Effect of tool axis offset and relative position of materials on the performance of dissimilar friction stir welded aluminium alloy joints—an overview

K Subrahmanian¹,²,⁴ K K Ramachandran¹ and Rajeev Vamadevan³

¹Department of Mechanical Engineering, Government Engineering College Thrissur, Kerala, India
²APJ Abdul Kalam Technological University, Kerala, India
³Department of Mechanical Engineering, College of Engineering Trivandrum, Thiruvananthapuram, Kerala, India
⁴E-mail: subrahmaniank.k@gmail.com

Abstract. At present most of the manufacturing sectors are looking for high strength lightweight structures with high specific stiffness and good corrosion resistance. In this context, combined use of different types of aluminium alloys are required and warrants efficient joining of the dissimilar alloys. But, efficient joining of dissimilar aluminium alloys by fusion welding techniques is very difficult due to the poor weldability of dissimilar aluminium alloys. It is reported that FSW being a solid state welding technique can avoid all problems associated with fusion welding and is a potential candidate technique for joining difficult to weld materials including dissimilar aluminium alloys. With regard to FSW dissimilar aluminium alloys, the tool axis offset and relative positioning of alloys are also reported to be important. In this article, a comprehensive discussion on the influence of tool axis offset and relative positioning of the materials on the joint performance that reported in the literature is presented. The literature showed that there is uniqueness in the value and sign of the tool axis offset that can result defect free joint with good joint properties. With regard to relative positioning of the materials also, conflicting arguments are reported in the literature.

1. Introduction

Now a day, globally, aluminium alloys are considered as one of the most attractive group of structural material due to their high strength to weight ratio and excellent corrosion resistance. As per the aluminium association alloy and temper designation system, there are eight series of wrought aluminium alloys prefixed by AA, starting from AA1xxx to AA8xxx. 1xxx series consists of commercially pure aluminium with traces of Cu, Zn, Mg, Mn, etc. are impurities. The major alloying elements in other series are: 2xxx - Cu, 3xxx - Mn, 4xxx - Si, 5xxx - Mg, 6xxx - Mg and Si, 7xxx - Zn. And 8xxx – rare earth elements. The 2xxx, 6xxx and 7xxx series are heat treatable aluminium alloys and the strengthening is by solution heat treatment and aging. Whereas, the 3xxx and 5xxx series are not heat treatable and strengthening is by strain hardening. In the 4xxx series, both stain hardenable and heat treatable alloys exists.

Each aluminium alloy has its own unique characteristics and the use of dissimilar aluminium alloys in combination increases rapidly in many applications including automotive, aerospace, marine, rail, cryogenics, chemical industries, etc. The combined use of dissimilar aluminium alloys necessitates efficient joining of the dissimilar alloys. Joining of similar or dissimilar aluminium alloys by fusion
welding techniques is relatively difficult due to the evolution of defects such as porosity, hot crack, lack of penetration, loss of strength etc. Most of the defects are resulted from melting and solidification of the alloys during fusion welding. It is reported in the literature that friction stir welding (FSW) is capable to join aluminium alloys efficiently as the joining takes place without melting and solidification. FSW is a relatively new and promising welding technique developed by The Welding Institute (TWI), United Kingdom in 1991[1]. It is a solid-state metal joining process, that the objects are joined below the melting point with the help of mechanical mixing and forging. The heating and mechanical mixing is accomplished by a non-consumable rotating tool with a specially designed probe (tool pin) that will be plunged into the material and moved along the abutting surfaces of the plates to be joined. FSW is considered as an autogenous keyhole joining technique [2]. Figure 1 shows the schematic illustration of the principle of operation of the FSW process.

