 1964, Sarsilmaz & Caydas 2009).

The process parametric effect on the material flow, plasticity, and mechanical and metallurgical aspects requires a detailed investigation. This may be pertaining to theoretical and experimental investigations aided by empirical and simulation analysis.
1.8 OBJECTIVES

- Understanding the physical and chemical properties of AlB$_2$, TiB$_2$, and SiC reinforced AA6061 metal matrix composites
- Reviewing literature reports regarding joining techniques of Al based composites
- Investigations on challenges and problems faced by the fusion welding of Al based composites.
- Fabrication and friction stir welding of AA6061/AlB$_2$, AA6061/TiB$_2$, and AA6061/SiC composites.
- Friction stir welding machine process parametric investigations
- Effects of FSW process parameters on mechanical and metallurgical properties
- Developing the relationship between the FSW process parameters and weld joints strengths
- Finite element modelling of temperature distribution and residual stresses acting on the work specimens during friction stir welding
- Optimization of process parameters to produce effective and efficient weldments
- Practical implementation of produced weldments to the industrial purposes
1.9 OVERVIEW OF THE THESIS

Chapter 1 Introduction provides an insight into principles of friction stir welding, aluminium based metal matrix composites.

Chapter 2 Literature review briefs the reports regarding friction stir welding of AMC’s and problems associated with the traditional welding techniques.

Chapter 3 Materials and experimental methods for composite fabrication, FSW tool design, and equipments parameters.

Chapter 4 Investigations on effects of FSW process parameters on mechanical and metallurgical properties of AA6061/AlB$_2$ composite plates.

Chapter 5 Investigations on effects of FSW process parameters on mechanical and metallurgical properties of AA6061/TiB$_2$ composite plates.

Chapter 6 Investigations on effects of FSW process parameters on mechanical and metallurgical properties of AA6061/SiC composite plates.

Chapter 7 Finite element analysis simulated the temperature distribution profile and residual stresses in the weld region.

Chapter 8 Conclusions and future scope of work the major inferences drawn from this study and scope of future work.

1.10 WORKK FLOW SEQUENCE

Figure 1.5 shows the flow chart of work scheme adopted for this research study.
Figure 1.5 Work sequence flowchart