A review on Friction Stir Welding in Aluminium Alloys

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Abstract. Joining of aluminium alloys is always a challenging task due to its easily oxidising property in its molten stage. Although its application is huge in the building of aerospace structure, 2XXX and 7XXX series alloys are categorised as non-weldable aluminium alloys. Recent development in the application of friction stir welding process in the joining of these non-weldable alloys simplified the fabrication processes. In this review article, significance of friction stir welding comparing with other solid state metal joining process is addressed. Recent developments and application of this relatively new metal joining process in various industries are also discussed. Particular emphasis has been given to the mechanism responsible for the formation of this solid state joining technique. Apart from this, major process parameters that influence the formation of weld and weld defects caused by the improper selection of process parameters are also explained in detail.

1. Introduction

Aluminium became metal of choice for many applications due to its most economical and attractive characters like light weight, good appearance, fabric ability and corrosion resistance [1]. Aluminium has poor strength in its pure form. Its mechanical properties are improved by alloying with iron, silicon, manganese and magnesium to form non heat treatable alloys (1xxx, 3xxx, 4xxx and 5xxx series). Heat treatable high strength aluminium alloys (2xxx, 6xxx and 7xxx series) are developed by alloying pure aluminium with copper, magnesium silicate and zinc [2]. Depending on its physical and mechanical properties theses alloys are used in various fields like, airframes, engines, and ultimately, for missile bodies, fuel cells, and satellite components. In industries arc welding is one of the widely practiced contemporary manufacturing processes, which is carried out by heating the metal pieces to their melting point and fusing them together. The characters like forming aluminium oxide in molten stage, hydrogen solubility, thermal expansion and shrinkage during solidification makes aluminium alloys cannot be joined using conventional arc welding technique [3].

1.1. Weldability of aluminium alloys

MIG and TIG welding are the commonly used fusion joining methods in the fabrication of different aluminium alloys. Weldability of different alloys is shown in Fig.1. Fig.1 reveals that some alloy series have major problems in fusion welding. Fusion welding is carried in a temperature more than the solidus temperature of the base metal. Although oxide formation during fusion welding is completely avoided in TIG and MIG welding, there were many other problems associated with the thermal properties of aluminium.
Thermal conductivity of aluminium is much higher (3 times higher than steel). As fusion welding is carried out with higher heat input, heat affected zone experiences high temperature rise during the joining process [4]. Higher temperature rise in heat affected zone eradicates the mechanical properties and results poor strength in that zone. Apart from this, thermal expansions of aluminium alloys are about twice that of steel [5]. Solidification shrinkage in aluminium weld metal is about 6% by volume and it can be the main cause for distortion, especially in thicker welds. Inclusion of copper in Aluminium alloy 2xxx series results formation of solidification cracks in fusion welding. The cooper content which causes hot cracking and poor solidification in the microstructure and porosity in the fusion zone made the 2xxx series impossible to join using fusion welding [6].

1.2. Solid state welding

The major drawbacks of obtained casting structure in fusion welding like hot cracking, porosity and other macro and micro structural defects can be avoided in friction welding as the entire process is carried out below the solidification temperature of the base metal. In this process material is plasticised using the friction heat generated between the moving and stationary surfaces [8]. Once the material is plasticised a lateral force called “upset is applied to fuse the plasticised metal parts. As the entire joining process is carried out below the melting point of base metal, it does not require filler material. Defects linked with melting and solidification is completely eliminated in this solid metal joining process. Based on the relative motion between the moving and stationary surfaces they are classified as spin welding and linear friction welding.