![Figure 1. Schematic of the FSW process](image)

As stated above, joining of similar or dissimilar materials in FSW is achieved by intense deformation which allows the flow of material in the solid-state developing fine and equiaxed grains in the weld zone by dynamic recrystallization [3]. Generally, FS welding of dissimilar alloys is complex than similar alloys because of the difference in their mechanical, physical, and metallurgical behaviour. In addition, the large difference in softening characteristics at elevated temperatures (that influence the materials flow) of the materials is also a significant issue [4]. In a dissimilar joint, heterogeneous chemistry exists at the weld zone and the microstructure evolution that affects the joint integrity depends on this chemistry also. As in similar aluminium alloys, in FSW of dissimilar alloys also dissolution of strengthening precipitates causes reduction in joint strength. The difference in coefficient of thermal expansion of the dissimilar material would cause substantial increase in development of residual stresses and distortion of the joints fabricated [5]. Therefore, proper selection of FSW parameters is critical for the strength and integrity of the dissimilar FS welded aluminium alloys joints. Investigations reported by various researchers showed that the relative position of the dissimilar materials and tool axis offset are important parameters in dissimilar FSW of aluminium alloys [6,7]. A comprehensive discussion that mainly focuses on the effect of the relative material position and tool axis offset on the joint integrity that reported in the literature is presented in this article.
2. FSW Process Parameters

In the art of Friction stir welding, the important parameters (variables) that affect the weld quality are classified into three groups, namely, parameters associated with the tool, and other miscellaneous parameters [8]. The various FSW parameters and their classes are graphically illustrated in the cause and effect diagram shown in Figure 2. The welding speed, tool rotational speed, axial load, tool tilt angle, geometric parameters of the tool, tool axis offset, relative position of the material, thickness of the material, etc. are the important independent parameters which influence the weld quality. For a given base material, the magnitudes of the above parameters ascertain the peak temperature, the transverse force (x-direction force), torque and power requirement in FSW [6]. For dissimilar materials, in addition to the above parameters the tool axis offset and relative position of the base materials also have significant influence on the heat generation (peak temperature), transverse force, microstructural evolution, etc. and hence the quality of the weld joint produced.

![Cause and effect diagram for FSW parameters](image.jpg)

**Figure 2.** Cause and effect diagram for FSW parameters

2.1. Effect of tool axis offset

Tool axis offset is the distance from the tool axis or tool centreline to the facing surface of the work pieces as illustrated in Figure 3. Though, some studies reported that giving tool axis offset in similar FSW can enhance the joint integrity, in FSW of similar materials usually the tool axis offset is set as zero. In dissimilar FS welding, proper mixing of the materials plays an important role in developing sound joints with acceptable joint performance. It is well established that the heat generation at the advancing side of the joint is significantly higher than that at the retreating side. Thus, giving tool axis offset towards the softer or harder material will have opposing influence on the heat generation and hence the peak temperature. Thus, proper positioning of the materials and selection of tool axis offset can avoid or at least reduce the formation of undesirable precipitates and defects like voids and tunnels in dissimilar FSW.

Cavaliere et al. [9] investigated the effects of tool position on the mechanical properties of dissimilar FS welded aluminium alloys AA2024-T3 and 7075-T6 with 4 mm thickness in the butt configuration. The investigation revealed that upon increase in tool axis offset towards the stronger 7075 alloy, the mechanical properties of the welded joints gradually increased with the highest values at 1 mm offset. But, increase in tool axis offset beyond 1 mm resulted apparent decrease in mechanical properties. The authors reported that with 1 mm offset, both the base materials undergo proper plastic deformation, proper flow of materials around the tool and intermixing. The resulted very fine
equiaxed grains at the stir zone (SZ) due to dynamic recrystallization (DRX) and slightly elongated and fine grained microstructure at the thermomechanically affected zones (TMAZ) on either sides of the SZ, as shown in Figure 4(a), are responsible for the enhancement of mechanical properties. At higher tool axis offsets (1.5 mm), insufficient heat generation and resulted low plastic deformation caused bands of different grain size in the SZ as shown in Figure 4(b), resulted in inferior joint properties.

