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Friction Stir Welding of different Joint Configurations: A Review

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Abstract—*Friction Stir Welding (FSW) is a solid state joining process, which means that the metals are joined without reaching their melting point. Being a solid state joining process, it offers various advantages like low distortion, absence of solidification related defects, porosity etc. over conventional fusion welding process. FSW is considered as a most significant development in metal joining in the past decades and can be applied to a number of joint configurations such as butt joints and lap joints along with T-joints. In the present paper an overview of FSW of different joint configurations has been provided along with the basic principle of FSW and research survey and application in the field. Also the effect of FSW parameters on the resultant microstructures and mechanical properties are discussed.*

Keywords*: FSW; Joint configuration; Mechanical Properties; Microstructure.*

1. INTRODUCTION

Friction Stir Welding (FSW) is considered as a most significant development in metal joining in the last 25 years and was developed by Wayne Thomas at The Welding Institute (TWI), UK, in December 1991 [1]. This relatively new welding process has initially and particularly been applied for welding high strength aluminium alloys and other metallic alloys that are difficult to weld by conventional fusion welding. FSW, being a solid state process, takes place at the temperature below the melting point of the base material, and as a result it does not experience problems related to resolidification such as porosity, embrittlement, hot cracking, segregation and phase transformation due to temperature achieved during welding [2]. FSW was initially applied to aluminium alloys but the development of FSW in aluminium alloys and its successful implementation into commercial applications has motivated its application to more non-ferrous materials and other metals. Recently, its applications have been extended to the welding of high melting point materials such as various types of steels [3], Ti alloys [4], Ni-based super alloys [5], the welding of metal matrix composites and polythene [6]. FSW is being used in various industries such as aerospace, ship building, automotive, railway, defence etc., where dissimilar material joining is required that are not viable using conventional fusion welding techniques. With recent developments in technology of FSW, it is now possible to carry out dissimilar welding of various types of steels with alloys of aluminium, magnesium, copper, titanium and also other alloy combinations [11]. FSW is considered as a green technology because no gases are evolved during the process. Also, there are no toxic fumes or smoke produced during or after the welding process. FSW offers a number of advantages like: (a) Solid phase process (b) low distortion of workpiece (c) good dimensional stability (d) excellent mechanical properties of welded joints (e) fine recrystallized microstructure (f) absence of hydrogen embrittlement and stress corrosion cracking (g) energy efficient and environment friendly [7, 8, 9]. However, during FSW, inappropriate values of welding parameters like tool rotation speed, traverse speed, plunge depth, feed rate etc. may cause defects in the joints and deteriorate the mechanical properties of the welded joints. Some common defects associated with FSW process are kissing bond, tunnel, lack of fusion, voids, excessive flash [10]. During FSW of dissimilar materials, there are the number of factors which mainly influence the quality of welding. Some of them are, (a) different deformation behaviors of the materials which are to be joined, (b) formation of detrimental intermetallic compounds, (c) differences in physical properties such as thermal conductivity and melting point, (d) In two materials, which one should be at the advancing side and which one should be at the retreating side [14].

2. FRICTION STIR WELDING: THE PROCESS

In FSW, a rotating tool with a specially designed pin and shoulder is inserted at the edges of the plates to be joined and traversed along the joint interface as shown in Fig. 1. In this method, the stirring tool which rotates at high speed is slowly plunged into the clamped plates which is to be joined, until the shoulder of the tool touches the upper surface of the plate. The heat caused by the friction between the tool shoulder and the workpiece results in an intense local heating that does not melt the plates to be joined, but plasticizes the material around the tool. The plasticized material is pressed downwards by the tool shoulder, preventing the material from flowing away from the surface. As the tool traverses in the direction of welding, the leading edge of the tool transferred the plasticized material on the either side of the joint, to the back of the tool. As a result, a solid phase joint is produced. Upon reaching the end of the weld, the tool is withdrawn, after withdrawing the pin, it leaves a key hole at the end of the weld. This is the main disadvantage of FSW [13]. Despite of this disadvantage, FSW is the most attractive solid state joining process for high strength alloys. The side where the tool rotation is in the same direction of translation of the welding tool is called advancing side and where the two motions rotation and translation are in opposite direction is called retreating side [12].