Friction stir welding (FSW) is an upgraded version of conventional friction welding process. It is invented by Wayne Thomas at The Welding Institute (TWI), Cambridge, in 1991. In FSW, the frictional heat generated between the rotating non consumable tool and the stationary workpiece is
used as a major heat source to join the workpiece which is assisted by the heat generated through the plastic deformation of material during welding. Due to inherent potentials of FSW, it has become a process of choice for producing high-quality joints in both similar and dissimilar materials in just a short time span. FSW exhibits comparatively better weld quality in all aluminium alloys [9]. Sound joints obtained through friction stir welding rapidly replacing all fastening methods like riveting in many industries. In this review article, advantages of friction stir welding over other aluminium joining techniques are discussed. The currents state of understanding and developments of fiction stir welding are reviewed in detail.

2. Significance of Friction stir welding
FSW has now established itself to be a remarkable solid state welding technique to effectively join similar and dissimilar aluminum alloys. The process does not require any consumables (filler material, fluxes and shielding gas, etc.) for joining, produces no harmful emissions, safe to humans and is, therefore, considered to be an energy-efficient, environment-friendly, and clean material joining process, as summarised in Table 1 and Fig.3

| Metallurgical benefits | Environmental benefits |
|------------------------|------------------------|
| Solid phase process    | No shield gas required |
| Low distortion         | Minimal surface cleaning |
| Good dimensional stability and repeatability | No harmful emission |
| No loss of alloying elements | Eliminate solvent requirement |
| Excellent mechanical properties in joint area | Consumable material saving such as rugs, wire or any other gases |
| Fine recrystallized microstructure | Only 2.5 % of energy needed comparing with laser weld. |
| Absence of solidification cracking | Post FSW formability |

**Table 1.** Metallurgical and environmental benefits of FSW

![Figure 3. Significance of FSW](image-url)
2.1. Industrial developments and applications
Friction stir welding is the latest joining process has a huge number of applications in automobile industries. The Ford Motor Co. has produced thousands of Ford GT automobiles with a central tunnel assembled by FSW that isolates the fuel tank from the interior counterparts (Fig. 4). Mazda patented and employed plunge friction spot welding (PFSW) that is a spin-off technology of friction stir spot welding (FSSW) for producing the rear-door structure of almost 100,000 automobiles [10].

![Figure 4. Tunnel assembly in Ford and spot welded door in Mazda [10]](image)

In this method, even though there is a pull-out hole left on the spot weld, the fatigue life and the strength of the joint are satisfactory. The AUDI R8 used a three-sided re-entrant probe to accomplish the welding of tailored blanks for the center-tunnel closing panel in the AUDI R8. The same company has employed the FSSW process for overlap welding of side members in the BMW 5 series. Honda Motor Corporation has employed dissimilar FSW of aluminum alloy with steel to produce a component to be used in the front structure of a Honda Accord [11].

![Figure 5. Ship deck plate construction [12]](image)

In the ship building industries, Japan manufacturers are the leaders in employing the FSW process to construct the sections made of aluminum alloys. Fig. 5 shows ship deck plate assembly constructed using friction stir welding. In the aerospace industry, the friction stir (FS) welded lap joints are used as the rivet replacement technology to join the circumferential and longitudinal internal stiffeners and to attach doublers at door and window cutout locations [12]. As another application, Fig. 6 illustrates the Eclipse 500 business class jet constructed using FSSW. Better quality, stronger joints, and lighter structure at a reduced cost for assembly and production cycle time are some of the advantages of using FSSW in the Eclipse jet assembly [10].

![Figure 6. FSW lap joint in Eclipse 500 jet [10]](image)

Apart from normal conventional joints most challenging longitudinal and circumferential joints are successfully done in rocket fuel tank (Falcon 9) [13]. Fig. 7 illustrates the fuel tank assembly of a rocket fabricated by the FSW process in the Boeing Company. They replaced the tungsten inert gas (TIG) conventional fusion welding process with FSW, and obtained a staggering 99% reduction in the welding costs. Other few examples of major industries that use Friction stir welding as joining technique to manufacture their products are listed in Table 2.
Figure 7. FSW in rocket fuel tank [13]

Table 2. Friction stir welding applications in industry.

