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Friction Stir.Welding is an advance metal joining process: A Review

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Abstract
The friction stir welding is recently developed solid state welding process which overcome the problem associated with fusion welding technology. The properties achieved by friction stir welding is better than that achieve by fusion welding technique It has been invented as a solid-state joining technique and initially applied to aluminum alloys. FSW is used to replace rivets joints in the aeronautical industry. Recently the aircraft and military industries widely have been using aluminum alloys particularly because of their fine strength to weight ratio. However in compare with steels they represent welding difficulties and also lower ductility. In last years it has been observed that Friction Stir Welding (FSW) method represents better microstructure and mechanical properties than conventional methods in welding aluminum alloys. It has been widely investigated for mostly low melting materials, such as Al, Mg and Cu alloys. Aluminum is the most usable material in engineering application and a lot of improvement is needed in the area of its welding. The latest works on friction stir welding of aluminum have been directed towards improving the quality of weld, reducing defects and applying the process of FSW to aluminum for specific applications. This joining technique is energy efficient, environment friendly, and versatile. In particular, it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. FSW is considered to be the most significant development in metal joining in a last decade. The FSW of Aluminums and its alloys has been commercialized; and recent interest is focused on joining dissimilar materials. However, in order to commercialize the process, research studies are required to characterize and establish proper process parameters for FSW. This paper summarizes the trends and advances of this welding processes in the field of welding. Future aspects of the study are also discussed.
Keywords— FSW, Aluminium alloys , process parameters, tool rotation, transverse speed, tool design, mechanical properties, tensile strength, hardness, microstructure properties.

I. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining technique that has expanded rapidly since its development by Mr. Wayne Thomas in 1991 at TWI (The Welding Institute) and has found applications in a wide variety of industries, including aerospace, automotive, railway, and maritime. The FSW process exhibits a number of attractive advantages when compared to other welding processes, perhaps the most significant of which is the ability to weld alloys that are difficult or impossible to weld using fusion welding techniques. The FSW process takes place in the solid-phase, at temperatures below the melting point of the material, and as a result does not experience problems related to re-solidification such as the formation of second phases, porosity, embrittlement and cracking. In addition, the lower temperature of the process enables joining with lower distortion and lower residual stresses.FSW is also an energy efficient process that requires no filler material and, in most cases, does not require the use of a Shielding gas. Furthermore, the process lacks the fumes, arc flash, spatter, and pollution associated with most fusion welding techniques. For these and many other reasons, FSW has become an attractive joining process for many manufacturers. [1] Friction stir welding of aluminium is now a mature and robust process, which is becoming increasingly well established in the fabrication of critical components. It is true to say that FSW has extended the use of welding in certain materials and applications, in particular in the welding of 2xxx and 7xxx alloys for the aerospace industry. The qualities making the process attractive include reduced cost, minimal repair requirement, good properties and total automation leading to a high level of consistency. At the present time, FSW can compete with other welding processes for quality of welds and performance. It should be noted that FSW is still relatively new, and has been in commercial production for less than 15 years. As with fusion welding, FSW is basically a thermal process. Temperatures reached (typically around 500°C) are sufficient to cause major micro structural changes in precipitation hardened or work hardened alloys. Unlike fusion processes, FSW also involves extremely high shear strains and strain rates, which will have a profound influence on the development of microstructures. Friction stir welding is already one of the most energy efficient processes available, although improved process developments (in particular better tool designs) will no doubt further reduce the energy required to make the weld. Now industry has a welding process that can provide high quality and defect free welds in the high strength 2xxx and 7xxx alloys, development of improved alloys which can be welded without loss of properties is required, and this is a major challenge for the aluminium producers. [2]

To date, the predominant focus of FSW has been for welding aluminium alloys, although the process has been well developed for both copper alloys and magnesium alloys. Work is under way to develop the process for materials such as titanium alloys, steels, nickel alloys and even molybdenum. The welding process in these materials takes place at considerably higher temperatures, and 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 aluminium alloys. Furthermore the steady push to lightweight vehicles has largely been responsible for research in joining aluminium alloys to other metals, including aluminium to magnesium, aluminium to metal matrix composites, aluminium to steel and aluminium to copper. [1]

II. PRINCIPLE OF OPERATION – FRICTION STIR WELDING

A constantly rotated non consumable cylindrical-shouldered tool with a profiled nib is transversely fed at a constant rate into a butt joint between two clamped pieces of butted material. The nib is slightly shorter than the weld depth required, with the tool shoulder riding atop the work surface.

