CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents a literature review on friction stir welding of aluminium alloys and dissimilar alloys. Aluminum alloy 2219 (Al-6.5%Cu) is an age hardenable alloy frequently considered for aerospace applications. This is mainly because of its excellent weldability characteristics. The alloys of the 2000 series are age-hardenable and their high strength is attributed to the precipitation of the Al$_2$Cu($\theta$) phase upon solutionizing and artificial aging. Further improvement in strength can be achieved by cold working, preceding aging. The other elements, namely, chromium, manganese, zirconium and titanium are added in very small proportions to raise the recrystallization temperature range to restrict the grain growth, especially in mill products during hot working. The aluminum alloy 5083 (Al-4.5%Mg) is used for many of commercial marine applications. The main alloying element in the 5000 series is magnesium. A magnesium content of about 4.5% provides good strength and high corrosion resistance to sea water.

2.2 FUSION WELDING OF AA2219

The main application of the alloy 2219 is in the fabrication of aerospace pressure vessels and cryogenic tanks. The size of these tanks kept on increasing and some of the welds could not be made using EB welding. GTA welding continues to be the most widely used process to weld cryogenic tanks. There are no studies available on methods that can be applied to improve the tensile properties of 2219 GTA weld.
Earlier investigations by Robinson et al (1962) showed that aluminium alloy 2219 was by far the most weldable among all the high strength heat treatable alloys. They have compared the weldabilities of various heat treatable aluminium alloys belonging to 2000, 6000 and 5000 series. It was also shown that the alloy 2219 in not prone to solidification cracking and least sensitive to variations in welding parameters and process variations.

The improvement in joint tensile properties was obtained by using electron beam welding to join the alloy 2219 (Trazil and Hood, 1969). Use of low travel speed, low voltage and high amperage in electron beam welding was found to result in better joints. It was also shown by them that the width of the weld has significant effect on the tensile properties of EB welds. Narrow bead width resulted in improvement of yield strength from 193 MPa to 259 MPa in a weld made on 12.7 mm plates of 2219-T87 material. Another study conducted on electron beam welding of heavy gage (50 – 70 mm thick) 2219-T87 plates by Brennecke (1965) has shown that the joint efficiency can be raised to about 80% by using electron beam welding. Though extensive work was done to optimize the welding parameters and to evaluate mechanical properties no weld characterization studies were available on the electron beam welding of 2219 alloy.

Hartman et al 1987 reported that the removal of the crown and the root reinforcement of variable polarity plasma arc (VPPA) welds improved the tensile strength of the joint. In the same work they have reported low tensile values for VPPA welds, in both single pass and multi pass welds the yield strength of the joint was only about 140 MPa in the as welded condition. A small improvement of about 10 MPa in the yield strength was reported after machining off the crown and root reinforcement, where they have found copper rich regions leading to easier initiation of fracture.
2.3 FUSION WELDING OF AA5083

Aluminium alloy 5083 is one of the highest strength non-heat treatable aluminium alloys, with excellent corrosion resistance, good weldability and reduced sensitivity to hot cracking when welded with near-matching magnesium-alloyed filler metal. This alloy is considered as one of the best weldable aluminum alloys and exhibits a slight reduction of the strength of the Heat Affected Zone (HAZ), comparatively to the most of other Aluminum alloys. AA5083 is a non heat treatable Aluminum alloy and therefore conventional post welding treatments are not used.

Different filler metals were developed by adding scandium to existing fillers materials such as 5025 (Al-Mg) and 4043 (Al-Si) alloys which are frequently used as fillers (Bob Irving 1997). A clear increase in weld metal strength was noticed in case of welds made of these fillers. Welding trials were also made using scandium additions on some 7xxx and 6xxx series of alloys, which were known for solidification cracking, if welded autogenously. In case of 6061 alloy cracking got reduced to zero with a small addition of scandium. In case of Al-Mg-Sc alloys, It was shown (Lathabai and Lloyd, 2002) that the cracking susceptibility does not change at a scandium level of 0.26%, during a varestraint test, and the authors have suggested that weld metals might need higher levels of scandium content when compared to their wrought alloy counterparts to obtain a good strengthening effect and resistance to solidification cracking.

Wajira Mirihanage and Nanda Munasinghe (2004) studied the Gas Metallic Arc welded (GMAW) samples of AA5083 were subjected to controlled heating procedures and their mechanical properties. It was observed that there are certain differences of material properties in the test samples depending on heat treatment parameters and the pattern of variation was not uniform along the entire cross section of the weldment. Also the
studies were focused on to the potential improvements of the AA5083. The results shows that the case of HAZ potential of fractional restore of the AA5083 - H321 mechanical properties can be acquire through the heat treating at around the 473 K for approximately five minutes and heat treating 500 K does not make the improvements of hardness or ultimate tensile strengths.

2.4 FRICTION STIR WELDING OF ALUMINIUM ALLOYS

The influence of the friction stir process parameters on the formability of AA5083 was studied by Hirata et al (2006). The friction sir welds were fabricated using a tool shoulder diameter of 12 mm, pin diameter of 4mm and a tool inclination angle of 3°. The rotational speeds of the tool were varied from 500 rpm to 1000 rpm and the welding speed from 100 to 200 mm/min respectively. The yield strength of the specimens increased slightly with a decreasing rotational speed or welding speed. The tensile strength of the specimens was found to be the same for different friction stir welding conditions. The improvement in the ductility was observed during the changes in the combination of the rotational speed and welding speed.