| Application                  | Industries                                               |
|------------------------------|----------------------------------------------------------|
| Heat exchangers              | Marine Aluminum, Norway                                  |
| Shipbuilding                 | Marine Aluminum, Norway                                  |
| Delta II rockets              | Boeing, United States                                    |
| Shipbuilding                 | SAPA, Sweden                                              |
| Automotive components        | SAPA, Sweden                                              |
| Laser system housings        | General Tool, United States                              |
| Motor housings               | Hydro Aluminum (formerly Marine Aluminum), Norway         |
| Suburban trains               | Alstom, Germany, and Hydro Marine                        |
| Automotive components        | Showa, Japan                                              |
| Train bodies                 | Hitachi, Japan                                            |
| Automotive components        | Tower Automotive, United States                           |
| Aircraft structure           | Eclipse, United States                                   |
| Commercial shipbuilding      | Advanced Joining Technologies, United States              |
| Space shuttle external tank  | Lockheed Martin, United States                            |
| Shipbuilding                 | Friction Stir Link, United States                        |
| Automotive components        | Honda Motor Company, Japan                                |

3. Overview of macroscopic processes during FSW

Figure 8. Solid model of FSW fixtures
The BMs to be welded are rigidly held with the help of specially designed clamps. The clamps are designed in such a way that they do not protrude after being mounted on the anvil so as to avoid their obstruction with the welding tool. After placing the BM on the anvil, clamps are tightened to firmly hold the BM from top (Fig. 8). Unlike other conventional fusion welding techniques friction stir welding does not depend on external source for the heat generation during the process [14]. The frictional heat developed between the tool and the workpiece is the major heat source for the entire joining process. Frictional heat developed along the tool matrix interface completely depends on the relative velocity between the contacting surfaces. From the operational point of view, based on the relative motion between the tool and workpiece this processes is further divided into three different sequences of operations as shown in Fig. 9.

**Figure 9.** Sequence of operations in FSW [15]

Plunge and Dwell – Rotating tool allowed to plunge into the stationary workpiece in the weld line till the tool shoulder touches the top surface of the workpiece (Fig. 9). Frictional heat is generated in the tool/matrix contact surface. Rotating tool allowed to stay in the same position till the temperature is increased enough to plasticise the material. In this stage entire tool pin (probe) is plunged into the base metal. The rotating tool pin inside the base metal and rotating shoulder over the top surface of the base metal not only produce heat but also stir the plasticised material under the shoulder to flow from the advancing side to the retreating side and develops sound joint along the weld line.

**Figure 10.** Processes in material joining during FSW [16]

Traverse – Rotating tool allowed to slide along the weld line. This sequence of operation is also called as weld stage as the joining of metal happens along the weld line in this stage. Tool travel speed (revolutions / mm of linear movement) is the key factor for the sound join in this stage. Feed rate of tool is selected based on the thermal properties of material to be joined [17]. Optimum feed rate results defect free joints. As the entire joining process is done in lower temperature quality of joint is very sensitive to the selected weld parameters. Material along the weld line preheated in front of the tool, plasticised under the shoulder, extruded from the front of the tool and forged at the back side of the tool as shown in Fig. 10.
Retract – Once the welding is done the rotating tool is pulled upwards. This is a finishing stage. One of the draw of friction stir welding. During the upward motion of the tool, tool probe moves the material upwards which leaves key hole at the end point of the weld line. A new technique of self-refilling friction stir welding (SRFSW) relying on non-consumable joining tool has been developed to repair the keyhole left at the end of process [18].

4. Structural zone characteristics of FSW

Based on the post weld changes in the microstructure of joined base metal obtained weld joint divided into two different zones (Fig. 11).

4.1. Weld nugget or Stir zone (SZ)
This zone refers to a region which is affected by the rotational and traverse movement of the tool pin. The size of this region depends on the diameter of the tool pin. This region experiences grain refinement due to the dynamic recrystallization. Grains in SZ are equiaxed, and are extremely smaller in size compared to BM. Sometimes this region displays onion ring-type structure depending upon BM and process conditions. Hardness values are usually lower than the BM of heat-treatable alloys [20].

