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Friction Stir Welding of Aluminum Alloys: A Review

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***Abstract*—**Friction stir welding is a solid state joining process. High strength aluminum alloys are widely used in aircraft and marine industries. Generally, the mechanical properties of fusion welded aluminum joints are poor. As friction stir welding occurs in solid state, no solidification structures are created thereby eliminating the brittle and eutectic phases common in fusion welding of high strength aluminum alloys. In this review the process parameters, microstructural evolution, and effect of friction stir welding on the properties of weld specific to aluminum alloys have been discussed.

***Keywords*—**Aluminum alloys, Friction stir welding (FSW), Microstructure, Properties.

I. Introduction

FRICTION STIR WELDING (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid–state joining technique, and was initially applied to aluminum alloys [1]. In essence, FSW is very simple, although a brief consideration of the process reveals many subtleties. The principal features are shown in Fig. 1. A rotating tool is pressed against the surface of two abutting or overlapping plates. The side of the weld for which the rotating tool moves in the same direction as the traversing direction, is commonly known as the advancing side and the other side, where tool rotation opposes the traversing direction, is known as the retreating side. An important feature of the tool is a probe (pin) which protrudes from the base of the tool (the shoulder), and is of a length only marginally less than the thickness of the plate. Frictional heat is generated, principally due to the high normal pressure and shearing action of the shoulder. Friction stir welding can be thought of as a process of constrained extrusion under the action of the tool [2]. The frictional heating causes a softened zone of material to form around the probe. This softened material cannot escape as it is constrained by the tool shoulder. As the tool is traversed along the joint line, material is swept around the tool probe between the retreating side of the tool (where the local motion due to rotation opposes the forward motion) and the surrounding undeformed material. The extruded material is deposited to form a solid phase joint behind the tool. The process is by definition asymmetrical, as most of the deformed material is extruded past the retreating side of the tool.

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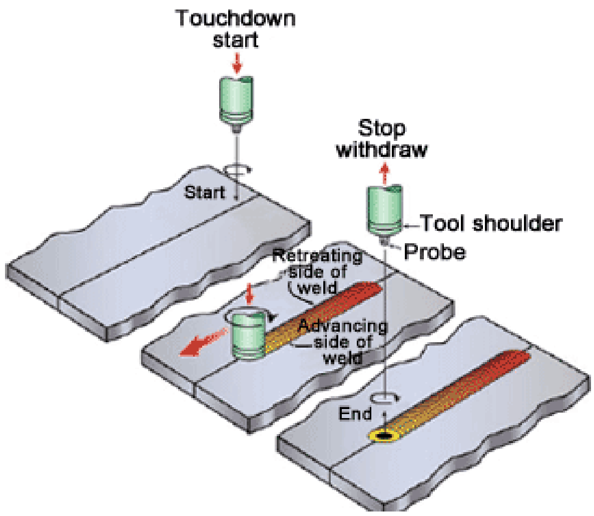

Fig. 1 Schematic diagram of FSW process [2]

Friction stir welding is therefore both a deformation and a thermal process, even though there is no bulk fusion [2]. Thermocouple measurements during FSW of aluminum alloys suggest that, in general, the temperature stays below 500°C [3]-[5]. To date, the prime focus of FSW has been for welding aluminum alloys, although the process has been well developed for both copper alloys [6], [7] and magnesium alloys [8], [9]. The welding process in these materials takes place at considerably higher temperatures, although the feasibility of the process has been demonstrated, further work is needed to improve the performance and longevity of tool materials. In addition considerable work has focused on using FSW to join dissimilar aluminum alloys [10], [11]. Coverage of the present review is confined to the FSW of aluminum alloys.

II. Process Parameters

FSW involves intricate material movement and plastic deformation. The tool geometry and welding parameters exert a significant effect on the microstructural evolution of the material.

