

# Friction Stir Welding of Wrought Aluminium Alloys - A Short Review

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**Abstract** - Friction stir processing (FSP) is one of the new and promising thermo mechanical solid state welding process that alters the microstructural and mechanical properties of the material with low production cost in less time using a simple and inexpensive tool. Preliminary studies of different FS processed alloys report the processed zone to contain fine grained, homogeneous and equiaxed microstructure. Several studies have been conducted to optimize the process and relate various process parameters like rotational, traverse speeds and plunge depth to obtain the ultra fine grained microstructure. In this paper, a detailed survey has been made for the suitability of friction stir welding for the various grades of aluminium alloys for their industrial and commercial applications.

**Key words** - Friction stir welding, Material flow, Weld zone, Weld quality.

## I. INTRODUCTION

Friction stir welding (FSW) is a solid-phase joining process in which a rotating, virtually wear-free welding pin is traversed along the weld path between the work pieces to be joined. The rotation of the tool in the firmly clamped parts to be joined generates frictional heat, which causes the material to plasticize. The subsequent advance motion, combined with continuing rotation of the tool, mixes the plasticized material in the joining area, resulting in a high-quality weld seam. Friction stir welding is especially suitable for the welding of non-ferrous metals with low melting points, such as aluminum and brass. The process can also be used for copper, titanium, magnesium, zinc and lead. As because of melting does not occur and joining takes place below the melting temperature of the material, a good-quality weld is created. This characteristic eventually reduces the ill effects of high heat input, including distortion, and eliminating the welding defects during solidification. The process originally was limited to low melting temperature materials because initial

tool materials could not hold up to the stress of stirring higher temperature materials such as steels and its alloys, other high-strength materials. This problem was addressed recently with the introduction of new tool material such as polycrystalline cubic boron nitride, tungsten rhenium, and ceramics. The principle of operation of friction stir processing is shown in figure 1.1.

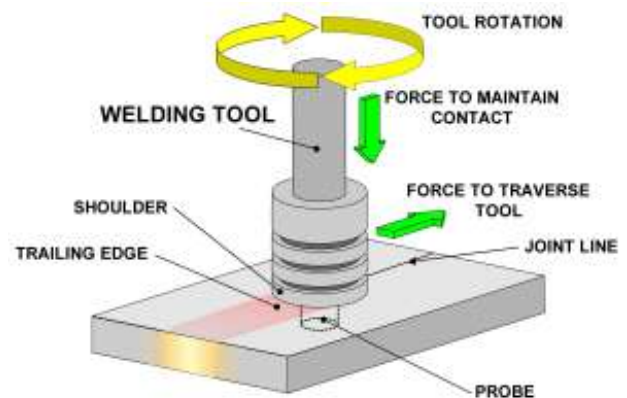


Fig. 1 Friction stir processing

There are various optimization studies for process parameters has been conducted by various researchers for the friction stir welding process. The process parameters are highly depends on the type of tool pin profile preferred for the stir welding. The various types of tools normally experimented for the process are plain cylindrical, conical, threaded, hexagonal and triangular. The material used for preparation of the tool pin profile for nonferrous metals are HSS or mild steel with special heat treatment. Tool material developments are advancing rapidly in different tool materials, each material offering specific advantages for different applications.

## II. HISTORY

Friction stir welding was invented by The Welding Institute (TWI) in December 1991. TWI then established Sponsored Project for the development of the New Friction Stir Technique for Welding

Aluminum," in 1992 to further study this technique. The development project was conducted in three phases. Phase I proved FSW to be a realistic and practical welding technique, while at the same time addressing the welding of 6000 series aluminum alloys. Phase II successfully examined the welding of aerospace and ship aluminum alloys, 2000 and 5000 series, respectively. Process parameter tolerances, metallurgical characteristics, and mechanical properties for these materials were established. Phase III developed pertinent data for further industrialization of FSW. Since its invention, the process has received world-wide attention, and today FSW is used in research and production in many sectors, including aerospace, automotive, railway, shipbuilding, electronic housings, coolers, heat exchangers, and nuclear waste containers.

