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# Friction Stir Welding: A Review

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## ABSTRACT

*Friction Stir Welding is a relatively new technique of welding using frictional heat as a heat source to join or weld 2 similar or dissimilar materials. It is most commonly used for aluminium alloys. In the present study, current developments in the field of Friction stir welding have been addressed. Welding parameters like tool design and geometry, tool rotation and speeds, tool tilt and depth; temperature distribution across the tool and material of weldment; microstructure and its elements like stir zone (nugget), thermo-mechanically affected zone (TMAZ), and heat affected zone (HAZ); physical and mechanical properties of the welded material; and scope of FSW for welding of other materials have been discussed.*

**Keywords:** *Friction Stir Welding; Tool Geometry; TMAZ.*

## 1.0 Introduction

Aluminum alloys are generally non-weldable by conventional welding processes like arc welding, gas welding, etc. because of poor solidification microstructure and porosity in the fusion zone. Also, losses in mechanical properties as compared to the base material are huge. Some aluminum alloys can be resistance welded, but the surface preparation is expensive, with surface oxide being a major problem.

Due to these drawbacks, welding of aluminum alloys used for aerospace structures was difficult before the introduction of a new welding process "Friction Stir Welding" by The Welding Institute (TWI) in the UK in December 1991.

It was initially applied to aluminum alloys but over the years, research and experimentation has been extended to other materials such as copper alloys, steels, titanium, etc.

Friction Stir welding is a solid state joining process which uses a non-consumable rotating tool to join the surfaces of the 2 work pieces without melting the material.

The tool has 2 parts: pin and shoulder which has a larger diameter than pin. Pin is inserted into the adjoining edges of plates which are to be welded and the bottom face of the shoulder is in direct contact with the surfaces of the 2 plates. Because of this contact and the combination of traversing movement of tool along the line of joint and its rotation about its axis, frictional force is experienced which generates heat.

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 tool is moved forward, the pin forces plasticized material from the leading face to the rear, where the high forces assist in a forged consolidation of the weld.

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 recrystallization of the base material. (Fig 1)[1]

Friction Stir Welding is considered a green technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, it consumes considerably less energy.

No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in conventional welding methods. [1]

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Various welding forces act on the tool which helps in forming stronger nugget with refined microstructure.

- Downwards force: maintains the position of the tool at or below the material surface.
- Transverse force: acts parallel to the tool motion and are positive in the traverse direction. Since this force arises as a result of the resistance offered by the material to the motion of the tool, it will decrease as the temperature of the material around the tool is increased.

**Fig 1: Friction Stir Welding**

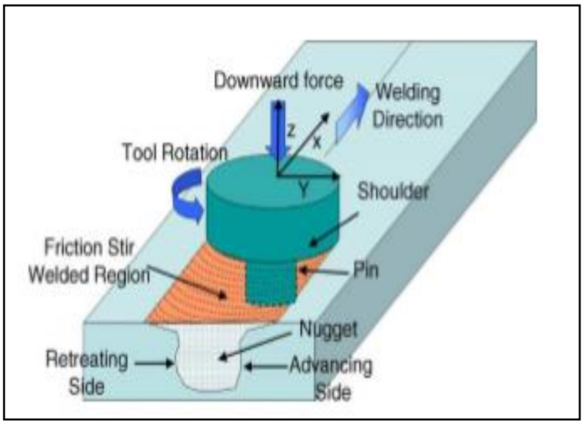
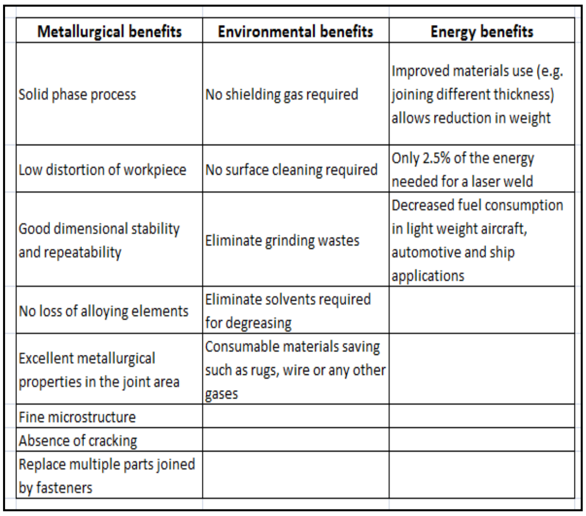


