CHAPTER 2

REVIEW OF LITERATURE

Friction stir welding (FSW) is a new and promising welding process that can produce low cost and high quality joints of heat treatable aluminium alloys and other materials because it does not consume filler materials (filler wire, flux or gas) and can eliminate some welding defects such as crack and porosity. Friction stir welding (FSW) is a solid state joining process that is gaining popularity in the manufacturing sector and, in particular, the aerospace industry. Since no melting occurs during FSW, the process is performed at much lower temperatures than conventional welding techniques and circumvents many of the environmental and safety issues associated with other welding methods. The action of rubbing two objects together causing friction to provide heat is one dating back many centuries as stated by Thomas et al (1991). The principles of this method now form the basis of many traditional and novel friction welding, surfacing and processing techniques. The friction process is an efficient and controllable method of plasticizing a specific area of a material, and thus removing contaminants in preparation for welding, surfacing/cladding or extrusion. In friction welding, heat is produced by rubbing components together under load. Some of the friction stir technologies are shown in the figure 2.1.

Work carried out at The Welding Institute (TWI) has demonstrated that several alternative techniques exist and are being developed to meet the requirement for consistent and reliable joining of mass production aluminium
alloy vehicle bodies. Three of these techniques (mechanical fasteners, lasers and friction stir welding) are likely to make an impact on industrial processing over the next 5 years. FSW could be applied in the manufacture of straight line welds in sheet and extrusions as a low cost alternative to arc welding (e.g. in the fabrication of truck floor walls). The development of robotized friction stir welding heads could extend the range of applications into three dimensional components.

Figure 2.1 - Schematic of friction stir technologies (Thomas et al. 1991)
(a) Radial friction welding, (b) Friction extrusion, (c) Friction hydro pillar processing (d) Friction plunge welding without containment shoulder
Mishra and Mahoney (2007) extended the FSW innovation to process AA7075 and AA5083 in order to render them super plastic. They observed that the grains obtained were recrystallized, equiaxed and homogeneous with average grain sizes < 5 µm. They had high angles of misorientation ranging from 20° to 60°. They had also performed high temperature tensile testing in order to understand the super plastic behaviour of Friction Stir Welded aluminium plates.

2.1 OPTIMIZATION OF MECHANICAL PROPERTIES OF WELDED JOINTS

Welding processes can have various effects on the base metal. High heat input may affect the mechanical properties of the base metal adversely. Cracking occurs when a material is unable to resist the stresses that are applied to it. The level of applied stress varies with the welding process. The joining may change the mechanical properties of the base metal, consequently, this factor must be considered in conjunction with usefulness after joining. The weld or HAZ may be different from the base metal especially in FSW applications in terms of hardness, strength, impact resistance, creep strength, and wear resistance. The mechanical properties of welded joint are the major factors deciding the welding quality. Knowledge of how welding parameters affect the mechanical properties of welds is important. Consequently, the aim of the designer is to optimize the mechanical properties in order to produce excellent welded joints. For accomplishing this purpose different methods and approaches have been developed and applied.

Flores (1998) found that the tensile properties of the joints made with different welding conditions resulted in lowest tensile strength and ductility at lower spindle speed for a given traverse speed. As the spindle speed increased, both the strength and elongation improved, reaching a maximum before falling again at high rotational speeds. It is clear that, in FSW, as the rotational speeds increase, the heat input also increases. Hence, the tool rotation speed must be
optimized to attain maximum tensile properties of the FSW joints. As the welding speed increases, the width of the strained region and the value of the maximum strain decreases and the location of the maximum strain gradually move to the retreating side from the advancing side of the joint. It is also observed that the ultimate tensile strength decreases significantly when the welding speed is increased. The softened area is narrower for higher welding speeds than that for lower welding speeds (Lee et al. 2004). Hence, the welding speed must be optimized to attain maximum tensile properties of the FSW joints.

Liu and Fuji (2003) suggest that at low axial force, the formation of non-symmetrical semi-circular features at the top surface of the weld shows poor plasticization and consolidation of the material under the influence of the tool shoulder. Though weld consolidation is good, formation of shear lips or flashes with excessive height on both advancing side and retreating sides of the weld line due to higher axial force resulted in excessive thinning of the metal in the weld area yielding poor tensile properties. Hence, the axial force must be optimized to attain maximum tensile properties.

Peel et al. (2003) studied mechanical properties, microstructure and residual stresses as a function of welding speed in aluminium AA 5083 friction stir welds. It has been found that the weld properties have been dominated by the thermal input rather than the mechanical deformation by the tool. The main results suggest that the recrystallization results in the weld zone having a considerably lower hardness and yield stress than the parent AA5083. During tensile testing, almost all the plastic flow occurs within the recrystallized weld zone. The peak longitudinal stresses increase as the traverse speed increases. This increase is probably due to steeper thermal gradients during welding and the reduced time for stress relaxation to occur. The base material is in an extremely work hardened state and this is reflected in the hardness profiles.
Park et al. (2004) evaluated the corrosion properties in a friction stir welded 304 stainless steel. The degree of the sensitization was small in the heat affected zone, but the advancing side of the stir zone was corroded significantly because of the formation of the sigma phase. Austenitic stainless steels are widely used in many industries utilizing high temperature components such as heat exchangers and chemical reactors because of their good mechanical properties at elevated temperatures and their excellent corrosion resistance.

Zhao et al. (2005) found that the pin profile plays a crucial role in material flow and, in turn, regulates the welding parameters of the FSW process. Friction Stir Welds are characterized by well-defined weld nugget and flow contours, almost spherical in shape, these contours are dependent on the tool design and welding parameters and process conditions used (Attallah and Salem 2005).

Minton and Mynors (2006) demonstrated conventional milling machine has been capable of performing FSW and producing reasonable welds using a relatively stout tool to join 6.3 mm thick 6082-T6 aluminium. Lesser quality welds were produced when joining 4.6 mm thick 6082-T6 aluminium. Further work is required to establish if the welds in the 4.6 mm can be improved, by enhancing the tool design, while ensuring the tool is sufficiently robust to survive the process. The methodology is tested by producing same thickness welds of 6.3 mm and 4.6 mm 6082-T6 aluminium sheets. The results from micro-hardness profiles across the tool shoulder diameter are presented in conjunction with tensile test results.

Fujii and Cri (2006) investigated the effect of the tool shape on the mechanical properties and microstructures of 5 mm thick welded aluminium plates. The simplest shape (column without threads), the ordinary shape (column with threads) and the triangular prism shape probes were used to weld three
types of aluminium alloys. It has been found that for 1050-H24 whose deformation resistance is very low, a columnar tool without threads produces welds with the best mechanical properties. For 6061-T6 whose deformation resistance is relatively low, the tool shape does not significantly affect the microstructures and mechanical properties. For a low rotation speed (600 rpm), the tool shape does not significantly affect the microstructures and mechanical properties of the joints.

