A Review on Process Parameters and their effects on Dissimilar Friction Stir Welding of Aluminium and Steel Alloys

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Abstract. Friction Stir Welding (FSW) presents numerous advantages over conventional fusion welding techniques such as eliminating the need for a shielding gas, requiring less energy per weld, and the lack of a flame or arc making it safer in the work place. Another advantage of FSW is its ability to join materials that are extremely difficult, or impossible to weld with conventional fusion techniques. The growing need for dissimilar welding relates to joining aluminium and steel base metals. Individually, both metals are utilized extensively in the automotive and aerospace industries due to various advantages respectively, including lightweight, high specific strength, and recyclability. Like conventional welding methods, the intermetallic compound formation represents the main problem issue in FSW. Heat cycle has a significant effect on Intermetallic Compounds thickening phase transformation and the elimination of the amorphous phase. The hybrid techniques utilized in FSW for Al-to-steel joints reveal high joint strength in conjunction with high costs of setup and equipment. These techniques modify the steel flow around the rotated pin by acting as an assisted heat source. Process parameters play the most important role in defining the quality of the weld to withstand. In this paper we are going to discuss the effect of different parameters on Dissimilar FSW.

1. Introduction
The advantages of Friction Stir welding are several in comparison with general welding techniques like, GMAW (Gas Metal Arc Welding), TIG (Tungsten Inert Gas Welding) and MIG (Metal Inert Gas Welding) etc. As it is a solid-state joining process, there is no need for an electrode or shielding gas and the energy required per weld is less than that of fusion welding. The welding of the materials is done with the heat developed between tool rotation and the traverse speed which means that there is no flame and guarantees the safety of the worker. The main advantage of Friction Stir Welding as shown in figure 1, is that it can join different materials whose melting points differ which are difficult to weld with the general welding techniques [1,2]. There is no melting of the parent material which can lead to the formation of unwanted and detrimental intermetallic compounds often present during the welding of two different materials such as steel and aluminium. National Aeronautics and Space Administration has adopted FSW for use in the circumferential welds of the spacecraft’s fuel tanks. Other applications of Friction Stir Welding include the Boeing Delta IV heavy rockets used to launch the Mars Phoenix Lander in July 2007. General Motors has begun funding research in FSW and has even started using FSW for some spot-welding applications in production.
Recently, there has been much development in the FSW of dissimilar materials. Different materials like copper, titanium, magnesium, aluminium, steels are successfully welded by using FSW [3, 4]. The welding process for Al-Fe alloys are quite arduous and challenging as like welding process for other Aluminium and steel alloys, because of its low melting temperature and high thermal conductivity. Several applications, as such for Al-Fe alloys, necessitate the alloys to be welded with the help of FSW. In this regard, the FSW is one approach that prospectively demonstrates high potential, uncomplicated and comprehensive proficiency to weld these alloys. [5, 6, 7]. In addition, the mathematical modelling has substantially increased widespread applications and appositeness in materials science and engineering fields [8].

![Schematic diagram of Friction Stir Welding](image)

**Figure. 1.** Schematic diagram of Friction Stir Welding

2. Dissimilar Friction Stir Welding of Aluminium and Steel

2.1 Process Parameters of FSW

Several researchers have successfully welded different kind of materials. The main things that attract a researcher in Friction Stir Welding are different parameters and their ability to define the joint strength. In this paper the following parameters are discussed:

- **Tool pin profile** – Different tool pin profiles are used for different materials depending upon the need for strength and to obtain a perfect weld. Majorly used tool pin profiles are cylindrical, threaded cylindrical, tapered, tapered cylindrical. Now a days the new pin profile called the “tri-flute” is being used to weld dissimilar materials.

- **Tool rotational speed** – The main technique of FSW is material flow, which can be controlled using the tool rotational speed. The churning of the material starts on the advancing side and is thrown away to the retreating side to form the joint.

- **Tool traverse speed** – While the stirring is being done, the movement of the tool in the horizontal direction makes the stirred material movement to the back which results in the formation of the weld.