Baeslack III et al (2006), in their studies on friction stir welding of AA8009, found that for the high rotational speed of 1200 rpm and traverse rate (258 mm/min) the significant softening associated with these regions, and the presence of occasional, irregularly-shaped voids near the boundary between the base metal and the weld zone on the advancing side of the weld, promoted a weld tensile strength of 60–70% of the base metal. The selection of a lower tool rotational speed of 428 rpm and a lower traversing rate (114 mm/min) showed fewer bands and a more uniform dispersoid distribution throughout the weld zone, and an absence of defects along the weld zone/base metal interface. The tensile strength of these welds approached 90% of the base metal. Fracture of the tensile specimens for both
weld types consistently occurred near the boundary between the weld zone and the base metal on the advancing side of the weld zone, with a tensile specimen ductility appreciably lower than that of the base metal.

Steuwer et al (2006) studied the effect of the process parameters on residual stress of dissimilar friction stir welds in AA5083 – AA6082. The rotation speed is more useful process variable when attempting to optimize the properties of friction stir welds. Lombard et al (2008) studied the optimizing friction stir welding process parameters to minimize defects and maximize fatigue life in 5083 –H321 aluminum alloy. A flute with threaded pin tool profile was used for this investigation. The rotational speed is the key parameter which governs the tool torque, temperature, and frictional power, and hence, the tensile strength of the FSW joint of AA5083-H32. The highest chance of defect free welds was between the rotational speeds 615 to 630 rpm.

D'Urso et al (2010) investigated the mechanical properties of friction stir welded AA6022-T4 aluminium alloy (lap joint) and performed experiments with sheets having a thickness of 1.2 mm, lap joined by means of a CNC machine tool. Several tests were conducted by varying process parameters (namely feed rate and rotational speed), joints configuration and tool geometry (two different tools were adopted for this purpose). The first tool was a very simple device with a flat shoulder and a cylindrical pin, and their second choice was a more complex tool, with a flat shoulder and a threaded probe. The test favoured the use of threaded pin tools, and indicated that the correct choice of the relative sheet positioning might lead to the improvement of the mechanical properties of the obtained joints. Moreover, the use of the threaded tool showed a certain reduction in welding forces, with respect to the simple tool. The complex, threaded probe was found to be effective in friction stir welding of AA6022-T4 aluminum alloy.
Elangoovan and Balasubramanian (2007) investigated the influences of the pin profile and rotational speed of the tool on the formation of the friction stir processing zone in AA2219 aluminium alloy. In their investigation irrespective of rotational speeds the square pin tool profile produced defect free FSP region. Better tensile strengths were observed when using 1600 rpm as the rotational speed.

Tensile properties and fracture locations of friction stir welded joints of 2017 – T351 aluminium alloy were investigated by Liu et al (2003). As the rotational speed increased, the strained region widened, and the location of maximum strain finally moved to the advancing side from the original retreating side. This implies that the fracture location of the joint was affected by the rotational speed of the tool.

Elangoovan and Balasubramanian (2008) investigated the influences of the tool pin profile and welding speed on the formation of the friction stir processing zone in AA2219 aluminium alloy. In this investigation the effect of welding speed and tool pin profile on FSP zone formation in AA2219 aluminium alloy were analyzed. Five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular, and square) were used to fabricate the joints at three different welding speeds. The results indicated that the square pin profiled tool produce mechanically sound and metallurgically defect free welds compared to other tool pin profiles irrespective of welding speeds. The joints fabricated at a welding speed of 0.76mm/s showed superior tensile properties than the 0.37 mm/s and 1.25 mm/s, irrespective of tool pin profiles. Also, the joint fabricated using square pin profiled tool at a welding speed 0.76 mm/s exhibited maximum tensile strength, higher hardness and finer grains in the FSP region than other combinations used for this investigation.
Friction stir welded joints of AA2095 retain greater than 90% of the base metal strength was observed by Atallah et al (2004). The strength of the joint was decreased with an increase in the rotational speed regardless of the traverse rate. The tensile strength of the joint was increased with decrease in rotational speed due to the decrease in grain size.

Leal and Loureiro (2008) investigated the effect of overlapping friction stir welding passes in the quality of the welds of aluminium alloys. In this investigation the overlapping passes were made in 3 mm thick plates of 5083-O and 6063-T6 alloys. Tunnel defects were detected in the first and second passes of welds in the 5083-O alloy but not in the 6063-T6 alloy. The first pass resulted in a small increase in hardness in the welds in the 5083-O alloy. However, in the 6063-T6 alloy, there was a substantial decrease in hardness and strength. Subsequent overlapping passes produced a modest increase in hardness and strength in both alloys as well the elimination of tunnel defects in welds in 5083-O alloy. The mechanical efficiency of the welds in alloy 5083-O is equal to one as opposed to welds in alloy 6063-T6 that show an efficiency around 0.47. An increase in efficiency of 15% was reached if tensile specimens were polished, in order to remove weld roughness.