Frictional heat is generated between the wear-resistant welding components and the work pieces. This heat, along with that generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without melting. As the pin is moved forward, a special profile on its leading face forces plasticised material to the rear where clamping force assists in a forged consolidation of the weld. [1]

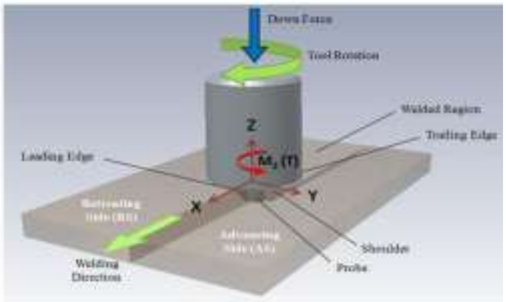

Fig. .1 Frictional stir welding process [3]

This process of the tool traversing along the weld line in a plasticised tubular shaft of metal results in severe solid state deformation involving dynamic re-crystallization of the base material.

2.1 ADVANTAGES OF FRICTION STIR WELDING THAN ALL OTHER WELDING PROCESSES [4, 5, 6, 7, AND 8]

- 2xxx and 7xxxx series Al-alloys and Al-Li alloy are easily joined in comparison to conventional welding process.
- Mechanical properties loss is less because heat input during process is very less.
- Distortion, shrinkage and residual stress are very small in this plate.
- Due to solid state welding process, no chance of occurrence of cracking and porosity is comparison to conventional fusion welding process.
- Welding without filler material.
- No need of further process of surface cleaning.
- Typically 1 Km long welding can be achieved with the same tool.
- It is suitable for automation and robotic application.
- Improved safety due to the absence of toxic fumes or the spatter of molten materials.
- Easily automated on simple milling machines, lower setup costs and less training.
- Can operate in all position (horizontal vertical, etc.) as there is no weld pool

Table 1. Typical applications in FSW [9]

Industrial category	Specific application	Present process	Advantage of using FSW
Electrical	Heat–sink welded lamination	Gas metal arc welding	Higher density of fins-better conductivity
Electrical	Cabinets and enclosures	GMAW	Reduction cost, weld through corrosion coating
Aerospace	Floors, wings and	Rivets	Higher quality,

	fuselages.		cheaper (no rivets and holes)
Rail industry	Rail car body, window, side wall and coupling gears	GMAC	High quality joints.
Automotive	Wheel rims and suspension arms	GMAW, MIG	Better joint integrity

Table .2.Benefits of the FSW process [10].

Metallurgical benefits	Environment benefits	Energy benefits
Solid phase process	No shielding gas required for materials with low melting temperature	Improved materials use
Low distribution	Minimal surface cleaning required	Only 2.5% of the energy needed for a laser weld
No loss of alloying element	Eliminates grinding wastes	Decreased fuel consumption in lightweight aircraft
Multiple parts joint is replaced by fasteners	No harmful emissions	
In joint area mechanical properties is good	No consumable materials required	
Alloying element loss is negligible		

2.2 Microstructure Classification of weld zone

The first attempt at classifying FSW microstructures was made by Threadgill. This work was focused solely on aluminium alloys, and was limited to features distinguishable by light microscopy. However, work on other metallic materials has demonstrated that the behaviour of aluminium alloys is not typical of most metals and alloys, and this initial classification was inadequate [1]. Consequently, a revised set of terms was suggested and then subsequently revised and adopted in the American Welding Society Standard D17·3M These micro structural terms are illustrated in Fig 2, and are defined below along with alternative terms commonly found in the literature:

