CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In the previous chapter, a brief introduction to Friction Stir Welding (FSW) process, microstructural zones in friction stir welded aluminum alloys, objectives and scope of the work were presented. Since its invention, FSW has been a very active area of research in the field of metal joining. FSW initially applied for joining aluminum alloys, has been implemented in joining the alloys of steel and other non-ferrous alloys with the advances in tooling. Microstructural characterization, evaluation of mechanical properties and optimization of process parameters, analysis of heat transfer and material flow in the workpiece are a few important areas that researchers have focused. Estimation of mechanical properties and process parameter optimization involve the application of an optimization algorithm. Heat transfer studies help in estimating the efficiency of the process, i.e., the amount of heat transferred into the work piece and into the tool. When coupled with structural models, heat transfer studies help in predicting residual thermal stresses generated and forces acting on the tool. This chapter presents a review of literature on similar and dissimilar FSW of aluminum alloys, microstructure and mechanical properties of FS welded aluminum alloys, effect of process parameters, aspects of heat transfer and material flow during FSW.
2.2 MECHANICAL PROPERTIES AND MICROSTRUCTURAL STUDIES

The microstructure evolution and consequent properties due to FSW depends on several factors. Some of the factors include FSW process parameters, the base metal, its composition and temper, tool geometry and tool material. The mechanical properties and microstructural studies carried out for aluminum alloys are presented in this section.

Rhodes et al (1997) joined AA7075 plates using FSW at a welding speed of 5 in/min and studied the changes in microstructure of the alloy due to FSW. The nugget was found to be recrystallized, the dislocation density was lowered and the strengthening precipitates were found to be solutionised.

Mahoney et al (1998b) studied the effect of FSW and subsequent thermal aging on the longitudinal and transverse properties of 7075T651 aluminum alloy. The HAZ was found to be the weakest zone with a reduction in yield strength and ultimate tensile strength in the longitudinal tensile tests. Post weld thermal aging increased fraction of fine hardening precipitates thus improving the strength but a loss in ductility was observed. The precipitate-free-zones (PFZ) at grain boundaries resulted in inter-granular fracture. Transverse tensile test showed shear mode fracture, away from nugget, indicating softening due to thermal effects. Post weld thermal aging reduced transverse tensile strength and elongation.

Flores et al (1998) friction stir welded 1100 aluminum alloy containing micro-dendritic equiaxed precipitate cell structure in the as-cast and 50% cold-rolled condition. Even as particulation and deformation of precipitates occurred in the as-cast workpiece, there was little change in weld zone hardness. The dislocation density in the FSW zone was less than that in
the base plate, indicating that work piece microstructure has little effect on FSW process compared to Tool Rotation Speed (TRS).

Benavides et al (1999) reported studies of FSW 2024 Al alloy at room temperature (30°C) and low temperature (-30°C). Low temperature FSW of 2024 aluminum produced equiaxed, fine grains of about 0.8 µm compared to grain size of about 10 µm in FSW made at room temperature. The maximum weld zone temperatures did not exceed 140°C in the welds made at low temperature, while in welds made at room temperature, the maximum temperature was measured to be 330°C.

Sutton et al (2004) studied the microstructural features of FSW AA2024 Al alloy. Microstructural bands with regions rich and poor in hard particles were observed alternately and related to onion ring pattern. The band spacing was directly correlated with the welding tool advance per revolution. Well defined variation in grain size, micro-hardness, and concentration of base metal impurity particles (i.e. constituent particles) between different zones of friction-stir welded joints of AA2024 was noted. This banded microstructure affects the fracture process in the welded material and the fracture path was along regions of high particle density.

Krishnan (2002) discussed the formation of onion rings, their significance and effect on properties of friction stir welds. The frictional heating due to tool rotation and extrusion of the metal due to forward movement of the tool forms the onion ring. The spacing of the onion rings is equal to the forward movement of the tool in one rotation and the spacing was wider at the centre and narrower at the edges. The spacing was inversely proportional to TRS.
Lockwood et al (2002) reported that the transitions from the TMAZ to the HAZ and from the HAZ to the base material for AA 2024 are gradual. The zones were not distinguished by any sharp change in the microstructure.

Sato et al (2002) friction stir welded aluminum alloy 6063 at temper condition of T4 and T5 at different rotation speeds. Increase in rotation speed caused an increase in maximum temperature of the welding which resulted in an exponential increase of the grain size. 6063-T5 showed a reduction in hardness around weld center, while the hardness was homogenous for 6063-T4. Increase in hardness due to post weld aging was small in the stir zone of welds produced at low rotation speeds, due to increase in volume fraction of PFZ’s.

Peel et al (2003) friction stir welded AA5083 aluminum alloys under varying conditions. The effect of welding speeds on the microstructure, mechanical property and residual stress was studied. The weld properties were dominated by thermal input rather than mechanical deformation. Weld zone was recrystallised and an increase in welding speed reduced weld zone size. Residual stress in the weld zone was tensile both in the transverse and longitudinal directions. The peak longitudinal residual stress increased with welding speed.

Liu et al (2003) studied the relation between welding parameters and tensile properties of FSW 2017-T351 joints. For a micro and macro defect free FSW joint, the tensile properties of the tailored joint were only dependent on the micro hardness distributions across the joint. When the weld pitch was greater than 0.13 mm/rev, void defects occur in the joint. No defects occurred and tensile properties were higher when the pitch was less than 0.13mm/rev. Void free joints failed near or at the interface between the nugget and the TMAZ on advancing side. Defective joints failed at the weld
center. At an optimum pitch of 0.07 mm/rev, the ultimate strength of the joint was equivalent to 82% of base material.

Squillace et al (2004) investigated the microstructure and corrosion resistance of weld butt joints of AA 2024-T3 fabricated by Gas Tungsten Arc Welding (GTAW) and FSW processes. GTAW resulted in a decay of properties in the HAZ due to high temperatures experienced. The lower temperatures and severe plastic deformations induced by tool motion in FSW produced a complex thermo-mechanical situation. Re-crystallization and formation of fine grain structure resulted in a slight recovery of hardness in flow arm and nugget zone, with respect to TMAZ. A minor decay of mechanical properties was noted in the nugget zone, flow arm and thermo-mechanically affected zone (TMAZ), while a light improvement of properties was observed in the HAZ. The tensile failures generally occur outside the nugget and fatigue properties are comparable with parent metal.