Friction Stir welding has been proven to be an effective process for welding non ferrous metals like aluminum, brass, copper, and other low melting temperature materials. The latest development in FSW research has been focussed on expanding the usefulness of this procedure in high melting temperature ferrous materials, such as carbon and stainless steels and nickel-based alloys, by developing special tools that can sustain high temperature and pressure needed to join these metals. American Welding Society designations for wrought aluminium alloy groups and their basic temper designations applicable to heat-treatable aluminium alloys are demonstrated in the below Table 1.

TABLE 1

DESIGNATIONS OF WROUGHT ALUMINIUM ALLOY GROUPS

Wrought alloy groups		Basic Temper designation	
1xxx	Unalloyed 99% Al	F	As fabricated
2xxx	Copper principal alloying element: gives substantial increases in strength, permits precipitation hardening, reduces corrosion resistance, ductility and weldability.	O	Annealed: there may be a suffix to indicate the specific heat treatment.

3xxx	Manganese: increases strength through solid solution strengthening and improves work hardening.	H	Strain hardened (cold worked): it is always followed by two or more digits to signify the amount of cold work and any heat treatments that have been carried out.
4xxx	Silicon: increases strength and ductility, in combination with magnesium produces precipitation hardening.	W	Solution heat treated: applied to alloys that precipitation harden at room temperature (natural aging) after a solution heat treatment. The designation is followed by a time indicating the natural aging period.
5xxx	Magnesium: increases strength through solid solution strengthening and improves work hardening ability.	T	Thermally aged: T1: cooled and naturally aged T2: cooled, cold worked and naturally aged T3: solution heat treated, cold worked and naturally aged T4: solution heat treated and naturally aged T5: cooled and artificially aged T6: solution heat treated and artificially aged T7: solution heat treated and over aged or stabilised T8: solution heat treated, cold worked and artificially aged T9: solution heat treated, artificially aged and cold worked
6xxx	Magnesium-silicon.		
7xxx	Zinc-magnesium: substantially increases strength, enables precipitation hardening, can cause stress corrosion.		
8xxx	Other elements - Li, for example,		

	substantially increases strength and Young's modulus, provides precipitation hardening, decreases density.		
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### III. LITERATURE REVIEW

Naresh Nadammal et al.[1] worked on the optimization of process parameters of commercial aluminium alloy 2024-T3 plate. This study attempted a bottom up approach to optimize major independent parameters of the process such as plunge depth, tool rotation speed and traverse speed. A maximum of 93% of base metal tensile strength has been achieved during the micro tensile test. The microstructural observation reveals a significant grain refinement with less variations in grain size across the thickness and large amount of grain boundary precipitation compared to the base metal. K. srinivasa Rao et al.[2] have studied the influence of temperature on tool pin profile and microstructure, corrosion behaviour of aluminium copper blend alloy at nugget zone with various pin profiles such as conical, triangular, square, pentagonal and hexagonal. This study found that, there is an extensive deformation at the nugget zone and the evolved microstructure strongly influences the hardness and corrosion properties of the joint during friction stir welding. Rambabu et al.[3] have conducted the optimization studies in 2xxx series alloy and developed a mathematical model using RSM ( Response Surface Method). This model is optimized using a simulated annealing algorithm optimizing technique to maximise the corrosion resistance. Vijayakumar et al.[4] presented a study on, the effect of post weld treatment verses peak aging and retrogression and reaging on the microstructural, mechanical properties and pitting corrosion. The study concluded that the hardness and strength of weld were comparatively high in peak aged T6 condition. The resistance to pitting corrosion were improved and the mechanical properties were maintained by RRA treatment.

