CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

Aluminium based composites reinforced with hard ceramic particles have created considerable interest because they can be easily processed and can have isotropic properties in comparison to fibre-reinforced composites. In addition, these composites exhibit high strength and stiffness, creep resistance and superior wear resistance apart from providing good electrical and thermal conductivity.

The friction stir welding process, a novel solid state joining technique is being successfully employed in joining of Aluminium alloys and Aluminium metal matrix composites. Research efforts in developing commercially viable FSW techniques are gathering momentum. Investigations in FSW include:

1. Understanding of the FSW process and its parameters
2. Prediction of required results and inference
3. Theoretical and numerical studies that are based on mathematical equations governing the fundamental physical phenomenon such as adiabatic heat generation due to stir, material flow due to plastic deformation, heat transfer etc,
4. Experimental studies for validation of results of theoretical and numerical studies.
This chapter presents details of literature survey carried out on the fabrication of Al – MMCs which includes the methods of manufacture of the MMC employed by different researchers, the parameters selected and their influence on the formation of different phases of the composite. The various works carried out in the FSW process development with a focus on its application for Al – MMCs are also provided. Studies on the selection of FSW parameters and their influence on the mechanical and metallurgical properties of the welds are presented. Past research on the effect of FSW tool in the production of quality welds is also summarized. Literature on the technique of Design of Experiments (DOE) and its application to the friction stir welding process is included. Literature on the Finite element analysis of the FSW process is also presented.

2.2 FABRICATION OF METAL MATRIX COMPOSITES (MMCs)

Aluminium matrix composites (AMCs) refer to the class of light weight high performance aluminium centric material systems. The reinforcement in AMCs could be fibres, whiskers or particulates. By selection of appropriate conditions of matrix, reinforcement and process procedure, desired properties can be imparted to AMCs for specific applications. Present day manufacturers follow different routes for manufacturing several grades of AMCs. Depending on the type of reinforcement AMCs can be classified into the following four types:

i. Particle reinforced
ii. Whisker or short – fibre reinforced
iii. Continuous or long fibre reinforced
iv. Mono filament reinforced

Although the concept of MMCs was introduced about three decades ago, full-fledged engineering application of this class of materials is yet to take place, the major reason being the problems associated with their processing. With
conventional casting techniques for metals, it is difficult to control the microstructure and the metal-ceramic interface, both of which are essential for achieving better mechanical properties, during processing. Even though during 80s a lot of research effort was put into the production of metal matrix composites a satisfactory production method did not emerge. The properties of the composites were either only marginally better or even worse than that of the un-reinforced metal or the processing costs became unacceptably high. Thus, after about two decades of constant development of traditional metal processing methods it became clear that if MMCs were ever to be produced in an economically acceptable way, new and innovative production methods, dedicated for metal matrix composite materials, were needed. The MMCs produced by these new methods have been defined as second generation MMCs.

The MMCs reinforced with ceramic particles are currently fabricated using different established methods and some specific patented methods. The principles of fabricating the MMCs using traditional methods are briefed in this section. The traditional methods are powder metallurgy, mechanical alloying, stir casting, squeeze casting, compo casting and spray deposition. The processing method influences the mechanical behaviour of the MMCs (Kennedy & Wyatt 2000). The successful incorporation of ceramic particles into the matrix alloy and achieving good bonding between them will help to enhance the properties. All processing methods are grouped into two categories which are namely solid state processing and liquid state processing. This grouping is based on the processing temperature which is above (liquid state) or below (solid state) the melting point of the matrix material. The processing temperature of all processes is well below the melting point of ceramic particles. Each process has a limitation to produce MMCs with certain combinations of matrix alloy and ceramic particles. Therefore lot of research emphasis is given to develop the processing methods to fabricate new kind of MMCs whose behaviour may be superior to the existing MMCs.
2.2.1 Fabrication of MMCs

Large scale primary processing for manufacturing of AMCs can be grouped into two main classifications viz., solid state processing and liquid state processing. Solid state processing includes powder grinding followed by consolidation, diffusion bonding and vapour deposition techniques. Stir casting, infiltration, spray casting and reactive in-situ processing methods fall under liquid state processing.

2.2.1.1 Solid State Processing

2.2.1.1.1 Powder Metallurgy Processing

Powder Metallurgy involves the blending of rapidly solidified powders with particulates, platelets or whiskers, through a series of steps. The sequence of steps include sieving of rapidly solidified particles, blending of the particles with the reinforcement phases, compressing the reinforcement and the matrix mixture to about 75% density, degassing and final consolidation by extrusion, forging, (Brown et al 1990) rolling or any other hot working method. Blending of metallic powder with ceramic fibres or particulate for MMC production is usually followed by cold compaction, canning, evacuation, degassing and a high temperature consolidation process. Achieving a homogeneous mixture can be difficult, particularly with fibres. Generally, in Al MMCs manufactured through powder route, fine plate-like oxide particles are present. Such particles, a few tens of nm thick, constitute about 0.05 - 0.5 volume %, depending on powder history and processing conditions. This fine oxide tends to act as a dispersion strengthening agent and often has a strong influence on the matrix properties, particularly at high temperature.

MMCs produced by powder blending are commonly extruded. This can generate alignment of fibre parallel to the extrusion axis, but often at the expense of
progressive fibre fragmentation. The degree of fibre fracture decreases with increasing temperature and decreasing local strain rate. Extrusion of consolidated MMCs, such as castings, can reduce the level of clustering and inhomogenities in the material.

In a study by Salvador et al (2003), a series of Al6061 aluminium matrix composites with 5, 10 and 15 weight percentage of TiB₂ particles were manufactured through the powder metallurgy route followed by hot extrusion. No evidence of reaction products was observed in samples heated up to 500°C during heat treatment. Second intermetallic phases of Ti₃(Al, Si) were found at the reinforcement / matrix interfaces. A major improvement of mechanical behaviour was observed in composites reinforced with 10% TiB₂ due to a better distribution of the reinforcement phase in the matrix. It was noted that at high temperatures (300°C) the presence of reinforcement particles resulted in very low tensile strength i.e., as low as 120 MPa with presence of 5% particulate.

2.2.1.1.2 Diffusion Bonding

Mono filament-reinforced AMCs are mainly produced by the diffusion bonding (foil-fibre-foil) route or by the evaporation of relatively thick layers of aluminium on the surface of the fibre. 6061 Al-boron fibre composites have been produced by diffusion bonding via the foil-fibre-foil process. However, the process is more commonly used to produce Ti based fibre reinforced composites (Surappa 2003).