Attallah and Salem (2005) friction stir welded AA 2095 under various FSW parameters and investigated the effect of WS and TRS on the swirl zone (SWZ) and extent of abnormal grain growth (AGG) in the as welded and heat treated condition. SWZ appears within the TMAZ of the weld and was dependent on welding parameters. AGG occurred due to the thermal instability of the fine grain structure created in the welds. Both TRS and WS affected the extent of AGG, while AGG dominated welds made with low TRS and high WS.

Cavaliere et al (2006a) analysed the effect of process parameters on the mechanical and microstructural properties of AA6056 friction stir welds. Room temperature tensile tests indicated that material ductility decreased with increasing TRS and WS. Highest TRS and highest WS produced highest tensile strength. At low TRS and WS, hardness profile was very uniform. At higher TRS and WS hardness profiles became less uniform. Microstructure of
the material in the nugget appeared as very fine equiaxed grains in all the conditions.

Cabibbo et al (2007) reported fine and recrystallized grain structure due to stirring and forging of the parent alloy for FSW of Al 6056. Nugget shows highly refined grains and equiaxial grain structure, with a very distinctive transition in grain size on the advancing and retreating side. Sutton et al Sutton et al (2004) also reported very fine grain size at the top surface of the nugget where contact with the tool shoulder occurred.

De Giorgi et al (2009) investigated the influence of tool shoulder on residual stress state, microhardness profile and the mechanical properties of 1.5 mm thick friction stir welded AA6082-T6 joints. Three tool geometries namely, a shoulder with scroll (T_{FS}), a shoulder with a shallow cavity (T_{FC}), and a flat shoulder (T_{F}) were used. Room temperature longitudinal and transverse tensile tests were performed to evaluate the mechanical properties of the joints and stirred zone. Fatigue tests were performed on transverse specimens. T_{F} shoulder produced the coarsest recrystallized grains. Tensile strength was not affected by shoulder geometry. Joints fabricated with T_{FS} showed worst fatigue behavior, while T_{F} and T_{FC} shoulders produced excellent fatigue properties.

Fratini et al (2009) utilized artificial neural network (ANN) linked with finite element model to predict the average grain size values. The ANN was trained with the experimental results and then the simulated results and was then tested on further butt, lap and T-joints.

Yan and Reynolds (2009) investigated the effect of initial temper (T7451, T62 and W) of base metal on mechanical properties of 4 mm thick AA7050 friction stir welded using nearly identical welding parameters, followed by post-weld heat treatment. The results indicated that the initial
temper of base metal had significant effect on the mechanical properties of the friction stir welds. Post weld aging of friction stir welded AA7050 in the W condition, increased the strength of the joint and transverse elongation, and changed the fracture location from HAZ to weld nugget.

Arora et al (2010) FS welded aluminum alloy 2219 using an adapted milling machine. Metallographic studies revealed fine equiaxed grains in weld nugget. TEM studies indicated coarsening and/or dissolving of precipitates in nugget. The frictional heat and deformation resulted in microstructural changes in thermo-mechanically affected zone. The axial force was found to be dependent upon shoulder diameter and rotational speed, whereas force along welding direction was dependent on welding speed and pin diameter. Tensile strength of the joints was significantly affected by welding speed and shoulder diameter. Percentage elongation was affected by welding speed.

The effect of FSW parameters on the microstructure and mechanical properties of 5.6 mm thick 2219Al-T6 joints was investigated in detail by Zhang et al (2012). Sound FSW joints could be obtained under lower TRS of 400–800 rpm and welding speeds of 100–800 mm/min. Higher TRS of 1200–1600 rpm easily led to the tunnel and void defects. The FSW thermal cycle resulted in low hardness zones (LHZs) on both retreating side (RS) and advancing side (AS). The LHZs may be located at the interface between the nugget zone (NZ) and the TMAZ, or at the TMAZ, or at the HAZ under the varied welding parameters. The tensile strength of FSW 2219Al-T6 joints increased for increasing values of welding speed from 100 to 800 mm/min, and was weakly dependent on the TRS from 400 to 1200 rpm. The FSW 2219Al-T6 joints fractured along the LHZ on the RS.
2.3 PROCESS PARAMETERS IN FSW

One advantage with Friction stir welding is that the parameters can be controlled thus controlling the energy input to the system. The TRS and the WS are the two most important process parameters that affect the thermal history, material flow, micro structural evolution and the properties of the joint. The down force applied parallel to the axis of rotation is another process parameter that affects heat generation. Other factors that affect the weld characteristics in FSW process include initial heat treatment condition of the work piece, material type and hardness of the tool, material and thickness of backing plate, type of cooling arrangement and the clamping fixture. Selection of friction stir welding parameters that produce acceptable mechanical, micro structural, fatigue and corrosion properties is a primary requirement to obtain efficient, defect free friction stir welded joints. The tool geometry (size and profile) and the process parameters affect the heat generation, material flow, microstructure evolution and the properties of the joint. The tool life depends on the process parameters used. The effect of process parameters and tool design on thermal history and temperature distribution, material flow, microstructure evolution and properties has been extensively studied and reported in literature. The effect of post weld heat treatment on the mechanical properties, microstructure and corrosion behaviour has also been studied. Mishra and Ma (2005) presented a detailed review on Friction stir welding, mechanisms responsible for the formation of welds and microstructural refinement, and effects of process parameters on resultant microstructure and final mechanical properties.

Lee et al (2003b) studied the joint characteristics of friction-stir-welded A356 alloys and reported improvement of mechanical properties at the weld zone, with various welding speeds. The mechanical properties and hardness of the weld zone were greatly improved in comparison to that of the
base metal (BM). A remarkably reduced defects and greatly elevated tensile strength of the SZ were also reported.

Liu et al (2003) studied the relation between welding parameters and tensile properties of 2017-T351 aluminum alloy. They reported a weld tensile strength equivalent to 82% of base material at a tool rotation speed of 1500 rpm and welding speed of 100 mm/min and occurrence of fracture at the interface between WN and TMAZ.

Peel et al (2003) FS welded AA5083 alloy under varying conditions and reported the results of microstructural analysis, mechanical tests and residual stress analysis. It was found that the thermal input rather than the mechanical deformation by the tool dominated the weld properties.

Boz and Kurt (2004) investigated the effect of stirrer geometry on the FSW of aluminum AA1080. Five different stirrers, one with square geometry and the other with cylindrical geometries with different screw pitch were used. Bonding was better with square stirrer, but mechanical and metallographic properties were poor due to a large mass transfer. Tensile fracture occurred in the base metal and a UTS of 110 MPa was achieved with 0.85 and 1.1 mm screw pitched stirrers.