1. Unaffected material or parent metal: material remote from the weld, which has not deformed and which, although it may have experienced a thermal cycle from the weld, is not affected by heat in terms of detectable changes in microstructure or properties
2. Heat affected zone (HAZ): the region close enough to the weld for the weld thermal cycle to have modified the microstructure and/or properties, but no apparent plastic deformation is detected by light microscopy although it is recognised that some plastic deformation will have occurred, as is typically the case in any weld HAZ.
3. Thermo mechanically affected zone (TMAZ): in this region, the material has been plastically deformed by the FSW tool, and heat from the processing has also affected the material. In the case of aluminium, it is possible to generate considerable plastic strain without recrystallisation in this region, and there is generally a distinct boundary, at least at a macroscopic level, between the recrystallised and deformed zones of the TMAZ.
4. Stir zone: The stir zone (also nugget, dynamically recrystallised zone) is a region of heavily deformed material that roughly corresponds to the location of the pin during welding. A unique feature of the stir zone is the common occurrence of several concentric rings which has been referred to as an "onion-ring" structure.

When presenting micrographs it is also conventional to show the advancing side of welds on the right

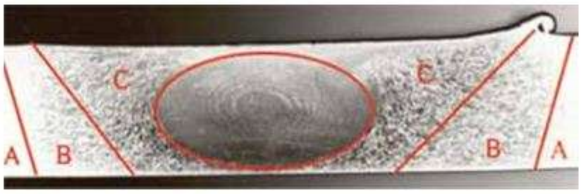

Fig. 2. Micro structural zone classification in a friction stir weld in Al 2024 alloy (A: parent material, unaffected by process; B: HAZ, thermally affected but with no visible plastic deformation; C: TMAZ, affected by heat and plastic deformation) [1]

2.3 Materials used in FSW:

Frictions stir welding process used in joining many types of materials and materials combination. TWI has concentrated most of its efforts to optimizing the process for the joining of aluminium and its alloy.

- 2000 series aluminium alloy (Al-Cu)
- 5000 series aluminium (Al-Mg)

- 6000 series aluminium (Al-Mg-Si)
- 7000 series aluminium (Al-Zn)
- 8000 series aluminium (Al-Li)

Continuing development of the FSW tool, its design and materials have allowed preliminary weld to be successfully produced in:

- Copper and its alloy
- Lead
- Titanium and its alloy
- Magnesium alloy ,magnesium to aluminium
- Zinc
- MMCs based on aluminium (metal matrix composite)
- Other aluminium alloy of the 1000 (commercially pure), 3000(Al-Mg) and 4000(Al-Si) series.
- Plastic
- Mild steel

Single pass butt joint with aluminium alloy have been made in thickness ranging from 1.2 to 50 mm without the need for a weld preparation .Thickness of up to 100 mm can be welded using two passes one from each side with 6082 aluminium alloy. Parameters for butt welding of most aluminium alloys have been optimised, is thickness range from 1.6 to 10 mm. Special lap joining tools have also been developed for aluminium with thickness of 1.2 to 6.4 [11].

2.4 FSW Tool materials

FSW tools are made by different materials. Tool is chosen as for the requirement of material to be welded. Tool materials depend upon the melting temperature of the materials and the desired travelling speed.

Table 3 Summary of current friction stir welding tool materials [12]

Alloy	**Thickness (mm)**	**Tool materials**
Aluminium alloy	< 12 < 26	Tool steel, WC-CO MP159
Magnesium alloy	< 6	Tool steel ,WC
Copper and copper alloy	< 50 < 11	Nickel alloy, PCBN, tungsten alloy Tool steel
Titanium alloy	< 6	Tungsten alloy
Stainless alloy	< 6	PCBN, tungsten alloy
Low alloy steel	< 6	Tungsten Carbide (WC), PCBN