Figure 3. Schematic illustration of the tool axis offset

Figure 4. Microstructure of the weld zone (a) Optical micrograph of joint produced with 1 mm tool axis offset (b) Optical micrograph of joint produced with 1.5 mm tool axis offset[9]

Anilkumar et al. [10] reported the influence of FSW parameters on the tensile properties of FSWed dissimilar 4 mm thick aluminium alloys, AA5083-H111 and AA6082-T6. The experimental trials were carried out with three different tapered square pin FSW tools having tool shoulder diameter of 16 mm, 18 mm and 20 mm; at tool tilt angle of 0°, 1°, and 2° and tool axis offset values of -2 mm to +2 mm from the joint interface. It is reported that highest joint tensile strength was observed for joints produced using FSW tool with 18 mm shoulder diameter at zero tool offset and 1° tool tilt angle. The authors concluded that though the tool shoulder diameter has significant influence on the joint tensile properties, the tool offset of ±2 mm has negligible influence on the tensile properties of the joints produced. The variation in tensile strength of the joints upon change in tool shoulder diameter indicates that the amount heat generation during the FSW process has apparent influence on the joint integrity. Therefore, the relatively low variation in flow stress of the base materials could be the probable reason for the insensitivity of tool axis offset on the joint performance. Mastanaiah et al. [11] successfully friction stir welded 5 mm thick dissimilar aluminium alloys AA2219 and AA5083. It was demonstrated that the intermixing of the dissimilar alloys in the weld zone is significant at zero tool axis offset condition. The authors reported that defect-free joints were produced at tool rotational
speed in the range from 400-2000 rpm, at constant welding speed of 30 mm/min and tool axis offset in the range from -2 to +2 mm. The optical macrographs of the joint interface at different tool axis offsets are shown in Figure 5. From figures 5(a, b), it can be seen that at tool axis offsets of ±2 mm, the level of intermixing is low due to the low plasticization as a result of the low heat generation at the side where the tool penetration is less. Significant change in heat generation on either side change of the joint may create considerable differences in viscosities of the material on either side. The study inferred that for better joint integrity, the tool axis offset should be about +1 mm. Further, the authors opined that better plasticisation and the resulted proper intermixing due to near optimal heat generation could be the probable reason for the better joint integrity at +1 mm tool axis offset.

![Image](image1.png)

**Figure 5.** Optical micrographs of the joint interface of dissimilar FS welded AA2219 and AA5083 alloys (a) at -2 mm tool axis offset (b) at +2 mm tool axis offset (c) at +1 mm tool axis offset[11]

Ashok Kumar et al.[12] in their investigation confirmed that about 2 mm tool axis offsettowards the softer material is good for better joint integrity with regard to FSW of dissimilar AA6101-T6 and AA1350 alloys. The SEM micrographs shown in Figure6 demonstrate the appearence of the SZ of the dissimilar joints produced at different tool axis offsets. The formation of some unbounded region seen in Figure6(a) is reported to be due to the insufficient diffusion and reaction at zero tool offset condition. When tool offset was given to the high strength material side, the SZ appears to have a strong bonding,apparently due to the base metals undergone sufficient plastic deformation and intermixing as shwon in Figure 6(b). Also, the authors inferred that the low growth of fine grains formed at the SZ as a result of the near optimal heat input contributed for the enhanced tensile strength of the joiths. The formation of continuous cracks and improper bonding that are evident from Figure
6(c) caused reduction in tensile properties of the joints with tool offset towards the softer material. This is a clear indication that when the relatively very soft alloy grades such as 1xxx is joined with moderate to high strength alloy grades, plastic flow heat generation is significant and tool offset towards the high strength material is essential for better joint integrity.