The yield strength and tensile strength of friction stir welded joints are lower than that of the base materials AA2219, irrespective of the tool rotational speeds of the joints; this was observed by Elangovan et al (2008a). The tensile strength of the friction stir welded joint was lower at lower rotational speed (1400 rpm). The rotational speed increased from 1400 rpm to 1600 rpm the tensile strength also increased and reached a maximum value at 1600 rpm. The rotational speed of 1600 rpm yielded superior tensile properties of the welded specimens, and on further increasing the rotational speed the tensile strength of the joint was decreased.
Kimapong et al (2004) studied the welding of aluminium with steel and found the effect of pin rotation speed, position of the pin axis, and pin diameter on the tensile strength of the welded region and recorded 86% tensile strength of the base metal. The FSW was not successful as fusion welding process with steels because of cost effective tools.

Bruni et al (2010) studied the effect of the ratio between the rotational speed and welding speed ($\omega/v$) on the mechanical properties, such as the ultimate tensile strength and ductility; of friction stir welded joints in AZ31 alloy sheets. In this investigation FSW experiments were performed with different values of the $\omega/v$ ratio and the influence of the sheet thickness was also investigated. It was observed that an increase in the $\omega/v$ ratio produces an increase in the UTS and strain to failure up to a peak followed by a decrease, and that an increase in the sheet thickness leads to a reduction of the $\omega/v$ ratio at which the peak values are obtained.

Beathe Heinz et al (2002) studied the micro-structural and mechanical properties of friction stir welded aluminium alloy 6013 in the T4 and the T6 tempered conditions, after the welding and after applying a post weld heat treatment (PWHT) to the T4 condition. The microstructural studies revealed that the elongated pancake microstructure of the base material (BM) was transformed into a dynamically re-crystallized microstructure of considerably smaller grain size in the weld nugget. Also, the strengthening precipitates that were present before welding in the T6 state were dissolved during welding in the nugget, while an over-aged state with a much larger precipitate size was established in the heat-affected zone (HAZ). The micro-hardness measurements and tensile tests showed that the HAZ was the weakest region of the weld and the welded sheet exhibited reduced strength and ductility as compared to the base metal.
Madhusudhan Reddy et al (2009) studied the microstructure and mechanical property correlations in AA6061 aluminium alloy friction stir welds. The results indicate that a softened region occurred in the FSW joints due to the dissolution of the strengthening precipitates/coarsening of the precipitates. Post Weld Solution Treatment and Aging (PWSTA) results in coarsening of the grains in the weld zone. The tensile failure location was observed in the HAZ of advancing side of the weld material. In PWSTA treatment the ultimate tensile strength of the joint was increased and ductility was decreased.

The hardness profile across the weld was not consistent with grain size distribution. This was because the hardness profiles in the age hardenable aluminum alloy depend strongly on the precipitate distribution rather than on the grain size. The tensile strength of the joint is lower than that of the parent metal. The as-weld and post weld heat treated samples did not fail in the bend test. The transverse residual stresses in the as-welded condition exhibit an ‘M’ like curve with maximum lying at a distance corresponding to the edge of the tool shoulder.

Ma et al (2006) investigated the FSW to cast aluminum alloy A356 plates, to enhance the mechanical properties through micro-structural refinement and homogenization. The study disclosed that these micro-structural changes led to a significant improvement in both strength and ductility. The higher tool rotation rate (900 rpm) and traverse speed (203 mm/min) was the most effective parameter to refine coarse Si particles, heal the casting porosity, and consequently increase the strength. The post-FSW aging increased the strength of materials processed at higher tool rotation rates of 700 to 1100 rpm, but exerted only a marginal effect on samples prepared at the lower rotation rate of 300 rpm. The T6 treatment of the FSW specimen had higher ultimate tensile strength and ductility than those of cast A356.
Malarvizhi et al (2011) studied the effect of the post weld aging treatment (175°C for 12 hours) on the fatigue properties of square butt joints of alloy 2219 without filler metal addition, using Gas Tungsten Arc Welding (GTAW), Electron Beam Welding (EBW) and Friction Stir Welding (FSW) processes. It was observed that the post-weld aged FSW joints showed superior fatigue performance compared to the EBW and GTAW joints. This was mainly due to the formation of very fine, dynamically re-crystallized grains and uniform distribution of fine precipitates in the weld region. The FSW process offered better reduction in fatigue notch and notch sensitivity factors compared to the other two processes, and the post weld aging treatment was found to be beneficial to enhance the fatigue strength of the weld by approximately 10-12%.

Kwon et al (2003) investigated the mechanical properties of fine-grained aluminium alloy produced by the friction stir process. The results show that the grain size was increased by increasing the rotational speeds. The FSP resulted in generation of the grain size of 0.5, 1-2 and 3-4 mm in AA1050 at tool rotation speeds of 560, 980, 1840 rpm respectively, at a constant traverse speed of 155mm/min. Similarly, the influence of processing parameter on the microstructure of FSW/FSP aluminium alloys were investigated by Ma et al (2002), Sato et al (2002). The results show that the recrystallized grain size was reduced by decreasing the tool rotation speed at a constant tool traverse speed or decreasing the ratio of tool rotation speed/traverse speed.

Oertlelt et al (2001) studied the effect of thermal cycling of friction stir welds of 2195 aluminium alloy. The result of this study showed that the dynamic recrystallized zone (DRZ) contained a fine grain structure and small precipitates present within the grain. The FSW joint showed the lack of symmetry along the centre line of the weld, and this was attributed to the nature of the plasticized metal movement around the rotating tool during welding.
An analysis of friction welds using the inverse problem approach in the friction stir welding of AA2517-T87 aluminium alloy was studied by Fonda and Lambrakos 2002. The study showed that the softening at the TMAZ/HAZ boundary was due to the coarsening and transformation of the strengthening precipitates during the welding process, and the fracture location corresponds to the region with least precipitate strengthening.