A. Tool Geometry

The tool geometry plays an important role in material flow and in turn decides the traverse rate at which FSW can be carried out. A FSW tool has two basic functions: (i) localized heating, and (ii) material flow. In initial stage of the tool plunge, the heating results primarily from the friction between pin and workpiece. The tool is plunged till the shoulder touches the workpiece. The friction between the shoulder and the workpiece results in the biggest component of heating. From the heating feature, the relative size of the pin and shoulder is critical. The second function of the tool is to stir and move the material. A tool should perform the following functions [12]: (i) reduce the welding force, (ii) enable easier flow of plasticized material, (iii) facilitate the downward augering effect, and (iv) increase the interface between the pin and the plasticized material, thereby increasing the heat generation. From the available literature, it is known that a cylindrical threaded pin, truncated cone and concave shoulder are widely used welding tool features.

B. Welding Parameters

In FSW, two parameters are important: (i) tool rotation rate, and (ii) tool traverse speed along the line of joint. The rotation of the tool results in stirring and mixing of the material around the rotating pin and traverse motion of the tool moves the stirred material from the front to the back of the pin and finishes welding process. Higher tool rotation rates generate higher temperature because of higher friction heating and results in more severe stirring and mixing of material. In addition to tool rotation rate and traverse speed, tool tilt is also an important process parameter. A suitable tool tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material and move material efficiently from front to the back of the pin.

III. MICROSTRUCTURAL EVOLUTION

Due to severe plastic deformation and high temperature in the stirred zone during FSW recrystallization and microstructure evolution occurs in stirred zone and precipitate dissolution and coarsening within and around the stirred zone. On the basis of microstructural characterization of grains and precipitates, three different zones, Nugget (stirred) zone, thermo-mechanically affected zone (TMAZ), and heat affected zone (HAZ) have been identified. The microstructural variations in different zones have considerable effect on post weld mechanical properties.

A. Nugget Zone

Intense plastic deformation and frictional heating during FSW results in generation of a recrystallized fine-grained microstructure within the stirred zone. This region is commonly referred as weld nugget.

1. Shape of Nugget Zone

Depending on the process parameter, tool geometry, temperature of work piece and thermal conductivity of the material, various shapes of nugget zone have been observed. Basically, nugget zone can be classified into two types, basin-shaped nugget that widens near the upper surface and elliptical nugget [12]. The formation of basin shaped nugget zone has been reported in many investigations [13]-[15]. Lombard et al. [16] investigated the effect of varying welding parameters on the properties of friction stir welded AA5083-H321 aluminum alloys and found concentric rings (onion skin structure) in the weld nugget and the width of the nugget was of the order of the pin diameter. Cavaliere et al. [17] reported the formation of elliptical onion structure in the weld centre.

2. Grain Size

Dynamic recrystallization during FSW results in formation of fine and equiaxed grains in nugget zone [17]-[20]. FSW parameters, tool geometry, workpiece composition, temperature of the workpiece, vertical pressure exerts important influence on the size of the recrystallized grains. Table I presents a brief summary of the grain size values for different aluminum alloys.

TABLE I
A SUMMARY OF GRAIN SIZE IN NUGGET ZONE OF FSW ALUMINUM ALLOYS

Material	Plate thickness (mm)	Tool geometry	Rotation rate (rpm)	Traverse speed (mm / min)	Grain size (μm)	Reference
AA6082	4	Cylindrical threaded	1600	40, 56, 80, 115, 165, 325, 460	2 –2.8	[28]
AA6056	4	Cylindrical	500, 800, 1000	40, 56, 80	4.5 –5.5	[17]
Al2024-W	3	Truncated cone	2140	40	4 –8	[15]
Al2024-T4	3	Truncated cone	2140	40	10 – 16	[15]
Al2024-T6 (100ºC – 10 h)	3	Truncated cone	2140	40	10 – 16	[15]
Al2024-T6 (190ºC – 10 h)	3	Truncated cone	2140	40	10 – 16	[15]
Al2024-O	3	Truncated cone	2140	40	6 – 10	[15]
2219-O	14	Truncated cone	400 - 600	60 - 100	Fine and equi-axed	[20]
AA2195	12.5	-	300	150	10	[13]
AA 2195 and AA 7075	12.5	Cylindrical pin	300	150	Fine and equi-axed	[14]
Al 2024-T4	3	Truncated cone pin	2140	40	-	[21]