Cavaliere et al (2006) studied the effect of processing parameters on mechanical and microstructural properties of AA 6056 joints produced by Friction Stir Welding. Different samples were obtained by employing rotating speeds of 500 rpm, 800 rpm and 1000 rpm and welding speeds of 40 mm/min, 56 mm/min and 80 mm/min. The mechanical properties of the joints were evaluated by means of micro hardness (HV) and tensile tests at room temperature.

Tveiten et al (2006) proposed some simple and flexible methods to enhance the fatigue life of welded aluminium components. Besides enhancement of the fatigue life, their proposed methods can easily be implemented in manufacturing processes. The key element of the methods is to change residual stresses from tension to compression at locations vulnerable to fatigue. This was accomplished by mechanical prestressing using elastic pre deformation or by thermal prestressing using induction heating. The specimens tested are welded aluminium rectangular hollow section T-joints. Prior to fatigue testing, welding FE simulations were carried out to verify the magnitude and pattern of the residual stress fields (through process modeling). Fatigue testing was later carried out on four different batches. One batch was produced using elastically predeformed chords, two batches were treated by means of thermal prestressing (induction heating). Based on statistical evaluation of S/N data it was reported that the introduction of superimposed compressive stress fields significantly
improved fatigue life. Among the different batches, induction heating turned out to be the most promising method with a fatigue strength improvement factor of 1.5 on stress, compared to “as welded” components.

Elangovan and Balasubramanian (2008a) studied the influence of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA2219 aluminium alloy. AA2219 aluminium alloy has gathered wide acceptance in the fabrication of lightweight structures requiring a high strength-to-weight ratio and good corrosion resistance. Five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) with three different shoulder diameters were considered in their work to fabricate the joints. The formation of FSP zone has been analyzed macroscopically. Tensile properties of the joints have been evaluated and correlated with the FSP zone formation. From the investigation they found that the square pin profile tool with 18 mm shoulder diameter produced mechanically sound and metallurgically defect free welds compared to other tool pin profiles.

Kulekci et al. (2008) determined the effects of the tool pin diameter and tool rotation on the fatigue behaviour of friction stir welded (FSW) lap joints. FSW lap joints of AA 5754 aluminium alloy plates were produced by means of a conventional semiautomatic milling machine. It was reported that the Increasing tool rotation for a fixed tool pin diameter reduces fatigue strength of joints. Increasing tool pin diameter for a fixed tool rotation, decreases fatigue strength of joints. In FSW lap joints, an optimisation between tool pin diameter, tool rotation and tool traverse speed is needed to obtain better fatigue strength. An index derived from tool rotation, traverse speed and tool geometry can be used to identify optimum parameters in FSW. For the FSW lap joints of studied material an index of 6 can be used to select the studied parameters.
Lakshminarayanan and Balasubramanian (2008) used the Taguchi parametric design and optimization approach. Taguchi approach was applied to determine the most influential control factors which will yield better tensile strength of the joints of friction stir welded RDE-40 aluminium alloy. The effect of process parameters such as tool rotational speed, traverse speed and axial force on tensile strength of friction stir welded RDE-40 aluminium alloy is evaluated. Through the Taguchi parametric design approach, the optimum levels of process parameters were determined. The results indicate that the rotational speed, welding speed and axial force are the significant parameters in deciding the tensile strength of the joint. The predicted optimal value of tensile strength of friction stir welded RDE-40 aluminium alloy is 303 MPa.

Sarsilmaz and Caydas (2009) were experimentally investigated the effect of friction-stir welding (FSW) parameters such as spindle rotational speed, traverse speed, and stirrer geometry on mechanical properties of AA 1050/AA 5083 alloy couples. Ultimate tensile strength (UTS) and hardness of welded joints were determined. The full factorial experimental design was conducted to obtain the response measurements. It was reported that; the UTS and nugget hardness increase with traverse speed. The UTS and nugget hardness decrease with tool rotational speed. The most important factor on UTS was found as traverse speed (71.62%), while the rotational speed was the second ranking factor (10.59%) and stirrer geometry was the least (7.03%). The most important factor on nugget hardness was found as traverse speed (72.57%), while the rotational speed was second ranking factor (21.19%) and stirrer geometry was the least (0.89%). The combinations of F3N1T2 and F3N1T1 were the optimal welding conditions for UTS and hardness, respectively. The wideness of the nugget was varying throughout the cross section of the welding zone. Ductile fracture characterization was observed after tensile tests, as expected. The fracture surfaces were covered with a broad population of microscopic voids of different dimensions and shapes.
Jayaraman et al (2009) established an empirical relationship to predict the optimum FSW process parameters to fabricate defect free joints with high tensile strength from the known base metal properties of cast aluminium alloys. The FSW process parameters such as tool rotation speed, welding speed and axial force, etc. play a major role in deciding the weld quality. FSW Joints of cast aluminium alloys A319, A356, and A413 were made by varying the FSW process parameters and the optimum values were obtained. The tensile strength and hardness of the cast aluminium alloys play a major role in deciding weld quality of FSW joints. The empirical relationships established in this investigation can be effectively used to predict the optimum FSW process parameters to fabricate defect free joints with high tensile strength from the known base metal properties of cast aluminium alloys.

Fazel-Najafabadi et al (2010) found that by adjusting the friction stir welding parameters can achieve defect-free dissimilar lap joint of CP-Ti and 304 stainless steel. Titanium as a softer material was selected to be on the lap joint top side. The joint stir zone was found to have two main regions; the dominant fine dynamically recrystallized titanium grains in the upper region and a minor composite type microstructure of fragments of 304 stainless steel in a matrix of fine dynamically recrystallized titanium grains in the lower region. The stir zone was separated from the 304 stainless steel side by an interface layer of Ti-Fe based crystal structure. Joint shear strength was measured; a maximum failure load of 73% of that of CP-Ti was achieved. This was associated with the occurrence of fracture at the joint inter-metallic based interface. The failure load value of the fabricated joints is related to the thickness of the inter-metallic interface.

Arora et al (2010) were reported the work which was carried out in adapted milling machine. Process forces (Fz and Fx) are critical for the selection of a suitable milling machine. Axial thrust is affected significantly by shoulder
diameter and slightly by both tool rotational and welding speeds. Whereas, Fx is affected strongly by welding speed and slightly by tool rotational speed and pin diameter. Deterioration of tensile properties is experienced in case of welded specimens as compared to the base material values. Tensile strength of the welds is significantly affected by welding speed and shoulder diameter and slightly by welding speed. Welding speed is the most significant parameter affecting percentage elongation. Vickers hardness value is lowest in the nugget where TEM studies showed the dissolution and coarsening of second phase particles. Microstructure in nugget consisted of recrystallized grain structure with an average decrease in grain size by a factor of 10. Microstructural changes in TMAZ resulted from the combined effect of heat and deformation. GMA-weld microstructure showed liquation in the PMZ of the weld. This led to the embrittlement of grain boundaries and subsequent decrease in strength of the GMA weld joint.

