# FRICTION STIR WELDING - AN OVERVIEW

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## Abstract

*The earliest reference of the use of frictional heat for solid phase welding and forming appeared over a century ago. After 50 years, in 1941 the friction surfacing was developed. After another 50 years, the recent development friction stir welding (FSW) was invented. In this review an account is given on the research that has been carried out on FSW. The process established itself as a prominent technology for joining conventionally un-weldable metals. In this paper the basics of the process, joint configurations, microstructures, thermal analysis, residual stress, distortion and materials flow behavior are discussed. The recent development of the process FSW of composites is also discussed.*

## Introduction

Friction stir welding is the most remarkable and potentially useful new welding technique that has been invented and developed in last decade. The process was invented by W.M.Thomas in December 1991 [Principal research engineer, Friction & forge process dept., TWI, UK] and developed by TWI at Cambridge UK[1]. This process enables the advantages of solid phase welding to be applied to the fabrication of long butt and lap joints, with very little post weld distortion. Moreover, it is simple to operate, very cost-effective machine tool technology offering many advantages.

The first commercial application took place at marine aluminum (Norway) in the year 1997, welded panels designed for use in the construction of fast ferries.

## Principle:

Friction stir welding, the new technique, based on friction heating at the faying surfaces of two pieces to be joined, by means of a non-consumable rotating tool, results in a joint created by interface deformation, heat, and solid state diffusion[2]. A schematic of the process is shown in fig1.

The rotating tool is a specially designed cylindrical tool with a profiled pin, made from a hard and wear resistant material relative to the material being welded. A typical FSW tool is shown in fig2.

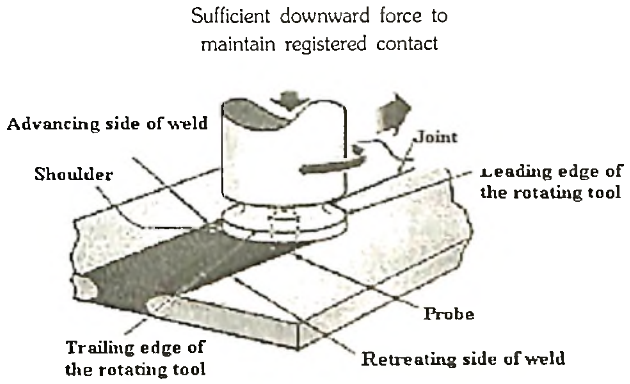


Fig. 1 Friction Stir Welding (Ref. 1)

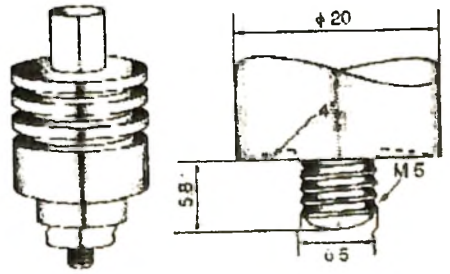


Fig. 2 A Specially Designed FSW Tool

The tool rotates with a speed of several hundred rpm and slowly plunged into the joint line of work piece to be joined. The pin may have a diameter one-third of the cylindrical tool and typically has a length slightly less than the thickness of the work piece. The pin is forced into the work piece at the joint until the shoulder contacts the surface of the work pieces. The tool rotates at a certain peripheral speed and transitioned along the joint line. The rotating tool develops frictional heating of the material, causing it to plasticize and flow from the front of the tool to the back where it cools and consolidates to produce high integrity weld, in the solid phase. The weld is left in a fine-grained, hot worked condition with no entrapped oxides or gas porosity$^3$. The maximum temperature created by this process is usually less than 0.8 melting temperature.