B. Thermo-Mechanically Affected Zone

The thermo-mechanically affected zone (TMAZ) lies between the heat-affected zone (HAZ) and nugget zone (NZ). The grains of the original microstructure are retained in this region, but in a deformed state. The TMAZ experiences both temperature and deformation during FSW. The initial grains are rotated in the TMAZ [15], [20], [21] and the recrystallization begins at TMAZ/nugget boundary. The TMAZ grain size of the joints was considerably larger than that of the NZ and high density of precipitates was observed within each grain. Similar results have been reported by other researchers [14], [16] and [22].

C. Heat-Affected Zone

Beyond the TMAZ there is a heat-affected zone (HAZ). In the HAZ the plastic deformation is absent or insufficient to modify the initial grain structure [14], [15], [22]. This zone is subjected to only thermal alterations. In HAZ the hardening precipitates can dissolve or coarsen depending upon the base material condition and thermal exposure. Sullivan and Robson [22] investigated the effect of friction stir welding on the microstructure of 40 mm thick AA7449 aluminum alloy in TAF as well as in T7 temper conditions. They reported that in HAZ, the grain size is the same as in the original parent material, but measurements of particle size shows a marked change which becomes more distinct closer to the TMAZ/nugget zone. FSW process results in dissolution, phase transformation, coarsening of precipitates and formation of large precipitate free zone. Additional post-weld heat treatment resulted in marginal increase in the coarsening of precipitates in the HAZ.

IV. Properties

Frictions stir welding results in a significant microstructural evolution within and around the stirred zone. This results in a substantial change in the post weld mechanical properties. In the sections to follow, typical mechanical properties, such as hardness, strength, ductility, residual stress and fatigue are briefly reviewed.

A. Hardness

Many researchers use hardness data as an initial assessment of mechanical properties. Aluminum alloys are classified into heat-treatable (precipitation-hardenable) alloys and non-heat-treatable (solid-solution-hardened) alloys. A number of investigations established that the change in hardness in the friction stir welds is different for precipitation-hardened and solid-solution-hardened aluminum alloys. Many studies on the mechanical properties of FSW joints of heat-treatable aluminum alloys such as 2219-O [15], [19], [21], [23], [24] have indicated that FSW gives rise to softening of the joints and results in significant degradation of the mechanical properties. Xu et al. [20] showed that in case of friction stir welded thick 2219-O aluminum alloy, the hardness presents an asymmetrical distribution through the weld centre line and the maximum hardness was obtained at the weld top on the advancing side because of the piling of materials on advancing side. The weld top was significantly harder than the weld bottom.

Cavaliere et al. [25] investigated the effect of processing parameters on the mechanical and metallurgical properties of dissimilar AA6082-AA2024 joints produced by friction stir welding. The joints were produced with different alloy positioned on the advancing side of the tool. The joints were realized with a rotation speed of 1600rpm and by changing the advancing speed from 80 to 115mm/min. It was reported that the highest value of microhardness were reached in the case of dissimilar AA2024-AA6082 when the 2024 alloy was on the advancing side of the tool and the welding speed was 115 mm/min. When 6082 alloy was employed on the advancing side of the tool, the microhardness profile in the weld nugget appeared more uniform, indicating a better mixing of the material. The hardness in the nugget zone was slightly higher than that in the base material, and the maximum hardness was located in the TMAZ. In all the cases of welding, minimum hardness was reported in the HAZ because of overaging effect. Bousquet et al. [26] reported that the AA2024-T351 friction stir welded joint exhibited a significant microhardness evolution through the weld due to modifications in microstructure.

