Chapter 2

Literature Review

2.1 INTRODUCTION

Friction Stir Welding (FSW) is widely applied for joining aluminium alloys, which finds wide range of industrial applications to produce lightweight components in shipbuilding, aerospace, automobile and other manufacturing industries. The aluminium alloy, which is welded with conventional processes, is very sensitive to weld cracking depending on alloying elements (Barnes and Pashby, 2000). Fusion welding of aluminium is generally assumed to be more difficult than welding steel due to oxides, reflectivity, low-melting alloying elements etc. Also, the high expansion factor makes it sensitive for distortions and the shrinkage of aluminium alloys is higher than that of ferrous alloys. FSW can be used to join all common aluminium alloys, which include 2xxx, 7xxx and 8xxx series which are normally challenging or impractical by using conventional fusion welding processes.

FSW is a solid state process, which enables long lengths of weld without melting of parent materials and provides important metallurgical advantages as compared with fusion welding. In addition, the stirring and forcing actions produce a fine-grain structure in the weldment, which results in good quality welded joints. In order to increase weld quality and to minimize welding defects, it is important to study the relationship between friction stir welding parameters, heat generation and material flow during welding process (Mishra and Ma, 2005).

This chapter enumerates a broad review of the literature related to the FSW of aluminium alloys. The FSW process parameters, heat generation, tool design, monitoring techniques such as, acoustic emission, electrical motor current and soft computing methods are reviewed. The gaps in literature are identified.
2.2 FRICTION STIR WELDING OF ALUMINIUM ALLOYS

The predominant focus of FSW has been on the welding of aluminium alloys from inception, even though the process can be applied for steel, alloys of copper, magnesium, titanium, nickel and molybdenum. As the aluminium alloys have extended use in aerospace, marine, automotive applications, their weldability for friction stir welding need to be studied.

2.2.1 WELDABILITY OF ALUMINIUM ALLOYS

Weldability refers to the property of being easily weldable and the capacity of a material to undergo welding process without defects. Weldability of aluminium alloys mainly depends upon the metallurgical characteristics of alloying elements. Many researchers have studied the weldability of aluminium alloys and aluminium alloys with other materials. So far, friction stir welds have been successfully produced on commercial aluminium alloys, which include the series 1xxx (Murr et al, 1997), 2xxx (Christner and Sylva, 1996; Strangwood et al, 1999), 3xxx and 4xxx (Rodriguez et al, 2005), 5xxx (Svensson et al, 2000; Peel et al, 2003), 6xxx (Haagensen et al, 1995; Sato et al, 1999) and 7xxx (Rhodes et al, 1997; Mahoney et al, 1998; Jata et al, 2000) as well as Al-Cu-Li alloys (Kinchen et al, 1999; Jata and Semiatin 2000).

Further studies have been carried out to understand the mechanical characteristics of friction stir welded dissimilar aluminium alloys and other metals such as steel, magnesium, aluminium composites, etc. Kwon et al (2008) performed FSW of dissimilar metals with aluminium to magnesium. Chao et al (2001) found that the friction stir welding reduced the yield strength for aluminium alloys AA2024-T3 and AA7075-T735, under high strain rate and quasi-static loading conditions. It was found that strain hardening was similar for both materials at various strain rates, which indicated good material flow characteristics and load carrying capacity. The weldability of aluminium alloy 6061-T6 with 6082-T6 by FSW was studied by Moreira et al (2009) and intermediate mechanical properties are compared with base material. Minak et al (2010) compared the weld quality of friction stir welded aluminium alloy matrix composites with base material and correlated with micro structural modifications. Chen et al (2009) investigated the weldability,
microstructure evolution and mechanical properties of an AA6063 aluminium alloy and composite materials. A joint efficiency higher than 60% was observed and increased to over 80% after artificial ageing.

It can be observed that FSW of aluminium alloys has attained a level of maturity, which enables commercial utilization of this technique. Much more research work needs to be carried out to optimise the process to improve the weld quality.

2.2.2 HEAT GENERATION AND OPERATING REGIMES

Friction stir welding differs from the conventional welding processes, such as arc and laser welding, which uses an external heat source or power. In FSW, the joining process utilizes the self generated heat. The heat generation is a complex function of the process variables, such as traverse feed, rotation speeds, tool down force, work material and tool design. The heat generation aids the fine grain formation and ease of tool movement. According to Colegrove et al (2000), heat is generated due to the material shearing at the FSW tool pin interfacial surface. The total heat generated by the tool pin is the sum of heat produced by material shearing and frictional force on contact surfaces.