- **Tool shoulder** – The different shapes of the tool shoulder make an impact on the weld. The three different type of shoulders used are flat, concave and convex. The shape of the face of the tool shoulder also plays an important role in the stirring of material.
2.2 Effect of Tool Pin Profile
A cylindrical threaded tool was used to weld AISI 1018 steel and Aluminium 6061 plates of thickness 6 mm with the combined effects of FSW and fusion welding. The existence of the intermetallic phases Al5Fe2 and Al13Fe4 were found in the weld nugget. A perfectly stable heterogeneous joint was obtained using this combined effect process and the damage of the tool was identified in the microstructural analysis [9]. A cylindrical pin was used to attain 86% of the aluminium base metal joint strength with a small amount of IMC’s (Intermetallic Compounds) formation at the starting part of the weld. Along the weld joint, it has been observed that there were no intermetallic compounds at the end of the weld. The stirring effect made many parts of the steel to scatter in the aluminium material and because of the rubbing motion on the faying surface the oxide film has been removed. The rotation pin was in contact with the face of the steel plate while welding.

A straight cylindrical pin was used to weld SS 400 and Aluminium 6061 plates to find the better conditions to operate and to find the suitable parameters. Charpy Impact test was used to determine the quality of the weld, depending on the achievable impact value. The lower the welding speed and the rotational speed the higher are the Charpy impact values. The acceptable tensile strength and good impact values are obtained with low traverse speed of 1 mm/s with a rotational speed of 560 rpm [10].

2.3 Effect of Tool Rotational Speed
Different tool rotational speeds are used to check the hardness of the stainless steel and aluminium 6014-T4 joints in different zones of the joint like nugget zone, Thermo Mechanically Affected Zone (TMAZ) and Heat Affected Zone (HAZ). It has been observed that the hardness value is less on the retreating side when compared to the thermo mechanically affected advancing side. Hardness in the weld nugget is different at various points because of the uneven scattering of the steel particles in the nugget zone. The researchers found the minimum hardness in the heat affected zone which is 5 to 12 mm from the nugget centre on the retreating side. They discovered that the fatigue properties of the joint were almost 30% lower than that of aluminium 6013-T4 base metal [11].

Along with different rotational speeds the tool offset also plays a major role in dissimilar friction stir welding of aluminium and steel alloys. Because of the offset position the churning and the flow of material mostly done on the aluminium alloy. Microstructural analysis have been done on different weld zones including the base metal. It has been found that the grain size and shape were mainly affected during the welding process. This has resulted in achieving the joint strength as close as 80% of the aluminium alloy base metal. The High-Speed Steel side had shown no plastic deformation during the tensile test. the whole deformation was on the aluminium alloy [12]. A new technique called friction stir spot welding was found where the rotational speed plays the important role. It helped to weld mild steel and 6061 aluminium alloy plates of thickness 1 mm. Different pins of length 1, 1.3 and 1.5 mm with different rotational speeds were used to produce sound joints between the plates. The FSSW was conducted on a round dent which was already made on the back of the plates. The authors found that the maximum shear load can be 3607 N [13].

2.4 Effect of Traverse Speed
The traverse speed is important when the joints are made with tool offset towards the aluminium side. 304 stainless steel and aluminium 5050 plates were welded with an offset of 1.5 mm towards the aluminum which helped in decreasing the voids caused in the nugget zone which has increased the tensile strength without offset. The authors achieved sound joints by changing the traverse speed. They have achieved a perfectly sound joint with a traverse speed of 80 mm/min. The annealed joint has increased the elongation and UTS by 10% [14].

A lap joint was made between 6061 aluminium and 316 stainless steel plates by using zinc as a filler material. Most of the zinc was moved to aluminium side during the stirring process, making retreating side as the zinc occupied side. EDS analysis found that there were tiny parts of FeZn10 but there was no sign formation of intermetallic compounds when the pin is plunged into the zinc foil. The maximum
strength of the joint was achieved with the influence of zinc layer mixing with aluminium and steel. The XRD patterns show that different solid solutions were found in the fracture parts of the joint [15].