Lim et al (2004) examined the effect of TRS and WS on the tensile behavior of FSW 4-mm thick AA6061-T651 alloy. The plates were friction stir welded with varying tool speeds of 1000, 1400, 1600, 2000 and 2500 rpm, and welding speeds of 0.1, 0.2, 0.3 and 0.4 m/min. Yield strength, ultimate tensile strength and tensile elongation were affected by the parameters, with elongation decreasing with decrease in WS and increase in TRS. The clustering of coarse Mg$_2$Si precipitates, due to whirling and hurling action by severe plastic flow in the weld zone, was the cause for the tensile behavior.
Low WS and high TRS encourages plastic flow and hence the clustering of precipitates.

Chen et al (2005) reported significant improvement in the tensile strength of the FSW joints of 2219-O aluminum alloy through a Post Weld Heat Treatment (PWHT) process. The PWHT joints fractured in the Weld Zone.

Zhao et al (2005) investigated the effect of tool pin geometry on the welding structure and the mechanical properties of aluminum alloy AA2014 using different pin geometries. The plastic flow of material differs for different pin geometries. Microscopic examination of the weld zone and the mechanical property tests showed that the screw pitched taper stir pin produced the best bonding. The appearance of the weld showed no obvious defects. The grain of the weld nugget was very fine with fine distribution of precipitates.

Cavaliere et al (2006a) analysed the effect of process parameters on mechanical and microstructural properties of AA6056 joints produced by FSW at different TRS of 500, 800 and 1000 rpm and welding speeds of 40, 56 and 80 mm/min. Optical microstructure analysis, room temperature tensile tests, microhardness (H_v) tests and axial fatigue tests (LCF and HCF) were carried out on the welds for all the WS and TRS used in the study. It was observed that the specimens welded at the WS of 56 mm/min showed the best behaviour in the low cycle regime.

Minton and Mynors (2006) presented a methodology for determining if a conventional milling machine is capable of being used to undertake friction stir welding and finding the process window.
Okuyucu et al (2007) developed an artificial neural network model to correlate the mechanical properties of friction stir welded aluminum alloys with the process parameters. The model input parameters were TRS and WS, while tensile strength, yield strength, elongation, hardness of weld metal and hardness of heat effected zone (HAZ) were the output. The influence of the parameters on the mechanical properties were simulated and a good agreement between the predicted and measured data was obtained.

Ren et al (2007) investigated the effect of welding parameters on the tensile properties and fracture behaviour of friction stir welded 6061-T651. The WS was found to be a dominant factor in determining the tensile properties and fracture mode of the welds. The fracture paths matched with the low hardness distribution profiles in the joints. When the WS was high (400 mm/min), welds exhibited higher tensile strengths with 45° shear fracture. The tensile strength was low and the fracture paths were vertical when the welding speed was low (100 mm/min).

Scialpi et al (2007) studied the effect of different shoulder geometries on the mechanical and microstructural properties of 5 mm thick 6082-T6 aluminium alloy friction stir welded joints. Three shoulder geometries namely scroll and fillet, cavity and fillet, and only fillet were used for the study. Results indicated that for thin sheets, shoulder with fillet and cavity produced the best joint.

Sheikhi and dos Santos (2007) studied the influence of welding parameters and welding tools on weld quality and mechanical properties of tailor welded blanks of 6181-T4. Weld efficiencies greater than 90% were achieved. Surface finish was satisfactory.

Tozaki et al (2007) investigated the influence of the stirring pin and pressing tool shoulder on the microstructural softening during FSP and
subsequent natural aging behavior for a 6061-T6 aluminum alloy. The frictional heating from the tool shoulder was found to be the main cause for microstructural softening and also for natural aging observed in the dynamic recrystallized zone and thermomechanically affected zone.

Elangovan and Balasubramanian (2008a) studied the effect of different tool pin profiles and shoulder diameters on the formation of friction stir processing zone formation in AA6061 aluminum alloy. It was reported that square pin profiled tool with 18 mm shoulder diameter produced mechanically sound and metallurgically defect free welds.

Kulekci et al (2008) reported the effects of the tool pin diameter and tool rotation on the fatigue behaviour of friction stir welded lap joints of AA 5754 aluminium alloy plates. Defect free FSW lap joints were produced on alloy plates at a constant traverse speed but with different tool pin diameter and tool rotation. The results indicated that an optimisation is required for the studied parameters, in order to obtain reasonable fatigue strength.

Liu and Ma (2008) friction stir welded 6 mm thick 6061Al-T651 plates with varied welding parameters and tool dimensions. The hardness values of the low hardness zones (LHZ) were mainly dependent on the welding speed. The density of precipitates, tended to decrease with increasing welding speed. The fracture of the welds occurred along the LHZs, and the tensile strength of the welds increased with increasing WS and was independent of the tool dimension and TRS.

Lombard et al (2008) reported that the TRS is the key parameter governing tool torque, temperature, frictional power and hence tensile strength and fatigue performance of AA5083-H321. Tensile strength and the fatigue life in 5083-H321 alloy were governed by frictional power through its effect on plastic flow processes in the TMAZ. The results obtained showed
that welds, obtained with the maximum tool rotational speed and the minimum traverse speed, have improved mechanical properties relative to the base material. The occurrence of certain defects are related to plastic metal flow and influence the crack paths. Weld residual stresses are governed by heat input into the weld.

Rajamanickam et al (2009) presented the effect of tool rotation and weld speed on temperature distribution and mechanical properties of friction stir welded aluminum alloy AA2014. Temperature under the tool was strongly dependent on the tool rotation speed while the weld speed could be the main input parameter that had the highest statistical influence on mechanical properties.

Rodrigues et al (2009) analysed and compared the microstructure and mechanical properties of friction stir welds produced in 1 mm thick plates of AA 6016-T4 aluminium alloy, with two different tools.

Arora et al (2010) reported studies on friction stir welding of AA 2219. The downward force was found to be dependent upon shoulder diameter and rotational speed whereas longitudinal or welding force was found to be dependent on welding speed and pin diameter. Tensile strength of welds was significantly affected by welding speed and shoulder diameter whereas percentage elongation was affected by WS.