4.2. Thermo-mechanically affected zone (TMAZ)
This zone exist between SZ and heat affected zone. This represents the entire deformed zone under the shoulder other than the nugget zone. Material in this region experiences thermal cycles as well as mechanical deformation due to the rotary motion of the tool shoulder. Thermal effects on this region are comparatively lesser than the stir zone which indicates lower degree of deformation and partial recrystallization of grains. In this region, hardness reaches to the minimum value due to partial precipitate dissolution and grain growth caused by attainment of high temperature at some local area in TMAZ [21].

4.3. Heat affected zone (HAZ)
This zone can be observed in all metal joining processes. In friction stir welding this region represents the area which is not mechanically deformed but affected by the thermal cycles developed during the joining process. When this region subjected to the temperature more than the recrystallization temperature of the material, grain are coarsened and the density of the strengthening agents in the alloy is reduced. Normally this region is the low strength region in Friction stir welded joint [22]. When this region experiences lesser temperature than recrystallization temperature during the process, then the low strength region shifts from HAZ to TMAZ in a joint. Hardness value of this region is always lesser than the base metal.

4.4. Unaffected zone
Region adjacent to the HAZ away from joint is the BM that does not deform. However, it experiences thermal cycle but not to the extent to bring significant changes in microstructure. Chart shown in Fig. 12 summarises the microstructural evolution in different zones.
**5. Effects of process parameters:**

Optimum range of process parameters for a friction stir welding process depends on resulting joint efficiency and production rate. Although the process is affected by so many direct and indirect parameters, the key factors and their effects are listed in Table. Selection of these parameters for a joining process depends on the thermal and mechanical properties of base metal and the heating and cooling boundary conditions.

**Table 3.** Process parameters and its effects

| Parameter          | Effects                                                      |
|--------------------|--------------------------------------------------------------|
| Tool rotational speed | Heat generation, mixing material and breaking oxide layer |
| Welding speed       | Effective heat input and weld appearance                    |
| Downward force      | Frictional heat generation                                  |
| Tool tilt angle     | Enhancing material flow and weld appearance                 |

**5.1. Tool rotational speed**

Tool rotation speed is responsible for the heat generation as well as uniform material flow in the joining process. Increase in process temperature is achieved through the increase in heat supply. The simple way to increase heat supply is by increasing the tool rotational speed. McClure et al [23] recorded 40°C increases in temperature with an increase in tool rotational speed form 300 to 650 rpm. But the temperature raise did not increased considerable at higher speed. Swaminathan [24] observed only 20°C temperature rise when the tool rotational speed increased form 900 rpm to 1200 rpm. This indicates that increase in tool rotational speed beyond a limit does not have much influence on heat generation. Lower rotational speed causes defects due to the insufficient material flow in stir zone and higher tool rotational seed results excess heat and eradicates post weld properties in heat affected zone. Therefore, tool rotational speed has to be optimised based on the optimum heat supply.
5.2. Weld speed

Forward motion of the tool assists the movement of the plasticised material under the tool shoulder from advancing side to the back of the immersed pin. Apart from that, effective heat input to the material to be joined depends on the weld speed. High weld speed drastically reduces the effective heat supply during welding [25]. Reduction in heat supply reduces the process peak temperature and results insufficient material flow around the tool pin in stir zone. Insufficient material flow leads to tunnel defect in stir zone. Selection of higher welding speed increases torque in the tool and develops excess stress in tool pin [26]. As tool pin is completely immersed in the material the excess stress on tool pin results tool pin breakage. Decrease in weld speed not only leads to the excess heat supply but also increases production time.