## Welding variables:

1. Spindle speed or rotational speed.
2. Travel speed.
3. Down ward pressure or welding pressure.

1. *Spindle speed or rotational speed:*
   Spindle speed is an important parameter in determining the maximum interface temperature and hence the final joint metallurgy. High speed produces overheated structures where as low speed can produce insufficient heating.
2. *Travel speed:*
   Travel speed indirectly measures the duration of heating. If the travel speed is high with low spindle speed is called cold welding, where as low travel speed with high spindle speed is called hot process.[5]
3. *Welding pressure:*
   It depends on the thickness of the material and the type of material to be joined. The applied pressure differs with rotational speed.

Schematic of FSW with all the variables is represented in fig3.

## Joint configurations:

The process research to date has concentrated on conventional butt and lap joints$^6$. The friction stir welding technique however is suited to several other joint configurations. The joint configurations illustrated (fig4) offer further design opportunities for numerous industrial applications and consequently will be investigated.

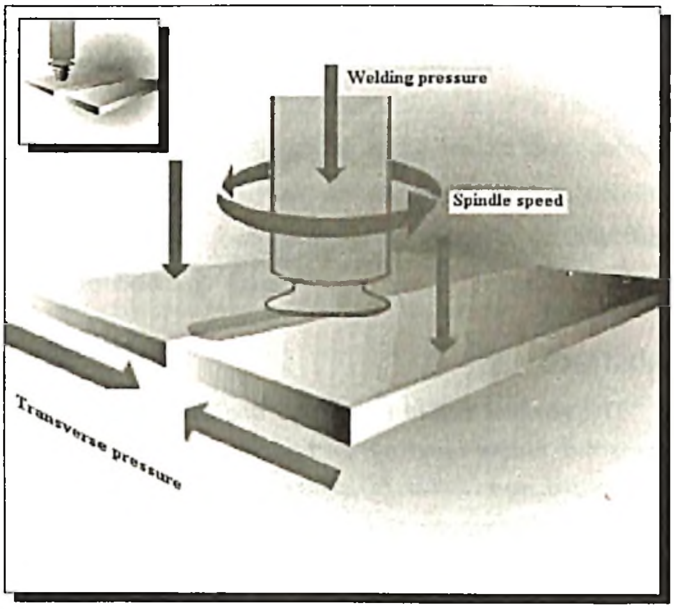


*Fig. 3 Forces on friction stir weldment*

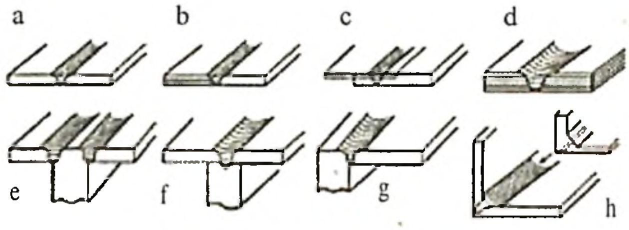


*Fig. 4 Joint configurations for FSW*

a. Square butt
b. Combined butt and lap
c. Single lap
d. Multiple lap
e. 3 piece T butt
f. 2 piece T butt
g. Edge butt
h. Possible corner fillet weld

## Microstructure Classification

The first attempt at classifying microstructures was made by P L Threadgill (Bulletin, March 1997). This work was based solely on information available from aluminum alloys. However, it has become evident from work on other materials that the behaviour of aluminum alloys is not typical of most metallic materials, and therefore the scheme cannot be broadened to encompass all materials. It is therefore proposed that the following revised scheme is used. This has been developed at TWI, but has been discussed with a number of appropriate people in industry and academia, and has also been provisionally accepted by the Friction Stir Welding Licensees Association. The system divides the weld zone into distinct regions as follows:

### 1. Unaffected material or parent metal:

This is material remote from the weld, which has not been deformed, and which although it may have experienced a thermal cycle from the weld is not affected by the heat in terms of microstructure or mechanical properties.

