Emerging Friction Stir Welding for Aluminium and its Applications

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Abstract
Friction Stir Welding (FSW) was invented by Wayne Thomas at TWI (The Welding Institute), and the first patent applications were filed in the UK in December 1991. FSW offers numerous benefits in the fabrication of all aluminum products. Friction Stir Welding (FSW) has become a major joining process in the aerospace, railway and ship building industries especially in the fabrication of aluminum alloys. The process uses a spinning non-consumable tool to generate frictional heat in the work piece. Heat is generated between the tool and material then mechanically intermixes the two pieces of metal at the place of the join, then the softened metal (due to the elevated temperature) can be joined using mechanical pressure. This paper looks at the review, on friction stir welding process, various welding variables, generation and flow of heat, Microstructural features and material flow during FSW. The study indicates that Friction stir welding is most suitable joining technique for similar and dissimilar aluminum alloy. It is found that weld quality of FSW joint is excellent than other joining process. The estimated thermal profiles are compared with experimental results at similar welding conditions, thus validating the developed heat transfer model.

INTRODUCTION

A material joining is a key enabling technology which impacts competitiveness and reliability in almost all manufacturing sectors. Virtually all manufactured products are made from components which must have been joined. Continuous improvements and effective application of emerging technology for joining are essential for manufacturers to remain competitive [1]. The recorded use of frictional heat for solid-phase joining techniques dates back over a hundred years. The friction welding process, however, to a large extent has been restricted to round, square, or rectangular bars. More recently, Friction Stir Welding (FSW) is a new welding technique invented and developed at TWI [2]. This technique has already made an impact on the aluminum producer and aluminum user industries and offers great potential for sectors such as ship building, automotive and aerospace. The technique brings the benefits of solid-phase friction welding to material forms e.g. plate, previously regarded as unsuitable.

A constantly rotated cylindrical-shouldered tool with a profiled nib is traversal fed at a constant rate into a butt joint between two clamped pieces of butted material as shows in Fig. 1. The nib is slightly shorter than the weld depth required, with the tool shoulder riding a top 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 plasticized metal to the rear where clamping force assists in a forged consolidation of the weld. This process of the tool traversing along the weld line in a plasticized tubular shaft of metal results in severe solid state deformation involving dynamic recrystallization of the base material [3].

The conventional fusion welding of aluminum and its alloys has always been a great challenge for designers and technologists. The difficulties associated with this kind of joints are mainly related to the presence of a tenacious oxide layer, high thermal conductivity, high coefficient of thermal expansion, solidification shrinkage, and high solubility of hydrogen and other gases in molten state [4].

Figure 1 Basic principle FSW [3]

The conventional fusion welding of aluminum and its alloys has always been a great challenge for designers and technologists. The difficulties associated with this kind of joints are mainly related to the presence of a tenacious oxide layer, high thermal conductivity, high coefficient of thermal expansion, solidification shrinkage, and high solubility of hydrogen and other gases in molten state [4]. Friction stir welding joining technique has been shown to be viable for joining aluminum alloys. The commercial aluminum alloy 2xxx has a brittle behavior under welding pressure due to that ductility and elongation percent decreases but micro-hardness of weld joint and HAZ increases as welding pressure increase [5]. Generally the 2xxx (Al–Cu alloy) series of aluminum alloys have poor weldability because of the copper content which causes hot cracking, poor solidification microstructure and porosity in the fusion zone. Therefore, the fusion welding processes are not
suitable for joining of these alloys. Benavides et al. [6] study the microstructural evolution during friction stir processing and found to be beneficial in improving hardness and wear resistance of Al 2xxx alloy. The alloys that are less affected from softening are the 3xxx and 5xxx series materials. In such alloys, improvement in tensile and fatigue properties is expected for those welding conditions inducing higher levels of heat input if compared with precipitation hardening alloys [7].

A commercial friction stir weld in AA6xxx is a medium strength aerospace aluminum alloy used primarily for wing skins and fuselage structures. FSW is a feasible method for altering the microstructure of AA6xxx alloy exhibiting a refined and homogenized grain structure with good joint strength [8]. Aluminum Alloy AA7xxx is one of the strongest aluminum alloys in industrial use today. Its high strength-to-weight ratio, together with its natural aging characteristics, makes it attractive for a number of aircraft structural applications. Kimura and co-workers have studied the joining phenomena during friction welding of AA7xxx. They found that the mechanism of AA7075 friction welding was similar to that of low carbon steel and attributed this to the similarities in their strength properties [9].