Simultaneous action of heating and stirring of material in stir zone leads to grain refinement in stir zone. Recrystallization of material in stir zone is affected by the increase in tool rotational speed and decrease in welding speed. Refined grains in weldment ensure better weld quality. Tool rotation and traversing speed must be selected to ensure efficient welding. Lower rotational speed combined with higher traversing speed results in colder weld whereas, higher rotational speed along with lower traversing speed results in hotter weld. Being easily controllable weld parameters many researches (Table 4) has been done to optimise the tool rotational speed with respect to the tool feed rate.

**Table 4. Literature survey on optimum process parameters**

| Material | Analysed parameter levels | Optimum outcome value | Reference |
|----------|--------------------------|-----------------------|-----------|
|          | Tool traverse speed (rpm) | Tool rotational speed (mm/min) | Tool traverse speed | Tool rotational speed |          |
| AA1050   | 800 to 1600              | 100 to 300            | 1200       | 100                   | [27]      |
| AA2024-T3| 800 to 1600              | 35 to 140             | 1200       | 35                    | [28]      |
| AA2024-T4| 560 to 1800              | 11 to 45              | 900        | 35                    | [29]      |
| AA2024-T6| 1100 to 1900             | 10 to 70              | 1500       | 40                    | [30]      |
| AA4047   | 500 to 1100              | 45 to 55              | 1100       | 55                    | [31]      |
| AA5083   | 500 to 1400              | 16 to 40              | 950        | 28                    | [32]      |
| AA6061-T6| 900 to 1120              | 20 to 40              | 1120       | 40                    | [33]      |
| AA7075-T6| 630 to 1250             | 20 to 60              | 1000       | 20                    | [34]      |

5.3. Downward force and plunge depth

Vertical force exerted to the workpiece through the tool is one among the easily controllable parameter. Proper selection of vertical force ensures quality weld even if there are tolerable thickness variations in the materials to be joined. As vertical force is one among the key factor on frictional heat generation during the process, higher vertical force enables high speed welding [35]. Plunge depth is the depth of penetration of shoulder surface in the workpiece as shown in Fig. Plunge depth increases heat generation as well as it controls the forging of flow material in the stir zone [36]. Axial force can be increased through increasing plunge depth which results higher heat generation. Higher plunge depth affects grain growth in stir zone and affects ductile strength of the joint [37]. Lower plunge depth reduces vertical force which in turn reduces heat supply and leads to improper material flow around the tool [38]. Therefore, appropriate plunge depth is important for producing good-quality joints by ensuring adequate forging pressure required to consolidate flowing material properly as well as full penetration of the tool inside BM.

5.4. Tool tilt angle

Inclination of tool rotational axis with respect to the base metal surface is tool tilt angle as shown in fig. It has its own influence on frictional heat generation, material flow and consolidation of flowing material around the tool [39]. Peak process temperature rise is directly proportional to the tool tilt angle [40]. Tool tilt angle helps to prevent excess spill out of material during the joining process. Rajendran et al. [41] identified that tool tilt angle controls the size of the stir zone which indicates its
effects on material flow during the process. Tilting the tool by some degree in such a way that the front of tool is higher than its rear, helps in adequate forging of the plasticized material behind the tool to complete the joint.

Figure 13. FSW tool with plunge depth and tilt angle.

Apart from this direct process influencing parameters, other parameters like tool geometry, base metal material properties, workpiece thickness, heat dissipating boundary conditions and tool material properties also have its own indirect effect on weld quality. The chart shown below (Fig.14) explains the parameters and its effects in the joining process.