Lee et al (2003 a) reported that in AA6061 friction stir welded joints, the area of the stir zone reduced with a decrease in the tool traverse rate. Higher the tool rotating speed produced high temperature in the weld zone and slow cooling rate in the weld after welding. Under the low rotational speed conditions less heat were produced due to lack of stirring. Also, under high rotational speed conditions, the excessive stirred materials moved to the upper surface, which resulted in voids defect in the weld zone. The grain size in the weld zone increased with increasing the rotational speed of the tool.

The ultimate tensile strength of AA5083 decreased significantly when the traverse speed was increased. The voids were formed due to poor consolidation of the weld interface when the tool travelled at higher transverse speeds, and hence there were lower heat inputs. The reduced plasticity and rates of diffusion in the material might have resulted in a week interface. Low transverse rates resulted in a weld with higher strength (Peel et al 2003). Higher traverse speeds were associated with low heat inputs, which results in faster cooling rates of AA5083 FSW joint. This could significantly reduce the extent of metallurgical transformations taking place during welding, and hence, the local strength of the individual regions across the weld zone (Lomolino et al 2005).

Chen et al (2006) reported that for lesser welding speed, defect free welded joints were produced and defect welds were produced when the welding speed was higher than the critical value. The void defects were
present in the upper part of the weld on the advancing side of AA2219-O. The fracture location and tensile properties depends upon the micro hardness distribution and weld defects of the joints. Lee et al 2003b found that the tensile strength of FSW joint had a proportional relationship with welding speed of aluminum alloy 6005. At higher welding speed the softened area was narrower than the lower welding speed in the weld nugget.

Lakshminarayanan and Balasubramanian (2008) found that the tensile strength of FSW on RDE-40 aluminium alloys increases with an increase in the welding speed and decreases when welding speed increases after 45 mm/min. The percentage of contribution of friction stir welding process parameters was calculated. It was found that the traverse speed made 33% contribution to the tensile strength of welded joints and the optimum value of the process parameter of traverse speed is 45 mm/min.

Elangovan et al (2008b) studied the influences of the tool pin profile and axial force on the formation of friction stir processing zone in AA6061 aluminium alloy. The tensile strength of FSW joints was lower at lower welding speed (0.25 mm/s). The tensile strength joint increases when the welding speed was increased from 0.25 mm/s, and reaches a maximum value at 1.25 mm/s. Further, when the welding speed was increased above 1.25 mm/s, the tensile strength of the joint decreased. This trend was common in all the FSW joints, irrespective of the tool process parameters.

Lakshminarayanan and Balasubramanian (2009) observed that at lower welding speed (less than 22 mm/min) the friction stir welded 7039 aluminium alloy joints were produced with a pin hole defect, due to the excessive heat input per unit length of the weld. The tunnel defect was found at the bottom during high rotational speed (75 mm/min) on the retreating side due to the inadequate flow of material caused by insufficient heat input. Response surface methodology (RSM) and artificial neural network (ANN)
models were developed for predicting the tensile strength of the FSW specimens. It is concluded that the rotational speed has more influence on ultimate tensile strength, followed by welding speed and tool axial force. The optimum parameters of the FSW joints were 1460 rpm as rotational speed, 40 mm/min welding speed and the axial force was 6.5 kN.

2.5 FRICTION STIR WELDING OF DISSIMILAR ALUMINIUM ALLOYS

Khodir and Shibayanagi (2008) fabricated the Friction stir welding of dissimilar AA2024 and AA7075 aluminum alloys and found defect-free welds. Firoudzer et al (2010) conducted a test on the FSW welded 6061 Al and AZ31 Mg and studied the effect of the tool position on the weld region. It was found that increasing the heat input can increase liquation (i.e. liquid formation, even though the FSW is solid-state welding), and hence, cracking and brittle Al$_3$Mg$_2$ and Al$_{12}$Mg$_{17}$ could severely weaken the joint.

Kumar et al (2010) showed that this asymmetry can be important even for dissimilar aluminum alloys that have much higher thermal conductivity than steels. The comparison between the tensile strength and ductility of FSW welded similar and dissimilar aluminum alloys showed that the position of the tool with respect to the original joint interface affects the strength and ductility of the joints. The optimal strength and ductility of the weld can be obtained only if the tool offset distance is optimized.

The performance of dissimilar metal FSW joints depends upon the loading conditions. The effects of the loading conditions on the failure modes of dissimilar aluminum alloy FSW spot welds were examined by Tran et al (2010). The experiment showed that the failure occurred at a much lower load during tensile loading than during shear loading.
Tavares et al (2010) compared the yield strength (YS), ultimate tensile strength (UTS), elongation and fatigue strength of FSW welds of dissimilar aluminum alloy butt joints and T joints. The yield and ultimate tensile strengths were similar for the two configurations, whereas the elongation and fatigue strength were somewhat lower for the T-joints. Mechanical property characterization is needed prior to the commercial application of any weld configuration.

Yan Yong et al (2010) investigated the dissimilar friction stir welding between 5052 Al alloy and AZ31 Mg alloy with the plate thickness of 6 mm. Sound welds were fabricated for the rotation speed of 600 rpm and welding speed of 40 mm/min. The microstructure studies showed that the stir zone of the FSW joint was more refined than that of the base materials. Microhardness values present an uneven distribution, due to the complicated microstructure of the weld, and the maximum value of the microhardness was twice that of the base materials in the weld zone. The tensile fracture was observed at a distance of 2.5 mm from the weld joint center on the advancing side (aluminum side), where the hardness values decreased from the weld zone to the 5052 base material.