Lertora and Gambaro (2010) presented an approach to optimise FSW process parameters which govern the tensile strength and the fatigue life of AA8090 Al-Li alloy. A close relationship existed between microstructure, fatigue performance, the typical plastic flow of a FSW joint and the occurrence of defect types.
Tutum and Hattel (2010) predicted the optimum process parameters in friction stir welding using genetic algorithm. A transient, two-dimensional thermo mechanical model with sequential coupling was used to predict the residual stresses. Residual stress generated for various TRS and WS was predicted using the model. Optimisation of TRS and WS for the minimisation of the peak residual stresses and the maximisation of the welding speed was investigated using genetic algorithms. Higher welding speed for a fixed rotational speed resulted, in slightly higher stress levels in the tension zone. Higher rotational speed for a fixed welding speed produced lower peak residual stress, but along with, a wider tension zone, resulting in a substantially higher residual tensile force.

Zimmer et al (2010) presented the results of an experimental investigation, conducted on the FSW plunging stage to better understand the relation between the process parameters and the forces and torque generated. The influence of the main plunge process parameters on the maximum axial force and torque were analysed and, a diagram presenting the maximum axial force and torque according to the process parameters was presented.

2.4 HEAT TRANSFER AND MATERIAL FLOW STUDIES

A clear picture of the thermal history and material flow during the friction stir welding process is a need to understand the process phenomena and effect of process parameters. Experimental and numerical approaches have been used in the past for heat transfer and material flow studies. Analytical and numerical modeling studies, based on frictional and viscoplastic heat generation, heat transfer theories and fluid mechanics have been developed in the past to explore the friction stir welding process mechanism. The computational methods are cost effective and have been comparatively faster means, for analysing heat transfer and material flow.
2.4.1 Experimental Studies

Initial studies on FSW were experimental, using thermocouples to measure temperature at various locations in the workpiece. Experimental studies on material flow were accomplished by inserting markers, at different locations in the welded plates and tracing their position and the path traced after welding.

Tang et al (1998) measured experimental temperature data for FSW of AA6061-T6 and concluded that the heat generation in FSW was dominantly due to friction at the tool shoulder.

Hwang et al (2008) determined the thermal histories and temperature distributions in a workpiece during a friction stir butt welding of AA6061-T6. Temperature histories in the welding during FSW at different locations on the workpiece were measured using different types of thermocouple layouts. A second order polynomial curve was found to best fit the experimental temperature values in the width direction of the workpiece. The vickers hardness test and tensile tests were also carried out, and compared with that of the base metal.

Li et al (1999) reported flow patterns observed on metallographic cross sections in friction stir welds made between dissimilar aluminum alloys 2024/6061 using differential etching. The presence of complex vortex, whorl and swirl features characteristic of chaotic-dynamic mixing was reported.

Colligan (1999) used 0.38 mm diameter steel balls as tracers to study the material flow during FSW. The balls embedded at various positions in the weld path and a “stop action” technique was used to study the material movement patterns in FSW. The welded specimens were analysed using radiography to observe the position of markers, after welding. The material in the upper portion of the path of the welding tool only was stirred, and it was
forced down by the threads on the pin and deposit in the weld nugget, while much of the material movement took place by simple extrusion. The inertia of the balls was found to affect the accuracy of the analysis.

Seidel and Reynolds (2001) and Reynolds (2000) analysed material flow in friction stir welds of AA 2195-T8, based on a post weld determination of the position of AA5454-H32 markers placed in the faying surface of the weld. Full 3D plot of the deformed markers were obtained from the positions of material before and after welding in the thermo-mechanically affected zone by a serial sectioning technique. The results indicated the effect of pin diameter on the size and shape of dynamically recrystallized weld nugget (DRX) zone and material deformation. The larger the pin diameter, larger was the DRX zone and material deformation. Material did not flow around the leading edge of the pin, and a well defined interface between leading and trailing sides of the weld was seen. The rotation of the tool heats the material by friction and does not play direct role in weld formation.

Terry Dickerson et al (2003a) studied material flow in FSW using tracers and analyzed the effect of tracer on material flow. For better definition of material flow, it was suggested, that the tracer metals should have better X-Ray definition characteristics. It is found that, when the copper tracers were placed along the faying surface at the top third of the joint line, the material flow in the through thickness could be analyzed.

Liming Ke et al (2004) presented experimental results of material flow during FSW of aluminum alloys and proposed a cavity model to explain the flow phenomena. The plasticized metal coming from both the sides of the weld to rear of the pin may meet at the weld center. Shear stress between pin surface and plasticized material and internal pressure were the driving force for the material flow. Defect formation happens when plasticized material
flowing from both the directions does not come into contact and bond in the middle of the weld. Advancing side has more chances for defect formation as larger onion ring forms in it.

Schmidt et al (2006) experimentally investigated tracer flow and estimated the average velocity of material flow through shear layers during FSW of aluminum alloy. The estimated average velocity was found to be a fraction of the shoulder rotational speed. The tracer technique showed the final position of the tracer but did not provide information about the actual flow path of the material.

Zhao et al (2006) investigated material flow in friction stir welded aluminum alloy AA2014 using a marker insert technique (MIT). Flow visualisation revealed asymmetry in the material flow during the FSW process, with different flow patterns observed on advancing and retreating sides. There was a vertical and circular motion around the longitudinal axis of the weld. ‘Hole’ defect occurred when column and taper pins were used. Vertical material flow was obvious with the taper with screw thread pin and there was no distinct 'hole'.

Kumar and Kailas (2008) have divided the material flow in two ways, pin driven flow and shoulder driven flow. The former executes a material transfer that takes place in the form of layers and the latter causes a bulk material transfer and their synergetic action leads to the classical onion ring formation.

Muthukumaran.S and Mukherjee.S.K (2008) analyzed the formation of onion rings which indicates the proper formation of weld in two modes i.e. shoulder mode and pin mode. The metal transferred by the shoulder offers compressive force on the metal transferred by the pin and attributes compactness to the weld leading to elimination of weld defects.
normally caused by inadequate compactness. The author states that the reason behind the layered metal flow phenomenon can be attributed to stick and slip conditions caused by the variation in the contact pressure.

Colligan and Mishra (2008) investigated material flow in FSW of 6061 and 7075 aluminum alloys using several initial configurations of steel balls. The positions of the balls after welding were determined using radiography. The “stop-action-technique” was used, in which the forward motion of the pin was suddenly stopped and then unscrewed from the workpiece. This left the threading in the keyhole intact. Metallographic examination of the trailing edge of the keyhole revealed microstructural banding of extruded material. Vertical striations at the bottom indicated material flow in the upward direction, caused due to pin-threads. Horizontal striations close to the shoulder indicate the rotational material flow.