### 2. Heat affected zone (HAZ):

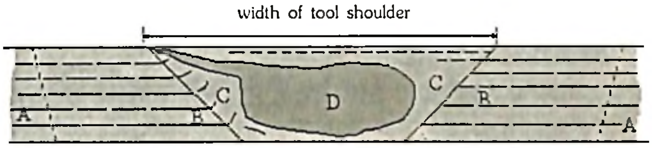
In this region, which clearly will lie closer to the weld centre, the material has experienced a thermal cycle, which has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area

### 3. Thermo-mechanically affected zone (TMAZ):

In this region, the friction stir welding tool has plastically deformed the material, and the heat from the process will also have exerted some influence on the material. In the case of aluminum, it is possible to get significant plastic strain without recrystallization in this region, and there is generally a distinct boundary between the recrystalized zone and the deformed zones of the TMAZ

### 4. Weld Nugget:

The recrystalized area in the TMAZ in aluminum alloys has traditionally been called the nugget. Although this term is descriptive, it is not very scientific. Some researchers named this zone as dynamically recrystalized zone (DXZ).



A. Unaffected material
B. Heat affected zone (HAZ)
C. Thermo-mechanically affected zone (TMAZ)
D. Weld nugget or Dynamically recrystalized zone (DXZ)

*Fig. 5 Microstructure Classification of friction stir weldment (Ref. 1)*

## Materials welded by friction stir welding

The given below are some of the friction stir welding process parameters for different alloys available in literature.

**Table 1** Process parameters of friction stir welding of different alloys

| Alloy | Thickness mm | Tool rotation speed, rpm | Transition speed, mm/s | Reference |
|---|---|---|---|---|
| 7075-T6 Al | 6.35 | - | 1 | 2 |
| 6061-T6 Al | 6.3 | 300-1000 | 1.5-2.5 | 3 |
| 6061-T6 Al | 6.4 | 400 | 2 | 4 |
| 6061-T6 Al | 5.0 | 800-1400 | 1 | 5 |
| 6061-T6 Al | 6.0 | 400 | 1 | 7 |
| 6061-T6 Al | 6.4 | 300-1200 | 2 | 17 |
| 6061-T6 Al | 6.0 | - | 3-4 | 18 |
| 2024Al/6061 Al | 6.0 | 400 | 1 | 7 |
| 6061 Al/Cu | 4.5 | 650 | 1 | 7 |
| 6061T6+20 vol% $Al_2O_3$ (MMC) | 5.0 | 1000 | 1-9 | 23 |

**Table 1** (Contd.)

| Alloy | Thickness mm | Tool rotation speed, rpm | Transition speed, mm/s | Reference |
|---|---|---|---|---|
| 2024 Al-6061Al | 6.5 | 400-1200 | 1 | 29 |
| 1100 Al | 6.3 | 400 | 1 | 8 |
| 6063-T5 | 6.0 | - | - | 9 |
| AA 5083-O | 6-15 | - | 0.46-1.32 | 10 |
| AA 6082-T6 | 5-10 | - | 2.6-7.5 | 10 |
| Al-Cu-Mg-Ag | 4.0 | 850 | 1.2 | 12 |
| AL-Li-Cu | 7.6 | - | - | 13 |
| 2024Al/2014+ 20 vol% $Al_2O_3$ | | 1120 | 2 | 24 |
| 2195 Al | 5.8 | 200-250 | 1.59 | 27 |
| 7050-T7451 | 6.35 | 400 | 1.5 | 28 |
| 6082-T6 | 4.0 | 2200-2500 | 1-2 | 30 |
| 316L SS | 3.2 | 300-500 | 1.7 | 22 |
| A356 Al/6062 Al | 4.0 | 1600 | 1.45-4.45 | 31 |
| AA 7010 T7651 | 6.4 | 180-450 | 1.5 | 32 |
| 2024 Al | 6.5 | 650 | 1 | 33 |
| AZ61 Mg a | 6.3 | 1220 | 1.5 | 34 |