**Table 1: Benefits of Friction Stir Welding[1]**



| Metallurgical benefits | Environmental benefits | Energy benefits |
|---|---|---|
| Solid phase process | No shielding gas required | Improved materials use (e.g. joining different thickness) allows reduction in weight |
| Low distortion of workpiece | No surface cleaning required | Only 2.5% of the energy needed for a laser weld |
| Good dimensional stability and repeatability | Eliminate grinding wastes | Decreased fuel consumption in light weight aircraft, automotive and ship applications |
| No loss of alloying elements | Eliminate solvents required for degreasing | |
| Excellent metallurgical properties in the joint area | Consumable materials saving such as rugs, wire or any other gases | |
| Fine microstructure | | |
| Absence of cracking | | |
| Replace multiple parts joined by fasteners | | |

- Torque: required to rotate the tool. It depends on the downwards force and friction coefficient (sliding friction) and/or the flow strength of the material in the surrounding region (stiction).

## 2.0 Literature Review

### 2.1 Welding parameters

Welding parameters like tool geometry, rotation, joint design etc. effect the material flow pattern and temperature distribution, which influence the micro-structural evolution of material. These parameters have been addressed in this section

### 2.2 Tool geometry and design

The design and geometry of the tool is a critical and most influencial factor as a good tool can improve both the quality of the weld and the maximum possible welding speed. The tool geometry plays a critical role in material flow and in turn governs the traverse rate at which FSW can be conducted. A Friction Stir Welding tool consists of a shoulder and a pin as shown in Fig. 2 [1]. The tool serves two functions: (a) heating of work piece, and (b) movement of softened material to produce the joint. From the heating aspect, the relative size of pin and shoulder is important because major source of heat generated is friction between the surfaces of shoulder and work piece.

TWI has developed tools specifically designed to increase the penetration depth and thus increasing the plate thicknesses that can be successfully welded. Whorl design uses a tapered pin with a variable pitch thread to improve the downwards flow of material. Triflute design has a complex system of three tapering, threaded re-entrant flutes that increase material movement around the tool. The Trivex tools use a simpler, non-cylindrical, pin and reduce the forces acting on the tool during welding. Different tool pin profiles such as cylindrical, triflute, trivex, conical, triangular, square, pentagonal, hexagonal, octagonal, thread-less and with threads have been studied by various authors for different FSW systems [1]. Optimum pin profile depends on types of materials and variations in thicknesses.

Elangovan et al.[2] studied the influence of tool pin profile and shoulder diameter on the formation of friction stir processing zone while welding AA6061 aluminium alloy (Al–Mg–Si alloy), and reported that the pin profile plays a crucial role in material flow.

Mehta et al. [3] studied welding of AA 6061-T651 with electrolytic tough pitch copper of 6mm thickness and reported that welding defects decreased as the polygonal edges (no. of sides) of the pin increased and defect free macro joint was reported for cylindrical tool pin profile.

Ahmed et al. [4] created an analytical model of heat generation for eccentric cylindrical pin in friction stir welding of a low deformation resistant AA1050-H12, and a relatively high deformation resistant AA5754-H24 alloy, and concluded that peak temperature generated using eccentric cylindrical pin is lower than in cylindrical pin without eccentricity, and increasing the pin eccentricity leads to decrease in peak temperature.