2.4.2 Analytical and Numerical Modelling

Modeling of heat transfer and material flow in FSW has been accomplished using Lagrangean, Eulerian or Arbitrary Lagrangean Eulerian approaches. Finite difference method (FDM), Finite element method (FEM) and Finite volume method (FVM) have been the preferred numerical methods, for the simulations while other methods have also been used. The results from these models have been validated by experimental data. Heat transfer and temperature distribution in the work piece were found to be asymmetric due to asymmetry in strain rate and viscous dissipation. Material flow was found to be dependent on contact of the material with the tool.

Heurtier et al (2002) used an analytical model to predict workpiece temperatures. Schmidt and Hattel (2004) developed an analytical model for heat generation in friction stir welding. The model accounted for both the contact surfaces and contact conditions. The contact condition between the
tool surface and workpiece were defined as sliding, sticking or partial sliding/sticking. Heat generation mechanism for each contact condition was different. The contact condition was determined from experimental results for each plunge force and torque. The sliding condition provided a proportional relationship between plunge force and heat generation. However, this was not well demonstrated through experimental validation.

Roy et al (2006) developed a dimensionless correlation to estimate the peak temperature during friction stir welding. The correlation used thermal properties of the workpiece and tool, tool shoulder area, tool rotation speed and traverse speed of the tool.

Heurtier.P et al (2006) proposed a semi analytical thermo mechanical model based on the velocity fields to obtain the strains, strain rates, and estimations of the temperatures and micro-hardness in the various weld zones. The micro hardness profile was derived from the thermal history and it denoted the in-homogeneity of the weld which can be reduced by reducing the average temperature by increasing the tool velocity. The model also predicted the weakened weld zone due to oxide distribution after the welding process.

2.4.3 Solid mechanics Based Modeling

The main principle of Lagrangean model is to analyze the FSW process in the way of Computational Solid Mechanics. With this approach, the thermomechanical modeling and residual stress analysis can be performed efficiently. With particle tracking, material flow during FSW can also be analysed.
Gould and Feng (1998) developed a simple heat flow model to relate the temperature field variation with the welding parameters. The model that used point heat source derived from Rosenthal (1938) and Rosenthal (1941) had considered only frictional heating at the shoulder. Many simplifying assumptions were used to obtain a closed-form solution for the result.

Chao and Qi (1998a) developed the first 3-D thermal and thermo-mechanical model for FSW based on FEM. The heat generation due to the frictional contact between tool shoulder and the work piece was only considered. The model uses thermal convection and temperature-dependent material properties. The model included backing plate, and a reduced yield stress was used for the nugget. The total heat input to the weld and heat transfer from the bottom were iterated in a trial-and-error manner, until the predicted temperatures matched with validation experiments. Post weld residual stress and distortion could be predicted using the calculated temperature distribution. The model considered frictional heat generated between the shoulder and the workpiece and the effect of the tool pin was not considered in the model.

Frigaard et al (2001) developed a 3D heat flow model for FSW based on FDM. An ideal contact surface and pressure at the tool/material interface was assumed. The model includes transient heating and cooling period in FSW with many simplifications. Hardness in the weld nugget was predicted using the obtained temperature profiles and the peak temperatures.

Khandkar and J.A.Khan. (2001) developed a 3D finite element thermal model for overlap FSW. Convective heat transfer due to plastic flow was considered in the model, in addition to heat generation due to rotation and translation of the tool. The contact conductance between the backing plate and the work piece were assigned according to contact pressure across the
interface. The analysis was iterated until the predicted temperatures and experimentally measured temperatures matched.

Dong et al (2001) explicated the temperature distribution, and the material flow in friction stir welding using a series of simplified models. The heat input to the model includes heat generation due to frictional contact and the plastic deformation of the material in the stir zone. A constant friction coefficient is input to the model. The model predicts the highest peak temperature at the bottom of the pin which contradicts the experimental results, predicting the same at the top surface of the pin. A slip band, correlating with the nugget is found to be formed. The model results suggested that frictional heating is dominant in the upper region of the weld zone, while in the lower region of the weld, heating due to plastic deformation dominates. A slip surface between the nugget and TMAZ was formed, as observed by Colligan (1999).

Ulysse.P (2002) used a three dimensional model to estimate the temperature and to analyze the tool forces during FSW of thick AA 7050 T7451 plates. The material was assumed to be rigid visco-plastic material with strain rate and temperature dependent flow stress. Temperature dependent thermal properties were used. The heat generation was expressed as the product of the effective stress and effective strain rate. Thermo-couple measurements were made during welding trials and data from thermocouples measuring highest temperatures were presented. The traversing force on the tool increased with increase in traverse speed and decreased with the increase in the rotational speed.

Song and Kovacevic (2003) developed a 3-D heat transfer model in a moving coordinate system. The frictional heat generation at the tool shoulder/work piece and pin/ work piece interfaces were considered. The FDM was applied to solve the governing equations. The temperature contours
in the work piece during the penetration and welding period of the FSW process were predicted. However, the stirring effect of the pin was neglected, and the temperature profile was assumed to be symmetrical to centre line of the weld. Constant thermal properties of the material were used in the model.

In another work, Chen and Kovacevic (2003) developed a finite element based thermomechanical model for FSW. The heat source in the model was due to the friction between the tool shoulder, the pin and the work piece. A constant friction coefficient was applied to the model. The stress distribution in the weld was calculated using the estimated temperature distribution. Similar studies on analysis of force generated during FSW and the effect of parameters on these forces were presented by Chen and Kovacevic (2004).

Terry Dickerson et al (2003b) calculated the heat flow into the tool during the FSW process using FEM and suggested that the grooves introduced in the tool, reduced the heat transferred into the tools considerably and increased the efficiency of the weld.

Buffa et al (2006a) proposed a Langrangian, three dimensional, coupled rigid–viscoplastic FE model for friction stir welding process. The distribution of temperature and strain in the HAZ and the weld nugget were studied using the model, Results were validated with experimentally measured force and temperature distribution. It was found that the effective strain distribution was non-symmetric, while the temperature profile and material flow were symmetric in the weld zone. An increase in TRS and a decrease in WS, were found to increase HAZ width. Thermal profile was affected by tool rotation speed, while the material flow was affected by both TRS and WS.

Buffa et al (2006b) simulated the effect of varying tool geometry (cylindrical and conical) and advancing speeds on FSW of AA 7075 using a three dimensional coupled rigid-viscoplastic finite element model. The model
predicted process variables, material flow pattern and grain size of the welded joints. The results were used to find optimal tool geometry and advancing speeds.

Fratini.L et al (2006) investigated the material flow in FSW of AA 7075 using numerical simulations and experiments, by varying TRS, WS and tool pin shape. Material flow was studied by using a thin foil of copper as marker. The results indicated that the material bonding occurred in the advancing side of the FSW joints. The conical tools produced a more uniform material flow, by inducing vertical material movement and thus avoiding formation of defects.