2.2.1.1.3 Physical Vapour Deposition

The physical vapour deposition process involves continuous passage of fibre through a region of high partial pressure of the metal to be deposited, where condensation takes place so as to produce a relatively thick coating on the fibre. The
vapour is produced by directing a high power electron beam onto the end of a solid bar feed stock. Typical deposition rates are $5 - 10 \ \mu m$ per minute. Composite fabrication is usually completed by assembling the coated fibres into a bundle or array and consolidation in a hot press operation.

2.2.1.2 Liquid State Processing

In liquid state processing of composite materials, three procedures are mainly used:

- Compo-casting or melt stirring
- Gas pressure infiltration
- Squeeze casting or pressure casting.

2.2.1.2.1 Compo-Casting or Melt Stirring

Both the terms compo-casting and melt stirring are used for stirring particles into a light alloy melt. Figure 2.1 shows the schematic operational sequence of this procedure. The particles often tend to form agglomerates, which can be only dissolved by intense stirring. Careful attention must be paid to the dispersion of the reinforcement components, so that the reactivity of the components used is coordinated with the temperature of the melt and the duration of stirring, since reactions with the melt can lead to the dissolution of the reinforcement components.

Because of the lower surface to volume ratio of spherical particles, reactivity is usually less critical with stirred particle reinforcement than with fibres. The melt can be cast directly or processed with alternative procedures such as squeeze casting or thixocasting. Melt stirring was used by the Duralcan Company for the production of particle strengthened aluminium alloys (San Diego 1992). At the Lanxide Company a similar process was used, with additional reactions between the
reinforcement components and the molten matrix being purposefully made to occur to obtain a qualitatively high-grade composite material (Newark 1995).

![Figure 2.1 Schematic Operational Sequence during Melt Stirring (San Diego 1992)](image)

2.2.1.2.2 Gas Pressure Infiltration Process

In gas pressure infiltration, the melt infiltrates the pre-form with an inert gas applied from the outside. The melting of the matrix and the infiltration take place in a suitable pressure vessel. There are two procedure variants of gas pressure infiltration: in the first variant, the warmed up preform is dipped into the melt and then the gas pressure is applied to the surface of the melt, leading to infiltration. The infiltration pressure can, thereby, be coordinated with the wettability of the pre-forms, which depends, among other things, on the volume percentage of the reinforcement. The second variant of the gas pressure infiltration procedure reverses the order: the molten bath is pressed to the pre-form by the applied gas pressure using a standpipe and thereupon infiltrates the bath as shown in Figure 2.2.
The advantage of this procedure is that there is no development of pores when completely dense parts are present. Since the reaction time is relatively shorter with these procedures, more reactive materials can be used than those in the case of compo-casting technique. In gas pressure infiltration, the response times are clearly longer than those in squeeze casting, so that the materials must be carefully selected and coordinated, in order to produce the desired composite material for any specific application.

2.2.1.2.3 Squeeze Casting or Pressure Casting

Squeeze casting or pressure casting is the most common manufacturing method for MMCs. After a slow mould filling the melt solidifies under very high pressure, leading to a fine-grained structure. In comparison with die-casted parts, the squeeze-casted parts do not contain gas inclusions, which permit thermal treatment of the produced parts. Figure 2.3 helps in differentiating between direct
and indirect squeeze casting. With direct squeeze casting, the pressure for the infiltration of the prefabricated preforms is applied directly to the melt. The die is, thereby, part of the mould.

The disadvantage with the direct procedure is that the volume of the melt must be determined exactly, since no gate is present and thus the quantity of the melt determines the size of the cast construction unit. The appearance of oxidation products, formed in the cast part during dosage is another disadvantage of the process. Whereas, in indirect squeeze casting, where the melt is pressed into the form via a gate system, the residues will remain in this gate. The flow rate of the melt through a gate is, due to its larger diameter, substantially less than that in the case of die casting.

Of all, vortex or stir casting technique is the simplest and commercially successful one. The vortex technique involves the introduction of pre-treated ceramic particles into the vortex of molten alloy created by the rotating impeller. Microstructural non-homogeneities can result in particle agglomeration and sedimentation during melting as well as solidification. Vortex mixing technique for

Figure 2.3 Squeeze Casting Process: (a) Direct and (b) Indirect (San Diego 1992)
the preparation of ceramic particles dispersed aluminium matrix composites was originally developed by Surappa & Rohatgi (1981) at the Indian Institute of Science (Surappa 2003 and Lloyd 1999). Subsequently several aluminium companies further refined and modified the process which is currently employed to manufacture a variety of AMCs on commercial scale.

2.2.1.2.4 Spray Deposition

Spray deposition techniques fall into two distinct classes, depending on whether the droplet stream is produced from a molten bath (or spray) or by continuous feeding of cold metal into a zone of rapid heat injection (thermal spray process). The process has been extensively explored for the production of AMCs by injecting ceramic particle/whisker/short fibre into the spray. AMCs produced in this way often exhibit inhomogeneous distribution of ceramic particles. Depositions of this type are typically consolidated to full density by subsequent pressing. AMCs produced by spray deposition technique are relatively inexpensive with costs that are usually intermediate between stir cast and powder metallurgy processes.

2.2.1.2.5 In-situ Processing (Reactive Processing)

There are a number of processes falling under this category. They include liquid-gas, liquid-solid, liquid-liquid and mixed salt reactions. In these processes, refractory reinforcements are created in the aluminium alloy matrix. Exothermic dispersion process is a popular in-situ technique for composite processing. This process is used to produce TiB₂ reinforced aluminium matrix composites. London and Scandinavian Metallurgical Company has developed an in-situ technique, which utilizes reaction between mixed salts to produce a dispersion of the fine TiB₂ particles in an aluminium matrix (Davies et al 1992). The same technique has been employed in this research work also for the manufacturing of Al-TiB₂ composite.
For preparing metal matrix composites, ‘in-situ’ processing offers significant advantage over the conventional processing from both technical and economical stand points (Tjong & Ma 1997). The technique of salt-metal reaction is an attractive ‘in-situ’ approach developed typically for preparing Al-TiB₂ MMCs.

The TiB₂ particles, in-situ formed in the matrix of pure Al, could be very small in size, as small as 1 µm (Feng & Froyen 2000). They generally stick together appearing as strings or clusters of particle agglomerates, leading to an inhomogeneous distribution. In order to obtain a useful composite with good properties, one has to achieve less agglomeration and more uniform distribution of the TiB₂ particles.

Feng & Froyen (2000) studied the influences of processing parameters on the kinetics of TiB₂ formation as well as on the microstructure of the composite products. Strings as well as clusters of particulate agglomerates were identified to be the distinct microstructural features of the composites manufactured. Commercial pure Al blocks (99.5%) were used by them as base metal and K₂TiF₆ and KBF₄ as the salt powders.