2.5 Tool design:

Heat generation, the power required, plastic flow and the uniformity of the welded joint depend upon the tool design. Tool geometry such as probe length, probe shape and shoulder size are key parameters because it would affect the heat generation and plastic material flow for welding [13]. Tool is important part it consist of shoulder and pin. Main function of tool profile is material flow and in turn regulates the welding speed of FSW process. Main function of shoulder is to generate most of heat and prevents the plasticized materials escaping from the work piece while both the shoulder and the tool pin affect the material flow. A tool should perform following function (i) reduce the welding force, (ii) enable easier flow of plasticized material, (iii) facilitate the downward angering effect and (iv) increase the interface between the pin and the plasticized material, thereby increasing the heat generation. Commonly five pin profile i.e. strength, cylindrical, tapered cylindrical, threaded cylindrical, triangular and square pin to fabricate the joints, in FSW as shown in Fig. .3 [13].

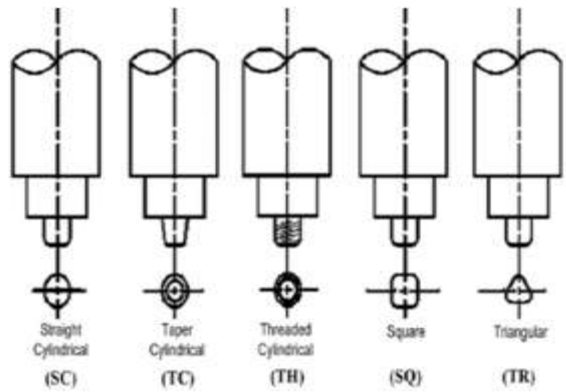

Fig.3. Types of tool pin profiles [14].

2.6 Manufacturing of FSW tool:

Manufacturing of five different FSW tools were made of high carbon high chromium Steel. Different tool pin profiles of straight square (SS), tapered square (TS), straight hexagon (SH), straight octagon (SO) and tapered octagon (TO) without draft were manufactured using CNC turning centre and wire cut electrical discharge machining to get accurate profiles. Each tool had configuration of shoulder diameter of 18 mm, pin diameter of 6 mm and pin length of 5.6 mm, and shoulder to work piece interference surface with 3 concentric circular equally spaced slots of 2 mm in depth on all tools. The tools were oil hardened [15]. The image of manufactured tools is shown in Fig..4.

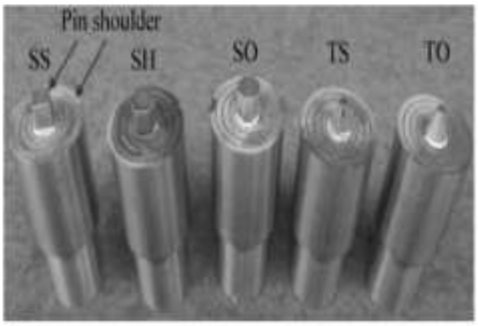

Fig.4. Image of manufacture tool with different tool profile [15]

III. Important FSW process parameters

3.1 Tool rotation and traverse speeds

There are two tool speeds to be considered in friction-stir welding; how fast the tool rotates and how quickly it traverses the interface. These two parameters have considerable importance and must be chosen with care to ensure a successful and efficient welding cycle. The relationship between the welding speeds and the heat input during welding is complex but, in general, it can be said that increasing the rotation speed or decreasing the traverse speed will result in a hotter weld. In order to produce a successful weld it is necessary that the material surrounding the tool is hot enough to enable the extensive plastic flow required and minimize the forces acting on the tool. If the material is too cold then voids or other flaws may be present in the stir zone and in extreme cases the tool may break Excessively high heat input, on the other hand may be detrimental to the final properties of the weld. Theoretically, this could even result in defects due to the liquation of low-melting point phases (similar to liquation cracking in fusion welds). These competing demands lead onto the concept of a "processing window": the range of processing parameters viz. tool rotation and traverse speed that will produce a good quality weld. Within this window the resulting weld will have a sufficiently high heat input to ensure adequate material plasticity but not so high that the weld properties are excessively deteriorated.[1]

3.2 Tool tilt and plunge depth

The plunge depth is defined as the depth of the lowest point of the shoulder below the surface of the welded plate and has been found to be a critical parameter for ensuring weld quality. Plunging the shoulder below the plate surface increases the pressure below the tool and helps ensure adequate forging of the material at the rear of the tool. Tilting the tool by 2–4 degrees, such that the rear of the tool is lower than the front, has been found to assist this forging process. The plunge depth needs to be correctly set, both to ensure the necessary downward pressure is achieved and to ensure that the tool fully penetrates the weld.