## Microstructural studies on friction stir welded aluminum alloys

The effect of friction stir welding process on microstructure of aluminum alloys had been studied by a number of investigators. Rhodes et al. reported the microstructural changes in 7075 aluminum alloy as affected by FSW.[2] They reported the crystallization of the elongated grains and the solution of the fine (10-20nm) hardening precipitates in the weld nugget. Liu et al. in their paper[3] reported the dynamic continuous recrystallization microstructure in friction-stir weld zone of 6061-T6 aluminum alloy. They also reported a reduction of hardness values in weld zone as compared with base metal. However the weld zone grain size averaged 10μm in contrast to 100μm of workpiece. Lawrence et al, in their publication[7] vividly described the friction-stir welded microstructures of cast 1100 aluminum, 6061-T6 aluminum, 2024 aluminum welded to 6061 aluminum and 6061 aluminum welded to copper. They reported variations in grain refinement of the base metals by dynamic recrystallization. No changes are observed in the hardness values of 1100 Al weld zone in contrast with base metal. In 6061 Al weld zone a 52% reduction of hardness is reported. The FSW zone softening is attributed to dynamic recrystallization and limited grain growth. Olga et al. studied the friction stir welded microstructures of as-cast and cold rolled (50% reduction) 1100 aluminum alloy and inferred that the initial base plate microstructure has no effect on FSW process[8]. Yutaka et al. had conducted a detailed study on microstructures of friction stir welded 6063-T5 aluminum. They reported the relationship between precipitate distribution vs. hardness profile and also precipitation sequence during FSW. Svensson et al. studied the microstructure and mechanical properties of AA 5083 and AA 6082 aluminum alloys[10] and reported the transverse tensile strength values of welded joints, which are adequate as per design standards. The fatigue strength values well above the design limits. The publication of Su et al. reveals a detailed microstructural investigation of friction stir welded 7050-T651 aluminum. They proposed that dynamic recrystallization in the weld nugget is a continuous dynamic recrystallization based on dynamic recovery. Subgrain growth associated with absorption of dislocations into the boundaries as in continuous dynamic recrystallization mechanism. Repeated absorption of dislocations into subgrain boundaries is the dominant mechanism for increasing the misorientation between adjacent subgrains during continuous dynamic recrystallization. The friction stir weld zone microstructures of Al-Si-Mg[11, 12] alloy and Al-Cu-Mg-Ag alloys shows a fine dynamic recrystalized grain structure in the weld center. Jata et al investigated the friction stir welds of Al-Li-Cu alloy and concluded that recrystalized grains in the weld zone are formed by dynamic recrystallization mechanism and the grain size depends on Zener-Hollomon parameter as in material deformed via conventional hot working process[13].

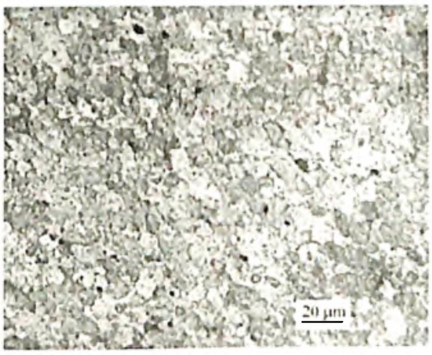


*Fig 6 Equiaxed grains in 7075 Al alloy friction stir weld (Ref 4)*

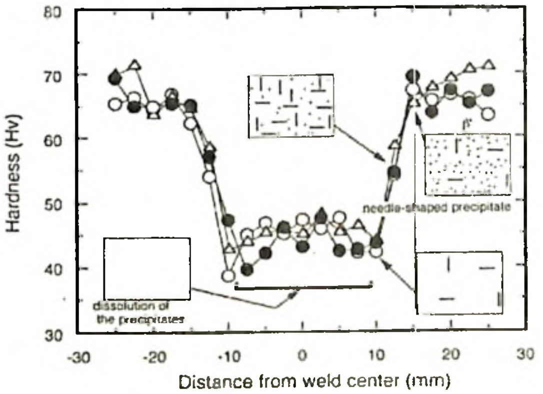


*Fig. 7 Relationship between precipitate distributionand hardness profile (Ref. 9)*