Yousef (2005a) measured the latent heat evolved during solidification of commercial-purity Al (99.7%) based MMC reinforced with TiB₂ particulate (9.3 wt %). Latent heat values measured by differential scanning calorimetry for all the in-situ formed Al-TiB₂ composites were found to be up to 10% less than those predicted using the rule of mixtures between pure TiB₂ particles and matrix. They concluded that the substitution of Al for Ti in TiB₂ particles was the cause for such a difference. This particular study is of considerable significance because, solidification modelling, which can be used to optimize the manufacture of composites via the casting route, is facilitated by the accurate measurement of the physical properties. One of the important properties required is latent heat (Lee et al 1991).
The reaction kinetics between the ‘Ti’ containing $\text{K}_2\text{TiF}_6$ and ‘B’ containing $\text{KBF}_4$, which were chiefly used in the in-situ manufacture of Al-TiB$_2$ composites, were analyzed by Nahed et al (1999). Addition of the two salts separately, consecutively and simultaneously was made at 800 and 1000$^\circ$ C. Their investigation revealed that when adding $\text{K}_2\text{TiF}_6$, emulsification of the salt occurred. No evidence of emulsification of $\text{KBF}_4$ was found, leading to the conclusion that the two salts reacted individually with Al.

The behaviour of TiB$_2$ particles in molten Aluminium was investigated by Yousef et al (2005b) by conducting casting experiments at different cooling rates and particle addition levels, starting with a master alloy containing in-situ formed TiB$_2$ particles. They also studied the particle pushing/engulfment phenomenon and particle clustering effects for two matrix alloy systems viz., commercial purity aluminium and an Al-4% Mg (A514) alloy. The relevance of this work to MMCs lies in the following:

When a molten metal or other liquid phase containing dispersed second phase particles solidifies, interactions take place between the advancing solidification front and the particles. These interactions result in changes in the front morphology as well as distribution of the particles. The particles are either pushed or engulfed by the solidification front. Consequently, they are found at the grain boundaries, or the interdendritic regions, or they are found within the primary grains. This phenomenon is relevant to many solidification processes including solidification of particle metal matrix composites (PMMCs) (Morteson & Jin 1992).

Yue et al (1999) established a thermodynamics model describing the formation of in-situ TiB$_2$ reinforced metal matrix composite. Based on thermodynamics principles they evaluated the Gibbs free energies of formation of TiB$_2$, AlB$_2$ and Al$_3$Ti followed by experimental investigations to verify the validity
of thermodynamics model. Again, KBF₄ and K₂TiF₆ were used to synthesize in-situ particulates in molten Al at different temperatures.

The clustering of reinforcement particles in cast metal matrix composite material has a number of deleterious effects on its mechanical properties and castability. This necessitates studies on the clustering behaviour and such a study on clustering behaviour of TiB₂ in molten commercial purity aluminium was carried out by Watson et al (2005). They developed a novel method of sampling in order to investigate the clustering behaviour as a function of holding time at 700°C. They also found that the initially clustered distribution of TiB₂ became increasingly dispersed with increased holding time. It was suggested that the cause of clustering was that Al₃Ti present on the particle surfaces acted as a glue between adjacent particles. Many Researchers studied the phenomenon of agglomeration. Agglomeration of the reinforcement phase was shown to have deleterious effects on tensile strength, flow stress (Kennedy & Wyatt 2000, Hong et al 2003 and Conlon & Wilkinson 2001), ductility (Kennedy & Wyatt 2000 and Murphy et al 1998) and fatigue performance (Llorca 2002).

2.3 FRICTION STIR WELDING

2.3.1 Fundamentals of Friction Stir Welding

In FSW, two discrete metal work pieces are butted together, along with the tool (with a probe), as shown schematically in Figure 2.4. During the friction stir welding process, the cylindrical-shouldered tool, with a specially profiled probe (nib or pin) is rotated at a constant speed and fed at a constant traverse rate into the joint line between two pieces to be welded as seen in Figure 2.5.
The parts have to be clamped rigidly onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. The length of the probe is slightly less than the weld depth required and the tool shoulder should be in intimate contact with the work surface. The nib is then moved against the work, or vice versa. Frictional heat is generated between the wear-resistant welding tool shoulder and nib, and the material of the work pieces. This heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without reaching the melting point, allowing the traversing of the tool along the weld line. As the FSW tool is moved in the direction of welding, the leading face of the tool forces plasticised material to
the back of the tool while applying a substantial forging force to consolidate the weld metal. The joining of the material is facilitated by severe plastic deformation in the solid state, involving dynamic recrystallization of the base material.

The solid-state nature of the FSW process usually results in the different zones in the weld/adjoining areas as shown in Figure 2.6. The composite used in this particular study was as-forged AA2124/SiC/25p (Uzun 2007).

Figure 2.6 Different Zones in FSW Weldment (Uzun 2007)

- The stir zone (also called nugget & dynamically recrystallized zone): A unique feature of the stir zone is the common occurrence of several concentric rings which has been referred to as an ‘onion-ring’ structure.
- The Thermo-Mechanically Affected Zone (TMAZ) occurs on either side of the stir zone. In this region, the strain and temperature are lower and the effect of welding on the microstructure is correspondingly smaller.
- The Heat-Affected Zone (HAZ), which is subjected to a thermal cycle but is not deformed during welding.

2.3.2 Important FSW Parameters

Tool rotational speed, tool traverse speed (also termed as welding speed), tool material, tool tilting angle, axial downward force etc., are some of the
parameters that have considerable importance and must be chosen with care while carrying out the friction stir welding process. The relationship between the welding speeds and the heat input during welding is complex but, in general, it can be said that increasing the rotational speed or decreasing the traverse speed will result in a hotter weld. In order to produce a successful weld, it is necessary that the material surrounding the tool is hot enough to enable the extensive plastic flow required. On the other hand, excessively high heat input may be detrimental to the final properties of the weld.

2.3.3 Tooling for the FSW Process

The design of the tool and the tool material are critical factors as a good tool can improve both the quality of the weld and productivity. In general, it is desirable to increase the travel speed and minimize the heat input.

It is desirable that the tool material is sufficiently strong, tough and wear-resistant, especially at elevated welding temperatures. Further, it should have a good oxidation resistance and a low thermal conductivity to minimise heat losses. Hot-worked tool steel such as AISI H13 has proven perfectly acceptable for welding aluminium alloys within thickness ranges of 0.5-50 mm (Tjong et al 1997), but more advanced tool materials are necessary for more demanding applications such as joining highly abrasive metal matrix composites (Feng & Froyen 2000) or higher melting point materials such as steel or titanium.