### 2.3 Tool rotation and speeds

Tool rotation (v, rpm) in clockwise or anticlockwise direction and tool traverse speed or feed rate (n, mm/min) along the line of joint are 2 important parameters that influence welding. The rotation of tool results in stirring and mixing of material around the rotating pin and the translatory motion of 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 result in more intense stirring and mixing of material. [1,6]

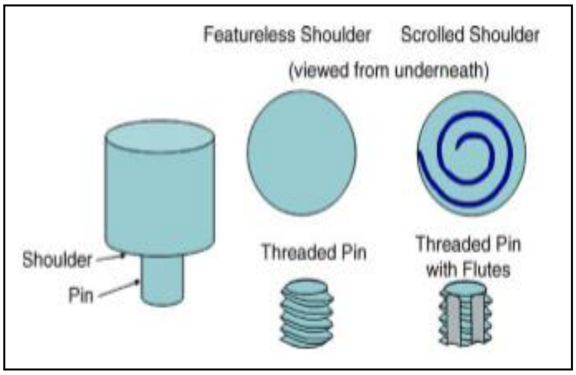
Sinha et al. [5] studied microstructure and mechanical properties of similar and dissimilar joints of AA6351 and pure copper by friction stir welding and concluded that the grain size of Stir Zone, TMAZ and HAZ for all the joints increased with the increase in tool rotational speeds.

Sharma et al. [8] conducted experiments on dissimilar welding of AA6061 and Mg AZ31 alloys and concluded that lower values of tool rotational speed and welding speed are better for FSW of dissimilar alloys under consideration when using HCHCr tool material.

### 2.4 Tool tilt and depth

A tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the molten stirred material by threaded pin. The insertion depth of pin into the work-pieces is important for producing strong and complete nuggets. It is associated with the pin height. When the insertion depth is too shallow, the shoulder of tool does not come in contact with the work-piece surface and so not enough frictional heat is generated and rotating shoulder cannot move the stirred material efficiently. This results in generation of incomplete welds with inner channels or grooves [1].

**Fig 2: FSW Tool**



### 3.0 Temperature Distribution

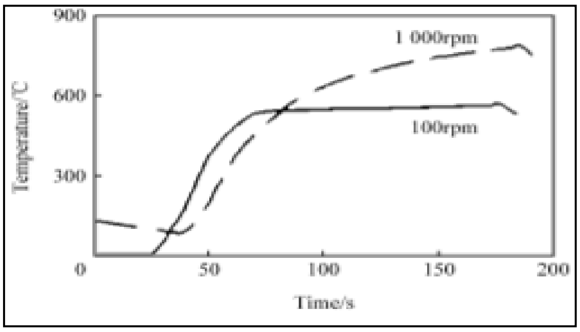
FSW results in plastic deformation around rotating tool and friction between tool and work-pieces. Both these factors contribute to the rise of temperature within and around the stir zone, which directly influences the microstructure of the welds, such as grain size, grain boundary, and resultant mechanical properties of the welds. [1]

Sinha et al. [5] studied microstructure and mechanical properties of similar and dissimilar joints of AA6351 and pure copper by friction stir welding and reported that fine recrystallised grains in the stir zone are due to the generation of high temperature and deformation during FSW.

Lee et al [7] conducted experiments on FSW of AA2195 with Li and reported that the temperature in advancing side is higher than retreating side since material flow around tool is moving from advancing side to retreating side and frictional heat under the shoulder gives higher temperature.

Sabari et al. [9] conducted experiments on a relatively newer modification of FSW which is called Under Water Friction Stir Welding with AA2519-T87 aluminium alloy. UWFSW can maintain low and constant heat input along the weld line. They recorded that the peak temperature experienced by the UWFSW joint was 547 °C which is higher compared to that by FSW joint. However, UWFSW joint resulted in higher cooling rate and higher temperature gradient than FSW joint due to severe and even heat absorption capacity of the water cooling system. Kalvala et al. [6] conducted experiments on of FSW on P91 Steel using low temperature and found out that typical temperatures recorded with 100 and 1000 RPM rotation speed of the tool, at the tip of the tool was about 560 °C and 775 °C respectively. The temperature was more or less stable with welding time for 100 RPM weld whereas for 100 RPM weld, it increased gradually as shown in the figure 3