B. Strength and Ductility

Chen et al. [23] studied the effect of post-weld solution-ageing heat treatment on the tensile properties and fracture locations of 2219-O aluminum alloy FSW joints. Their finding suggests that heat-treated joints exhibits higher tensile strength and lower elongation than the as-welded joints and post-weld heat treatment process has a significant effect on the fracture location of the joints. The welding parameters have a significant effect on the ductility and strength of friction stir welded aluminum joints [20], [25], [27], [28].

Rajamanickam et al. [29] investigated the statistical significance of process parameters such as tool rotation and weld speed on thermal history and mechanical properties of aluminum alloy AA2014. From analysis of tensile property data of joints, it was concluded that the weld speed was the main input parameter that had the highest statistical influence on tensile properties. Elangovan and Balasubramaniam [30] investigated the effect of tool pin profile and tool shoulder diameter on the friction stir processing zone formation in AA6061 aluminum alloy. Five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) with three different shoulder diameters were used to fabricate the joints. Their investigation revealed the following two observations. First, from macrostructure analysis, it was inferred that formation of defect free friction stir processing zone depends on tool profile and tool shoulder diameter. Second, the transverse tensile properties are also dependent on the pin profile and tool shoulder diameter.

Liu et al. [31] studied the effect of FSW parameters on the tensile properties and fracture locations of FSW 2017-T351 aluminum alloy. It was reported that for revolutionary pitch greater than a definite value, some void defects exist in the joints, the tensile properties of the joints were considerably low, and the joints fractured at the weld centre.

Hatamleh [14] investigated the local tensile properties at the different regions of the weld of AA 2195 joint produced by friction stir welding using digital image correlation technique. Highest tensile properties were located in the heat affected zone and the lowest in the weld nugget. More recently Malarvizhi and Balasubramaniam [32] compared the tensile behaviour of AA2219 joints produced by GTAW, EBW and FSW. They reported that of the three welded joints, FSW joints exhibited superior tensile properties compared to EBW and GTAW joints.

C. Residual Stress

As FSW takes place at lower temperatures compared to fusion welding, residual stresses are generally lower than in fusion welds. However, the heating cycle the material experiences during FSW, and the rigid clamping arrangement used can have an impact on residual stresses in the weld [13]. The residual stresses developed during the welding can severely affect the fatigue behavior of the weldments. In order to improve the fatigue life of the weldments, it becomes essential to understand residual stresses and methods to moderate them. The metal flow and the heat generation due to friction forces is greatly affected by operating parameters such as the height and the shape of the pin as well as the shoulder surface of the tool. Furthermore, the force superimposed on the rotating tool during the process itself has to be chosen properly since the generated pressure on the tool shoulder surface and under the pin end determines the heat generation during the process. The high thermal input in FSW can result in tensile residual stresses in the weld region [20], [24].

Pouget and Reynolds [24] measured the residual stress distribution on FSW AA2050 welds. The stress intensity factor profiles due to longitudinal residual stresses were determined in compact tension specimens using cut compliance technique. The welds were made parallel to the rolling direction and specimens were tested both as welded and post-weld heat treated. In both the cases the residual stresses were compressive when approaching the weld, in the heat affected zone and tensile in the weld zone. Residual stresses induced by FSW were quite significant and the peak value was 30% of the HAZ yield stress and almost 50% of the nugget yield stress in the as-welded condition. After the post-weld aging treatment, the amplitude of the residual stresses was smaller, indicating that some relaxation of the residual stresses has occurred during heat treatment.