In general, the heat input to the FSW is a frictional heat between the rotating tool and work pieces (Chen and Kovacevic, 2003). Song and Kovacevic (2003) observed that a definite amount of the heat is dissipated through the backing plate and the FSW tool. A relationship between process parameters and heat generated at the tool shoulder, work material interface was established. Peel et al (2003) found that the weld properties were dominated by the thermal input relatively than mechanical deformation and a relationship was established for weld strength with weld crack, tool traverse speed and tool size. Khandkar et al (2003) introduced a process model of temperature distribution for FSW process. Colegrove et al (2007) carried out the process modelling using computational flow dynamics, which has been used to explore the sensitivity of the heat generation, tool forces and size of deformation zone, as a function of tool design and FSW process conditions.

It has been understood that the heat generation and subsequent material flow are the important characteristics of FSW, which decides the quality of the weld joints.
2.2.3 FLOW MECHANISM AND TOOL DESIGN

The fundamental phenomenon in the friction stir process is the flow of softened material around the tool. The material in the weld area is extruded between the rotating pin and the surrounding cold material, which is stressed to a very small deformation. This flow mechanism can be illustrated by using two-dimensional simulations, describing streamlines around the rotating tool, for the steady flow of material as shown in Fig. 2.1 (Nandan et al, 2006). The stream lines show the presence of rotational zone, which clearly indicates the recirculating flow of material around the tool pin.

![Fig. 2.1: Simulated Stream traces on top surface of a 304 stainless steel plate during FSW process (Nandan et al, 2006)](image)

FSW plastic flow models have been used to predict flow velocities around the tool pin. The velocities were estimated from strain rates, which were obtained from the correlation between grain-size and strain-rate (Jata and Semiatin, 2000). It is also observed that the material flow and compaction on retreating side are well influenced by FSW process parameters and subsequently lead to improved joint mechanical properties. The numerical modelling of plastic flow is found to be useful for FSW tool design and optimisation of weld quality (Bhadeshia, 2008).

As the FSW process has been well established, advanced modifications in FSW tools have been emerged, such as tools with rotating pin and non-rotating shoulders, independently rotating shoulder and pin, retractable pin tools, as well as a
bobbin tool with a shoulder. Tool design has been reviewed in detail by Fuller (2007), Dubourg and Dacheux (2006). Fig. 2.2 shows TWI’s innovative Whorl type FSW tools designed with specific shape to provide superior flow and adequate stirring action and thereby reduce or eliminate the occurrence of voids.

Studies were carried out to determine optimum dimensions for FSW tool shoulder and pin diameters based on plate thickness and materials types. Colligan (1999) found that profiled pin causes additional heating and extensive plastic flow in the work piece material on either side of the butt joint as the tool rotates. Elangovan and Balasubramanian (2007) analyzed the influence of tool pin shape and tool rotational speed on friction stir processing and observed that the FSW weld parameters and tool pin shape take part in a major role in deciding weld quality. Elangovan et al (2007) investigated the influences of rotational speed and pin profile of FSW tool on friction stir processed (FSP) zone formation in AA2219 aluminium alloy. FSW tools with different tool pin profiles, such as cylindrical, tapered, threaded, triangular and square were used to fabricate the FSW joints. The pin length of the welding tool need to be shorter than the work plate thickness to avoid contact with the backing plate surface and bringing fragments into the weld (Chao et al, 2003). Deqing et al (2004) made the FSW tool pin diameter which is equal to one third of shoulder diameter to make good quality welds. Mustafa and Adem (2004)
investigated the influence of tool pin design on the welding process with different tools. It is found that the material flow and the quality of weld joints are primarily influenced by tool geometry and process parameters (Won et al, 2004).


It is observed that the design of FSW tool is imperative to the accomplishment of proper welding process and the tool pin profile improves weld nugget structure with good tensile strength and hardness.