**Fig 3: Temperature Profiles Recorded with 100 and 1000 RPM. [6]**



### 3.1 Microstructure

The combined action of intense plastic deformation and high-temperature within the stirred zone (nugget formed) during FSW leads to recrystallization and development of texture within the stirred zone and precipitate dissolution and coarsening within and around the stirred zone. Based on microstructural characterization of grains and precipitates, three distinct zones, stirred (nugget) zone, thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ), have been categorized as reported by many authors in their studies [1, 5-8]

**Fig 4: A Macrograph Showing Various Microstructural Zones in FSP 7075Al-T651 (Standard Threaded Pin, 400 rpm and 51 mm/min). [1]**

### 3.2 Nugget

The stir zone (nugget) is a region of heavily deformed material that is left behind in the path of the traversing tool during welding. The grains within the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material. [10] A unique feature of the stir zone is the common occurrence of several concentric rings, also known as "onion rings".[11] The interface between the recrystallized nugget zone and the parent metal is relatively diffused on the retreating side of the tool, but quite sharp on the advancing side of the tool [1]

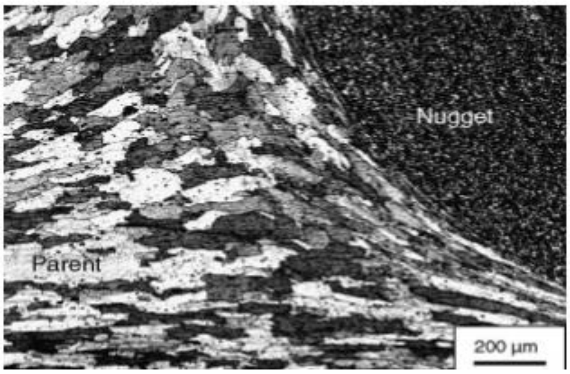
### 3.3 Thermo-mechanical affected zone

The thermo-mechanically affected zone (TMAZ) occurs on either side of the stir zone. In this region the strain and temperature are lower and the effect of welding on the microstructure is smaller than stir zone. Unlike the stir zone the microstructure is recognizably that of the parent material, though significantly deformed and rotated.

### 3.4 Heat affected zone

The heat-affected zone (HAZ) is a region subjected to a thermal cycle but does not deform during welding. The temperatures are lower than those in the TMAZ but may still have a significant effect if the microstructure is thermally unstable.

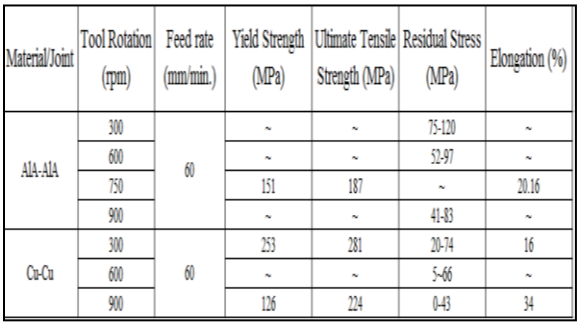
**Fig 5: Microstructure of SZ and TMAZ of 7075Al. Notice Elongated Grains of TMAZ [1]**



Sinha et al [5] reported that the grains in stir zone were refined and recrystallised, while in the TMAZ region were elongated and semi recrystallised. In the HAZ coarse grains were observed for all FSW joints, i.e. for AlA-AlA, Cu-Cu and AlA-Cu joints. The grains are fine in the SZ because of high temperature achieved due to high frictional heat which is generated if the speed of rotation is high. The size of grains in AlA–AlA, Cu–Cu and AlA–Cu FSW joints was found to be affected by the heat generated in the stir zone.