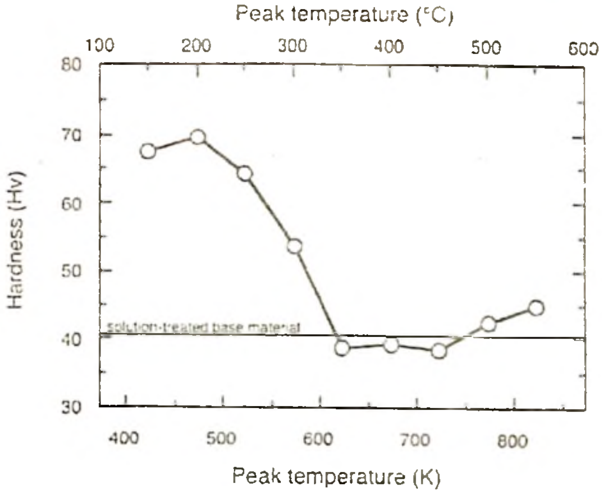


*Fig. 8 Effect of peak temperature on hardness (Ref 9)*

## Onion rings in friction stir welds

Onion rings are the most prominent feature of most friction stir welds (fig 9). Billas et al.[14] explained the formation of onion rings was due to the reflection of the material flow from the cooler walls of the HAZ. The induced circular motion leads to circles that decrease in radii and form the tube system. Threadgill[15] guessed that the onion ring formation was associated with the forward motion of the tool in one revolution. A vivid description on formation of onion rings was given by Krishnan[16]. He attributed the appearance of onion rings to a geometrical effect in that a section through a stack of semicylinders would appear like onion rings with ring spacing being wider at the centre and narrower towards the edge. The formation of the onion rings is due to the process of friction heating due to the rotation of the tool and the forward movement extrudes the metal around to the retreating side of the tool. The spacing of the rings is equal to the forward movement of the tool in one direction. Fig. 10 represents a schematic of onion rings as observed in FSW process.

*Fig. 9 Onion rings in the cross-section of a FSW (Ref. 16)*

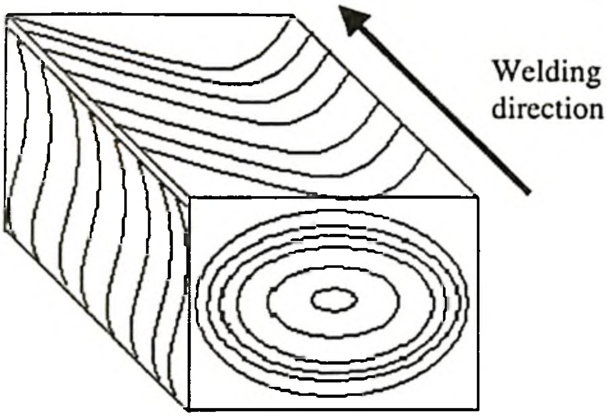


*Fig. 10 Schematic of the various microstructural features in FSW. (Ref. 16)*

## Thermal analysis of friction stir welds

While considerable experimental work has been done to refine the FSW process, there is surprisingly little work done in thermal analysis of friction stir welds. Tang et al. experimentally investigated the heat input and temperature distribution during friction stir welding[18]. Gould et al. developed a preliminary thermal model for friction stir welding[19]. This is predominantly an analytical model. Chao et al. developed a model for studying friction stir welding process[20]. This includes both heat transfer analysis for the temperature development during the friction stir welding process and a post weld residual stress and distortion determination. A finite element computational procedure is used in this work.

Welding relies on the heat generated during the process to join the work piece together. As for friction stir welding there are two possible heat sources[20].

a. The friction at the interface between the tool shoulder and the work piece; and

b. The plastic deformation of the weldmetal in the vicinity of the rotating pin.

The first heat source by friction is considered as the major heat source, and is the only heat included in most of the models.

J E Gould et al., predicted from his model that the leading edge of the tool is considerably colder than the trailing edge. It is because the leading edge supplies heat to cold material, while the trailing edge supplies heat to material already preheated by the leading edge of the tool.