Fratini and Zuccarello [33] examined the through-thickness residual stresses using the hole-drilling method that occur on aluminum joints, after the welding process. Lombard et al. [16] investigated the effect of varying welding parameters on the residual stress profiles in friction stir welds of aluminum alloy AA5083-H321. They reported that the residual stresses are generally tensile in the weld region, with balancing compressive stresses in the parent plate. Fratini et al. [34] determined the residual stress intensity factor by cut-compliance method in friction stir welds produced in 2024-T351 aluminum alloy. They reported tensile residual stresses inside the weld with the heat affected zones subjected to compressive residual stress. Chen and Kovacevic [35] developed a three-dimensional model based on finite element method to study the thermal impact and evolution of the stresses in the weld considering the effect of the tool.

D. Fatigue

In many applications, like transport vehicle, aerospace structure and bridge construction fatigue properties are critical. Due to widespread interest in the possibilities offered by FSW, it is important to understand the fatigue characteristics of FSW welds.

1. S-N Behavior

In the past few years, several investigations were carried out on the S-N behavior of friction stir weld [12]. There studies revealed that the fatigue strength of the FSW weld was lower than that of the base material. However, the fatigue strength of the FSW weld was higher than that of TIG welds [36] and MIG welds [37]. The finer and uniform microstructure after FSW leads to better properties as compared to fusion welds. Malarvizhi and Balasubramaniam [32] studied the effects of three welding processes namely gas tungsten arc welding (GTAW), electron beam welding (EBW) and friction stir welding on the fatigue properties of AA2219 aluminum alloy joints. Fatigue tests were carried out for both unnotched and notched specimens. Fatigue strength of welded joints at 2 X 106 cycles was taken as the endurance limit for comparison. Their investigations lead to the following observations. First, all the three welding process were found to be detrimental on the fatigue strength of AA2219 aluminum alloy. Second, of the three joints, the joints fabricated by FSW exhibited very high fatigue strength. The fatigue strength of FSW joint was 10% lower as compared to the base metal. The fatigue strength of EBW and GTAW joints were 25% and 45% lower than that of the base metal. Third, for the notched specimens, of the three joints, the joints fabricated by FSW exhibited a higher fatigue life and the joint produced by GTAW exhibited a lower fatigue life.

Moreira et al. [38] investigated the influence of FSW on the fatigue life of specimens of aluminum alloy 6063-T6, containing notches in the TMAZ. Both welded and unwelded notched specimens were fatigue tested under load control at different stress levels. They further used strain-based approach to fatigue for life prediction. Their study revealed the following three important observations. First, the fatigue life of specimens containing a notch machined in the material directly affected by stirring process was higher than the fatigue life of similar notched specimens of parent material. The increase in fatigue life was present at all stress levels. Second, lower fatigue notch sensitivity was observed in friction stirred specimens in comparison to the base material. Further, surface quality of the FSW weld exerts a significant effect on the fatigue life. Third, the effect of FSW parameters on the fatigue strength is complicated and no consistent trend is available so far.

2. Fatigue Crack Propagation Behavior

In recent years, several investigations were carried out to evaluate the effect of FSW on the fatigue crack propagation behavior. The investigated materials and the specimen geometries are summarized in Table II. John et al. [39] investigated the effect of residual stresses on near-threshold crack growth in friction stir welds in aluminum alloy 7050-T7451. Crack growth rates in the weld regions were characterized using edge-crack (compact tension and eccentrically loaded single edge) and centre-crack configurations. Crack growth analysis using equivalent residual stresses were conducted to understand the influence of low residual stresses on the near-threshold crack growth. The study revealed following important observations. First, at lower R-ratio of 0.05, the compact tension specimen exhibited significantly higher fatigue threshold and low crack growth rate compared to the middle cracked tension specimen. Second, at higher R-ratio of 0.8, the differences in crack growth rate between the compact tension and middle cracked tension geometry were considerably reduced. Third, ΔK-Kmax behavior near threshold showed evidence of the dominant influences of residual stresses. Fourth, specimen geometry exhibited a considerable effect on the fatigue crack propagation behavior of FSW welds.