Shanmuga Sundaram and Murugan (2010) have analyzed dissimilar FS welded joints, which are fabricated using five different tool pin profiles. With the help of Central composite design with four parameters, five levels, and 31 runs, response surface method (RSM) is employed to develop the model. Mathematical regression models were developed to predict the ultimate tensile strength (UTS) and tensile elongation (TE) of the dissimilar friction stir welded joints of aluminium alloys 2024-T6 and 5083-H321. Joints fabricated using Tapered Hexagon tool pin profile have the highest tensile strength and tensile elongation, whereas the Straight Cylinder tool pin profile have the lowest tensile strength and tensile elongation, irrespective of the operating parameters. The increase in tool rotational speed results in the decrease in tensile elongation, whereas tensile elongation increases with increase in welding speed. The tensile elongation decreases with increase in tool axial force.
Padmanaban and Balasubramanian (2010) developed an empirical relationship which was used to predict the tensile strength of the laser beam welded AZ31B magnesium alloy by incorporating process parameters such as laser power, welding speed and focal position. Based on a three factor, three levels, central composite face centered design matrix with full replication technique, the empirical relationship can be used to predict the tensile strength of laser beam welded AZ31B magnesium alloy joints at 95% confidence level. The results indicate that the welding speed has the greatest influence on tensile strength, followed by laser power and focal position.

Gopalakrishnan and Murugan (2011) studied the effective utilization of Aluminium matrix composite (AMC) in particulate reinforced metal matrix composite (MMC). It was based on not only its production but also on fabrication methods. Aluminium matrix titanium carbide reinforced composite (Al–TiCp) was produced in an inert atmosphere by indigenously developed modified stir casting process with bottom pouring arrangement (3–7% TiC by weight). Friction stir welding process (FSW) was employed to make weld joints. The welding parameters such as axial force, welding speed, tool rotation speed, percentage TiC addition etc., and profile of the tool were considered for analysis. The FSW specimens without any post-weld heat treatment belonging to a different set of parameters tested. This exhibited a high joint efficiency (most of them ranging from 90% to 98%) with respect to the ultimate tensile strength of the base material AA6061. It was reported from the analysis of the model that the tool pin profile and the welding speed have a more significant effect on tensile strength.

2.2 FRICTION STIR WELDING IN ALUMINUM ALLOYS

Liu et al (1997) studied microstructural aspects of the friction stir welding of 6061-T6 aluminium. They stated that LM (Light Microscope) and TEM (Transmission Electron Microscope) have been used to characterize the
microstructures in the FS weld zone and compared them with the original 6061-T6 aluminium alloy plate. They have also measured the associated microhardness profile extending from the work piece and through the weld zone. A series of butt welds and simulated welds in solid plate sections have been conducted, at rotational speeds ranging from 300 rpm to 1000 rpm, and translation (traverse) speeds of 0.15 cm/s to 0.25 cm/s. The hardened carbon steel welding head pin was 0.63 cm in diameter and its length was 58 cm. The main results have been obtained suggests that the FS weld zone in 6061-T6 aluminium is characterized by what appears to be a dynamic continuous recrystallization microstructure. Second phase particles in the work piece were essentially “stirred” into the weld zone where the residual hardness varies from 55 WHN near the top of the weld to 65 WHN near the bottom, in contrast to a work piece hardness which varies between about 85 and 100 WHN. The weld zone grain size averaged 10 µm in contrast to 100 µm for the work piece.

Rhodes et al (1997) studied the effects of FSW on microstructure of 7075 aluminium. They stated that the technique, based on friction heating at the faying surfaces of two pieces to be joined, resulted in a joint created by interface deformation, heat, and solid-state diffusion. The weld was characterized by a recrystallized nugget having a 2-4 µm grain size.

Benavides et al (1999) studied low temperature FSW of 2024 aluminium. It has been demonstrated to involve dynamic recrystallization producing ultra fine, equiaxed grain structures to facilitate super plastic deformation. The 2024 Al alloy has been FS welded at a starting temperature of -30 °C, and maximum weld zone temperatures did not exceed about 140 °C. The residual FSW zone grain structure consisted of equiaxed, fine grains having a uniform size of about 0.8 µm throughout. This compares with a central weld zone grain size of about 10 µm in 2024 Al FSW at a starting temperature of 30°C, where the maximum weld zone temperature was measured to be 330°C.
Figure 2.2 (a) and (b) shows the comparison between polished and etched FSW cross sections of 2024 aluminium from room temperature (Figure 2.2 (a)) and low temperature (Figure 2.2 (b)) welds. Figure 2.2 (c) shows corresponding microhardness traverses along the reference lines indicated by the arrows in figure 2.2 (a) and (b).

![Figure 2.2 - Microhardness Comparison](image)

Figure 2.2 – Microhardness Comparison (Benavides et al 1999)
(a) room temperature, (b) low temperature (c) microhardness - Open triangles are room temperature data; solid circles are low temperature data.

Jata and semiath (2000) studied a continuous dynamic recrystallization during FSW of high strength aluminum alloys. They stated that the stir welded plates of an Al-Li-Cu alloy (Al-1.8, Li-2.7, Cu-0.33, Mg-0.33, Mn-0.04, Zr-0.7) have been used which had been hot rolled, homogenized, solution heat treated, water quenched, and naturally aged prior to joining. Optical microscopy (OM) has been performed to reveal the general microstructure of the weld and the base metal.
Chao et al (2001) studied the effect of FSW on dynamic properties of AA2024-T3 and AA7075-T7351. Dynamic, compressive stress-strain curves have been obtained of AA2024-T3 and AA7075-T7351 aluminium alloys and their welds as produced by the FSW process. The experimental results that have been obtained imply that the FSW reduces the yield stress of the weld metal to below that of the base metal, both materials exhibit the strain rate effect. Yield stresses of both base and FS welded material of AA2024-T3 exhibited rate sensitivity. In addition, AA7075-T7351 base metal had some rate dependence. However, no rate effect has been found for AA7075-T7351 FS welded material up to the strain rate of 500/Sec. FSW reduced the yield stress of both AA2024-T3 and AA7075-T7351 under both high strain rate and quasi-static loading conditions.

Salem (2003) used friction stirring technology to join dynamically recrystallized Al base thin sheets for structural parts brought about the need for the macro and micro structural evolution and hardness characterization. FSW at 1000 rpm rotational speeds and 4.2 mm/s feeding rate have been successfully performed with almost no grain growth for the welds. FSW augmented the formation of fine equiaxed structure with high grain boundary misorientation angles. The thermal and mechanical effect associated with FSW controlled the particle size and distribution within the weld nugget and hence the hardness profile. FSW has proven its capability of creating very fine grain structures in the stirred region. This result from the intense plastic straining associated with the movement of material from the front to the back of the rotating pin. Because of the frictional effect as well as shear deformation, the material undergoes localized heating and hence relative softening, which facilitates plastic deformation.