Saad Ahmed Khodir and Toshiya Shibayanagi (2008) investigated that the effects of welding speed and fixed location of base metals on microstructures, hardness distributions, and tensile properties of the welded joints of 2024-T3 Al alloy to 7075-T6 Al alloy. The increase in the welding speed led to the formation of kissing bond and pores, especially, when the 2024 Al alloy was located on the retreating side. The formation of the onion ring patterns was observed, as also different equiaxed grain sizes and heterogeneous distribution of alloying elements in the SZ, regardless of the welding speed for the fixed locations of base metals. The minimum hardness values were observed in the HAZ of both sides and their values increased
with welding speed. The wider scattering of hardness was observed in the SZ corresponding to the onion ring pattern. Defect-free joints were fractured in the HAZ on 2024 Al alloy side, where the minimum hardness value area and the FSW joints failed in stir zone. The tensile strength value of the joints was a maximum of 423MPa at a welding speed of 1.7 mm/s when 2024 Al alloy plate was placed on the advancing side.

Cavaliere et al (2009) studied the effect of the processing parameters on the mechanical and microstructural properties of dissimilar AA6082–AA2024 joints produced by friction stir welding. The FSW joints were fabricated with a rotation speed of 1600 rpm and the welding speed increased from 80 to 115 mm/min. The vertical force was increased with the increasing in traverse speed for all the fabricated joints. The best tensile and fatigue properties were obtained for the joints with the AA6082 on the advancing side and welded with a traverse speed of 115 mm/min. The fatigue behavior of the joints was strongly controlled by the material placed on the advancing side of the tool. The welding speed does not influence the fatigue behavior so strongly, when the aluminium alloy 2024 was placed on the advancing side.

Amancio-Filho et al (2008) studied the microstructure and mechanical properties of dissimilar friction stir welds in aircraft aluminum alloys 2024-T351 and 6056-T4. The rotational speed (500–1200 rpm) and the welding speed (150–400 mm/min), while axial force and tool geometry are the process parameters. The result of this study showed that there was nil or very limited chemical mixing of the base materials in the stir zone, with the experimental techniques used in this investigation. Only an intimate physical contact between the base materials was observed. The tensile test results showed that the joint efficiency in terms of tensile strength (around 56.0% of the 2024-T351 and 90% of the 6056-T4 alloys) but poor efficiency in terms of
elongation at the rupture (9.0%). The crack was initiated in the weakest region within the weld zone of TMAZ of 6056-T4 aluminum alloy. The microscopic investigation and mechanical properties suggested that mechanical mixing was the major material flow mechanism in the formation of the stirred zone.

Jamshidi Aval et al (2011) investigated the thermo-mechanical behavior and microstructural evolution in similar and dissimilar friction stir welding of AA6061-T6 and AA5086-O. It was observed that the hardness in AA5086 side mainly depends on the recrystallization and generation of fine grains in weld nugget while hardness in AA6061 side varies with the size, volume fraction and distribution of the precipitates in the weld line and adjacent heat affected zone as well as the aging period after welding. Natural aging in AA6061 after both similar and dissimilar welding occurs, however, its effect on mechanical properties is more obvious in similar welding of AA6061/AA6061. The peak temperature and cooling rate in similar joints of AA6061/AA6061 were higher than the other joints under the same welding conditions employed in the research. Grain refinement occurs in stirred zone for in all samples; however, the finer grain size distribution is achieved within the AA6061 side both for similar and for dissimilar joints, where higher strain rates are produced.

Shanmuga Sundaram and Murugan (2010) investigated the tensile behavior of dissimilar friction stir welded joints of aluminum alloys AA2024-T6 and AA5083-H321. Friction stir welding tools with five different pin profiles were used to fabricate the joints. Regression modeling equations were developed based on the experimental values of ultimate tensile strength and tensile elongation of the joint, and they were validated. The developed models were used to predict the ultimate tensile strength and tensile elongation of the dissimilar FS welded joints of the above alloys within ±10% of their experimental values at 95% confidence level. The tapered hexagon tool
produced higher pulsating effect and smooth material flow, which resulted in
the highest tensile strength and tensile elongation, whereas the Straight
Cylinder tool produced the lowest tensile strength and tensile elongation of
the dissimilar FS welded joints. The increase in the tool rotational speed or
welding speed leads to the increase in the tensile strength; and it reaches a
maximum value and then decreases. The increase in the tool axial force leads
to the increase in the tensile strength of the dissimilar friction stir welded
joints. The tensile strength decreases after it attains a maximum value. The
dissimilar FS welded joints fabricated with Tapered Hexagon tool have the
highest tensile elongation, whereas Straight Cylinder tool have the lowest
tensile elongation, irrespective of the operating parameters used. The increase
in the tool rotational speed results in the decrease in the tensile elongation,
whereas tensile elongation increases with an increase in the welding speed.
The tensile elongation decreases with an increase in the tool axial force.