Rajamanickam et al (2009) presented a FEM based three dimensional transient thermal model for thermal history during FSW of 2014 aluminum alloy. The effect of tool rotation and weld speed on temperature distribution and mechanical properties of AA2014 joined by FSW was also investigated. A three level full factorial experiment was conducted. Experiments and ANOVA indicated that the tool rotation speed affects the temperature, while welding speed affects the mechanical properties.

The above models have the advantage to predict the temperature profile of the workpiece, the distribution of the heat, and the stress distribution in the workpiece. But information like the strain rate of the material in the weld and the material flow around the welding tool could not be calculated by these models. The friction coefficient distribution and the shape of the weld, which are important factors for the heat generation, depend on assumptions in these models.
2.4.4 Material Flow Modeling

Modeling of material flow in FSW using models that consider the effect of material flow is a recent area of research. There are two essential approaches in the modelling of material flow, namely, Eulerian approach and Arbitrary Lagrangean Eulerian (ALE) approach. In Eulerian approach, the plastically deformed material is treated as a highly viscous fluid and the computational fluid dynamics (CFD) is used to obtain the flow field. In the ALE, solid mechanics is used for analysing plastic deformation and the displacement field is found using the finite volume method.

2.4.5 Eulerian Model

Eulerian models are based on CFD, with the results obtained by solving the equation of continuity, momentum and energy to obtain the required results. CFD approach is convenient for predicting the temperature distribution and material flow. The method has the advantage that particle tracking is not required as in the case of Lagrangean method, as the material flows through the domain.

Seidel and Reynolds (2003) developed a fully coupled two dimensional FSW process model based on fluid mechanics in which FSW process was simulated as a laminar, viscous flow of a non-Newtonian fluid past a rotating cylinder. The material within the pin diameter was transported only in the rotating direction around the pin. The model predicted deviation from normal flow for certain combinations of process parameters, thus could predict defect formation.

Colegrove and Shercliff (2004) analysed material flow during FSW of AA7075 using CFD based model. The model was applied to analyse the material flow around Trivex and MX-Trivex tools. The results were compared against the analysis results of Triflute tool. The results from
the analysis indicate that transverse and down forces were reduced with Trivex tool. Stream-lines around the tools were used to examine the material flow. The downward force was found to increase with the Triflute tool. The strong auguring action of the triflute tool caused this increase.

Reynolds et al (2005) used weld thermal simulation to provide time–temperature histories for a series of welds made in aluminium alloy 7050-T7. The heating and cooling rate during FSW of aluminium alloy 7050 was affected by WS. The temperatures during FSW correlated well with weld power and the peak temperature was a complex function of TRS and WS. Maximum nugget hardness corresponded to the highest weld temperature.

Colegrove and Shercliff.H.R (2005) has analyzed the three dimensional material flow and temperature around a threaded tool by varying the rotation speed and rake angle of the tool. The model over predicted the size and temperature distribution of the deformation zone as the softening of the material occurring above the solidus temperature and the slip between the tool and the interface were not incorporated into the model.

Cho et al (2005) developed a two dimensional steady state heat transfer and material flow model for the FSW of 304 L stainless steel. The model uses Eulerian formulation that considers coupled viscoplastic flow and heat transfer in the vicinity of the tool pin. The flow stress was calculated using the simplified model given by (1976, Hart (1976). The finite element solution procedure included Isotropic strain hardening and the workpiece temperature was computed assuming various tool temperatures and heat transfer coefficients. The results indicated that the temperature was higher on the advancing side than at the retreating side.

Zhao.Y.H et al (2006) used a viscoplastic model to predict temperature and strain rate during FSW. With the results of temperature and
strain rate from the model, the micro hardness along the weld zone was predicted using the Hall-Petch relation. A good correlation of experimental and simulated value of hardness was observed.

Nandan et al (2006a) developed a complete three-dimensional heat transfer and material flow model for the FSW of aluminum alloy. The equations of conservation of mass, momentum and energy were solved using spatially variable thermo physical properties and non-Newtonian viscosity. The peak strain rate occurred at locations where the velocity gradient was the highest. The strain rate was found to drop sharply a few millimetres below the top surface. The significant decrease in velocity due to viscous dissipation caused a drop in strain rate. The computed strain rates were somewhat higher than the values reported by Frigaard et al (2001). The variation of strain rate with distance was said to cause this difference.

Crawford et al (2006) examined defect development during FSW of AA6061-T6 at different weld pitches and the related process forces and torque. In addition a 3-D numerical model was implemented using CFD to simulate and investigate the parametric quantification of the forces and torques during FSW. Couette and the visco-plastic fluid flow models were simulated and compared with the experimental data.

Colegrove et al (2007) presented a model for predicting heat generation in FSW from the hot deformation and thermal properties of material, the process parameters, the tool and plate dimensions. The model was used to illustrate the optimisation of process conditions such as rotation speed in a given alloy and to demonstrate the sensitivity to key parameters such as contact radius under the shoulder, and the choice of stick or slip conditions. The aim of the model was to provide a predictive capability for FSW temperature fields directly from the material properties and weld conditions, without recourse to complex CFD software. This would enable
simpler integration with models for prediction of, for example, the weld microstructure and properties.

Atharifar et al (2009) presented a CFD model for simulating material flow and heat transfer in the FSW of AA6061-T6 aluminum alloy and analyzed the viscous and inertia loads applied to the FSW tool by varying the welding parameters. Carreu viscosity model was used to model the workpiece and simulated results were validated with experiments. Both the inertial and viscous forces had the same order of magnitude in initiating the longitudinal force but the viscous force had an insignificant role in initiating the axial force and inertial forces were insignificant in initiating the lateral forces. The total required power was affected mainly by the angular velocity and the effect of linear velocity on power could only be realized at high angular velocities.

Kim et al (2009) simulated the strain rate and temperature history to compute the nucleation, growth, and coarsening of precipitates using microstructural modeling. With the distribution of the precipitates, the yield stress of the joint was calculated.