Lee et al (2003) studied the improvement of mechanical properties of Friction Stir welded A356 Al alloy with 87 mm/min, 127 mm/min, 187 mm/min,
and 267 mm/min FSW speeds. The optical micro-structural changes of the stir zone (SZ) with welding speeds were discussed. The Si particles have been homogeneously distributed in the whole SZ regardless of the welding speeds, but the portion of the Si particles in the SZ decreases as welding speed increases. The hardness of the SZ showed more uniform values than that of the BM due to finer and uniformly dispersed Si particles. The transverse ultimate and yield strength had similar values with the BM. All the specimens have been fractured at the unaffected BM. The longitudinal ultimate tensile strength has 178 MPa, which is a 20% improvement on that of the BM, and the yield strength also shows higher value. The mechanical properties of the SZ have been improved by the dispersed Si particles and the homogeneous microstructure compared with that of BM.

Dickerson et al (2003) studied a weld marker technique for flow visualization in friction stir welding. They stated that the technique was based on the use of a marker material that had been redistributed during welding. Copper strips (0.1 mm thick) had been used as markers. After welding various methods have been used to investigate the marker movement including, radiography, tomography and metallurgical sectioning.

Wert (2003) studied microstructures of FSW joints between an aluminium-base metal matrix composite and a monolithic aluminium alloy. They stated that microstructures in FS welds between monolithic AA2024 and AA2014 reinforced with 20 vol.% particulate Al$_2$O$_3$ reveal that the narrowest layers of each material are about 0.1 mm thick. Thus, each material retains its identity in the weld zone and convoluted macro interfaces. When the harder material was on the advancing side of the tool the macro interface span is larger, this can be understood qualitatively by considering how the relative hardness affects material transport. The welds also exhibit eutectic melting. The liquid phase has the traditional form of grain boundary films in the thermo-mechanical
process zone. Particle strings and fragmentation fracture zones have been observed, these may also result from eutectic melting.

Sato et al (2004) studied a friction stir welding of ultra fine grained Al alloy 1100 produced by accumulative roll bonding (ARBed). FSW resulted in the reproduction of fine grains in the stir zone and small growth of the ultra fine grains of the ARBed material just outside the stir zone. FSW suppressed large reductions of hardness in the ARBed material, although the stir zone and the TMAZ experienced small reductions of hardness due to dynamic recrystallization and recovery. Consequently, FSW effectively prevented the softening in the ARBed alloy.

Fonda et al (2004) studied a development of grain structure during friction stir welding. They stated that a stop action friction stir weld has been prepared in Al–Li 2195 to “freeze in” the dynamic deformation field surrounding the FSW tool. Analysis of a plan view section of this weld revealed important new details of the grain structure evolution and texture development occurring around the FSW tool. Bands of refined grains developed ahead of the fully refined region, likely reflecting different relative stabilities of the original grain orientations to the applied deformation. Fine sub grains were formed in response to the predominantly simple shear deformation field and gradually developed greater misorientations to produce the refined grains were observed adjacent to the tool.

Sutton et al (2004) studied a banded microstructure in 2024-T351 and 2524-T351 aluminium friction stir welds for mechanical characterization. They stated that a series of micro mechanical experiments have been performed to quantify the FSW process affects the material response within the periodic bands. Micromechanical studies employed sectioning of small samples and micro tensile testing using digital image correlation to quantify the local stress–
strain variations in the banded region. Results indicate that the two types of bands in 2024-T351 and 2524-T351 aluminium FSW joints have different hardening rates with the particle-rich bands having the higher strain hardening exponent, exhibit a periodic variation in micro hardness across the bands and the individual bands in each material have the same initial yield stress.

Cavaliere et al (2006) studied mechanical and microstructural behavior of 2024–7075 aluminium alloy sheets joined by friction stir welding. The resulted microstructure due to the FSW process had been studied by employing OM and SEM either one as welded specimens and on the tests specimen after rupture occurred. The main results have been obtained that the dissimilar 2024 and 7075 aluminium alloy in the form of 2.5 mm thick sheets have been successfully joined by friction stir welding. The specimen fracture surfaces after testing have been deeply analyzed by using a FEGSEM microscope, revealing the defects topology and location after the friction stirring process and the microscopic mechanisms occurred during high stress deformations and final failure.

Scialpi et al (2007) studied the influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminium alloy. In this work, they considered three shoulder geometries and AA 6082 T6 1.5 mm thick sheets for investigation. The welding process was carried out rotating the tool at 1810 rpm and at a feed rate of 460 mm/min. By visual inspection the crown and root quality has been evaluated. The tools with dissimilar shoulders produce very different crown quality. The bead obtained by the TFC tool (fillet + cavity) was characterized by a smooth surface and very little flash, which was produced but it was removed during the process as a continuous chip. TFC tool crown can be considered the best in terms of crown quality. The resulting microstructure was widely investigated by optical microscopy putting out the influence of shoulder geometry on the nugget grain
size. In the transverse tensile test the three joints showed good strength and non-considerable differences were observed, while great differences were observed in the longitudinal tensile tests of the stirred zone, because TFS (fillet + scroll) and TFC showed a higher and higher strength and elongation respect to the TF (only fillet). With 460 mm/min and 1810 rpm, TFC can be considered the best tool because the combination of fillet and cavity increases the longitudinal and transverse strength of the joint and provide the best crown surface.

Moreira et al (2008) studied Fatigue crack growth in friction stir welds of 6082-T6 and 6061-T6 aluminium alloys. In this work, a comparative study between fatigue crack growth behaviour of friction stir welds of 6082-T6 and 6061-T6 aluminium alloys was carried out. Fatigue crack growth curves were determined for cracks growing in different locations of the weldments, including the base material, the heat affected zone and the welded material. Generally, friction stir material exhibited lower strength and ductility properties than the base material. However, an enhanced crack propagation resistance was observed in the welded material. The 6082-T6 and 6061-T6 base materials exhibited very similar crack propagation behaviour. On the other hand the friction stir 6061-T6 material showed lower crack propagation rates than corresponding 6082-T6 friction stir material.

Scialpi et al (2008) underwent mechanical analysis of ultra-thin friction stir welding joined sheets with dissimilar and similar materials. A deep analysis of the mechanical behavior of two different Al alloys joined by FSW technique was carried out. The analysis included both similar and dissimilar joint configurations in 6082-T6 and 2024-T3 alloy sheets. An important aspect of the study was represented by the plate thickness, which was limited to only 0.8 mm. For this reason, joining process can be correctly classified as FSW. The resulting microstructure has been investigated by optical microscopy and the nugget zone has shown a equiaxed fine grain structure with an estimated grain size <3 µm.
Elangovan et al (2008) had been made investigation to understand the effect of axial force and tool pin profiles on FSP zone formation in AA6061 aluminium alloy. Five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) have been used to fabricate the joints at three different axial force levels. Tensile properties of the joints have been evaluated and correlated with the FSP zone formation. From this investigation it is found that the square tool pin profile produces mechanically sound and metallurgically defect free welds compared to other tool pin profiles. An axial force of 7 kN produces a defect-free FSP region, irrespective of tool pin profiles. Fifteen joints were fabricated in this investigation; the joint fabricated using the square pin profiled tool at an axial force of 7 kN showed superior tensile properties. The formation of FSP zone has been analysed macroscopically. A defect-free FSP region, smaller grains with uniformly distributed finer strengthening precipitates in FSP region and higher hardness are the reasons for superior tensile properties of the above joints.