Sivaraj et al.[5] experimented the effect of post weld heat treatment on tensile properties and microstructure characteristics of FSP on 7xxx series aluminium alloy. The tensile properties evaluated and correlated with micro hardness and microstructural features. Raza Moshwan et al.[6] has been conducted experiment on effect of tool rotational speed on force generation, microstructure and mechanical properties of friction stir welded

aluminium-Mg-Cr-Mn of AA 5xxx series. In this study, different weld specimen were produced by considering a constant tool traverse speed of 120 [mm/min] and by varying the rotational speed from 800 to 3000 rpm. The test results revealed that, except the tool rotational speed of 3000 rpm all other speeds given out quality welded joints with smooth surface. The investigation also proved that the joint produced at 1000 rpm submissive a maximum tensile strength of 132 MPa which has 74% of the base parent metal strength. Karthikeyan et al.[7] has conducted an experimentation on mechanical property and microstructural changes during friction stir processing of cast aluminium 2xxx series alloy. This study carried out with different feed rate of 10, 12 and 15 [mm/min] under two different feed speed 1400 and 1800 rpm. On experimentation, the study divulge a considerable increase in tensile, yield strength and ductility property after FSP.

J.F Guo et al.[8] presented a technical test results after conducting an experimental investigation on dissimilar aluminium alloys of 6xxx and 7xxx series. This study was focussed on the process parameters namely the effect of material position, welding speed on material flow, microstructure, micro hardness distribution and tensile property. Khaled J Al- Fadhlah et al.[9] worked on AA6xxx series with multi pass friction stir welding. This study over looked by varying overlapping percentage such as 25, 50 and 75 between consecutive passes of FSP and its behavioural studies during Solution Heat Treatment Aging (SHTA). The result shows that SHTA led to grain growth with an average grain size of 35 µm. Hina Gokhale et al.[10] presented a work on optimization of AA 2xxx series by Response Surface Methodology (RSM). A mathematical model with process parameters and tool geometry to predict the responses of FSP has been formulated and the test results were compared and validated. The experiment concluded with hexagonal tool pin profile have the highest tensile strength and elongation, where as the joints fabricated with conical tool pin profile have the lowest tensile strength and elongation. Yong Zhao et al.[11] have studied, the characterization and mechanical properties in underwater friction stir welding of aluminium and Mg dissimilar alloys. The test reveals that dissimilar joint with good mechanical properties can be obtained by underwater FSP with tensile strength of 152.3 MPa and Maximum micro hardness of 142 HV appeared in the middle of the weld specimen. Thomas et al.[12] focuses on the relatively new joining technology called friction stir welding (FSW). Friction stir welding can be used for joining most aluminium alloys series and the presence of surface oxide could no effect on the process. This study was concluded that, number of

light weight materials suitable for the automotive, rail, marine and aerospace transportation industries can be adopted with FSW process. Ying et al.[13] used the plates of AA 2024 and AA6060 series having thickness of 6 mm each for FSW. The tool rotation speed was varied between 400 to 1200 rpm. Dislocation spirals and loops are observed in AA 2024 intercalation regions within the weld zones at elevated speeds (>800 rpm). Micro hardness profiles shows microstructural variations which result in a 40% reduction in micro hardness in AA 6061 and a 50% reduction of hardness in AA 2024 outside the FSW zone.

Sutton et al.[14] worked on, weld joints of 7 mm thickness using 2024-T351 aluminium rolled sheet material by FSW. Metallurgical, hardness and quantitative energy dispersive X-ray measurements were performed. The tests demonstrated a segregated, banded, microstructure consisting of alternating hard particles. Since the band spacing is directly correlated with the welding tool advance per revolution, the results indicated that the opportunity exists to manipulate the friction stir weld process parameters in order to modify the weld microstructure and improve a range of material properties, including fracture resistance. Lee et al.[15] focussed on A356 alloys sheets using friction-stir-welding to observe the effect of mechanical properties at the weld zone by varying the welding speeds. The microstructures of the weld zone are divided into SZ (stir zone), TMAZ (thermo-mechanical affected zone) and BM (Base metal). The microstructure of the SZ and BM were compared and the microstructure of TMAZ, shows the original grains were greatly deformed, which is characterized by dispersed eutectic Si particles aligned along the rotational direction of the welding tool. The test results reveals that, the mechanical properties of weld zone were greatly improved in comparison to that of the base metal.