Figure 14. Process parameters and its effects on joining process in FSW
6. Weld defects and causes

Improper selection of process parameter leads to insufficient/excess heat supply during the process which in turn causes insufficient/excess flash of material flow in the joint. It creates weld defects in friction stir welding. Various commonly observed weld defects and its causes are given in Table 5.

| Defect                | Macroscopic appearance | Location                                                                 | Causes                                                                                           | Ref |
|-----------------------|------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-----|
| Tunnel                |                        | Between SZ and TMAZ in the advancing side                                 | - Low tool rotational speed.                                                                      | [42]|
|                       |                        | Advancing side of the SZ                                                  | - High feed rate.                                                                                 |     |
|                       |                        |                                                                           | - Insufficient plunge depth.                                                                     |     |
|                       |                        |                                                                           | - Improper pin offset.                                                                           |     |
|                       |                        |                                                                           | - Insufficient material flow.                                                                    |     |
|                       |                        |                                                                           | - Improper removal of oxide layer form faying surface.                                          |     |
|                       |                        |                                                                           | - Insufficient heat input.                                                                      | [43]|
|                       |                        |                                                                           | - Inadequate forging pressure.                                                                  |     |
|                       |                        |                                                                           | - High tool traverse velocity.                                                                  |     |
| Void                  |                        | Under the weld surface or the advancing and retreating sides of the weld | - Local variations in the plate thickness.                                                        | [44]|
|                       |                        |                                                                           | - Improper tool design.                                                                         |     |
|                       |                        |                                                                           | - Inappropriate plunge depth.                                                                   |     |
| Incomplete root       |                        | Below the SZ at the interface of the faying surface                      | - Improper tool design.                                                                         | [44]|
| penetration           |                        |                                                                           | - Inappropriate tool tilt angle.                                                                 |     |
|                       |                        |                                                                           | - Insufficient heat supply                                                                      |     |
|                       |                        |                                                                           | - High tool rotation speed.                                                                     |     |
|                       |                        |                                                                           | - Low weld speed.                                                                                | [45]|
|                       |                        |                                                                           | - High vertical force.                                                                          |     |
| Hooking               |                        | Both retreating and advancing sides of TMAZ                              | - Improper tool design.                                                                         |     |
|                       |                        |                                                                           | - Inappropriate tool tilt angle.                                                                 |     |
|                       |                        |                                                                           | - Insufficient heat supply                                                                      |     |
|                       |                        |                                                                           | - High tool rotation speed.                                                                     |     |
| Excess flash          |                        | Outer edges of the weld joint                                            | - Low weld speed.                                                                                | [46]|
|                       |                        |                                                                           | - High vertical force.                                                                          |     |

7. Conclusions

Temperature dependent shear strength of the aluminium alloy is the key factor that decides the material flow and defect free joint formation in friction stir welding. Heat generation and heat flow during the process depends on the chemical composition of base metal, surrounding environmental influence on cooling through heat dissipating boundaries. For the chosen process parameters there always be a maximum amount of temperature rise and for any chosen combination of parameters process peak temperature cannot be increased more than the material solidus temperature. Heat energy developed during the process cannot be completely utilised for the formation of stir zone. Optimised processing conditions necessitate that the material reaches a processing temperature which ensures thermal softening takes place and this also means that a degree of slip must occur between the FSW tool and the workpiece material. Tool pin has to be designed in such a way that it increases the material strain rate in the stir zone and decreases the clagging of material with the tool surface. Clagging of base material with tool results weld defects and reduces joint strength. Optimum heat generation during the process is a function of a number of quantitative factors like,

- Thermal conductivity of the tool material.
- Initial temperatures of the tool and base metal.
- The contribution of heat generation through plastic deformation of material in SZ.
- Frictional heat generated along the tool/matrix interface.
- The ability to retain constant temperature gradient during the process by maintaining constant balance between heat input and heat loss through the heat dissipating boundaries.

Optimum heat supply conditions depend on so many other environmental factors like spindle construction, clamping and backing bar employed to produce the joint. In order to understand the relationship between temperature rise and material flow during the process every single parameter that directly and indirectly influences the process should be taken into consideration. Hence, for any aluminium alloy the set of process parameters cannot be fixed as constant and it can only be defined as an optimum range based primarily on the geometry of the joint, construction of the workpiece restraint system and design of the FSW machine.

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