Karthikeyan et al (2009) studied the mechanical property and microstructural changes during friction stir processing of cast aluminium 2285 alloy. On friction stir processing, the mechanical properties and microstructure of cast aluminium Al 2285 alloy was altered substantially. It was observed around thirty percent improvement in yield and tensile strengths over the parent material. The ductility values too increased around four fold on friction stir processing of parent material. Increase in tool rotational speed for a feed enhances the mechanical properties. Samples processed with a tool transfer feed of 12 mm/min and 1800 rpm rotational speed were found to have better mechanical properties. The defects present in cast aluminium alloys were eliminated in the area of processing.

Elangovan et al (2009) developed a mathematical model to predict tensile strength of the friction stir welded AA6061 aluminium alloy by
incorporating FSW process parameters. Four factors, five levels central composite design has been used to minimize number of experimental conditions. Response surface method (RSM) has been used to develop the model. Statistical tools such as analysis of variance (ANOVA), student’s t-test, correlation coefficient etc have been used to validate the developed model. The developed mathematical model can be effectively used to predict the tensile strength of FSW joints at 95% confidence level. A mathematical model has been developed to predict the tensile strength of friction stir welded AA6061 aluminium alloy joints by incorporating welding parameters and tool profiles using statistical tools such as design of experiments, analysis of variance and regression analysis. The joints fabricated using square pin profiled tool with a rotational speed of 1200 rpm, welding speed of 1.25 mm/s and axial force of 7 kN exhibited superior tensile properties compared to other joints.

Rajakumar et al (2011) developed empirical relationships to estimate the grain size and hardness of weld nugget of friction stir welded AA 6061-T6 aluminium alloy joints incorporating FSW tool and process parameters. A linear regression equation was established between grain size and hardness of the weld nugget of friction stir welded AA6061-T6 aluminium alloy joints. The developed relationships can be effectively used to predict the grain size and hardness of friction stir welded AA6061-T6 aluminium alloy joints within the range of parameters.

2.3 DOUBLE SIDE FRICTION STIR WELDING

Klingensmith et al (2005) described the formation of different microstructural zones in friction stir welded superaustenitic stainless steel (AL-6XN) using results from various characterization techniques. The microstructure of AL-6XN plates joined via a double-sided friction stir weld has been investigated. The microstructural zones that develop during friction stir welding (FSW) reflect decreasing strains and less severe thermal cycles with increasing
distance from the weld centerline. The nugget has a refined structure of equiaxed grains as a result of the extreme strain and temperatures experienced during welding. Several features were seen within the nugget, one of the most prominent being a steady stream of tungsten inclusions created by accelerating tool wear. The heat-affected zone consists of a mixture of relatively large austenite grains and smaller recrystallized grains present at grain boundaries. These fine grains were shown to be austenite and no evidence of sigma phase in this region was apparent. The thermo mechanically affected zone, located between the nugget and heat-affected zone, shows a microstructural transition from the completely refined structure to a structure very similar to the base metal. Unlike fusion welding, micro segregation has been avoided during FSW. Due to the changing microstructure from base metal to the weld zone, there are corresponding changes in hardness. Moving toward the centerline from the base metal, hardness increases due to refinement of grain size.

Aarici and Sinmaz (2005) studied the effects of double passes of the tool on friction stir welding of polyethylene. They welded PP sheets with a single pass of the tool. It created the root defect, which was defined as an area at the bottom of the joint that is not welded. The bottom of each joint was not stirred, and thus left unwelded. This defect was responsible for all tensile and bending failure. In the first pass the plate was welded approximately half of the material thickness, and then turned back and clamped the sample for the second pass of the tool. After the second pass of the tool, no root defect appeared.

2.4 COMPARISON BETWEEN MIG, TIG AND FSW

Ericsson et al (2003) studied the influence of welding speed on the fatigue strength of friction stir welds, and compared with MIG and TIG. They investigated the influence of welding speed on fatigue strength of FS welds and compared the fatigue results with results for conventional arc welding methods. The Al–Mg–Si alloy 6082 was FS welded in the T6 and T4 temper conditions,
MIG-pulse and TIG welded in T6. The T4-welded material has been subjected to a post weld ageing treatment. They have been concluded that at a significantly lower welding speed, the fatigue performance has been improved possibly due to the increased amount of heat supplied to the weld per unit length. The MIG pulse and TIG welds showed lower static and dynamic strength than the FSW. The TIG welds had better fatigue performance than the MIG pulse welds. The experimental results have been obtained that the fatigue strength of FS welded Al–Mg–Si alloy 6082 is higher than that of MIG pulse and TIG welds of the same material. The TIG welds show better fatigue performance than MIG.

Squillace et al. (2004) carried out an experimental investigation on microstructure and corrosion resistance of weld butt joints of AA 2024-T3. They considered two different welding processes: TIG and FSW. Micro-hardness measurements allow pointing out a general decay of mechanical properties of TIG joints, mainly due to the high temperatures experienced by the material. In FSW joint, instead, lower temperatures involved in the process and severe plastic deformations induced by tool motion causes decay of mechanical properties in weld zone. Polarization curve tests and electrochemical impedance spectroscopy, were assessed a generalized nobler behaviour of weld bead with respect to parent alloy. The differences between the three examined zones are not so evident as in TIG joint; retreating zone shows a behaviour nobler than advancing one in FSW joint.

Lakshminarayanan et al. (2009) evaluated the mechanical properties of GMAW, GTAW and FSW joints of AA6061 aluminum alloy. The joints fabricated by FSW process exhibited higher strength values and the enhancement in strength value is approximately 34% compared to GMAW joints, and 15% compared to GTAW joints. Hardness is lower in the weld metal (WM) region compared to the HAZ and BM regions irrespective of welding technique. Very low hardness is recorded in the GMAW joints (58 VHN) and
the maximum hardness is recorded in the FSW joints (85 VHN). The formation of fine, equiaxed grains and uniformly distributed, very fine strengthening precipitates in the weld region are the reasons for superior tensile properties of FSW joints compared to GTAW and GMAW joints.

2.5 MICROSTRUCTURE AND MICROHARDNESS OF FSW

Li et al (1998) studied flow visualization and residual microstructures associated with the friction stir welding of 2024 aluminium to 6061 aluminium. They stated that the FSW of 0.6 cm plates of 2024 AA to 6061 AA was characterized by residual, equiaxed grains within the weld zone having average sizes ranging from 1 µm to 15 µm, exhibiting grain growth from dynamically recrystallized grains which provide a mechanism for super plastic flow, producing intercalated, lamellar like flow patterns. These flow patterns are visualized by differential etching of the 2024 AA producing contrast relative to 6061 AA. The equiaxed grain and sub grain microstructures have been observed to vary according to estimated temperature profiles referenced to the rotating tool axis. Dislocation spirals and loops have been also observed in the 2024 AA intercalation regions within the weld zones at higher speeds (> 800 rpm) corresponding to slightly elevated temperatures introducing dislocation climb, and residual micro hardness profiles follow micro structural variations which result in a 40% reduction in the 6061 AA work piece micro hardness and a 50% reduction in the 2024 AA work piece micro hardness just outside the FSW zone.