For welding speeds above 6 mm/s, the tool wear in the friction-stir welding of Al359+20% SiC MMC produced a self-optimized shape which when achieved resulted in excellent welds without any additional tool wear. Tool wear rate was observed to decrease linearly and to effectively cease at welding speeds above 11 mm/s. The weld nugget was characterized by the onion-ring flow patterns. The homogeneous distribution of SiC particles in the work piece was essentially
preserved in the weld nugget. There was no weld-related degradation and the weld nugget hardness was 30% higher than that of the base metal (Shindo et al. 2002).

The influence of different parameters such as axial pressure, rotational speed, and traverse speed on the weld properties has been evaluated earlier but there are some important parameters yet to be thoroughly investigated. In a study by Abbasi et al. (2006), an effort was made to determine the influence of different ratios of rotational speed to traverse speed on mechanical properties of different zones of friction stir welded AZ31 magnesium alloy. Mechanical properties of different zones were determined by a shear punch test. It was found out that increasing the aforementioned ratio led to a slight decrease in yield and ultimate strength of the stir zone and the thermo mechanically affected zone. It was also observed that increasing the ratio of rotational/traverse speed increased the weld nugget size and decreased the incomplete root penetration.

Fernandez & Murr (2004) reported that the tool wear for threaded steel pin tools declined with decreasing rotational speed and increasing traverse or welding speed in the friction stir welding of Al359 + 20% SiC metal-matrix composite (MMC). Less than 10% tool wear occurred when the threaded tool eroded to a self-optimized shape resembling a pseudo-hour glass at weld traverse distances in excess of 3 m. The weld nugget became more homogeneous for efficient welding with optimized parameters, and there was a reduction in the weld nugget grain size due to dynamic recrystallization which actually facilitated the solid-state flow.

Boz & Kurt (2004) investigated the effect of tool pin profile design on the properties of FS welded Al 1080 alloy. Five different tool pin profiles, one with square pin profile and other tools having cylindrical threaded pin profile having pitch of 0.85, 1.10, 1.40 and 2.1 mm were used. The specimen welded using cylindrical threaded pin profile having pitch of 0.85 mm and 1.10 mm exhibited identical mechanical and metallographic properties. Microscopic examination of the
weld nugget and the tension test results showed that the best bonding was obtained with cylindrical threaded pin profile having a pitch of 0.85 mm.

Scialpi et al (2007) studied the effect of different shoulder geometries on the mechanical and microstructural properties of 1.5 mm thick friction stir welded 6082 T6 aluminium alloy joints. The effect of the three shoulder geometries viz., scroll and fillet, cavity and fillet, and only fillet was analysed by visual inspection, macrograph, HV microhardness, bending test and transverse and longitudinal room temperature tensile test. The investigation results showed that, for thin sheets, better weldment was achieved by a shoulder with fillet and cavity with a welding speed of 460 mm/min and tool rotational speed of 1810 rpm.

Padmanaban & Balasubramanian (2009) made an attempt to select proper tool pin profile, tool shoulder diameter and tool material for FSW of AZ31B magnesium alloy. Five tool pin profiles, five tool materials and three tool shoulder diameters were used to fabricate the FSW tools. It was found that the joint fabricated using threaded pin profiled tool made of high carbon steel with 18 mm shoulder diameter produced mechanically sound and metallurgically defect-free welds compared to their counterparts.

Yu Zhang et al (2008a) applied FSW to commercial purity titanium alloy using a polycrystalline cubic boron nitride tool and reported that the stir zone consisted of fine equiaxed α grains surrounded by serrate grain boundaries, which were produced through the β → α allotropic transformation during the cooling cycle of FSW. The fine α grains caused higher hardness than that in the base material. A lath shaped α grain structure having highest hardness containing Ti borides and tool debris was observed in the surface region of the stir zone.

Badarinarayan et al (2009) performed friction stir spot welding on 5083 Al alloy using tools with a conventional cylindrical pin and the proposed triangular
pin. The tool-pin geometry affected the hook shaped appearance of the weld. Under the same process condition, welds made with the cylindrical pin had a continuous hook which bypassed the stir zone pointing downward towards the weld bottom. By contrast, for welds made with the triangular pin, the hook was directed upwards and then arrested at the periphery of the stir zone. Static strength of welds made with the triangular pin was twice that of welds made with the cylindrical pin, which was attributed to the finer grain size as well as tensile failure mode as a result of the arrested hook.

Ouyang et al (2002) observed that the axial force was directly responsible for the plunge depth of the tool pin into the work piece and with higher axial force, sound welds with full penetration were obtained.

2.3.4 Advantages and Disadvantages of FSW

A significant benefit of FSW is that it has fewer process parameters to control. In a fusion weld, depending upon the type of welding process, there are many process parameters that must be controlled such as purging gas, voltage, amperage, wire feed rate, travel speed, shielding gas, arc length, etc. However, in FSW some of the process variables such as tool rotational speed, tool travel speed, axial downward force etc., are easily controllable. The weld quality is excellent, with none of the porosity that can arise in fusion welding, and the mechanical properties are at least as good as the best achievable by fusion welding. The process is environment-friendly as no fume or spatter is generated.

Another major advantage is that, by avoiding the creation of a molten pool which shrinks significantly on resolidification, the distortion and the residual stresses are found to be low. With regard to joint fit up, the process can accommodate a gap of up to 10% of the material thickness without impairing the quality of the resulting aluminium welds. As far as the rate of processing is
concerned, again in the case of 2 mm thick aluminium sheets, welding speeds of up to 2 m/min can be achieved, and for 5 mm thickness, up to 0.75 m/min (Johnson et al 1999). Recent tool developments are confidently expected to improve on these figures.

However, the FSW process does suffer from some disadvantages too as mentioned below:

- Heavy downward forces required necessitating special clamping devices to hold the plates together.
- Less flexible than manual and arc processes, especially when the thickness varies.
- Slower welding speeds compared with some fusion welding techniques.

2.3.5 Effects of FSW Parameters on Weld Quality

The material flow behaviour in the weld nugget is predominantly influenced by the tool profiles, tool dimensions and FSW process parameters such as tool rotational speed, tool traverse speed, axial force and weight % of reinforcement particles in the aluminium matrix (Yingchun et al 2006, Gopalakrishnan & Murugan 2011, Elangovan et al 2008, Shanmugasundaram & Murugan 2010). Since FSW is a solid state process, it is best suited for welding aluminium and Aluminium Matrix Composites (AMCs). The application of Al-TiB$_2$ MMCs in the industries will be limited if there are no procedures for processing them such as machining, forming or welding (Ceschini et al 2007a). Selection of proper tool and process parameter becomes essential to achieve defect free welds.