#### IV. MATERIAL FLOW IN FSW

The in depth metal flow and heat generation in the softened material around the weld tool are fundamental to the friction stir process. Material deformation generates and redistributes heat, producing the temperature field in the weld zone. But since the material flow stress is temperature and strain sensitive, the distribution of heat itself governed by the deformation and temperature fields. In fact their control lies at the core of almost all aspects of FSW, for example, the optimisation of process speeds and machine loading, the avoidance of macroscopic defects, the evolution of the microstructure, and the resulting weld properties.

Almost all the material in the welded region is extruded between the rotating tool pin on the retreating zone and the surrounding material which is too cold and too lightly stressed to deform. In its simplest form, this flow mechanism can be demonstrated by a two-dimensional simulation delineate streamlines round a rotating tool placed in a steady flow of material [16, 17] which is shown in Figure 2.

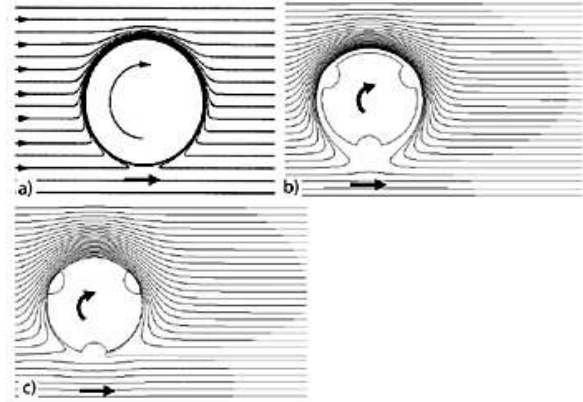


Fig. 2 a. Flow path of plate material with pin rotation in clock wise direction. b & c. Interfacial boundary condition (courtesy Reynolds et al)

#### V. FRICTION STIR WELDING ZONES

The microstructural terminology of an FSW process greatly depends on the various heat affected zones of the weld [18]. These zones are classified as, unaffected material zone or parent metal, heat affected zone (HAZ) and Thermo mechanically affected zone (TMAZ). These microstructural zones are illustrated in Figure 3. Parent zone is a region which has not deformed and not affected by heat in terms of detectable changes in microstructure or properties. HAZ is the region close to the weld where the modified microstructure and property variations can be seen. Thermo mechanical region is the zone where the materials has been plastically deformed by the FSW and the heat from the welding also affected by the material.



Fig.3 Microstructural zone classification in a friction stir welding.

A. parent material, unaffected zone; B: HAZ, thermally affected but with no visible plastic



deformation; C: TMAZ, affected by heat and plastic deformation ( Courtesy TWI, Abington, UK)

## VI. WELD QUALITY

Various experimental results and its comparisons by eminent researchers from literature review reveals a better applicability of FSW in the manufacturing and research sector. Apart from the workability nature, the friction stir welding process extends its wide progress especially in light metals due to its features like low distortion, low shrinkage, no porosity, no lack of fusion and no change in metal.

## VII. CRITICAL WELDING PARAMETERS IN FSW

Even though the friction stir welding promises a excellent workability especially in nonferrous light metals, there are certain quality parameters that need to be considered during the working process like tool rotation and traverse speed, tool tilt and plunge depth, tool design, welding force and flow of material during the welding process.

High tool rotation speed causes higher temperature and slower cooling rate in stir processed zone after welding. More over higher tool speed result excessive release of stirred materials to upper surface, which eventually result voids in FSP zone. Lower heat input condition due to lower tool rotation speed resulted in lack of stirring. The area of the FSP zone decreased with the decreasing tool rotation speed and influenced the temperature distribution in the FSP zone.

Besides the tool rotation speed the other quality parameter associated with FSP tool is tilt angle. Normally this figure varies from  $1.5^{\circ}$  to  $3^{\circ}$ . The tilt angle of the tool spindle protect the shoulder of the tool to support the stirred material through threaded pin and transfer material from front to back side of the pin.

The effect of heat production, material flow and power requirement during FSP is greatly affected with tool design. Shoulder and pin are the important part of an FSP tool. The profile of the tool pin plays an important role in controlling speed of friction stir process and material flow. An enormous amount of heat is generated by the pin and shoulder and that stops the plasticized material which run away from the work-piece, where in tool pin and shoulder influences.