Harris and Norman’s (2003) suggested that the variation of the micro-hardness values in the welded area and parent material was due to the difference between the microstructures of the base alloy and weld zone. As compared to base material, considerable softening occurs throughout the weld zone due to the elimination of strain-hardening effect by dynamic recrystallisation.
Chen and Kovacevic (2004) studied joining of AA 6061 alloy to AISI 1018 steel by the combined effects of fusion and solid state welding. The process has been derived from FSW but with an adjustable offset of the probe location with respect to the butt line. Metallographic studies by OM, EDM, and the utilization of the X-ray diffraction technique have been conducted. It has been found that the intermetallic phases Al$_{13}$Fe$_4$ and Al$_6$Fe$_2$ exist in the weld zone.

Jones et al (2005) reported the correlation between microstructure and micro hardness in a friction stir welded 2024 aluminium alloy. They discussed that: the HAZ on the retreating side of a friction stir welded 2024-T351 aluminium alloy has been found to contain two distinct hardness minima on either side of a maximum. The inner hardness minimum close to the TMAZ was found to be due to coarsening and over aging of the S phase occurring during the thermal cycle. The outer hardness minimum was thought to be due to the dissolution of the very fine S phase occurring towards the outer edge of the HAZ. The hardness maximum inter adjacent to these two minima was seen to be due to the presence of very fine S phase precipitates, and was likely to be a result of optimum aging conditions being achieved. The nugget zone was found to be typically fine grained and contained complex dislocation structures within the grains, together with evidence that fine scale S and larger X phase precipitation had occurred from a solutionized state.

Shusheng et al (2007) studied the influence of zigzag-curve defect on the fatigue properties of friction stir welds in 7075-T6 Al alloy. The weld nugget was characterized by a recrystallized, fine equiaxed grain structure because the precipitates have fully or partially gone into solution and reprecipitation during the joining process.

Zadpoor et al (2008) investigated the microstructure of friction stir welded tailor-made blanks. Onion ring structures can be seen in microstructures.
The stirring zone tends to have a heterogeneous texture. A vortex-shape zone, which is coincident with the chemical mixing zone, was observed. The microstructures of the base metals are typical for the cold-rolled aluminium sheets with elongated grains in the rolling direction. The grain size was not the same for different thicknesses of the same material. The size of the WN was found in all cases to be slightly greater than the pin diameter (Reynolds 2000).

The size of the TMAZ was measured to be about 0.4 µm – 0.5 µm for configuration number 1–4. For configuration number 5, the size of the TMAZ was very small. The classic “onion rings” structure has a different morphology (asymmetric vortex-shaped) for the dissimilar-alloy configuration. The asymmetric vortex-shaped region was slightly to the right of the weld centerline and coincides with the chemical mixing zone. One of the features of the onion rings most often referred to is the decreasing distance between the rings when progressing from the center towards the periphery (Krishnan 2002).

First, Biallas et al (1999) suggests that the onion rings were generated due to the reflection of the material flow from the cooler wall of the heat affected zone, creating the necessity for thorough mixing of the two sides of the weld. A second hypothesis was provided by Threadgill (1999) and Krishnan (2002) who argue that the onion rings are related to the forward motion of the welding tool making FSW simply an extrusion process in which a number of semi-cylinders are extruded by the welding tool (Krishnan 2002). The results of the EDS analysis show a very narrow chemical mixing zone, smaller than what expected based on the reflection of the material. The material behind the tool would have to be in the fluid state contradicting the observations reviewed (Mishra and Ma 2005). In fact, the FSW process is mostly considered (Arbegast et al 2003) to work as a localized cold-working process combining conventional metal working zones of pre-heat, plastic, extrusion, forging, and cool-down.
The welded sheets from the same-alloy configurations have two dominant grain orientations, one dominating in the advancing side and the other in the retreating side. This suggests that the large plastic deformations result in a preferred grain orientation. Quantitative texture studies of the FS welds have shown that the effects of the tool shoulder on texture evolution are limited to the upper surface of the sheet and the texture evolution in the weld nugget is largely due to the pin motion (Sato et al 2001). It was shown that the measured texture at the weld centerline is mainly composed of a shear component (Sato et al 2001). Due to different velocity fields, in the advancing side, the shear component rotates around the pin axis in the counter-clockwise direction and on the retreating side; the shear component rotates around the pin axis but in the clockwise direction resulting in two different orientations on either side of the weld (Sato et al 2001).

The dominant grain orientation is significantly different from configuration number 4. The grain orientation distribution is much more complicated. In the advancing side (2024), no dominant grain orientation can be recognized but on the retreating side there are sub-areas with a dominant grain orientation. This is in agreement with the findings of Prangnell and Heason (2005). The rings have apparently resulted from the periodic flow of material around the rear of the pin (Prangnell and Heason 2005, Hassan et al 2003).

The spacing between onion rings is approximately equal to the tool advancement per revolution. Another interesting feature of the welds is the gradient in grain orientation of single rings. The orientation of the grains, within the ring, gradually changes progressing from the advancing side to the retreating side. The heterogeneous nature of the texture as well as the ring-shape structure of the texture is in agreement with the findings of previous researchers (Field et al 2001). In summary, for the same-alloy configurations, the basic microstructural features of the weld zone are not much affected when the
thickness ratio of the sheet changes. Furthermore, the microstructural features of the weld zone for the different-alloy configuration are different from those of the same-alloy configurations.

Figure 2.3 - FS welded AA6082-T6 joint microstructure (Moreira et al. 2009)  
(a) stirred material limit microstructure; (b) nugget structure detail;  
(c) base material microstructure

Moreira et al. (2009) characterized metallurgically the FSW joints of AA6061-T6 with AA6082-T6. The Figure 2.3 (a) represents the transition of the stirred material to non-stirred material, the flow patterns can be easily identified on the left side of the microstructure. Figure 2.3 (b), nugget microstructure detail, can be directly compared with figure 2.3 (c) which represents its base material.

Sakthivel et al. (2009) reported from their investigation that the microstructure of the weld nugget consists of fine equiaxed grains. These grains are more homogeneous at lower welding speed than at higher welding speed. Similarly, size of the weld zone becomes wider when decreasing the traverse
speed as a result of a large amount of frictional heat and easy material flow. Weld zone hardness is decreasing as compared to the parent metal, but the hardness slightly increases with the increase of welding speed. The ultimate tensile strength is observed to increase when decreasing the traverse speed. However, the best mechanical properties are obtained at lower traverse speed presumably due to the occurrence of homogeneous grains and higher heat input.

2.6 MODELING OF FRICTION STIR WELDING PROCESS

2.6.1 Thermal modeling

The heat generated and the temperature history during the FSW process is the first step towards understanding the thermo-mechanical interaction taking place during the welding process. The initial modeling approaches focused on approximate estimation of heat generated during the FSW process. Gould and Feng (1999) developed a preliminary thermal model to predict the temperatures of friction stir welds using the Rosenthal (1946) and Rykalin (1974) equations to describe a moving heat source. The heat input was described as a function of process parameters such as tool rpm and force on the tool.