2.2.4 EFFECT OF PROCESS PARAMETERS

For a given work material and work plate thickness, with a selected FSW tool, the FSW process variables that are influencing the weld quality are down force, tool tilt angle, tool plunge, rotational speed and traverse feed rate. Experimental studies were carried out to explore a set of process parameters to produce sound welds without macroscopic defects for FSW process (Threadgill et al, 2009). Fig. 2.3 shows the relationship between the welding parameters and the FSW process window for an aluminium die casting alloy.
Fig. 2.3: Range of optimum FSW conditions for various tool plunge down forces for 4 mm thick Al-Si casting alloy (Threadgill et al, 2009)

Experimental investigations have been carried out to study the effects of process parameters such as traverse feed rate, spindle speed and tool size on fatigue life, tensile strength, weld crack and residual stress of FSW (Nakata et al, 2001; Reynolds et al, 2003). Liu et al (2003) observed that the tensile properties and fracture locations of the joints are significantly affected by the welding process parameters. It has been reported that there is a notable variation in mechanical properties of FSW within a definite range of tool feed rate (Ericsson and Sandstrom, 2003; James et al, 2003).

The rotation speed of the spindle is considered as a most significant process parameter (North et al, 2000). Tool rotation results in stirring and mixing of material around the rotating pin and generates adequate heat to soften the material. The properly plasticized material prevents void formation and tool fracture. Bahemmat et al (2008) carried out an experimental study to investigate the effect of tool rotational speed and pin profile on yield strength and elongation of the weld joints. Tra (2012) investigated the effect of tool rotation speed and welding speed on the mechanical properties of the FSW joint of AA6063-T5. Takahiko et al (2006) carried out friction stir butt-welding of aluminum alloy plate with a mild steel plate and investigated the
effects of a tool rotation speed on joint tensile strength, microstructure. The maximum tensile strength of the welded joint was observed as 86% of the parent aluminium metal.

Tool tilt angle is a parameter to improve the stuffing of the material by the tool shoulder. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by tool pin and move material efficiently from the front to the back of the pin. For aluminium welds, a tilt angle from 0° to 3° gives a remarkable change in the microstructure development and material flow. A larger tilt angle gives a tighter weld and a uniform material flow (Shinoda, 2001).

Plunge depth of tool shoulder affects the generation of frictional heat and down force for plasticizing and compacting the work material. Haagensen et al (1995) reported that the downward force influence surface texture and fatigue performance of FSW components. The extreme downward force results in excessive shoulder penetration into the material, which produces excessive flash along the edges of the shoulder on the weld nugget area (Midling et al, 1994). This excessive plunge depth results in higher forces, torque and temperature in tool. In addition, it also causes lower tensile and bend strength in the work material (Hua, 2006). The inadequate plunge depth of tool causes a low downward force and low heat generation at the tool and work plate interface.

It can be observed that the FSW of aluminium alloys has reached a level of development to obtain cost optimization with reliable weld quality and it is important to monitor and control the welding process, so that the possible fabrication of a low quality weld can be detected and avoided by regulating FSW process parameters.

2.3 MONITORING TECHNIQUES FOR FSW PROCESS

Friction stir welding is usually carried out in machine tools, hence the monitoring techniques which are widely employed in machine tool applications, can be implemented for FSW process. Presently, limited standards are available for evaluating the quality of friction stir welds and further research work is required to develop suitable techniques for monitoring the FSW process.
2.3.1 FORCE AND TOOL TORQUE MONITORING TECHNIQUES

Force and torque measurements during the FSW process were used as an important data to understand the FSW process. Hattingh et al (2004) analyzed the forces generated during FSW and its relationship with process parameters to optimize weld performance and tool design. Online force monitoring technique enables quality control assessments during the FSW production process (Johnson, 2001). Paul Fleming et al (2008) developed a methodology for in-process gap detection in friction stir welding by means of force measurement. Force signals were collected from a number of lap welds containing differing degrees of gap faults. Statistical methods were used to derive representations of force data, which provided good insight into the property of the weld. The downward force of the FSW tool appreciably depends upon tool penetration depth in the work plates (Satoshi et al, 2001). The force generated by the rotating tool during FSW process in the transverse direction is compensated by the clamping system. It was observed that the inadequate side transverse forces due to improper clamping cause subsurface void formation on the advancing side of the weld (Andrews, 1999).