2.4.6 Arbitrary Lagrangean Eulerian Models

Arbitrary Lagrangep Eulerian (ALE) formulation is a finite element solution technique, in which, the computational system is not attached to a material (Lagrangean based), or is fixed in space (Eulerian-based). The mesh inside the domain can move arbitrarily, while the mesh on the boundaries moves with the material. ALE overcomes the drawbacks in Lagrangean-based and Eulerian-based finite element simulations. The ALE formulation helps to avoid unacceptable element distortion in the FSW simulations, by permitting adaptive meshing and local remeshing. Contact algorithms in the explicit form are less expensive than implicit algorithms.
Schmidt and Hattel (2005) analysed the thermomechanical conditions under which the cavity behind the tool was filled and weld formation occurred. A fully coupled thermo-mechanical 3-D finite element model was developed in ABAQUS/Explicit using the ALE formulation. Adaptive boundary conditions were used with the Johnson-Cook material law.

Zhang et al (2007) used finite element technique to simulate material flow in FSW under different process parameters. Results indicated that equivalent plastic strain correlates well with the distribution of microstructure zones in the weld. The gradient of equivalent plastic strain was higher on the advancing side, and the maximum of equivalent plastic strain also occurred on the advancing side. Axial load affected equivalent plastic strain in the nugget and a quasi-linear relation existed between the axial load and the variation of the equivalent plastic strain. The material flow in FSW mainly occurred by tangential movement of the material. Material in front of the pin moved upward, while material behind the pin moved downwards. Increase of the translational velocity and the angular velocity of the pin accelerated the material flow. The material flow in the swirl on the advancing side became faster with the increase of the translational velocity. In a similar approach, Zhang and Zhang (2007a) used FEM to study the 3-D material flow and mechanical features under different parameters. The developed model was applied to study the effect of axial pressure by Zhang and Zhang (2007b), effect of shoulder size by Zhang et al (2009a) and welding parameters by Zhang and Zhang (2009) on the temperatures and material behaviours in FSW. The results indicated that the axial force was a key factor and insufficient or excessive axial pressure caused failure of FSW.

Increasing axial pressure increased the maximum temperature. Increasing the shoulder size increased the maximum temperature and enlarged the stirring zone. Grain growth was controlled by temperature variation, while
the material deformation dominated recrystallisation, when strain and strain rate became smaller. The maximum temperature in the FSW process could be increased with increase of TRS, while increasing TRS and WS increased the power required. Material from advancing side entered the retreating side, made one or two revolutions and sloughed off from the tool and then entered the wake formed by the tool. Material particles from the top surface did not enter into the wake and just pile up at the retreating side and resulted in the formation of flash. Increasing the rotating speed and decreasing welding speed, increased the stirring effect and hence the quality of the weld. But higher welding speeds resulted in flash and hence had negative effect on the quality of the weld. Increase in welding speed must be accompanied with increase in rotating speed to avoid defect formation. Longitudinal residual stress was much higher than transverse stress. Simultaneous increase of rotation speed and welding speed increased residual stresses. When traverse speed was higher the stirring effect of the tool became weaker and contribution of deformation heating to temperature rise increased.

Grujicic et al (2010) modeled FSW of AA5083-H131 using a fully coupled thermo-mechanical finite element model. Plastic deformation and dynamic recrystallization were considered to account for the microstructure evolution in the nugget. Compressive residual stresses prevailed at larger distances from weld-line at advancing side. The residual stresses increased in magnitude as one approached the weld line and then became tensile at 15-20 mm from weld line. In the innermost portion of the nugget, tensile stresses decreased and as the distance increased on the retreating side, stresses gradually became zero. The computed post-FSW residual stress and material-strength distribution matched with measured results.
Arora et al (2011) developed a criterion to identify the optimum tool shoulder diameter for FSW of AA6061. The optimum tool shoulder was identified as the one that equally partitioned the torque between sticking and sliding. A 3-D heat transfer and visco-plastic flow model was used to predict the torque. For a TRS of 1200 rpm, a shoulder diameter of 18 mm produced superior tensile properties.

2.5 **STATISTICAL MODELING**

Friction stir welding process parameters affect the microstructure and mechanical properties of the joint. Process modeling primarily involves the optimization of process parameters to obtain superior mechanical properties. With the evolution of different heuristics, optimum process conditions that would result in the desired microstructure and properties can be determined.

Balasubramanian (2008) developed empirical relations to predict FSW process parameters that will produce defect free friction stir welds in five different aluminum alloys namely AA1050, AA6061, AA2024, AA7039 and AA7075. The quality of the weld was evaluated by macro structural analysis.

Elangovan et al (2008a) developed a mathematical model to predict the tensile strength of AA 2219 aluminum alloy. Tool profile, TRS, WS and axial force were considered as the influencing parameters. Response surface methodology and five level central composite design was used for developing model.

Elangovan et al (2008b) investigated the effect of axial force and tool pin profiles on FSP zone formation in AA6061 aluminium alloy. FSW was done using five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) at three different axial...
force levels. Empirical relation between base metal properties, tool rotational speed and welding speed was established. It was reported that the square tool pin profile produces mechanically sound and metallurgically defect free welds compared to other tool pin profiles.

Elangovan and Balasubramanian (2008a) investigated the effect of tool pin profile (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) and tool shoulder diameter on FSP zone formation in AA6061 aluminium alloy. Tensile tests were conducted and the formation of FSP zone was analysed macroscopically. It was found that the square pin profiled tool with 18 mm shoulder diameter produced mechanically sound and metallurgically defect free welds compared to other tool pin profiles.

Babu et al (2009) developed a mathematical model using response surface method to predict tensile strength of friction stir welded AA2219 aluminum. A central composite design with four factors and five levels was used. Hooke and Jeeves search technique was used to maximize the tensile strength of the friction stir welded AA2219 aluminium alloy joints. Microhardness ($H_V$) and tensile tests were performed at room temperature. The fatigue tests were conducted in the axial total stress-amplitude control mode employed under constant loading control up to 250 Hz sine wave loading, with $R = 0.1$. Microstructural evolution was studied using optical microscopy and SEM.

Jayaraman et al (2009) used Taguchi technique to optimize the linear velocity, rotational speed and axial force to maximize the tensile strength of A319 friction stir weld joints. The tool rotation was found to be the dominant factor affecting tensile strength followed by the linear velocity. A non linear regression model was developed to predict the tensile strength of the joints.
Rajakumar and Balasubramanian (2012) investigated the FSW joints made using six different grades of aluminium alloys (AA1100, AA2219, AA2024, AA6061, AA7039, and AA7075). Macrostructural analysis was carried out to identify the feasible working range of process parameters. The optimal welding conditions to attain maximum strength for each alloy were identified using empirical relationships developed using Response Surface Methodology (RSM).

Hasan Okuyucu et al (2005) developed an Artificial Neural Network model to predict tensile strength, yield strength, elongation, hardness of weld metal and hardness of heat effected zone (HAZ) with the tool rotational speed (TRS) and welding speed as inputs.