Chao et al (2003) formulated a boundary value problem for tool and work piece in order to study the heat transfer in friction stir welding. They determined the frictional heat flux from the measured transient temperature fields obtained in the finite element analyses. In an attempt to predict the flow of material around the tool, Colegrove (2000) presented a finite element based thermal model of FSW. Their model included the backing plate and the tool. In their work, the heat input was fitted through an iterative process for verification between the modeled and experimental values.

An input torque based thermal model for prediction of temperature in friction stir welds of Al-6061-T6 alloy was developed by Khandkar et al (2003).
In their model, the heat generated by tool rotation and linear traverse of shoulder and pin, has been correlated with actual machine power input. This estimated heat was applied as a moving heat to obtain the temperature distribution across the weld.

Song and Kovacevic (2004) proposed a coupled heat transfer model of both the tool and the work piece for FSW to include the tool penetration and pulling out phase. A moving coordinate was adopted to reduce the difficulty of modeling the heat generation due to the movement of the tool pin. The finite difference method was used for solving the control equations and the results obtained were in good agreement with the experimental results.

Vilaca et al. (2005) developed an analytical thermal model for simulation of friction stir welding process. The model included a simulation of the asymmetric heat field under the tool shoulder resulting from viscous and interfacial friction dissipation. The analytical model also considered the influence of hot and cold FSW conditions into the heat flow around the tool.

The focus of all the thermal models was to understand the process of heat generation and to predict the temperature distribution in the work piece and tool. A thermal model forms the basis for the development of mechanical and microstructural models.

2.6.2 Thermo-mechanical modelling

In order to estimate residual stress and distortions in work piece resulting from the welding process, thermo-mechanical models were developed and studied. One of the first thermo-mechanical models for FSW was studied by Chao and Qi (1998). A decoupled heat transfer and a subsequent thermo-mechanical analysis of Al 6061-T6 was used in their study. Heat generated from friction between tool shoulder and work piece was implemented as the heat
input. The empirical equation for calculating the heat input to the work piece is given by equation (2.1).

\[ Q(r) = \frac{3Q_t}{2\pi} \left( r_o^3 - r_i^3 \right) \quad (2.1) \]

Where \( Q(r) \) is the rate of heat input, \( r_o \) and \( r_i \) are the radii of the shoulder and the nib of the pin tool, and \( Q_t \) is the total rate of heat input to the work piece expressed as shown in equation (2.2).

\[ Q_t = \pi \omega \mu F \left( r_o^2 + r_o r_i + r_i^2 \right) / 45 \left( r_o + r_i \right) \quad (2.2) \]

Where, \( \omega \) is the tool rotational speed, \( \mu \) is the frictional coefficient, and \( F \) is the downward force. The total heat input and heat transfer coefficient were estimated by fitting the measured temperature data with the analytical model by a trial and error approach. The temperatures thus obtained from the analysis were used to determine the residual stress retained in the friction stir welds. The maximum residual stresses were reported to be 30\% of the yield strength of the material.

Chen and Kovacevic (2003) proposed a three dimensional finite element analysis model to study the thermal history and thermomechanical process in butt welding of aluminium alloy 6061-T6. The model incorporated the mechanical reaction of the tool and thermomechanical processes of the welded material. The friction between the material, the probe and the shoulder was included in the heat source. X-ray diffraction technique was used to measure the residual stresses developed on the plate and the measured results were used to validate the efficiency of the proposed model. From the study, it was reported that fixturing release to the welded plates affected the stress distribution of the weld.
Song and Kovacevic (2003) presented a three-dimensional heat transfer model for friction stir welding (FSW). A moving coordinate was introduced to reduce the difficulty of modelling the moving tool. Heat input from the tool shoulder and the tool pin were considered in the model. The finite difference method was applied in solving the control equations. A non-uniform grid mesh was generated for the calculation. FSW experiments have been done to validate the calculated results. The calculated results were in good agreement with the experimental results. The calculated result also showed that preheat to the work piece were beneficial to FSW.

Staron et al (2004) conducted an experimental study on residual stress states in FSW joints in 6.3 mm and 3.2 mm thick AA 2024 sheets that had been welded under mechanical tension. They were successful in reducing the tensile residual stress in the weld zone by induction of large compressive stresses through mechanical tension.

Zhu and Chao (2004) presented three-dimensional nonlinear thermal and thermo-mechanical simulations using finite element analysis code WELDSIM on 304L stainless steel friction stir welded plates. Initially, a heat transfer problem was formulated as a standard boundary value problem and was solved using the inverse analysis approach. The total heat input and heat transfer coefficient were estimated by fitting the measured temperature data with the analytical model. Later, the transient temperature outputs from the first stage were used to determine residual stresses in the welded plates using a three-dimensional elasto-plastic thermo-mechanical model.

Convection and radiation were assumed to be responsible for heat loss to the ambient on the surface. Their model provided a good match between experimental and predicted results. They reported that the residual stress on the welds after fixture release decreased significantly as compared to those before
fixture release. They also reported that about 50% of the total mechanical energy developed by FSW machine was utilized in raising the temperature of the work piece.

Soundararajan et al (2005) developed a finite element thermo-mechanical model with mechanical tool loading considering a uniform value for contact conductance and used for predicting the stress at work piece and backing plate interface. The non-uniform contact conductance was defined from pressure distribution contours and was used in predicting the temperatures in the thermal model. The thermo-mechanical model was then used in predicting the developed stresses. Khandkar et al (2006) developed coupled finite element models to predict residual stress in AA-2024, AA-6061 and SS 304L friction stir welds. In their models, the temperature history predicted by the thermal model was sequentially coupled to a mechanical model to assess the residual thermal stresses developed during the welding. It was found that clamping constraints and their locations had significant localized effects on the stress components in the unaffected base metal beyond the heat-affected zone.

Feng et al (2007) presented a more detailed thermal-metallurgical-mechanical model to study the microstructure changes and their effects on residual stress distribution in friction stir welding of Al6061-T6. In their approach, the first stage involved a transient nonlinear heat flow analysis to determine the temperature distribution. The frictional heating in the thin layer near the interface was treated as a surface heat generation term, Q, which was estimated by the equation (2.3).

\[ Q = 2\eta\mu Fr / 60 (r_o^2 - r_i^2) \] (2.3)

Where F is the downward force, \( \omega \) is the rotational speed, \( \eta \) is the process efficiency, \( \mu \) is the interpretive coefficient of friction, and \( r_i \) and \( r_o \) the radii of the pin and the shoulder respectively. In the second stage, using the
temperature history of the thermal model as input, the metallurgical calculations were performed in the mechanical analysis as a part of the material constitutive definition subroutine. It was reported that residual stresses had a strong dependence on the welding speed.