The fusion welding of dissimilar aluminum alloys leads to the melting and re-solidification of the fusion zone which results in the formation of brittle inter-dendritic structure and eutectic phases. The formation of brittle structure in the weld zone leads to the drastic decrease in the mechanical properties like lower in hardness, strength and ductility [10]. Since fusion welding processes are not suitable for the dissimilar welding of aluminum alloys AA2024 and AA5083, FSW welding process could be the best for the dissimilar welding of these alloys [11]. The inter diffusion of alloying elements and development of similar orientations in the nugget could have contributed to the better tensile properties of the friction stir welded AA5052-AA6061 specimens [12]. However, very few systematic studies have been performed on dissimilar F5 welding, and the relationships between the various welding parameters and the resulting weld properties have not been identified. Dissimilar welding of aluminum alloys is a core demand of the Aircraft industries to substitute the traditional joining technologies with low costs and high efficiency ones such as friction stir welding in the future advanced design.

**Experiments**

Join configuration: Friction stir welding (FSW) is capable of fabricating either butt or lap joints, in a wide range of materials thickness and lengths but also different configuration of weld joint is possible as shows in Fig. 2. During FSW, heat is generated by rubbing a non-consumable tool on the substrate intended for joining and by the deformation produced by passing a tool through the material being joined. It is important to note that no special preparation is needed for FSW of butt and lap joints. Two clean metal plates can be easily joined together in the form of butt or lap joints without any major concern about the surface conditions of the plates [13]. Important welding parameters: FSW involves complex material movement and plastic deformation. Welding parameters, Tool geometry and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of material. Therefore, welding speed, the tool rotational speed, the tilt angle of the tool, tool material and the tool design are the main independent variables that are used to control the FSW process. The main process parameters and there effects in friction stir welding are given below in Table 1.

| PARAMETER | EFFECTS |
|-----------|---------|
| Rotation speed | Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. |
| Welding speed | The grain size in the stir zone decreases with increasing welding speed due to lower heat input. The tensile strength increases with increasing welding speed. |
| Plunging force | Axial force has significant influences on the formation of defects, grain size and hardness of stir zone and subsequently tensile properties of friction stir weld |
| Tool design | The tool has two primary functions: (a) localized heating, and (b) material flow. In the initial stage of tool plunge, the heating results primarily from the friction between pin and workpiece. |
| Plunge depth | The plunge depth for a given tool rotation speed, traverse speed, material and test machine needs to be optimized so as to get a defect-free weld. |
| Joint geometries | During the initial plunge of the tool, the forces are fairly large and extra care is required to ensure that plates do not separate depend on joint geometries. |
| Tool Tilt angle | A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin. |

**Figure 2 a – g** Joint configuration: (a) square butt, (b) edge butt, (c) T butt joint, (d) lap joint, (e) multiple lap joint, (f) T lap joint, (g) filled joint [13]

Generation and flow of heat: The heat generated during the welding process is equivalent to the power input introduced into the weld by the tool. There are two processes due to which heat is generated at the interface of tool and work piece due to friction Qf and plastic deformation Qp. The heat generation due to friction Qf on an elemental area dA at the tool-work-piece interface, considering high rotational speed compared to traverse speed of the FSW tool, is given by:

\[
\Delta Q_f = (1 - \delta) \pi r^2 \text{constant} dA
\]
where \( \star \) <1 accounts the amount of frictional work dissipated into the workpiece, \( \Omega \) is angular velocity of tool and \( r \) is radial distance of elemental area \( da \) from axis. For sliding friction, the contact shear stress is \( \tau_{\text{constant}} = \mu \tau \) where \( p \) is the applied pressure. The heat generated due to plastic shear deformation \( Q_p \) leading to workpiece material sticking to the tool is given by:

\[
dq_p = \frac{d\tau}{\text{constant}} da
\]

(2)

Where \( \tau_{\text{constant}} = \mu \tau \) is the shear yield stress. Therefore, total elemental heat due to friction and plastic deformation is given by:

\[
dq_{FSW} = dq_f + dq_p
\]

(3)

All amount of generated heat can be assumed as a direct product of weld tool’s rotation and it is coming as a product of the adhesion and the deformation of the material around the tool. Heat generated from the traverse movement is significantly smaller amount than from the rotation. The total amount of heat in FSW is \( Q_{FSW} \), generated by the tool due to sliding and sticking friction conditions. Therefore, the heat energy generated at the contact interface between a rotating FSW tool and a stationary workpiece are subdivided as \( Q_1 \), \( Q_2 \) and \( Q_3 \) i.e. on the tool probe’s tip surface, tool probe’s side surface and tool shoulder’s tip surface, respectively. The analytical estimation of heat generation from the shoulder is expressed as [14].