The microstructure of the interface between the Al alloy and Mg
alloy joined by friction stir welding was characterized, using electron
microscopy. The interface of the FSW between the AA6040 Al alloy and
AZ31 Mg alloy was investigated using SEM and TEM. Two intermetallic
compounds (fine-grained Al$_{12}$Mg$_{17}$ and nanosized-grained Al$_3$Mg$_2$) were
observed. The formation of the nanosized-grained phase was a result of
complex processes that are associated with the solid state joining of dissimilar
materials (Kostka et al 2009).

Da Silva et al (2011) investigated the mechanical properties and
microstructural features as well as material flow characteristics in dissimilar
2024-T3 and 7075-T6 FSW joints. Welds have been performed at a fixed feed
rate (254 mm/min), varying the rotation speed in three levels (400, 1000 and
2000 rpm). The microstructure revealed that the sharp transition from
HAZ/TMAZ to SZ has been observed in the advancing side; while on the
retreating side such transition is more gradual. The minimum hardness value of naturally aged samples has been found in the HAZ on the retreating side (about 88% of 2024-T3 base material). The weld efficiency in terms of tensile strength for the 1000 rpm FSW condition is approximately 96%. Fracture of the specimens has occurred in the HAZ on the retreating side (2024-T3).

Material flow using the stop action technique was used, in order to understand the main features of the mixing process. No onion ring formation was observed; the boundary between both the base materials at the stir zone is clearly delineated, i.e., no material mixing was observed. A non-stable rotational flow inside the threads has been identified due to the formation of a cavity on the rear of the pin. The microstructural observation has revealed the development of a recrystallized fine-grained stir zone, with two different grain sizes resulting from the two different base materials.

Ghosh et al (2010) studied the optimization of friction stir welding parameters for dissimilar aluminum alloys (A356 and 6061) under tool rotational speed of 1000–1400 rpm and traversing speed of 80–240 mm/min. Processing at low tool rotation and traversing speed result in fine grain size of 6061 alloy near interface, reduce residual thermal stress, decrease extent of recovery–recrystallization, increase defect density, promote finer distribution of Si rich particles and improve consolidation of transported material at the back of the tool to eliminate discontinuities within weld nugget. All these factors have synergistic effect in improving the mechanical properties of the dissimilar assemblies. Therefore, the sample fabricated at the lowest tool rotational and traversing speed exhibits superior mechanical properties with respect to the others.

Xue et al (2011) studied the effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al–Cu butt joints. The experimental results revealed that sound defect-free
joints could be obtained under larger pin offsets when the hard Cu plate was fixed on the advancing side. Good tensile properties were achieved at higher rotation rates and proper pin offsets of 2 and 2.5mm; further, the joint produced at 600rpm with a pin offset of 2mm could be bended to 180° without fracture. A thin, uniform and continuous intermetallic compound (IMC) layer at the Al–Cu butted interface was necessary for achieving sound FSW Al–Cu joints. Stacking layered structure developed at the Al–Cu interface under higher rotation rates, and crack initiated easily in this case, resulting in the poor mechanical properties.

Leitao et al (2009) investigated the microstructure and mechanical behaviour of similar and dissimilar AA5182-H111 and AA6016-T4 thin friction stir welds. It was found that the mechanical behaviour of the AA5182-H111 similar welds was very similar to that of the base material. However, for the AA6016-T4 similar welds in alloy AA6016-T4 displayed a drop of 15% in hardness and around 20% in strength. This strength drop was followed by an important loss in ductility due to the localization of the plastic flow in the weakest TMAZ. The dissimilar welds between AA6016-T4-AA5182-H111 exhibit a hardness variation consistent with the microstructure evolution across the TMAZ. Contrary to the AA6016-T4 similar welds, no significant decrease in hardness was observed for the dissimilar welds and its strength efficiency was around 90%. However, its ductility decreases significantly relative to the base materials, due to the previously mentioned heterogeneous characteristics of these welds.

At the tool rotation speeds of 1000, 1200, and 1400 rpm, defect-free welds were successfully obtained, suggesting that there are optimum tool rotation speeds for the dissimilar FSW (A5052P-O and AZ31B-O) with thicknesses of 2 mm. In addition, the surface morphology of the SZ became smoother with an increase in the tool rotation speed. The relatively simple
bonded interface is clearly evident as zigzags near the center of SZ. No formation of a eutectic microstructure suggests that the dissimilar FSW was carried out in the solid state of the base metals. The maximum tensile strength was about 132 MPa, which was about 66% of the tensile strength of the A5052P-O alloy. However, there were no noteworthy changes in the tensile strength as a function of the tool rotation speed. The elongations of the samples were 2% or less, and did not significantly change as a function of the tool rotation speed (Kwon et al 2008). Nandan et al (2006) studied the different deformation behaviours of the dissimilar metals (aluminum alloys), and the possible formation of detrimental inter-metallic compounds, and differences in physical properties such as thermal conductivity, and such factors contributed to asymmetry in both the heat generation and the material flow in the weld region.

Choi et al (2010) showed that the placement of stronger steel on the advancing side reduces the weld nugget size and increases the extent of martensite formation, compared to placement in the retreating side. The research illustrates that the outcome of the FSW of dissimilar steels is significantly affected by the asymmetry in temperature and stress between the advancing and retreating sides. The extent of asymmetry depends on the properties of the two alloys and the welding parameters.