Record. J. H et al (2007) reported from his statistical investigation that the axial force was affected by the plunge depth and feed rate, while the longitudinal was affected feed rate, followed by pin length, and spindle speed. The location of the weld relative to the sides of the plate affects axial force and the tool temperature at the axis near the end of the pin was higher than the temperature near the root of the pin and at the outside edge of the shoulder.

2.6 STUDIES ON DISSIMILAR FSW

Friction stir welding of aluminum alloys was well established and many research publications are available. Recently, industrial requirements for light weight, cost effective and tailor welded blanks have made the joining of dissimilar materials indispensable. Welding dissimilar metals has been a major issue as many occasions demand varying properties at different locations.
Lee et al (2003a) reported about FSW of A356 to AA6061 dissimilar aluminum alloys. Mechanical properties of the weld mainly depended on the materials fixed at the retreating side. The stir zone had onion ring pattern that appeared like lamellar structure. Material fixed on retreating side influenced the mechanical properties of the weld.

Peel et al (2006b) explored the process window for FSW of AA 5083 to AA6082. The temperature under the tool was more strongly dependent on the TRS than WS. Good welds were produced at low values of TRS and high values of WS with AA6082 on the advancing side.

Peel et al (2006a) examined the hardness, grain size and precipitate distribution during FSW of AA5083 to AA6082 under varying values of TRS and WS. A thermal model developed by Peel et al (2006b) was coupled with hardness models to predict hardness variations across the welds.

Steuwer et al (2006) used neutron diffraction and synchrotron X-ray diffraction to characterise the residual stress for dissimilar friction stir welds between AA5083 and AA6082. The largest stresses occurred in the longitudinal direction. The dissolution of the hardening precipitates during welding caused a transient reduction in YS. Compressive stresses in the parent material balanced the tensile stresses around the weld line. The properties and residual stresses in the welds were substantially influenced by the TRS.

Cavaliere et al (2005) and Cavaliere et al (2006b) investigated the mechanical and microstructural properties of 2024 and 7075 aluminum alloys joined by FSW. Grain structure difference and precipitate distribution were caused due to FSW. Elliptical onion ring pattern was observed at the center of the weld with remarkably smaller grains. The micro hardness profile increased in both the 2024 and 7075 sides and then started to descend after 2
mm from the centre until reaching the hardness corresponding to the parent materials. Nugget zone consists of fine and equiaxed grains. The tensile properties showed a net increase in the longitudinal direction. Results of high cycle fatigue tests showed an increase in fatigue life when compared to fatigue life of FSW AA2024-T3 joints. The ultimate tensile strengths of dissimilar joint and joint of AA2024-T3 were almost the same and the elongation of the AA2024-T3 specimen was very high compared to the dissimilar alloy joints.

Khodir and Shibayanagi (2008) presented the effect of welding speed and location of base metals on microstructure, hardness distributions and tensile properties of dissimilar friction stir welded joints of 2024-T3 Al alloy to 7075-T6. Increase in welding speed produced kissing bond defect. Onion ring patterns, characterized by bands of different equiaxed grain sizes and heterogeneous distribution of alloying elements were formed. Hardness in the HAZ was low. Defect free specimens fractured in the HAZ, while defective joints fractured in stir zone (SZ). The maximum tensile strength of 423 MPa was achieved for the joint produced at welding speed of 1.67 mm/s when 2024 Al alloy was located on the advancing side.

Chen (2009) welded aluminum alloy AA6061 to stainless steel 400 type using FSW. The quality of the dissimilar metals butt joints was evaluated by the impact value and tensile strength. The Taguchi technique with ANOVA was also used to determine the significant factors of performance characteristics. Analysis showed that best quality of impact values, and an acceptable quality of tensile strength, were obtained at a WS of 0.9 mm/s, and a rotation speed of 550 rpm.
Acerra.F et al (2010) attempted to weld the AA7075-AA2024 combination of metals in T-configuration. To fulfil the maximum forging requirements, the diameter of the shoulder had to be large enough to produce the required amount of heat. In the case of coating blanks, the coating elements acted as a major force in the formation of defects.

Da Silva et al (2011) investigated the effect of joining parameters on tensile strength, hardness, material flow and microstructure of dissimilar friction stir welded joints between AA2024-T3 and AA7075-T6. No onion ring formation was observed and the boundary between base materials at the stir zone was clearly seen. Recrystallized fine grained stir zone, with two different grain sizes was developed.

2.7 SUMMARY

From the survey of published literature on FSW, it was found that the FSW process parameters, tool geometry (dimension and profile) and the base metal temper affect the thermal history, temperature distribution, heat transfer, material flow and hence microstructural evolution and properties of friction stir welding joints. The effect of process parameters and tool geometry on the heat transfer aspects and material flow was studied by experimental and modelling approaches. Eulerian model can be best implemented in determining the temperature and material flow that occurred during the welding process. In Eulerian configuration, the results are analyzed either by the implementation of heat flux on the respective faces as in Atharifar et al (2009) and Nandan et al (2006a) or by the viscous dissipation of the fluid due to the tool rotation as in Colegrove and Shercliff (2005) and Long and Reynolds (2006). Most of the literature focus its attention on modeling the temperature and material flow of similar metals. With the pattern of material flow around the tool for different process parameters, the formation of defects has been explained by Long and Reynolds.A.P (2006).
While modelling approach was fast and cost effective, the results had to be validated by experimental data. Dissimilar friction stir welding is a recent area of research with practical interest and challenges. The 2xxx series and 7xxx series alloys have potential application in modern and future aircrafts. For example, the AA7075 plates are FS lap welded as skin with the AA 2024 stringers in aerospace applications. Hence technologies to join these alloys should be evaluated and studied. FSW has paved way for joining alloys which present difficulty when joined by conventional fusion welding processes, and result in defective welds. Studies on the effect of process parameters on the heat transfer, material flow during dissimilar FSW and mechanical properties of dissimilar friction stir welded aluminum alloy joints is limited. Very few studies have been conducted on dissimilar FSW of AA2024 and AA7075, the high strength aerospace aluminum alloys. The aim of this work was to explore the effect of TRS, WS and SD on the thermal history, temperature distribution, and material flow during dissimilar FSW of aluminum alloys AA2024 and AA7075. The effect of the above mentioned factors on the mechanical properties and microstructure of the dissimilar friction stir welded joints was also studied. In this present study, dissimilar formed aluminum alloys are joined by FSW method with various welding conditions.