The effects of various tool pin profiles and process parameters on tensile strength and wear resistant properties of various aluminium alloys and aluminium matrix composites were already reported but for the Al-TiB$_2$ MMCs, the findings are hitherto not reported (Chen et al 2009, Fernandez et al 2004, Wert et al 2003,
Lakshminarayanan et al (2009) studied the effect of welding processes such as GTAW, GMAW and FSW on mechanical properties of Al6061 aluminium alloy. In such an alloy, the weld fusion zones typically exhibit coarse columnar grains because of the prevailing thermal conditions during weld metal solidification. This often causes inferior weld mechanical properties and poor resistance to hot cracking. They found that FSW joints of Al6061 aluminium alloy showed superior mechanical properties compared with GTAW and GMAW joints, and that was mainly due to the formation of very fine, equiaxed microstructure in the weld nugget.

Schneider (2009) produced FS Welded panels with varying degrees of known defects. Spatial analysis of data acquired at high sampling rates was analyzed in the time and frequency domain. This allowed data characteristics to be correlated with the resulting tensile properties along the length of the weld seam.

The effects of tool rotational speed and welding speed on the microstructure and tensile properties of AZ31B-H24 magnesium (Mg) alloy were evaluated by Afrin et al (2008). The grain size was observed to increase after FSW, resulting in a drop of microhardness across the weld region from about 70 HV in the base metal to about 50 HV at the center of the stir zone. The welding speed had a significant effect on the microstructure, resulting larger grains at a lower welding speed. The yield strength and ultimate tensile strength were increased with increasing welding speed due to a lower heat input.
In FSW, the base metal properties such as yield strength, ductility and hardness control the plastic flow of the material under the action of rotating non-consumable tool. The FSW process parameters such as tool rotational speed, welding speed, axial force, etc. play a major role in deciding the weld quality. In an investigation, Balasubramanian (2008) made an attempt to establish a relationship between the properties of Al alloys and FSW process parameters. Empirical relationships established between base metal properties and tool rotational speed and welding speed could be effectively used to predict the FSW process parameters to fabricate defect free welds.

The effect of FSW parameters on the mechanical properties of dissimilar AA6082–AA2024 joints was analyzed by Cavaliere et al (2009a). In this study, it was observed that the best tensile properties were obtained for the joints with the AA6082 on the advancing side and welded with a traverse speed of 115 mm/min.

Electromagnetic radiation (EMR) is emitted during the transient stage of elastic to plastic deformation of metals and alloys. In the research work carried out by Muthukumaran et al (2008a), the variation in EMR fundamental frequencies emitted during the tensile failure of the FS welds was analyzed by fuzzy modelling using MATLAB and it was observed that an increase in the first mode of metal transfer decreased the fundamental frequency. This work will be more useful for metal flow analysis as well as online condition monitoring of the welds which are used in critical applications.

Yu Zhang et al (2008b) applied FSW to join 3 mm thick Ti–6Al–4V plates under different rotational speeds and successfully produced defect-free welds at rotational speeds of 400 and 500 rpm. The base material (BM) had a deformed α/β lamellar microstructure. FSW produced a full lamellar structure with refined prior grains in the stir zone (SZ) having higher hardness than BM, while the HAZ contained a bimodal microstructure consisting of the equiaxed primary α and α/β
lamellar structure within the prior β structure having lowest hardness. An increase in rotational speed, the study noted, increased the sizes of α colonies and prior β grains.

Muthukumaran et al (2008b) analyzed the metal flow during FSW using a cylindrical tool and found that the movement of the tool transferred the metal from the front side to the rear side layer by layer. The layered metal flow phenomenon was proposed due to stick and slip conditions. The two modes of metal transfer as well as the formation of onion rings in friction stir welds were explained which could be used to model the FSW process for improving tool and fixture design.

Staron et al (2004) investigated the influence of a coolant applied during welding of Al sheets on the residual stress state of the FSW joint. Liquid CO$_2$ coolant was applied near the weld seam for rapid cooling of the weld nugget. It was reported that by applying a coolant, the magnitude of the tensile residual stress in the center of the weld could be reduced significantly.

The role of longitudinal residual stress on propagation of fatigue cracks was examined by Fratini et al (2009) in friction stir welds produced in 2024-T351 aluminium alloy. It was found that residual stresses were responsible for low crack growth rates outside the weld nugget during fatigue loading.

Chen et al (2009a) successfully joined Al–Si (ADC 12) alloy with pure titanium by using FSW process and reported that the maximum failure load of joints was found to be 62% of Al–Si alloy base metal and the location of the failure was at the interface. X-ray diffraction results showed that new phase of TiAl$_3$ formed at the interface by Al–Ti diffusion reaction which was found to be strongly dependant on welding speeds affecting the mechanical properties of joints.
Lombard et al (2009) investigated the effect of FSW parameters on the residual stress profiles determined non-destructively using synchrotron X-ray diffraction in friction stir welds of aluminium alloy AA5083-H321. The width and maximum of the residual stress profile showed clear linear correlation with the heat input, and in particular welding speed.

Cavaliere (2009b) applied thermoelastic stress analysis (TSA) to study crack propagation characteristics of friction stir welded aluminium sheets. The study evaluated the effects of joint-defect, as a function of welding parameters, correlating effects on crack growth rate and instabilities.

Abnormally low ductility has often been reported for the friction-stir-welded dissimilar metals. The mechanism(s) for such a low tensile ductility has, however, not been established. In a study, Lim et al (2004) investigated the tensile behaviour of friction stir welded A356-T6/Al 6061-T651 bi-alloy plate to understand the underlying mechanism for the reduced tensile ductility. It was demonstrated that the tensile ductility was substantially lower than that of the weighted mean value of the uni-alloy counterparts, including A356-T6 and Al 6061-T651 alloys. It was observed in the study that the tensile fracture occurred in the weld nugget of A356-T6.

2.3.6 FSW of Aluminium Metal Matrix Composites

Metal matrix composites are light-weight and have good stiffness and strength-to-weight ratio perfectly suited for aerospace and other modern industrial applications. However, MMCs are difficult to join by traditional fusion welding processes due to welding defects and poor joint strength.

Minak (2009) reported that FSW of as-cast particulate reinforced aluminium based composite viz., Al6061/22 vol. % Al2O3p, reduced the size of both particle
reinforcement and aluminium grains and also led to a significant increase in interparticle matrix microhardness.

The mechanical and microstructural properties of 6061 – T6 + 20% Al₂O₃ₚ and 7005 + 10% Al₂O₃ₚ aluminium based metal matrix composites joined by FSW were analyzed by Cavaliere et al (2004). It was reported that different composite structures were found in the ‘onion ring’ and TMAZ of the joints compared to the parent materials and also good mechanical properties with respect to the parent materials.