Park et al (2010) studied the locations of two dissimilar alloys that exerted a significant effect on material mixing between AA5052 and AA6061 in the weld nugget. By placing the stronger material on the advancing side the proper mixing was observed when alloy 5052 was placed on the advancing side. In contrast, a thinner weld nugget and inadequate mixing occurred with 6061 on the advancing side.
Sato et al (2010) evaluated the lap shear strengths of FSW spot welds of AA5083 aluminum alloy and AZ31 magnesium alloy combination and examined the results with the help of micro structural characterization of the weld region. Although inter-metallic compounds are generally considered to be harmful, and \( \text{Al}_3\text{Mg}_2 \) was present in the welds in many cases, the lap shear strengths of the welds were adequate. Micro structural examination revealed that the \( \text{Al}_3\text{Mg}_2 \) inter-metallic was sometimes embedded in the eutectic of a Mg and \( \text{Al}_{12}\text{Mg}_{17} \) and the welds had good lap shear strengths. The research illustrated the complexities of the FSW process and the need for detailed characterization of welds prior to qualifying them for service.

Weifeng Xu et al (2010) studied the pitting corrosion of different positions (Top, Middle and Bottom) of the weld nugget zone along the plate thickness in friction stir welded 2219-O aluminum alloy in alkaline chloride solution. The base material was more susceptible to pitting corrosion and presents the surface of grooves as a result of severe pitting corrosion. The corrosion resistance of the weld nugget zone improves greatly compared with the base material in alkaline chloride solution. The \( E_{\text{corr}} \), \( E_{\text{pit}} \) and \( E_{\text{rp}} \) increased the area of hysteresis loop and passive current density decreased from the bottom to the top, when the welding speed decreased from 100 to 60 mm/min or tool rotational speed 600 to 500 rpm.

Weifeng Xu et al (2009) investigated the effect of welding parameters on the microstructure and pitting corrosion of different positions along the thickness of the weld nugget zone in friction stir welded 2219-O aluminum alloy plate using scanning electron microscopy (SEM), polarization experiment and electrochemical impedance tests (EIS). It was found that the material presents significant passivation and the best corrosion resistance at the top when compared to the bottom and the base material. Corrosion resistance decreased with an increase in the tool traverse speed from
60 to 100 mm/min at a tool rotating speed of 400 rpm. Corrosion resistance at a rotating speed 600 rpm was lower than that at 500 rpm.

Ju Kang et al (2010) studied the surface corrosion behavior of an AA2024-T3 aluminium alloy sheet after friction stir welding by using an “in-situ observation” method. The density and degree of the pitting corrosion in the shoulder active zone were slightly larger compared to the other regions on the top surface as found out in the SEM observations. The origins of the pitting corrosion were in the regions between the S phase particles and the adjacent aluminum base. The effect of Al–Cu–Fe–Mn–(Si) intermetallic compounds on the pitting corrosion was attributed to their high self-corrosion potential which induced the anodic dissolution of the surrounding aluminum matrix.

The galvanic corrosion of dissimilar friction stir welded 2024-T3 Al/AZ31B-H24 Mg joints, using a water-based and a non-water-based polishing solution, were evaluated by Liu et al (2009). The results showed that the water-based polishing solution induced more easily the galvanic corrosion attack than the non-water-based polishing solution during the polishing process. The predominant locations of the corrosion attack were observed in the narrow regions of AZ31 alloy adjacent to the Al2024 areas, where there was a low ratio of anode-to-cathode surface area. The corrosion in the dissimilar friction stir welded joints was basically due to the establishment of a strong galvanic couple between the Mg and Al alloys. The low microhardness value with microcracks in the corroded region was attributed to the formation of the porous magnesium hydroxide layer.

Jariyaboon et al (2007) investigated the effect of welding parameters (rotation speed and traverse speed) on the corrosion behaviour of friction stir welds in the high strength aluminium alloy AA2024–T351. The tool rotational speed that played a vital role in controlling the location of
corrosion attack was found. The enhanced cathodic reactivity observed in the nugget region was due to the precipitation of coarse S-phase particles. The corrosion character of the welds was influenced by the processing parameters. The rotation speed was the main factor in determining the location of corrosion for welds fabricated with the processing parameters used for this investigation. For the joint fabricated with low rotational speed, the corrosion attack was in the weld nugget zone, due to the significant increase in anodic reactivity in this region. For the joint fabricated with the higher rotational speeds, the corrosion attack was in the HAZ zone, owing to the presence of sensitised grain boundaries in this region; the nugget zone was a net cathode owing to an enhancement of cathodic reactivity, which protects this region from the attack.

Omar Hatamleh et al (2009) investigated the effects of surface treatment techniques like laser and shot peening on the stress corrosion cracking (SCC) susceptibility of friction stir welded (FSW) 7075 aluminum alloy joints. The peening effects on stress corrosion cracking susceptibility in FSW samples by slow strain rate testing in a 3.5% NaCl solution, and the effects of peening on corrosion while submerged in a 3.5% NaCl solution with no external loads applied, were investigated. The results of this investigation showed that no signs of corrosion pitting or SCC were evident on any of the tensile samples during the slow strain rate testing. The friction stir welded plates exposed in 3.5% NaCl solution for 60 days were inspected periodically for signs of corrosion and stress corrosion cracking in the areas expected to have residual stresses due to welding. After 60 days of exposure pitting corrosion was seen on the samples, but no stress corrosion cracking was detected on any of the peened or unpeened samples.

Surekha et al (2009) investigated the effect of the tool rotation speed and traverse speed on the corrosion behavior of friction stir processed high strength precipitation hardenable 2219-T87 aluminum alloy. The results
of this investigation showed that the tool rotation speed had some influence on the corrosion behavior, while the traverse speed does not have any influence. The corrosion resistance was increased with the increase in the rotational speed.