The investigation on FS weldability of 6 mm thick dissimilar aluminium alloys, AA5052 and AA6101-T6 reported by Kasirajan et al.[13] showed that a tool axis offset of 1 mm towards the advancing side is advisable for higher joint strength. The authors have experimented tool axis offset of 0 – 2 mm towards the advancing side with tool rotational speed ranging from 760 – 1400 rpm using Taguchi L16 experimental design. At tool offset more than 1 mm towards the advancing side, the strength of the joints produced showed a drastically decreasing trend with a minimum value at 2 mm tool offset. Lack of material intermixing and material flow across the joint interface due to low plastic flow heat generation as the pin almost completely stirring through the material at the advancing side is suggested as the probable cause for the significant reduction in joint strength. Cole et al.[14] examined the temperature profile of the weld zone during FSW of dissimilar aluminium alloys AA6061-T6 and 7075-T6 (both 4.76 mm thickness) by varying the tool axis offset with two different tool pin geometries (threaded pin and conical pin with three flats). The study confirmed the fact that the heat generation is higher at the advancing side of the joint (higher temperature) and hence tool axis offset of 2 mm towards the retreating side has resulted better joint strength.

Figure 6. SEM images of SZ (a) zero tool offset (b) offset towards AA6061T6 (c) offset towards AA1350 [12]

In FSW of 3 mm thick dissimilar AA6061-T6 and AA8011-h14 aluminium alloys, Khanna et al.[15] observed that 1 mm tool axis offset towards the advancing side (AA8011-h14) was conducive for defect free joints with better joint strength. Kumar et al. [16] conducted an innovative experimental study on FSW of similar and dissimilar aluminium alloys to study the material flow and to establish the positional dependence of materials on joint strength. The experiment was conducted by using two different materials with different thicknesses. The materials utilised in this study were 4.4 mm thick AA7020-T6 and 1.65 mm thick AA2024-T3 that is designated as marker material. Figures 7 (a) and (b) illustrate the tool shoulder induced material flow and pin induced material flow patterns. The flow patterns clearly indicate that the degree of material adhesion on the tool shoulder and tool pin surface is very significant for proper intermixing and bonding of the materials. The investigation further reveals that the best interface position is about 0.5 - 1.5 mm from the tool axis at the advancing side of the joint (with regard to strength, ductility and defects free joints). When the interface is positioned 0.5 mm apart from the tool axis on the advancing side, the material stirring is better and the surface oxide layer at the surface gets distributed almost homogeneously in the weld zone. This aspect together with the asymmetric nature of material flow on either side of the joint interface is reported to be the possible reasons for the better joint properties at tool axis offset of 0.5 – 2 mm towards the advancing side.
2.2. Effect of relative position of materials

As stated above, another important factor that influences the properties of the joints produced in dissimilar FSW of aluminium alloys is the relative position of the base materials. During FSW of dissimilar aluminium alloys, the dissimilar base materials can be placed either on the advancing side or retreating side of the joint. A few investigations suggest that, for better joint integrity, the material with higher hot strength should be kept on the advancing side of the joint and some other studies claims the contrary. Kalemba-Rec I. et al. [17] reported that in FSW of 6 mm thick aluminium alloys AA5083-H111 and AA7075-T651, for defect free joints, the softer AA5083-H111 should be placed at the advancing side and AA7075-T651 at the retreating side of the joint. Though, in the reverse configuration, the joints were characterized by defects such as voids and discontinuities, the tensile properties of the joints were almost identical in both the cases. The authors concluded that the relative position of the materials plays a vital role in material flow and defect formation in the joint but not significantly influence the tensile properties of the joint.