Pirondi & Collini (2009) analyzed fatigue crack propagation resistance of FSW welded Al₂O₃ particulate metal-matrix composites butt joints. It was shown that the welding process affected fracture toughness and fatigue crack growth rate differently depending on the material.

Cavaliere et al (2008) investigated the metal matrix composite 7005 aluminium alloy reinforced with 10% of alumina particles friction stir welded by employing a tool rotational speed of 600 rpm and a welding speed of 250 mm/min. A fatigue life of $2 \times 10^7$ cycles was recorded at stress amplitude of 120 MPa.

Marzoli et al (2006) established a FSW process parameters envelope for an Al6061 alloy reinforced with 20% of Al₂O₃ particles. Joint efficiencies of over 80% for the yield strength and of slightly more than 70% for the ultimate tensile strength were reported with failure outside the stir zone. The parameter envelope determined in the study resulted in defect free and high strength welds.

Dinaharan & Murugan (2012), Kalaiselvan & Murugan (2013), Ashok Kumar & Murugan (2014) have also reported their work on FSW of metal matrix composites. They have carried out work on effect of FSW process parameters on
mechanical and metallurgical properties of FS welded metal matrix composites such as Al-ZrB$_2$, Al-B$_4$C and Al-AlN respectively.

2.3.7 Mechanical Characterization of Friction Stir Welds

FSW process leads to significant changes in the mechanical properties in the weldment when compared with those of the parent material.

Al 6013 was friction-stir welded by Heinz (2002) in T4 and T6 conditions and the mechanical properties were studied after welding and applying a post weld heat treatment (PWHT) to the T4 condition. Tensile tests indicated that the heat affected zone was the weakest region of the weld. The welded sheet exhibited reduced strength and ductility as compared to the base metal. PWHT restored some of the strength to the as-welded condition.

The changes in tensile properties after FSW of AZ31B-H24 magnesium (Mg) alloy were studied by Afrin et al (2008). It was reported that higher welding speeds led to reduction in tensile strength of the welded joint. Al–Si (ADC 12) alloy and pure titanium were lap joined by Chen et al (2009a) using FSW and it was found that the mechanical properties were strongly influenced by the welding speed.

2.3.8 Metallurgical Studies on Friction Stir Welds

Being a solid state process, friction stir welding is the most suitable method for joining particulate reinforced aluminium matrix composites. The possibility of formation of brittle solidification products is very much minimized; the energy input and distortion are significantly lower than that in fusion welding techniques, thus improving the joint properties.
To better understand the joining process in friction-stir-welded MMCs, investigation of the crystallographic texture of the weld and of the interface between the metal matrix and reinforcing particles is needed. The crystallographic texture and particle-matrix interaction of FS welded Al6061-10 vol. % alumina have been studied by Root et al (2009). Using electron backscatter diffraction (EBSD), the texture gradient of the FS welded MMC was shown to have similar trends to that of an unreinforced Al alloy, but with significantly larger grain size in general. Fracture and redistribution of the reinforcing alumina particles in the weld nugget were also observed in that study.

Storjohann et al (2003) compared the microstructures of fusion welded Al-MMCs to that of the friction stir welded. Fusion welding of Al-MMCs led to deleterious reactions within the weld metal upon solidification. The formation of aluminium carbide (Al₄C₃) needles in the fusion welded 2124/SiC composite drastically increased the hardness of the weld metal. In the fusion welded 6061/Al₂O₃ composite, it was found that the reinforcement particles were eliminated completely resulting in a soft weld metal. FSW of Al-MMCs produced a homogeneous microstructure with a uniform hardness profile when compared to fusion welded Al-MMCs.

Uzun (2007) demonstrated the feasibility of friction stir welding for joining of AA2124/SiC/25p composite material. The weld nugget exhibited relatively homogeneous SiC particle distribution. In addition, the nugget contained some porosity around the coarse SiC particles and cracking of some coarse SiC particles was also observed. The thermo-mechanically affected zone adjacent to the weld nugget, was plastically deformed and exhibited an elongated grain structure of Al alloy matrix along with SiC particle-free regions of the composite. The HAZ exhibited a microstructure which was almost similar to the base composite both at the retreating and advancing sides.
Microstructures in friction stir welds between monolithic AA2024 and AA2014 reinforced with 20 vol. % particulate Al₂O₃ studied by John et al (2003) revealed that layers of each material were about 0.1 mm thick. Thus, each material retained its identity in the weld nugget and convoluted macrointerfaces could be identified between material domains. When the harder material was on the advancing side of the tool, the macrointerface span was larger. Particle strings and fragmentation fracture zones were also observed.

Feng (2008) friction stir welded eight millimetre thick extruded 15 vol. % SiCp/Al–Cu–Mg composite and subjected the same to subsequent post-weld T4 temper. It was found that the nugget of the as-friction stir welded composite was characterized by fine and equiaxed recrystallized grains.

Yu Zhang (2008b) while applying FSW to 3 mm thick Ti–6Al–4V plates found that the stir zone exhibited higher hardness than the base metal due to the presence of a full lamellar structure with refined grains. The HAZ contained a bimodal microstructure consisting of the equiaxed primary α and α/β lamellar structure having the lowest hardness.

Butt joints of two different materials, namely AA2024-T4 and AA7075-T6, were investigated by Barcellona et al (2006) from a metallurgical point of view. When the materials were welded, even with a solid-state process such as FSW, the following phenomena were found to occur:

- An increase of temperature was observed, maintaining the considered material in the solid state but reaching the solubilisation temperature threshold.
- The recrystallization phenomena occurring in the stir zone contrasted the material softening due to decrease in precipitate density.
Evolution of the fine-grained structure in friction-stir processed aluminium was studied by Rhodes et al (2003) using a rotating-tool plunge and extract technique. Initial sizes of newly recrystallized grains were of the order of 25–100 nm. These grains, then, grew to a size of about 2–5 μm, equivalent to that found in friction-stir processed aluminium, after heating for a period of 1 to 4 min at 350–450°C.

From studying the solution treatment behaviour of high strength 7010Al alloy friction stir welds, Hassan et al (2003) established that the stir zone grain structure was inherently unstable at high temperatures, despite the presence of Al₃Zr dispersoids that inhibited grain boundary mobility. It was reported that low heat inputs resulted in an exceptionally fine nugget grain structure and abnormal grain growth occurred throughout the nugget zone. When welds were produced with higher heat inputs, instability was more marginal, as the grain structure after welding was coarser relative to the dispersoid density.