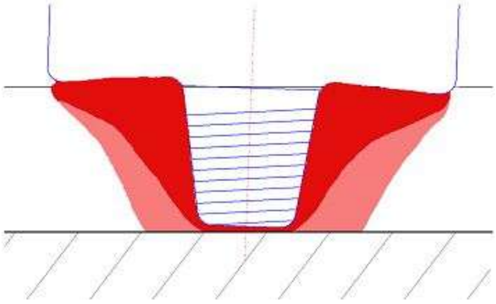

Fig. 5 drawing showing the plunge depth and tilt of the tool [1]

Given the high loads required, the welding machine may deflect and so reduce the plunge depth compared to the nominal setting, which may result in flaws in the weld. On the other hand, an excessive plunge depth may result in the pin rubbing on the backing plate surface or a significant under match of the weld thickness compared to the base material. Variable load welders have been developed to automatically compensate for changes in the tool displacement. [1]

3.3 Welding forces

A downwards force is necessary to maintain the position of the tool at or below the material surface. Some friction-stir welding machines operate under load control but in many cases the vertical position of the tool are preset and so the load will vary during welding. The traverse force acts parallel to the tool motion and is positive in the traverse direction. Since this force arises as a result of the resistance of the material to the motion of the tool it might be expected that this force will decrease as the temperature of the material around the tool is increased. The lateral force may act perpendicular to the tool traverse direction and is defined here as positive towards the advancing side of the weld. Torque is required to rotate the tool, the amount of which will depend on the down force and friction coefficient (sliding friction) and/or the flow strength of the material in the surrounding region. In order to prevent tool fracture and to minimize excessive wear and tear on the tool and associated machinery, the welding cycle is modified so that the forces acting on the tool are as low as possible and abrupt changes are avoided. [1]

3.4 Flow of material

Early work on the mode of material flow around the tool used inserts of a different alloy, which had a different contrast to the normal material when viewed through a microscope, in an effort to determine where material was moved as the tool passed. The data was interpreted as representing a form of in-situ extrusion where the tool, backing plate and cold base material form the "extrusion chamber" through which the hot, plasticised material is forced. In this model the rotation of the tool draws little or no material around the front of the pin instead the material parts in front of the pin and passes down either side. After the material has passed the pin the side pressure exerted by the "die" forces the material back together and consolidation of the join occurs as the rear of the tool shoulder passes overhead and the large down force forges the material.[1]

3.5 Generation and flow of heat

For any welding process it is, in general, desirable to increase the travel speed and minimise the heat input as this will increase productivity and possibly reduce the impact of welding on the mechanical properties of the weld. At the same time it is necessary to ensure that the temperature around the tool is sufficiently high to permit adequate material flow and prevent flaws or tool damage. When the traverse speed is increased, for a given heat input, there is less time for heat to conduct ahead of the tool and the thermal gradients are larger. At some point the speed will be so high that the material ahead of the tool will be too cold and the flow stress too high, to permit adequate material movement, resulting in flaws or tool fracture. If the "hot zone" is too large then there is scope to increase the traverse speed and hence productivity. Heat generation during friction-stir welding arises from two main sources: friction at the surface of the tool and the deformation of the material around the tool. The heat generation is often assumed to occur predominantly under the shoulder, due to its greater surface area, and to be equal to the power required to overcome the contact forces between the tool and the work piece. [1]

Table 4. Main process parameter of FSW process [16].