Tool torque is an important parameter, which is dependent on tool rotational speed and tool surface contact area with work material. Khandkar et al (2003) monitored the tool torque during FSW of aluminium plates and analysed the tool torque, tool temperature and forces exerted on the work material by the tool shoulder in response to changing weld conditions, such as tool rotational speed, traverse feed and down forces.

It is observed that, force and torque monitoring techniques are feasible for FSW process, but these techniques require setting up of complex instrumentations and sensors for on line monitoring of the FSW process.

2.3.2 ACOUSTIC EMISSION MONITORING TECHNIQUE

Acoustic emission technique is one of the advanced nondestructive evaluation tools which have the potential application for real time monitoring of machining process. Acoustic emission is the phenomenon by which transient elastic waves are generated by rapid release of energy from localized sources within a deforming
material. Hence, AE monitoring technique finds applications in machining, plastic deformation, sheet metal processing, welding and casting (Dornfeld, 1998). Acoustic emission monitoring technique has been used extensively to study various deformation and welding processes in different materials (Raj and Jayakumar, 1990; Raj et al, 1998). AE technique is found to be a feasible approach for detecting tool profile, material flow pattern, microstructures, and mechanical properties in FSW process (Suresha et al, 2003). FSW process generally produces signals that represent burst acoustic emissions, which characterizes the unsteady processes (Soundararajan et al, 2006). The experimental studies revealed that the frequency range considered for the friction stir welding process is between 100 kHz and 300 kHz. The schematic diagram for data acquisition and the conditioning circuit is shown in Fig. 2.4.

Fig. 2.4: AE signal acquisition, conditioning and pre-processing in FSW (Soundararajan et al, 2006)

The features of a typical AE signals are number of hits, rise time, amplitude, counts, duration and frequency. Cumulative AE counts were quantitatively correlated with the joint strength of welds during welding process (Sae-Kyoo et al, 1982). Yoona et al (2006) have studied the relationship between the tensile strength of weld joint and weld parameters using AE technique. Chen et al (2003) have worked with advanced signal processing techniques for monitoring the FSW process using the acoustic emission signals. Acoustic emission signals are detected and analyzed to investigate the feasibility of applying the AE technique for the in-process monitoring
of FSW process. The AE signal can be decomposed into various discrete series of sequences over different frequency bands using wavelet transform technique and features were extracted for FSW tool breakage detection. Zeng et al (2006) experimented with different worn out tools to weld 6061 aluminium alloy using FSW process. The acoustic emission sensing, metallographic sectioning and tensile testing were employed to analyse the process. The relationship between structure of the weld nugget and tool wear was analysed. Jirarungsatean et al (2013) applied AE technique for monitoring metal discontinuities during hot cracking.

The experimental studies have demonstrated that the AE sensing provides a potentially effective method for on-line monitoring of FSW process. As it requires simple experimental arrangements, it can be easily implemented for monitoring the FSW process.

2.3.3 MOTOR CURRENT MONITORING TECHNIQUE

A reliable and cost effective machine tool monitoring system is essential for the effective utilization of the machine tools, cutting tools and work pieces. A number of researchers have studied the application of motor current monitoring as a cost effective method for process control and machining operations. As FSW can descend into the group of end milling processes, motor current based monitoring methods can be easily implemented by using current sensors. The method of spindle motor current and voltage measurements were employed for online estimation of tool wear monitoring in milling operations (Bhattacharya et al, 2006). The current signals of a spindle motor were measured by a Hall Effect current sensor. The real time machine condition monitoring was successfully implemented using feed-motor current measured with inexpensive current sensors installed on the servomotor of a CNC turning centre (Xiaoli, 2001). This method of non-invasive and inexpensive electrical measurement increases the potential for industrial applications. Armature current of a machine tool feed drive system was analyzed for measuring the cutting force during machining operations (Altintas and Dong, 1990; Altintas, 1992). Uzun (2007) applied electrical conductivity measurements for investigating the mechanical property of FSW joints. Mehta et al (2013) proposed a methodology to monitor torque and traverse force in FSW from the electrical signatures of driving motors.
The literature shows that the motor current monitoring has been employed successfully in machine tool applications. However, the application of motor current measurement technique to FSW process is found to be very limited, although it can be used for monitoring FSW process.