Al 6013 was friction-stir welded by Heinz et al (2002) in T4 and T6 conditions and it was found that the strengthening precipitates, present before welding in the T6 state, were dissolved during welding in the nugget, while an overaged state with much larger precipitate size was produced in the HAZ. Microhardness measurements showed that the HAZ was the softest region of the weldment.

In a friction stir welding experiment by Schneider (2004), a rotating threaded pin tool was used. The dynamically recrystallized zone (DXZ) of an FSW cross section exhibited contrasting bands of the ‘onion-ring’ structure. An orientation image mapping (OIM) study suggested that the bands might correspond, respectively, to a ‘straight-through’ current of metal bypassing the pin tool in a single rotation or less and a ‘maelstrom’ i.e., a turbulent current, rotating a number of times around the pin tool.
Design of experiments (DOE) provides a scientific route for understanding the influence of input variables of a system on the output responses. DOE involves making a set of representative experiments with regards to a set of input variables at minimum time and expenses. A common approach in DOE is to define an interesting standard reference experiment which is then followed by new representative experiments. These new experiments are laid out in a symmetrical fashion around the standard reference experiment. Hence, the standard reference experiment is usually called the centre point (Montgomery 2001).

Design of experiments is useful for three preliminary experimental objectives: screening, optimization and robustness testing. Screening is to be done at the beginning of the experimental procedure. The objective is to explore many factors in order to reveal whether they have an influence on the response. Optimization is achieved after screening. The objective is to predict the response values for all possible combinations of factor within the experimental region and to identify an optimal experimental point. The third objective is robustness testing in which to ascertain that the method is robust to small fluctuations in the factor levels and if non-robustness is detected, to understand how to alter the bounds of the factors so that robustness may be achieved.

Experimental design methods play an important role in process development and process trouble shooting to improve performance. Experimental design is a powerful problem-solving technique that assists industrial engineers for tackling process quality problems effectively and economically. Experimental design consists of purposeful change of the inputs (factors) of a process to observe the corresponding change in the output (responses). Thus, experimental design is a scientific approach that allows the researcher to understand clearly a process and know how the inputs affect the response (Montgomery 2001). It is important to
identify the factors that affect the output of the process, and it is necessary to optimize these factors to obtain the desired output. Improved performance characteristics result from the identification of the critical factor levels that optimize the mean response and minimize the response variability. These improved performances also lead to the reduction of scrap and the need to rework, which greatly reduces costs. Various types of design of experiments such as full factorial design, Placket–Burman design, Box–Behnken design, Taguchi design, and Central composite design (CCD) are available. In the present research work, the CCD has been used.

2.4.1 Classification of Experimental Designs

There are numerous types of experimental designs; these may be classified as follows according to the treatment of factor combinations and the degree of randomization of experiments (Sung Park 1996).

1. Factorial design: For investigating all possible treatment combinations which are formed from the factors under considerations.

2. Fractional factorial design: For investigating a fraction of all combinations which are formed from the factors under investigation. This type of design is used when the cost of experiment is high and the experiment is time consuming.

3. Randomized complete block design: All possible factors are tested in these designs, but some form of restriction is imposed on randomization. Blocking is a technique used to increase the precision of an experiment.

4. Incomplete block design: If every treatment is not present in every block in a randomized complete block design, it is an incomplete block design.

5. Response surface design and mixture design: This is the design where the objective is to explore a regression model to find a functional relationship between the response variable and the factors involved, and to find the
optimal conditions of the factors. Central composite designs, rotatable designs, simplex designs, mixture designs and evolutionary operation designs belong to this class.

2.4.2 Response Surface Methodology (RSM)

It is a modeling approach using polynomials as local approximations to the true input/output relationship. The relationship between the response variable of interest and the input variables is usually not known. It is approximated by the system function with an empirical model of the form: \( y = f(x_1, x_2, ..., x_n) \) where, \( f \) is a first or second order polynomial. This is the empirical response surface model.

The variables are known as natural variables when they are expressed in physical units of measurement. In RSM, the natural variables are transformed into coded variables which are dimensionless. The successful application of RSM relies on the identification of a suitable approximation for polynomial. A lower order polynomial in some relatively small region of the independent variable space is appropriate. In many cases, either a first order or a second order model is used. The first order model is likely to be appropriate when the experimenter is interested in approximating the true response surface over relatively small region of the independent variable space in a location where there is a little curvature represented by function \( f \).

The first order model is called a main effects model as it includes only the main effects of the variables. If there is an interaction between these variables, interaction terms can be added and the model becomes first order model with interaction. Adding the interaction term introduces curvature into the response function.
Often the curvature in the true response surface is strong enough that the first order model is inadequate. A second order model will likely be required in this situation. The second order model is widely used in RSM for several reasons given below (Kathleen 2004):

1. Being very flexible, it can assume a wide variety of functional forms, hence, working well as an approximation to the true response surface.
2. Estimation of the parameters in the second order model is easy. The method of least square can be used for this purpose.
3. Practical experience shows that second order models work well in solving real response surface problems.

2.4.3 Benefits of DOE

The biggest advantage of using DOE is that it provides an organized approach, with which it is possible to address both simple and complex experimental problems. Thus, by means of DOE, more useful and precise information about the system to be studied can be obtained, because the influence of all factors is accessed. After checking the model adequacy, the importance of the factors is evaluated in terms of a plot of regression co-efficient, and interpreted in a response contour plot. The contour plot constitutes a map of the system, with a familiar geometrical interpretation and with which it is easy to decide about the next experimental step (Montgomery 2001).

The DOE concepts were used in various fields where experiments were required to be conducted. DOE was applied in various welding processes and the effects of process variables were analyzed. Few of the earlier works employing DOE technique are reviewed below.
Elangovan et al (2009) used four factors, five levels central composite rotatable design to minimize number of experimental conditions and RSM was used to develop the model to predict tensile strength of FSW joints. Statistical tools such as analysis of variance (ANOVA), student’s t-test, correlation co-efficient etc. were used to validate the developed model.

Murugan et al (1993) conducted experiments in submerged arc process where the effects of process variables on dilution and bead geometry were studied. They used a four-factor, five-level central composite rotatable factorial design to predict weld bead geometry within the workable region of the control parameters.

Apart from submerged arc process they studied the effects of MIG process parameters on the weld bead geometry using the same four-factor, five-level factorial technique emphasizing the importance of mathematical modelling and the use of DOE (Murugan & Parmar 1994).

Dowden & Kapadia (1996) studied the penetration depth in keyhole welding. The purpose of the analysis was to discover the relationships between the laser beam welding process parameters and the depth of penetration.