A comparison of the corrosion resistance of AA6060-T5 and AA6082-T6 jointed surfaces via Friction Stir Welding (FSW) and Metal Inert Gas (MIG), respectively, was reported by Stefano Maggiolino and Chiara Schmid (2008). The result indicated that the joint welded via Friction Stir is more resistant than that welded via the Metal Inert Gas technique. The corrosion resistance between the base material and the welded joint exists for the FSW does not have much difference. MIG welding results showed that the more critical zones were the interfaces around the thermal affected zone that forms during MIG welding process. The criticism was enhanced by the low area extension of the interfaces that could increase the corrosion rate.

Cristiano Padovani et al (2011) investigated the corrosion protections afforded by laser surface melting (LSM) AA7449-T7951 friction stir welds. The LSM produced the melting of the constituent particles and formation of a homogeneous 3-5µm thick layer. Electrochemical tests showed the reduction in cathodic reactivity after LSM. In situ and ex situ observation after immersion showed that LSM reduced the depth attack in the weld region (particularly the HAZ), affording sacrificial protection to the substrate.

Aluminum alloy friction stir welds exhibited corrosion susceptibility, where sensitization of the microstructure occurs. The response of the microstructure to the welding was intense, and intergranular corrosion, mainly located along the nugget’s heat-affected region, was promoted by coarsening of the grain boundary precipitates. Short-term post-weld heat treatments, with temperatures similar to the welding temperatures, modify the
microstructure and reduce the corrosion. The corrosion resistance of FSW was increased by modifying the microchemistry during welding. (Paglia and Buchheit 2008)

Electrochemical tests were undertaken to determine the optimum conditions in sea water for corrosion protection of friction stir-welded 5083-O aluminium alloy. Polarization observations showed that the limiting potential that avoids the effects of hydrogen embrittlement was -1.6 V, corresponding to the crossover point between concentration polarization and activation polarization. The optimum protection potential lies between -1.5 and -0.7 V since the current density at these values was low in the potentiostatic tests. The welds exhibit electrochemically stable trends when a galvanic cell was formed in the seawater. Welded parts in galvanic tests with various area ratios were stable and had excellent anticorrosion characteristics. (Sung-Hyeon PARK et al 2009).

Samar Jyoti Kalita (2011) investigated the microstructure and corrosion properties of diode laser melted friction stir weld of aluminum alloy 2024 T351. The noticeable increase in the pit nucleation resistance (390mV) after the laser surface treatment was observed. The repassivation potential was nobler to the corrosion potential after the laser treatment, which confirmed that the resistance to pit growth was improved.

2.6 TAGUCHI METHOD FOR OPTIMIZATION OF WELDING PROCESS PARAMETERS

The main objective of parameter design was to optimize the settings of the process parameters values for improving the performance characteristics and to identify the product parameter values under the optimal process parameters values (Montgomery 2001). In addition, it was expected that the optimal process parameter values obtained from the parameter design
are insensitive to the variation of environment conditions and other noise factors. Therefore, the parameter design was the key step in the Taguchi method to achieve high quality without increasing the cost.

Taguchi method uses a special design of orthogonal arrays to study the entire parameters with a minimum number of experiments. Taguchi defined a loss function to calculate the deviations between the experimental value and the desired value. He recommends the use of the loss function to measure the performance characteristics deviating from the desired value. The value of the loss function was further transformed into a signal to noise (S/N) ratio. For the analysis of the S/N ratio there were three categories of the performance characteristics that were the lower the best, the higher the best and the nominal the best. The S/N ratio for each level of process parameter was computed based on the S/N ratio analysis. The optimal levels for the process parameters were selected based on highest S/N ratio in the category of the performance characteristic and a statistical analysis of variance ANOVA was performed to see that the process parameters are statistically significant. The optimal combination of the process parameters was predicted with the help S/N ratio and ANOVA analysis. The confirmation test was conducted to verify the optimal process parameter obtained from the parameter design (Nian et al 1999).

Lakshminarayanan and Balasubramanian (2008) studied the process parameters optimization for friction stir welding of RDE-40 aluminium alloy using the Taguchi technique. The Taguchi parametric design and optimization approach was used to evaluate the effect of process parameters such as the tool rotational speed, traverse speed and axial force on the tensile strength of friction stir welded RDE-40 aluminium alloy. The results of these studies indicated that the rotational speed, welding speed and axial force were 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 was 303 MPa.

Mustafa Kemal Bilici (2012) investigated the application of the Taguchi approach to optimize the friction stir spot welding parameters of polypropylene. The investigation showed the experimental and numerical results of friction stir spot welding of high density polypropylene. The determination of the welding parameters played an important role for the weld strength. The experimental tests, conducted according to combinations of process factors, such as the tool rotation speed, plunge depth and dwell time at the beginning of welding, were carried out according to the Taguchi orthogonal table L9 in a randomized way. The Taguchi approach was used as a statistical design of experiment technique to set the optimal welding parameters. The coherence between the numerical predictions and experimental observations in different cases of weld strength was observed. The signal-to-noise ratio and the analysis of variance were utilized to obtain the influence of the friction stir spot welding parameters on the weld strength. The improvement in the weld strength from the initial welding parameters to the optimal welding parameters was about 47.7%.