2.3.4 SOFT COMPUTING TECHNIQUES FOR MONITORING FSW PROCESS

Monitoring of FSW process is quite complex, due to non-linear interaction between the process parameters, machine tools and drives dynamics. Hence it requires advanced soft computing techniques such as Neural Network, Fuzzy Logic, Neuro Fuzzy and Genetic Algorithm for developing intelligent monitoring systems.

Fuzzy logic is one of the artificial intelligent techniques, which is widely used, because of its applications in dynamic process control. Fuzzy modelling was used to analyse the emitted electromagnetic radiation fundamental frequencies during the tensile failure of the FSW welds produced at different process parameters. Muthukumaran et al (2008) analysed the fundamental frequency of electromagnetic radiation during weld tensile failures and developed fuzzy model. Tansel et al (2010) developed genetically optimized neural network systems to estimate the optimal operating condition of the friction stir welding process. Genetic algorithm is used to search the optimized parameters within the desired range. Vijayan et al (2010) presented the optimization of process parameters in friction stir welding of aluminum alloy AA5083 using orthogonal array with grey relational analysis. Zhang et al (2011) developed a systematic data-driven fuzzy modelling approach for AA5083 aluminium alloy to analyse microstructural features, mechanical properties and overall weld quality. Saumuy et al (2012) proposed a common monitoring technique that uses statistical methods to establish a process baseline, which is compared with production data to detect abnormal variations. In this technique, the manufacturing process conditions are monitored with baseline changes using generalized regression. Roshan et al (2013) carried out experimental investigations to model and optimize FSW of aluminium alloy using Adaptive Neuro-Fuzzy Inference System (ANFIS) and Simulated Annealing (SA) algorithm.

Soft computing techniques are essential to develop an intelligent monitoring system for FSW process, as the data processing is crucial. It is also found that the fuzzy logic approach is widely adopted for monitoring the machine tool operations.
2.4 SUMMARY OF LITERATURE

From the literature review, it can be observed that friction stir welding process has been successfully applied for joining aluminium alloys. Tool geometry and traverse feed rate, tool rotational speed, tool axial force and tilt angle are found to be important process variables in FSW process. For welding of aluminium alloys, steel is preferred as tool material (Mishra and Ma, 2005). Many investigations have been carried out to study the effect of tool design and process parameters on the tensile strength of weld joints. However, tool designs are generally proprietary to individual researchers and limited information is available in open literature. It has been revealed that the weld quality depends upon the welding parameters and tool conditions (Hashimoto et al, 1999; Biallas et al, 1999). In order to ensure the quality of welded joints during the process, these parameters need to be controlled using monitoring system for FSW process.

AE technique is found to be a feasible approach for detecting tool wear, material flow pattern, microstructures in FSW process. However, there is no clear relationship established for the AE signal parameters with the tensile strength of welded joints in FSW process. Since large forces are involved in FSW process, the application of spindle motor current monitoring and current signature analysis can be a more robust technology to investigate the FSW process. However, its application in friction stir welding process is found to be limited.

The literature shows that the data obtained from monitoring techniques are processed using soft computing techniques, which are essential for understanding and modelling the process. These models are used for process optimization and identifying significant contribution of process parameters. The literature reveals that the fuzzy logic approach is widely adopted for monitoring complex and non-linear processes.
2.5 LITERATURE GAPS

From the literature review on friction stir welding of aluminium alloys and process monitoring techniques, the following gaps have been identified:

- No sufficient experimental studies have been reported on the relationship between the acoustic emission signal parameters and the tensile strength of welded joint in FSW process with different tool pin profiles.

- Application of motor current based monitoring technique is not yet reported in the available literature for monitoring of tensile strength of weld joint in FSW process with different tool pin profiles.

- In addition, no adequate analysis have been carried out for developing an intelligent monitoring system for FSW process using soft computing technique such as fuzzy logic.

2.6 RESEARCH OBJECTIVES

The main aim of this research work is to develop process models for online monitoring of weld tensile strength and nugget hardness for friction stir welded aluminium alloy plates. In order to realize this objective, following tasks have been formulated:

(i) To investigate the relationship between AE signal parameters and mechanical properties of friction stir weld joints for different FSW tool pin profiles.

(ii) To study the variations in spindle motor current on mechanical properties of friction stir weld joints for different FSW tool pin profiles.

(iii) To propose a model based online monitoring system for estimation of weld mechanical properties of FSW components and validation using experimental results.