## VIII. DEFECTS IN FRICTION STIR WELDING

As like conventional welding, FSP also has defects during and after welding. The major defects usually noticed in stir welding are lack of penetration,

worm hole or tunnel effect and crown side over heating defect.

The lack of penetration defect is due to inadequate penetration of welding tool into the plate being welded. This leads to a crack or weakly bonded metal interface in the weld. Normally this defects may not be visible during visual appearance or crack detection test like die penetration technique. Destructive testing such as root bend and metallographic sectioning are the test which usually detect the crack. The occurrence of this defect can be minimised by controlling the space between the bottom of the tool and the backing plate.

The worm hole or tunnel defect is a volumetric defect that leads to surface braking. This defect can occur due to high or low tool advancement per revolution. This defect is more difficult to control in materials with high hot strength and low thermal conductivity. By modifying the welding parameter and tool design, this defects can be minimised.

The crown-side overheating defect is pertain to materials that can undergo localised melting with production of brittle solidification products. Highly alloyed aluminum alloys are particularly inclined to this defect. The defect is not necessarily detectable by visual inspection. however, crown surface spalling or blistering may be indicative of its presence. High welding speeds are desirable to minimize HAZ over aging in high strength aluminum alloys. Hence, crown side overheating can limit attainable strengths in high strength aluminum alloy FSW's.

Apart from the FSP defects discussed, flaws and void formation is one of the common effect during friction stir welding especially in aluminium based alloy. This could be due to excessive plunge depth or too much tool rotational speed leads to insufficient heat input and abnormal stirring. Being a solid state joining process, FSW preclude the problems of porosity and hot cracking. Figure 4 shows, few of the welding defects during the process of friction stir welding.

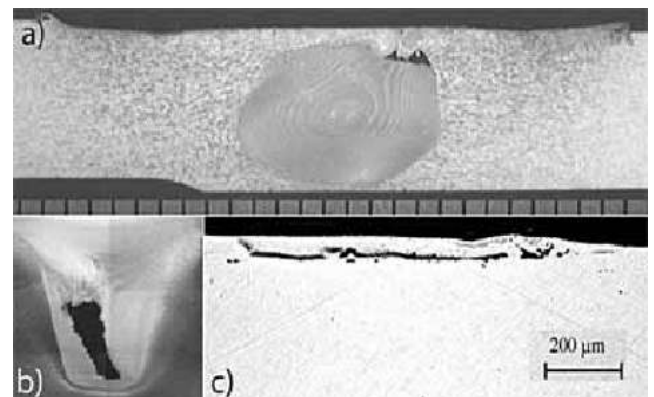


Fig. 4 Formation of void, flaws during friction stir welding.( Courtesy TWI USA) a. Volumetric Flaw

- b. Tunnel or worm hole defect  
c. Surface defect under shoulder

## IX. MERITS AND DEMERITS OF FRICTION STIR WELDING

- As FSP is a solid state process, it can be applied to all the major aluminium alloys and avoids defects like hot cracking, porosity, element loss, etc. common to aluminium fusion welding processes.
- FSW does not require specific skills as compared to conventional welding process.
- No gas shielding or filler material is required for aluminium alloys.
- FSP can achieve excellent mechanical properties as compared to arc welding process.
- Lower processing temperature results in less “damage” in the weld heat affected zone.
- Eco friendly process.
- High initial investment in tooling and equipments
- Special fixtures are required to hold work piece during FSW.
- Sensitive to joint tolerance.

## X. CONCLUSIONS

The friction stir welding is one of the new technology which has received a wide popularity in manufacturing sector especially in non ferrous light metals like aluminium and its alloys. The current evolutions in the field extends its viability not only in the category of non ferrous metals but also the ferrous metals like mild steel and other grades of steels. In this paper, an effective method of literature survey has been made and the possibility of FSP in different non ferrous materials, various terminologies of FSP, weld quality and critical parameters associated with different metal alloys during stir welding has been discussed. The review through the literature also reveals that, in FSP, there are further scope and possibilities in the field of alloy steel as the work piece and boron nitride as tool pin.

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