Parameter	Effect
Welding speed	Appearance, heat control
Rotational speed	Frictional heat, stirring oxide layer breaking and mixing of materials
Tilting angle	The appearance of weld shining
Down force	Frictional heat, maintaining contact condition

IV. Mechanical properties.

Friction stir welding results in a significant microstructural evolution within and around the stirred zone ,which change the mechanical properties ,such as hardness ,tensile strength, ductility, residual stress and fatigue are briefly reviewed.

4.1 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 aluminum alloys of are available. Xu et al. [17] 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. [18] 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 micro hardness 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 micro hardness 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 over aging effect. Bousquet et al. [19] reported that the AA2024-T351 friction stir welded joint exhibited a significant micro hardness evolution through the weld due to modifications in microstructure.

4.2 Strength and Ductility

The welding parameters have a significant effect on the ductility and strength of friction stir welded aluminum joints. Rajamanickam et al. [20] 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 Liu et al. [21] 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 [22] 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 [23] compared the tensile behavior 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.

4.3 *Residual stress*

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[24,25] Fratini and Zuccarello [26] examined the through-thickness residual stresses using the hole-drilling method that occur on aluminum joints, after the welding process. Lombard et al. [27] 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. [28] determined the residual stress intensity factor by cut compliance method in friction stir welds produced in 2024-T351 aluminum lloy. They reported tensile residual stresses inside the weld with the heat affected zones subjected to compressive residual stress. Chen and Kovacevic [29] 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.

4.4 *Fatigue*

It is important to understand the fatigue characteristics of FSW welds Moreira et al. [30] 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.

4.4 corrosion behavior

Various microstructural zones exhibit different corrosion susceptibility.it is because FSW exhibit different microstructural characteristics such as grain size, precipitate size and texture. Surekha et al. [31] 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 $CuAl_2$ particles

V. IMPORTANT PROBLEMS AND ISSUES TO BE ADDRESSED[32]

Some of the major key problems are discussed below

- Forming of FSW welds is still challenging due to the limit formability. The studies on the relationship between formability and microstructural stability of FSW joint are rare
- The essential drawback of this technique, however, is the low stability of the welded material against abnormal grain growth during subsequent annealing
- Welding speeds are somewhat slower than those of some fusion welding processes.
- There is a keyhole at the end of each weld seam.
- The evolution of microstructure and properties of friction stir welded joints.

So, the attainment of this milestone is well within the reach of the welding community within the next ten years.

VI. Outlook and remark

Despite the initial success of FSW, there are still many challenging problems that need to be overcome for its fully automated industrial application: the optimization of parameters, the detection of defects, and the control of the process. Extensive experimentation for joining a particular combination of materials helps in determining the process parameters for a particular weld setup. Effort has been concentrated on the modeling of the process in order to predict the thermo-mechanical conditions, to better understand the behavior of the workpiece and the conditions which result in successful weld formation and the lowering of residual stresses in the weldments. Process monitoring has been undertaken by capturing and processing the acoustic emission during welding for determining the quality of the weld and the status of the FSW tool (tool wear and tool breakage). Mechanical and microstructural characterization using tensile and peel tests, SEM micrographs and electron probe micro-analysis help in classifying the quality of the welds [33]In spite of its short history, it has found widespread applications in diverse industries. Hard materials such as steel and other important engineering alloys can now be welded efficiently using this process. The understanding has been useful in reducing defects and improving uniformity of weld properties and, at the same time, expanding the applicability of FSW to new engineering alloys. Some conclusions on future work are listed below:

- The future work is to analyses the influence of the processing parameters on the transition, plunging and welding stages
- Future work will be to perform the analysis on other heat treatable and non-heat-treatable aluminium series. The future work will also be focused on the investigation of the thermo-mechanical phenomenon, leading to the uncharacteristic force and torque behavior, etc

The demand of Aircraft Industries to substitute the conventional joining technologies with low costs and high efficient processes such as friction stir welding is considered as one of the most encouraging design challenge for the future So, with better quantitative understanding of the underlying principles of heat transfer, material flow, tool-work–piece contact conditions and effects of various process parameters, efficient tools have been devised. At the current pace of development, FSW is likely to be more widely applied in the future[32]

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