W Tang et al. measured the temperatures during friction stir welding process of 6061-T6 aluminum alloy by using 30 gauge, type K thermocouples imbedded in a series of small holes at different distances from the weld seam drills into the back surface of the work piece. They found that

a. For a given set of welding conditions, the maximum temperature of the weld zone is nearly constant throughout the center region of the weld.

b. Higher welding pressures causes higher welding temperatures. However, the temperature never exceeds the melting temperature.

c. Increasing rotational speed of the pin tool increases the welding temperature, but the incremental effect decreases with increasing rotational speed.

d. The shoulder dominates the friction stir welding process. It controls metal extrusion and cleans the specimen surface.

## Residual stress and distortion in friction stir weldment:

To study the residual stress and the distortion due to friction stir welding process, a thermo-mechanical analysis of weld is performed by Chao and Qi. Through their FEM analysis they found that:

1. The maximum final residual stress is in the longitudinal direction, i.e. $s_{xx}$ is due to the shrinkage of the weld.
2. The maximum final residual stress in the work piece is about twenty-five percent of the yield stress of the original base metal. This level of maximum residual stress is very low compared to the corresponding value in fusion welding where the maximum residual stress is typically close to the yield strength of the material.
3. The residual shear stress near the weld is very small.

These results indicate that the final distortion of the plate after friction stir welding process is very small relative to the fusion welding process. The V-shaped distortion in the transverse plane, i.e., YZ plane, normally encountered in the fusion welding is not seen here. This relatively low distortion is attributed to the low peak temperature experienced and the fixture used to clamp down the work piece during the welding process.

## Material flow behavior during friction stir welding

A keen understanding of material flow behavior during friction stir welding is presented by Colligan[20]. As the welding tool approaches, material from the mid-section of the plate directly in the path of the pin is lifted and extruded around the pin in the direction of pin rotation. Material from the mid section of the pin is also lifted but is less affected by the shear forces imparted by the rotating pin. On the advancing side of the weld, this marginal material may be captured by the pins rotational flow and carried around to the retreating side, or it may simply lift and be pushed away from the weld centerline. On the retreating side the mid-thickness material, which is aligned with the margin of the pin, is simply lifted as the surrounding material extrudes by the pin without much displacement laterally. Material that passes below the pin is not greatly displaced.

The welding tool affects material from the upper portion of the plate in a much different manner than in the case of the other positions within the weld. The material is curled directly into the threads of the welding tool pin and is then delivered deeper into the weld. The material curling into the thread space is attached to the base metal in front of the pin and not traveling around the pin with the rotation of the threads.

In friction stir welds, not all material influenced by the pin are actually "stirred" in the welding process. Much of the material movement takes place by simple extrusion from the upper portion of the path of the welding tool pin. The stirred material is forced, down in the weld by the threads on the pin and is deposited in the weld nugget. Other material in the weld zone simply extrudes around the rotating side of the welding tool pin, riding in weld as it goes around the pin.