TABLE II
A SUMMARY OF MATERIALS AND METHODS USED FOR EVALUATING FATIGUE CRACK GROWTH OF FSW WELDS

Materials	Testing method	Reference
7050-T7451	Compact tension; centre-crack tension	[39]
2024-T351	Compact tension	[34]
6061-T6; 6082-T6	Compact tension	[40]
AA 2195	Middle crack tension M(T)	[13]
AA2219	Centre cracked tension (CCT)	[32]

E. Corrosion Behavior

The different microstructural zones due FSW exhibit different microstructural characteristics such as grain size, precipitate size and texture. Therefore, various microstructural zones exhibit different corrosion susceptibility. The alloys and corrosive solutions used in various studies are summarized in Table III.

TABLE III
INVESTIGATED FSW MATERIALS AND USED CORROSIVE SOLUTIONS BY VARIOUS INVESTIGATORS

FSW material	Corrosive solution	Reference
7050-T7451	Nacl/H_2O_2	[42]
AA6082T6, AA6060T5	Acid salt solution	[41]
AA2219-T87	Nacl/H_2O_2	[43]
7075-T651	3.5 % Nacl	[13]
AA2219-T87	3.5 % Nacl with pH values of 4, 7 and 11	[32]

Maggiolino and Schmid [41] investigated pitting corrosion behaviour of two aluminum alloys (AA6082T6 and AA6060T5) with two different thicknesses that were welded by FSW technique and compared them with those of base alloys and MIG samples. For the two welding method, different areas of interest were considered. For the FSW samples areas of interest were the base material far enough from the welding zone and the weld bead. For the MIG samples four zones were considered: the base material, the interface between the base material and the thermal affected zone, the interface between the thermal affected zone and the weld bead and finally the area inside the weld bead. Their study revealed following important observations. First, friction stir welded sample has a better behavior concerning the pitting corrosion than that the MIG welded sample does. Second, no significant difference in the corrosion resistance between the base material and the welded joint existed for the FSW. Third, in case of MIG welding of all the zones high corrosion activity was observed in the thermal affected zone. The heat input causes grain coarsening in the TMAZ with partial dissolution of intermetallics that re-precipitates at the grain boundaries. The difference in the microstructure and composition incite the instauration of a macro corrosion cell making the TAZ interfaces more active than other zones. Paglia and Buchheit [42] carried out an immersion experiment in salty solution (NaCl/H2O2) to verify the influence of short-term post-weld heat treatments at temperatures similar to those taking place during friction stir welding on the corrosion behavior of friction stir welded 7050-T7451 aluminum alloy.

Surekha et al. [43] investigated the effect of processing parameters (rotation speed and traverse speed) on the corrosion behavior of friction stir processed high strength precipitation hardened AA2219-T87 alloy. Corrosion resistance of friction stir processed alloy was studied by potentiodynamic polarization, electrochemical impedance spectroscopy and salt spray and immersion tests. Anodic polarization and electrochemical impedance tests in 3.5% NaCl showed an improved corrosion resistance of the processed alloy, which increased with the number of passes. Salt spray and immersion tests also showed improved resistance to corrosion. The increased resistance to corrosion was attributed to the dissolution of CuAl2 particles.

V. CONCLUSION

In this review the process parameters, microstructural evolution and properties of the FSW have been discussed. On the basis of the review the following conclusion can be drawn:

- Tool geometry is important for producing sound welds. However, limited information on tool design is available in open literature.
- Welding parameters, including tool rotation rate, traverse speed, tool tilt and target depth are critical to produce sound and defect free weld.
- The material flow within the weld nugget during FSW is very complex and still poorly understood.
- Intense plastic deformation at high temperature result in significant microstructural evolution within the weld, i.e., fine recrystallized grains, texture, precipitate dissolution and coarsening and residual stresses with a magnitude much lower than that in traditional fusion welding.
- Compared to traditional fusion welding, FSW exhibits a considerable improvement in strength, ductility and fatigue properties.

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