6061 aluminium alloy and S235J steel are welded to improve the joint by changing the traverse speed with tool offset towards the aluminium side. There were tunnel defects with high traverse speed and if the offset was 0.2mm towards steel and the weld was not completed. 41.62 MPa tensile strength was achieved with a no offset and medium traverse speed. The best joints were achieved if the offset was 0.2 mm towards the aluminium side with low traverse speeds. The average tensile strength was 95.73 MPa. From all the experiments conducted it was found that the tunnel and void defects influenced in producing the joints which are low in tensile strength [16].

2.5 Effect of Tool Shoulder

Different tool shoulders have effects on the stirring process. A concave tool shoulder was used to weld steel DX54 and aluminium alloy AA5754-H22. The lap joint was innovative, and it has improved the quality of the welds. A wave shaped probe was used during the plunge, which created enough heat to stir the material with perfect interlocking. Several experiments are conducted with this new overlap weld technique and it was found that the welds are perfect with two passes. They achieved 50% of the tensile strength of aluminium base metal. Microstructural analysis shows that the intermetallic compound formation was uniform with a thickness of 1 μm throughout the weld joint [17].

A flat shoulder pin with a tilt angle of 1° was used to weld commercial pure aluminum and Interstitial free steel. They (Sorger, et al.) used different rotational speeds ranging from 600 to 1200 rpm with a fixed traverse speed of 100mm/min. In the weld nugget zone, it was found that Al3Fe IMC’s were observed, and the thickness of the IMC increased when the rotational speed was increased. The authors achieved a maximum tensile strength of 124 MPa with an elongation of 4.6% at the nugget zone of the joint [18, 19].

2.6 Defects in Dissimilar FSW with respect to Process Parameters

Weld quality in friction stir welding is affected because of various defects produced during the welding process. The friction stir welding defects includes Tunnel, Flash, Kissing bond, Void/Wormhole, Cavity/Groove, Cracks defect.

In figure 2(a), we can observe the formation of the tunnel and cavity which are formed because of insufficient heat and stirring between the plates. Flow in vertical direction is not possible if insufficient heat input is given which leads to tunnel defect. In figure 2(b), the formation of groove or wormhole can be observed which is due to very low rotational speeds and high welding speed. Mechanical properties are mainly affected by the groove defect. Tensile strength is decreased because of the formation of grooves in the weld. In figure 2(c), 2(d) we can observe the crack line defect which are formed during FSW welding of dissimilar materials beneath the tool shoulder. Selection of perfect parameters play an important role in producing defect free weld during friction stir welding.

Lack of heat input during the stirring process and incomplete movement of the material leads to the development of root defects. While using the flat shoulder if the pin depth is inadequate then different kinds of grooves appear in the nugget zone. Crack-line defects are formed if the plunge depth is not perfectly aligned with a tilt angle. The downward force must be enough to plasticize the metal with tilt angle or else it will lead to crack-line defect due to lack of plunge depth. So, in general with smaller or higher tilt angles there is a chance for the formation of crack-line defect.
Figure 2 Defects in FSW (a) Tunnel defect (b) Groove defect (c) and (d) Crack line defect.

3. Conclusions
The main challenge to weld dissimilar materials is selection of parameters because of the difference mechanical, chemical and physical properties. There is not enough research done on dissimilar materials such that the industries can rely and manufacture the products with this technology. The research of dissimilar materials should be extensively done so that it can move from a lab to industrial application. To achieve that goal the researchers must concentrate the combination of different materials and their performance in the long term. The focus of the researchers is on trying different combinations of the materials and the selection of different parameters to achieve good mechanical properties for a certain combination, instead of focusing of repeating the weld for a long-term reliability. The researchers who are working on Friction stir welding of dissimilar materials will face a lot of problems due to different welding conditions, formation of intermetallic compounds, welding defects which mainly occur in the nugget zone of the weld. If the focus is shifted towards selecting the perfect parameters and perfect material combination the FSW of dissimilar materials will be used in industries.

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