Gunaraj et al (1999) applied the response surface methodology for predicting weld bead quality in SAW of pipes. It was observed that RSM can be used effectively in analyzing the cause and the effect of process parameters on response. The RSM was also used to draw contour graphs for various responses to show the interaction effects of different process parameters.

Ramasamy et al (2002) employed a fractional factorial DOE study to examine the effect of polarity on stud welding.
Allen et al (2002) suggested that industries seeking higher production rates and weld quality improvements were increasingly interested in robotic gas metal arc welding. The authors compared three methods namely Taguchi method, Experimental design methods followed by the Classical DOE.


### 2.5 Finite Element Analysis

2.5.1 Developing Friction Stir Welding Models

Developing an effective mathematical model of friction stir welding looks like a simple task but during the execution of the model, it becomes labyrinthine. The reason for this complexity is due to the dynamic changes in the process parameters throughout the process. These changes affect the temperature evolution and material flow within the weld. These effects rely on the position, temperature, strain and strain rate. This determines the stress at any location of the weld and therefore the grain structure and its orientation can also be determined. The efficiency of the mathematical model will affect the degree of its accuracy versus experimental data. Many researchers have explored different parameters and assumptions to understand various aspects of FSW process.

2.5.2 Computational Costs and Model Accuracy

Several methods, assumptions and models have been explored to simplify the task of building a mathematical model to reduce the complexity. The reason for continuous research in developing model is due to the increase in the computational
needs for a highly accurate model as well as limited time and resources. As the desired degree of accuracy increases, there is a steep increase in the computational cost. The tool geometry, work piece geometry, material properties and process parameters will vary according to the materials involved and must be included in the model to increase the accuracy. Each material has different physical characteristics which are imparted by its constituent elements. Hoye & Shercliff (2003) meshed the model and the material properties and studied their effect on the computational time. They found that the finer meshes produced more nodes and thereby resulted in higher computational time. Askari et al (2001) have made meshes that had different volumes allowing for a smaller mesh unit closer to the tool and work piece interface. This is important because most of the action takes place in this zone and the objective is to obtain more accurate results where temperature and strain rate gradients are high (Bendzsak et al 2000 and North et al 2000).

2.5.3 Meshing Schemes

Friction stir welding is a unique process where there is a large amount of material distortion in various directions around the FSW tool in the X, Y, and Z planes. This chaotic mixing blends the material from the parent components to form the weld nugget. The FEA models are made as a mesh or network of elements and nodes. Researchers have used two major techniques for applying this information in numerical models. The first is the Eulerian technique which allows the material to “move” through the mesh while evaluating the results at each of the nodes (Askari et al 2001 and Colegrove 2002).

North et al (2000) validated a new computational program namely Forge 3 which used the Lagrangian technique and found that the program had the capability to analyse the FSW process. In the Lagrangian technique, the material properties are represented in same way as in the Eulerian method. The major difference is that the
mesh velocity and the material velocity are the same. This can prove to be an Achilles’ heel in some high distortion operations such as FSW. The major shortcoming in the Lagrangian technique is tangling and node inversion which results in improper and inconsistent values for the mesh (Askari et al 2001).

Askari et al (2001) used the CTH code which was based on the Eulerian (fixed in space) modelling approach and the finite-difference (finite-volume) space scheme rather than the more common finite-element. He was unsatisfied with the Lagrangian (fixed to the material) meshing due to the large deformations involved in FSW which would lead to entangling and improper results.

2.5.4 Modelling Heat Inputs

Accurate modelling of the FSW process is essential to correctly represent heat generation. Modelling heat evolution in the tool and work piece is an important step in understanding how it affects material flow and microstructure modification within and surrounding the weld. As the tool makes contact and moves through the work piece, the heating and shearing effects change the original microstructure of the parent material. Understanding how the particles move and what conditions promote what types of microstructures can help in predicting the proper arrangement to make quality welds (Ulysse 2002).

Improved knowledge of microstructure development and control in friction stir welded materials may yield other possibilities such as superior “as-welded” materials and localized alloying to improve mechanical properties. FSW focuses on the creation of better joints between two or more pieces. The best expected weld strength is a significant criterion for choosing what types of metals to join as well as choosing the appropriate process. Understanding the thermo mechanical progression in the FSW will help to predict the best mix of conditions to create a superior weld. Research assumptions have looked into understanding the heat
evolution through analysis using the Rosenthal equation (Song & Kovacevic 2003a, 2003b).

Dong et al (2001) pointed out that the Rosenthal equation determines the values assuming an idealized contact and pressure between the tool and the work piece. It is important to review the other bodies associated in the friction stir welding process that could modify the temperature gradients and therefore affect the outcome used in the Dickersen model of the welds. The tooling as well as the backing plate can greatly affect the amount of energy that stays within the weld and changes the process efficiency. The backing plate is not taken into consideration in most other research as it is felt that it is not a large source of heat loss (Ulysse, 2002).

The tool acts as a medium by which heat generated at the frictional interface can leave the work zone. Testing had shown that the heat loss was about 10% of the total heat generated. Tool designs were examined with the intent of keeping more heat in the immediate vicinity of the weld. It was reported that grooved tools helped to decrease heat loss through the tool (Dickersen et al 2003).

North et al (2000) simplified the tooling effects as a simple boundary condition. In order to improve the model’s accuracy the heating effects between the work piece and the tool will need to be included in the model to demonstrate how it changes the results. Further gains may be made by incorporating the effects of the tool holder and backing plate by defining them with thermal boundary conditions as well. The effects of heat transfer through the backing plate and through the tool and ambient air should help to improve accuracy further while at the same time a finer mesh will allow for more accurate modelling to be run during research simulations.

Ulysse’s (2002) considered the effects of tool feed rates and rpm settings to model the FSW process in three dimensions for joining thick Al plates. Parametric
studies were used in finding a combination of tool settings that promoted a good weld and avoided tool breakage from heat and shear stresses. A line of thermocouples was used to measure temperatures in the work piece and developed isotherms. This work showed that increasing the feed rate tended to increase shear in the tool pin while increasing the rpm reduced this force. Parametric tests have shown that there are nominal settings to maximize welding effectiveness while avoiding stress build ups that would cause the tool to fracture during a welding operation.

2.6 SUMMARY

The literature survey has given an overall view of MMCs, applications and properties. It also describes the current state of research on welding of MMCs, the process parameters affecting the weld quality and need for further investigation on this topic.

A very little work has been reported on welding of Al-TiB₂ MMCs. It is evident from the literature that there is plenty of scope for this material if it can be fabricated without defects and able to weld this composite successfully using FSW process. The literatures have also thrown some light on FEA of FSW process and the potentiality of the FEA process to predict the temperature distribution in the weldment if a proper mathematical model is used.