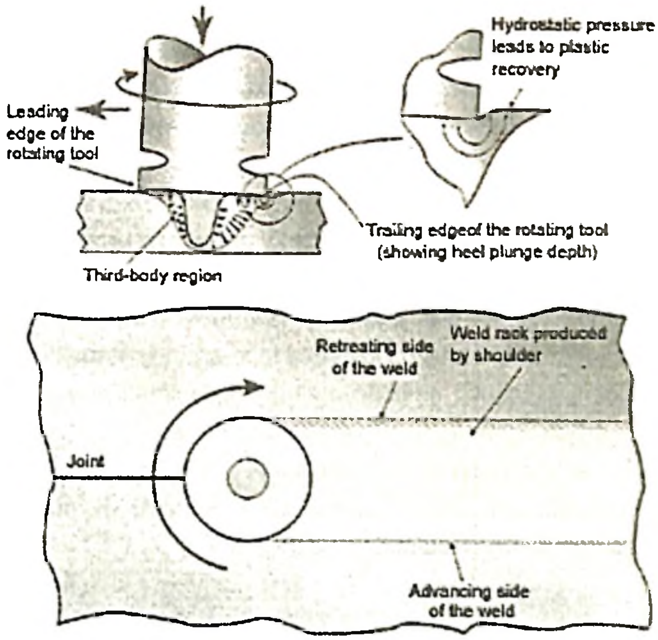


*Fig. 11 Material flow in friction stir welding*

## Friction stir welding of steels

The feasibility of welding steel by FSW process was first demonstrated by Thomas et al.[21] They successfully welded 12% chromium alloy steel to low carbon steel. Reynolds et al. reported the FSW of 3.2mm thick 304L stainless steel[22]. In their study the weld nugget shows equiaxed grains. The residual stresses produced by FSW process are similar to that of fusion welding processes. The sign of the transverse residual stress changes from tensile at the crown to compressive at the root.

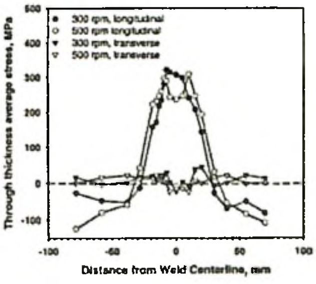


*Fig. 12 Average, through thickness, longitudinal and transverse residual stresses plotted against distance from the weld center line. (Ref. 22)*

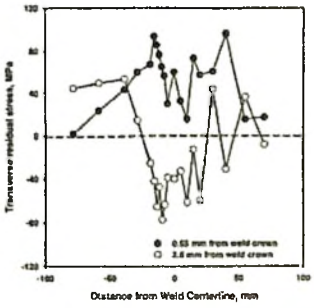


*Fig. 13 Near crown and near root side transverse residual stresses in the 500-rpm weld. (Ref. 22)*

## Friction stir welding of Composites

FSW process had been used for joining aluminum based metal matrix composites. Prado et al. welded Al

6061+20 vol.%$Al_2O_3$ composite[23]. They performed a detailed study on tool wear in FSW process. Microstructures in friction stir welds between monolithic AA2024 and AA2014 reinforced with 20-vol% particulate $Al_2O_3$ revealed that the narrowest layers of each material are about 0.1 mm thick[24]. Each material retained its identity in the weld zone and convoluted macro-interfaces can be identified between material domains. When the harder material is on the advancing side of the tool the macro-interface span is larger. The welds also exhibit eutectic melting. The liquid phase has the traditional form of grain boundary films in the thermo mechanical process zone. Particle strings and fragmentation fracture zones are observed; these may also result from eutectic melting.

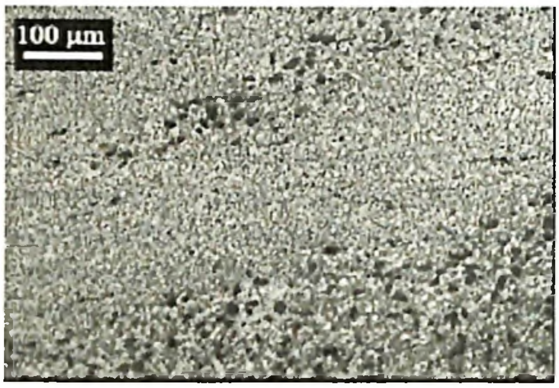


*Fig. 14 Friction stir weld in monolithic AA2024 and AA2014 reinforced with 20-vol% particulate $Al_2O_3$ (Ref. 24)*