Li et al (2007) presented a semi coupled thermo-mechanical finite element model containing both thermal load and mechanical load. Their model included an auto adapting heat source in the thermal model and fixtures were included in the mechanical model. They reported that in the case of 2024-T6 alloy, stresses at the retreating side of the weld were smaller than those on the advancing side.

Bastier et al (2008) used the computational fluid dynamics package to estimate the material flow and temperature field in 7050 aluminium alloy. They used the results to estimate residual state induced in friction stir welding process based on elasto-visco plastic constitutive law. They also reported from the parametric study that the welding speed and rotational speed had an influence on the level of residual stresses and distortions developed during welding.

Hwang et al (2008) conducted an experiment in friction stir welding (FSW) with butt joining configuration of 6061-T6 aluminium alloy. The temperature around the joint line was predicted by regression analysis with the experimental data. From the regression analysis they reported that the temperatures inside the pin can be regarded as a uniform distribution and that the heat transfer starts from the rim of the pin to the edge of the workpiece, approximately following a second-order polynomial equation. The appropriate temperatures for a successful FSW process are between 365ºC and 390ºC. The temperatures on the advancing side were slightly higher than those on the retreating side. The tensile strength and the hardness at the thermo-mechanically affected zone (TMAZ) are about one-half of the base metals. These experimental
results and the process control of temperature histories can offer useful knowledge of an FSW process of butt joining.

Dattoma et al. (2009) evaluated the residual stress fields in similar and dissimilar joints in 2024-T3 and 6082-T6 Aluminum alloy using hole-drill method. The findings from their study showed that in thicker joints very high longitudinal stresses were present and adequate shoulder geometries resulted in reduction of residual stress values.

Rajamanickam et al. (2009) investigated the effect of process parameters such as tool rotation and weld speed on temperature distribution and mechanical properties of aluminum alloy 2014 joined by friction stir welding. A three dimensional transient thermal model using finite element code ANSYS was developed and experimentally validated to quantify the thermal history. To systematically study the influence of input parameters, nine experiments based on full factorial design were performed. Samples were prepared and welded by varying input parameters such as tool rotation and weld speed. The analysis of variance (ANOVA) was employed to investigate the effect of input parameters on thermal history and mechanical properties of the weld. Temperature measurements and analysis of variance (ANOVA) indicated that the temperature under the tool was strongly dependent on the tool rotation speed than the weld speed. The results also indicated that weld speed could be the main input parameter that had the highest statistical influence on mechanical properties.

Fratini et al. (2009) studied the influence of material characteristics on plastomechanics of the FSW process for T-joints. Welding of T-joints were very challenging due to thin walls, poor location of the rib–web interface and the requirements for corner-fillets. They investigated the FSW of T-joints of two popular aluminium alloys, i.e. 2024-T4 and 6082-T6, and the role played by the material characteristics on joining. First, an experimental study was carried out
with specially designed fixture to determine the effect of process conditions. Then, the joints were metallurgically and mechanically evaluated. Finally using a numerical model of the process previously developed by the authors, the thermal and plastic flow fields for the two alloys were calculated and compared. It was found that the material dependent thermal and plastic fields affect the state of TMAZ, HAZ and nugget-region in the joint and that the low-strength high-work hardening alloy 6082 provided a much better joint integrity than the higher-strength low-hardening 2024 primarily due to the greater penetration of the plastic zone in the former.

Peel et al. (2003) investigated the microstructure, mechanical properties and residual stress as a function of welding speed for AA 5083 friction stir welds. They reported that the weld properties were characterized by thermal input rather than the mechanical deformation by the tool. They also reported that with the increase in traverse speed the weld zone decreases, while the peak longitudinal stress increases.

Zhang and Zhang (2007) presented the three dimensional finite element simulations based on solid mechanics. This has been carried out to understand the material flow, the deformations of material, and the formations of weld zones in the friction stir welding process. Comparisons with the experiments suggest that the models established in this paper can adequately help the understanding of the mechanisms of the friction stir welding process. The results under different process parameters can be meaningful to help obtaining better quality of the friction stir welds. Numerical results indicate that the tangent flow constitutes the major part in the material flow. The shoulder can accelerate the material flow on the top half of the friction stir weld. The distribution of the equivalent plastic strain can correlate well with the microstructure zones. Increasing the angular velocity of the pin, the material in the nugget zone can be more fully mixed, which improves the joining quality of
the two welding plates. The increase of speeds, including the rotational speed and the translational speed, can both accelerate the material flow, especially in front of the pin on the retreating side where the fastest material flow occurs. The contact pressure on the pin-plate interface is decreased with the increase of the angular velocity.

Zhang et al (2009) have been studied the influences of the shoulder sizes on temperature distributions and material deformations in FSW by using a fully coupled thermo-mechanical model. It was reported that the maximum temperature can be increased with the increase of the shoulder size. The temperature distribution under the shoulder becomes more uniform with the increase of the shoulder size. The increase of the shoulder diameter can lead to the increase of the efficient power for FSW process. The deformations of material on the advancing side are slightly higher than that on the retreating side. The temperature variation is the main factor for controlling the grain growth near the welding line. But, the recrystallization process can be dominated by the material deformations near the border of the stirring zone.

Rajamanickam et al (2009) detailed the non-linear thermo-mechanical finite element (NLTMEFE) model and studied the thermal history and stress distribution in FSW of aluminium alloy. They considered three welding cases with tool rotational speeds of 355 rpm, 710 rpm and 1120 rpm and reported that the thermal modeling was found useful to predict temperature near the tool shoulder. So the difficulty of determining temperature in weldment prior to welding has been reduced. For three welding cases, predicted temperatures matched with experiment data. Difference of maximum temperature at the same location (weld center) was less than 120 K. Maximum temperature from simulation for all three cases was less than melting point of Al 2014-T6. Using NLTMEFE model, stress fields in welded plates was simulated to find the nature of distribution. The effect of simulated fixture release after the welding was
included in the model. Longitudinal stress perpendicular to weld direction was predicted and validated with experimentally observed values using statistical error analysis. The magnitude of longitudinal residual stress in welded specimen was found proportional to tool rotational speed. This study will provide knowledge about residual stress contours along with thermal history in order to design stress relief techniques, while designing FSW based aluminium alloy structures.

2.7 SUMMARY OF LITERATURE REVIEW

From the above literature study it is evident that there is a potential for Friction Stir Welding of aluminium alloys in various fields. FSW continues to be the subject of investigations and further development and improvements in the joining of aluminium alloys. Even many studies have been performed; there is still a considerable need to further examine existing and new combinations of process parameters. Therefore, studies of the availability and optimization of different process parameters were highlighted in this research. Existing researches are constrained to the optimization of parameters to the particular thickness plate. Hence an attempt has been made to explore the optimization of parameters to different thickness plates. Experimental techniques that include statistical design of experiment, such as Taguchi method and response surface methodology were considered to achieve an optimal solution. There have been no data presented relating to the different weld conditions of different thickness plates on the mechanical properties. Study on various plate thicknesses of 6082 aluminium alloy was carried out. Process and tool parameters were optimized. The study on mechanical properties and microstructural observations were made for different weld conditions.