![Image](a) Shoulder induced flow (b) pin induced flow [16]

The investigations reported by [17,18,19,20] on FSW of heat-treatable and non-heat-treatable dissimilar aluminium alloys from AA7xxx and AA5xxx series suggest that for defect free joint with better mechanical properties, the relatively soft (low strength) alloys from the 5xxx series should be located at the advancing side of the joint. The authors opined that the joint properties predominantly dependent on the material at the retreating side of the joint and reasoned that it is due to the fact that the SZ is mainly composed of material at the retreating side. Cole et al. [14] reported that the advancing side of the weld is hotter than the retreating side and due to the higher temperature experienced on the advancing side during the FSW process, the flow stress and viscosity of the material will be reduced. Thus, if the harder (high strength) material is placed at the advancing side of the joint, the combined effect of reduction in flow stress and viscosity permit better material flow. Also, if the high flow stress material placed on the retreating side, the relatively low temperature and resulted low plasticization at the retreating side resist the material flow. A good number of studies reported in the literature support this logic that when the strength of the materials to be joined is significantly different, for defect free joints with good joint performance, the high flow stress material to be located at the advancing side of the joint [21,22,23].

With regard to material positioning in dissimilar FSW of aluminium alloys form the same alloy group or from the same category alloy groups (for example heat treatable alloys from 6xxx and 7xxx series), also, contradictory conclusions are reported in the literature. Hasan et al. [24] in their experimental studies on FSW of aluminium alloys AA7075-T6 and AA6061-T6 (3 mm thickness) using various tool pin geometries suggest that for better joint integrity and defect free joints, the relatively softer AA6061-T6 material should be located at the advancing side of the joint. The authors reported that the combined positive influence of the positioning of the softer material at the advancing
side together with the threaded tool pin profilepromoted intermixing and proper material flow to result sound and strong joints. Guo et al. [25], Raturi et al. [26] and V.Saravanan et al. [27] also reported that in FSW of dissimilar alloys from 6xxx and 7xxx series, it is advisable to place the softer alloy at the advancing side of the joint. But, Rodriguez et al. [28] in their experimental investigation on the characteristics of FSWed AA6061 and AA7050 alloys concluded that for defect free joints with good joint strength, the harder AA7050 alloy should be located at the advancing side of the joint. In the case of FSW of 5 mm thick aluminium alloys AA5083 and AA1050, Fattah-alhosseini et al. [29] also suggested that the stronger material AA5083 should be positioned at the advancing side for ensuring sound joints. It should be noted that in almost all the investigations referred above, the FS welding trials were carried out with different base material thickness using quite different welding parameter combinations such as welding speed, axial force (in most of the cases not controlled or welding carried out under position control mode), welding speed, tool tilt angle and tool geometry. Thus, it is rational to infer that for high strength defect free joints, the decision regarding the relative position of dissimilar alloys on the advancing side or retreating side is influenced by the values of welding parameters and material thickness also.

3. Conclusions
A comprehensive discussion on the influence of the two important FSW parameters, the tool axis offset and relative position of the dissimilar alloys on the joint performance in FSW of dissimilar aluminium alloys that reported in the literature is presented. The following conclusions can be derived from the discussion.

• There is no uniqueness in the reported magnitude or sign (offset towards advancing side or offset retreating side or zero offset) of tool axis offset that results defect free joint with good joint strength. For certain combination of primary FSW parameters, tool geometry and material thickness, tool axis offset of about 1 mm towards the advancing side of the joint has resulted favourable results and vice versa. But, for dissimilar materials with nearly identical mechanical properties, mostly, zero tool offset has resulted positive results.

• With regard to the relative positioning (advancing side or retreating side of the joints) of the dissimilar material, also, conflicting arguments are reported in the literature. In a few investigations, locating the softer material on the advancing side of the joint is suggested for better joint integrity but some other investigations suggest the contrary.

• In dissimilar Friction stir welding of aluminium alloys, it seems, both the tool axis offset and relative positioning of the materials dependant on the thickness of the materials to be joined and the magnitude of other FSW process parameters such as welding speed, tool rotational speed, axial force and tool geometry employed for welding.

• In most of the reported works, the primary FSW parameter, axial force is either not reported or controlled or the FS welding was conducted under position control mode. Since axial force is a very critical parameter for the joint integrity, more focussed investigations by controlling the axial force are required for meaningful conclusions on the influence of the two parameters.

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