\[
Q_1 = \int_0^{2\pi} \int_0^{\pi/2} \omega \tau_{\text{constant}} r^2 (1 + \tan \alpha) dr d\theta
\]

(4)

Heat generation from the probe are expressed as:

\[
Q_2 = \int_0^{2\pi} \int_0^{\pi/2} \omega \tau_{\text{constant}} R^2 dr d\theta = 2\pi \alpha \tau_{\text{constant}} R^2 \delta H_{\text{probe}}
\]

(5)

\[
Q_3 = \int_0^{2\pi} \int_0^{\pi/2} \omega \tau_{\text{constant}} R^2 dr d\theta = \frac{2}{3} 2\pi \alpha \tau_{\text{constant}} R^2 H_{\text{probe}}
\]

(6)

Therefore the total heat generation due to sliding friction is estimated as:

\[
\frac{2}{3} \alpha \tau_{\text{constant}} \left( \frac{Z_{\text{shoulder}} - Z_{\text{probe}}}{(1 + \tan \alpha)} - Z_{\text{probe}}^2 \right) + \frac{\tau_{\text{constant}}}{2} Z_{\text{probe}}^2 \]

(7)

A simplified heat source model is developed using constant value of \( \tau \). The plunging force applied to the plate surface by the tool creates a uniform pressure over the shoulder surface. The heat is generated from the work done by the friction force and plastic deformation. The distribution of heat flux over the plate surface due to the tool shoulder, pin-plate interface due to tool pin, and due to tool pin bottom surface is given as [15].

\[
Q_{\text{shoulder}} = \frac{3Q_1}{2\pi R_{\text{shoulder}}^3}
\]

(8)

\[
Q_{\text{probe}} = \frac{Q_2}{2\pi R_{\text{probe}}^3}
\]

(9)

\[
Q_{\text{bottom}} = \frac{Q_3}{2\pi R_{\text{probe}}^3}
\]

(10)

where \( \tau \) and \( \alpha \) in the expression of \( Q_1, Q_2 \) and \( Q_3 \) are applied according to sliding or sticking friction conditions. Therefore, total heat flux from the FSW tool is expressed as:

\[
q = q_{\text{shoulder}} + q_{\text{probe}} + q_{\text{bottom}}
\]

(11)

A three-dimensional finite element (FE) thermal analysis of friction stir welding (FSW) to determine the thermal history and temperature distributions in a workpiece and compare with experimentally calculated thermal histories and temperature distributions in a workpiece during a friction stir welding (FSW) process involving the butt joining of aluminium AA1100. In experiment we use K-types of thermocouple to measure the temperature histories during FSW at different locations on the workpiece in the welding direction. The finite element model is developed in ABAQUS by considering temperature dependent thermal property of aluminium alloy using “DFLUX” subroutine to apply heat flux and DCC3D8D brick elements with fine meshing in the weld zone. The analysis of the numerical results has revealed a peak temperature of 527°C which was recorded in the shoulder tool area as sown in Fig. 4. Fig. 5 shows temperatures profile comparison obtained from the results of thermal analysis and experimental data of FSW at traverse speed of 98 mm/min and tool rev/min of 600, using SS304 tool geometries with the shoulder and pin diameters of 20 mm and 6 mm, respectively.

Figure 3 Distribution of heat flux

Figure 4 Isometric view of temperature distribution at welding velocity 98 mm/min and rotational speed 600 rpm during simulation

Microstructural features: FSW is being targeted by the industry for structurally demanding applications to provide high-performance benefits. The weld zone consists of a stir zone, a thermo-mechanically affected zone (TMAZ), and a heat-affected zone (HAZ) as explain in Fig.6. The grain size in the stir zone is fine and equated, resulting in a higher mechanical strength and
ductility. The solid-state nature of the FSW process, combined with its unusual tool and asymmetric nature, results in a highly characteristic microstructure.

![Figure 5](image)

**Figure 5** Comparison of temperature profile of two points during experiment and simulation

As it discussed above in FSW there are three different zones which is affected by heat and mechanical action of tool. Fig. 7 shows the calculated isotherms of the peak temperatures in the welding zone compared to the experimentally obtained microstructure morphology. Weld zone is demonstrated the grains within the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material due to high temperature between 527 to 485 °C. In thermo-mechanical affected region temperature are lower and the effect of welding on the microstructure is correspondingly smaller so that temperature is between 485 to 443 °C and rest of part peak temperature range of 390 to 207 °C is heat affected zone.