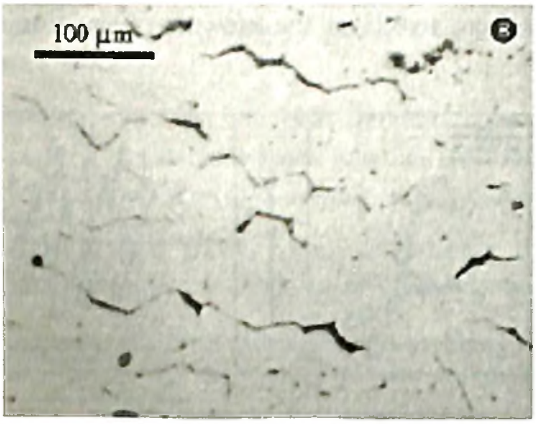


*Fig. 15 Evidence of grain boundary liquation in the thermo mechanical process zone. (Ref 24)*

Friction stir processing (FSP) is a novel technique developed for fabrication of surface composite. Al-SiC surface composites are made by FSP shows a well-distributed particles and very good bonding with aluminum substrate[25].

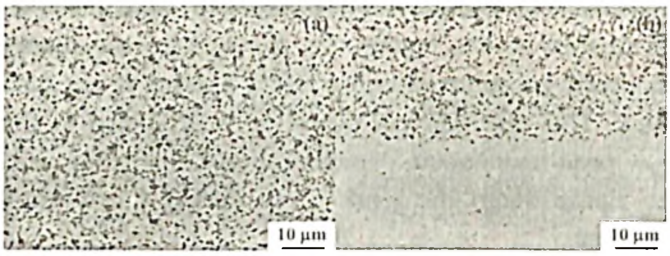


*Fig. 16 Optical micrograph showing (a) uniform distribution of SiC particles (~13 vol.%) in aluminum alloy matrix, and (b) perfect bonding between surface composite and aluminum alloy substrate (Ref 25)*

## Advantages of friction stir welding process[26]:

- The process is in solid phase, thus avoiding problems, which can occur in fusion welding, such as porosity, alloy segregation, hot cracking.
- No special edge preparation is required, only nominal square edged abutting plates are needed for a butt joint, thus saving material, time and money.
- The weldment have comparatively low distortion levels even in long welds
- Equipment is simple, with relatively low running costs.
- The surface appearance approaches that of a roughly machined surface, which in most cases reduces production costs in further processing and finishing.
- The weldment has excellent mechanical properties as proven by fatigue, tensile and bend test.
- The process is well suitable for automation and adaptable for robot use.
- The process is essentially an autogenous, non-consumable technique, eliminating problems associated with selection and storage of consumables.

## Limitations of friction stir welding process[26]:

- Welding speeds are moderately slower than those of some fusion welding process.
- It is necessary to clamp the work piece materials firmly to prevent the abutting plates moving apart
- It requires backing bar to prevent material breaking out through the under side of the joint

- Key-hole [run hole] is left at the end of each weld. This problem can be overcome by using run-on or run-off plates

### Applications of friction stir welding process[26]:

The following are some of the industries where friction stir welding process has potential applications.

**Table 2** Industries in which friction stir welding have major application.

| Industry | Applications |
|---|---|
| Aerospace | Airframes, fuel tanks, and attachment of special alloy skins |
| Aluminum producers | Large extrusions, seamed pipes. |
| Automotive | Chassis, space frames, wheels, bulk carrier tanks. |
| Construction | Bridges, offshore accommodation units. |
| Beverage | Beer barrels. |
| Railway rolling stock | Wagon and coach chassis and coachwork for high-speed trains. |
| Refrigeration | Cryogenic pipes and heat exchangers. |
| Shipbuilding | Hulls, decks and internal structures for lightweight, energy-efficient high-speed ships. |
| Pressure vessels | Liquid gas containers. |

### Summary

FSW established itself as a prominent joining technology of the current century. The process was proved successful for aluminum alloys. The process was successfully tried on soft metals like lead, zinc magnesium and their alloys. The feasibility of joining copper and steels is also demonstrated. Most of the work carried out in FSW is on aluminum alloys. The development of the better FSW tool will definitely explore the process for other alloys.

### Acknowledgements

The authors are thankful to the numerous researchers in the area of FSW, without whose work this review would not have been possible.

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