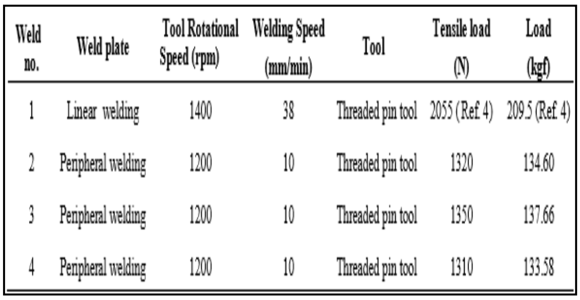
The size of grains present in all 3 zones increase as the tool rotation speed increases.

**Table 2: Mechanical Properties Studied by Sinha et al [5]**



| Material/Joint | Tool Rotation (rpm) | Feed rate (mm/min.) | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) | Residual Stress (MPa) | Elongation (%) |
|---|---|---|---|---|---|---|
| AlA-AlA | 300 | 60 | ~ | ~ | 75-120 | ~ |
| | 600 | | ~ | ~ | 52-97 | ~ |
| | 750 | | 151 | 187 | ~ | 20.16 |
| | 900 | | ~ | ~ | 41-83 | ~ |
| Cu-Cu | 300 | 60 | 253 | 281 | 20-74 | 16 |
| | 600 | | ~ | ~ | 5-66 | ~ |
| | 900 | | 126 | 224 | 0-43 | 34 |

**Table 3: Mechanical Properties of AlA-MgA Studied by Sharma et al [8]**



| Weld no. | Weld plate | Tool Rotational Speed (rpm) | Welding Speed (mm/min) | Tool | Tensile load (N) | Load (kgf) |
|---|---|---|---|---|---|---|
| 1 | Linear welding | 1400 | 38 | Threaded pin tool | 2055 (Ref. 4) | 209.5 (Ref. 4) |
| 2 | Peripheral welding | 1200 | 10 | Threaded pin tool | 1320 | 134.60 |
| 3 | Peripheral welding | 1200 | 10 | Threaded pin tool | 1350 | 137.66 |
| 4 | Peripheral welding | 1200 | 10 | Threaded pin tool | 1310 | 133.58 |

## 3.5 Properties

### 3.5.1 Residual stress

Residual stresses are internal stresses that remain even when the cause of stress is removed or there is no external load.

These are present in solid material that has undergone manufacturing processing (such as welding, machining, casting, forming, etc) and may arise due to any of the following reasons:

If the material has undergone plastic deformations, existence of non uniform temperature gradients due to uneven heating or cooling during thermal cycle, or non uniform volumetric or structural changes due to phase transformation.

### 3.5.2 Hardness

Lee et al [7] concluded that the values of hardness depend on the nature of the process experienced by the zones and all 3 zones had different measures of hardness. The base hardness for AA2195-T0 was 63.7 Hv.

The hardness of the SZ was found to be higher than that of the untreated material due to the grain refinement during welding and cooling. The highest hardness obtained was 124.3 Hv for the specimen welded at 300 mm/min.

Generally retreating side was found to have hardness higher than advancing side. This can be attributed to the fact that advancing side has exposure to higher temperature as compared to the retreating side.

The micro-hardness values were minimum at TMAZ and HAZ for the specimen welded with feed rate 180 mm/min due to gradual grain growth.

## 3.6 Materials (apart from aluminium)

### 3.6.1 Copper

Conventional welding of copper is usually difficult because of its high thermal diffusivity, which is much higher than that of steels and nickel alloys.

Therefore, the heat required for welding is much higher, resulting in quite low welding speeds. This problem can be solved by welding Copper and its alloys using FSW. [1]

### 3.6.2 Titanium

FSW of Titanium is a relatively new approach and it hasn’t been studied much. Titanium alloys require post welding heat treatment after being welded by conventional techniques.