![Figure 6](image)

**Figure 6** Typical weld cross-sections with four different zones in FSW

Flow of material: Material flow in friction stir welding is largely uncharacterized due to the difficulty in material flow measurement and visualization in metals. The researchers used a combination of thin copper strip inserts and a "frozen pin" technique, where the tool is rapidly stopped in place [16]. They suggested that material motion occurs by two processes as shown in Fig. 8:

1. Material on the advancing front side of a weld enters into a zone that rotates and advances with the pin. This material was very highly deformed and sloughs off behind the pin to form arc-shaped features when viewed from above (i.e. down the tool axis). It was noted that the copper entered the rotational zone around the pin, where it was broken up into fragments. These fragments were only found in the arc shaped features of material behind the tool.

2. The lighter material came from the retreating front side of the pin and was dragged around to the rear of the tool and filled in the gaps between the arcs of advancing side material. This material did not rotate around the pin and the lower level of deformation resulted in a larger grain size.

![Figure 7](image)

**Figure 7** Calculated isothermal view versus experimental microstructure morphology

Benefits and advantages: FSW is considered to be the most significant development in metal joining in a decade and is a "green" technology due to its energy efficiency, environment friendliness, and versatility. The key benefits of FSW are summarized in Table 2 Provides opportunities for new solutions to old joining problems.

| Table 2 Main Process parameters in friction stir welding |
|---------------------------------------------------------|
| **METALLURGICAL BENEFITS**                             |
| - No Solid phase process                               |
| - Low distortion of work piece                         |
| - Good dimensional stability and repeatability         |
| - No loss of alloying elements                          |
| - Fine microstructure                                  |
| - Absence of cracking                                  |
| **ENVIROMENTAL BENEFITS**                              |
| - No shielding gas required                             |
| - No surface cleaning required                          |
| - Eliminate grinding wastes                             |
| - Consumable materials saving, such as rugs, wire or any other gases |
| **ENERGY BENEFITS**                                    |
| - Improved materials use [e.g., joining different thickness) allows reduction in weight |
| - Decreased fuel consumption in light weight aircraft automotive and ship applications |

Industrial applications: r FSW is a solid state process which produces welds of high quality in difficult to weld materials such as aluminum and is fast becoming the process of choice for manufacturing light weight transport structures such as boats, trains and airplanes [5].

**Shipbuilding and Marine Industries**: The shipbuilding and marine industries are two of the first sectors that have adopted the process for commercial applications. The process is suitable
for the following applications: Panels for decks, sides, bulkheads and floors, Hulls and superstructures

**Aerospace Industry**: At present the aerospace industry is welding prototype and production parts by friction stir welding. Opportunities exist to weld skins to spars, ribs, and stringers for use in military and civilian aircraft.

**Railway Industry**: The commercial production of high speed trains made from aluminum extrusions, which may be joined by friction stir welding, has been established.

**Land Transportation**: The friction stir welding process is currently being used commercially and is also being assessed by several automotive companies and suppliers. Existing and potential applications include such as engine and chassis and floors, Hulls and superstructures.

**Automotive Applications** and other Industry Sectors.

FSW capability: Friction Stir Welding (FSW) is making a dramatic impact across a number of industries, including aerospace, defense, transportation, marine and electronics. In the automotive industry alone, for example, FSW is used to create everything from drive shafts and fuel tanks to hood panels and suspension links. We have found different weldable materials in literature. The compatibility range extends beyond these materials such as Aluminum (all alloys), Copper, Brass, Magnesium, Titanium, Steel Alloys, Stainless Steel, Tool Steel, Nickel, Lead etc.

**CONCLUSION AND FUTURE DIRECTION OF RESEARCH**

The fundamental knowledge of the FSW process and the knowledge of the evolution of the structure and properties needs to be combined to build intelligent process control models with a goal to achieve, defect free, structurally sound and reliable welds. Success of an undertaking will ensure availability of practically the entire quantitative knowledge base and reliable welds.

The study indicates that Friction stir welding is most suitable joining technique for similar and dissimilar aluminum alloy.

Compared to the traditional fusion welding, friction stir welding exhibits a considerable improvement in strength, ductility, fatigue and fracture toughness.

In addition to aluminum alloys, friction stir welding has been successfully used to join other metallic materials, such as copper, titanium, steel, magnesium, and composites. Because of high melting point and low ductility, successful joining of high melting temperature materials by means of FSW was usually limited to a narrow range of FSW parameters.

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

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**LIST OF USED SYMBOLS**

FSW – Friction Stir Welding  
TWI – The Welding Institute  
TMAZ – Thermo-mechanically affected zone  
HAZ – Heat affected zone