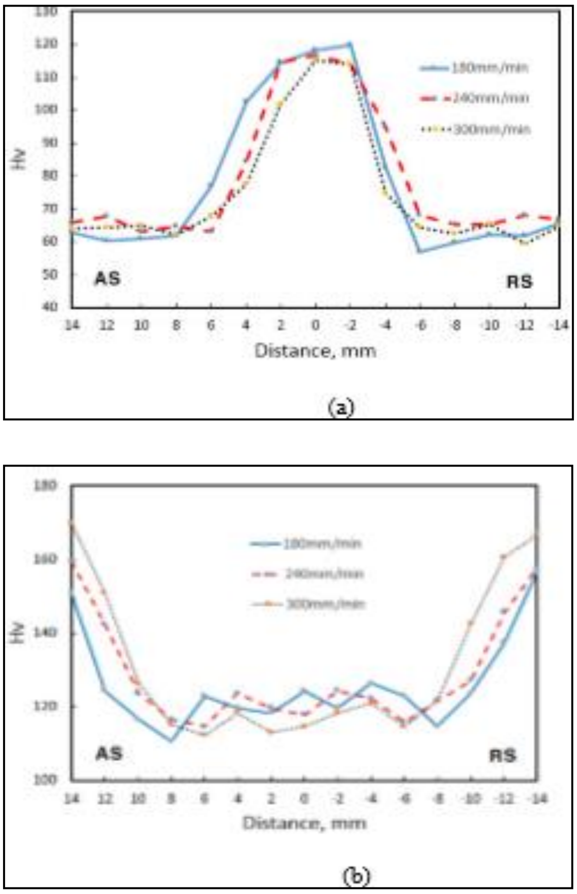
This increase production costs. FSW helps by somewhat eliminating this extra step. [1]

### 3.6.3 Dissimilar

Many dissimilar welded joints have been achieved and studied in the recent years. Most of the dissimilar joints have Aluminium as one of the material.

Dissimilar joints like Aluminium-Copper [3,5], Aluminium-Magnesium [8], Aluminium-Lithium [7], Aluminium-Steel [1]

**Fig 6: Result of Micro-Hardness Measurement in Nugget Zone Welded with 600 rpm of (a) AA2195-T0 and (b) AA2195-T8 [7]**



## 4.0 Conclusions

1. **Effect of tool geometry**: Increasing the no. of edges of a polygon shaped pin of the welding tool leads to reduction in welding defects and cylindrical shaped pin (infinite edges) combined with concave shaped shoulder is considered as the best tool geometry for FSW. Also, increasing the pin eccentricity leads to decrease in peak temperature.
2. **Effect of tool rotation and speed**: Higher tool rotation generates higher temperature because of higher friction heating and results in more intense stirring and mixing of material. The grain size of Stir Zone, TMAZ and HAZ for all the joints increases with the increase in tool rotational speeds. However, there is a requirement of lower values of tool rotational speed and welding speed for welding of dissimilar alloys.
3. **Effect of temperature**: FSW leads to high temperature within and around the weld. This leads to significant micro-structural evolution within the weld or stir zone: fine recrystallized grains, precipitate dissolution and coarsening, and lower residual stresses as compared to those in conventional welding techniques.
4. **Micro-structural properties**: There are 3 major zones that the microstructure of the material can be divided into:
   a. **Stir Zone (nugget):** it undergoes intense plastic deformation and high-temperature exposure and has fine and equiaxed recrystallized grains.
   b. **Thermo-mechanically affected zone (TMAZ):** it is the region surrounding the nugget and experiences medium temperature and deformation and has elongated (deformed) and semi-recrystallized grains.
   c. **Heat-affected zone (HAZ):** region experiencing only temperature and has coarse precipitated grains.

The size of grains present in all 3 zones increase as the tool rotation speed increases which increases the temperature.

5. **Physical and mechanical properties:** The hardness of the SZ is higher due to the grain refinement during welding and cooling and lower in the parent material (TMAZ, HAZ) due to gradual grain deformation due to less amount of heat. Almost 80%of the mechanical properties of the welded joints can be achieved with respect to base values of parent material.
6. In addition to aluminum alloys, friction stir welding has been successfully used to join other metallic materials, such as copper, titanium, steel, magnesium, lithium, and composites.

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