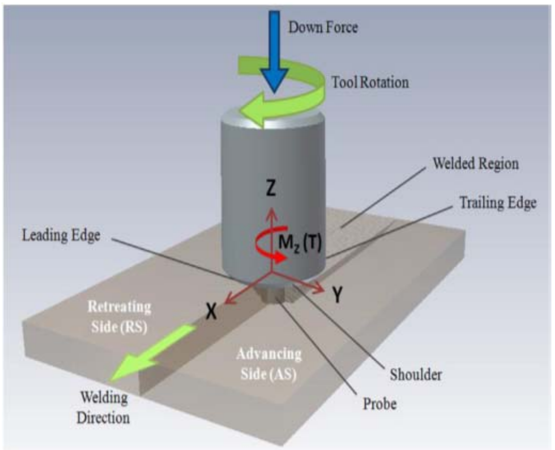

Fig. 1: Schematic representation of FSW. (Gibson et al. [23])

2.1. Process Parameter

FSW involves complex material movement and severe plastic deformation, which in turn is affected by process parameters such as tool geometry, welding parameters and joint design. Thereby influencing the microstructural evolution of material [10, 15, 16].

2.1.1. Tool geometry

The tool is the basic component of the FSW process and it consists of a shoulder and a specially designed pin. Pin profile plays a crucial role in material movement and thereby regulates the welding speed of the FSW process [19]. A friction stir tool has two primary functions: (a) heating of workpiece, and (b) movement of material. The heating of the workpiece(s) is achieved by the friction between the tool and the workpiece and the plastic deformation of the workpiece material. From the heating point of view, the relative size of the pin and shoulder is also very important. The shoulder also prevents the material from flowing away from the surface. The second function of the tool is to stir and move the material to produce a sound weld. From the available literature, it is clear that, generally a concave shoulder and threaded cylindrical pins are used [10, 15]. For butt joint configuration by FSW, generally a cylindrical tool with threaded pins are used. In case of thicker plates, conical tools with threaded pins should be used. In case of lap welding, a modified tool is required to break the stable oxide layer, especially in case of Al- alloys to obtain a better metallurgical bond [1, 21]. For T joints, generally non-threaded conical pin tools with concave shoulder are used [32].

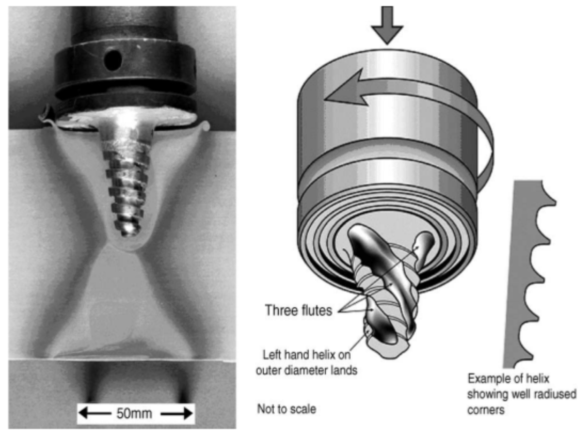

Fig. 2: Whorl^{TM} and MX Triflute^{TM} tools developed by The Welding Institute (TWI), UK (Copyright# 2001, TWI Ltd) (after Thomas et al. [17]).

By keeping these things in mind, The Welding Institute (TWI) has developed two special tools: (a) Whorl and, (b) MX Triflute as shown in Fig. 2. W. M. Thomas et al. [17] stated that the pins for both the tools are shaped as a frustum which replaces less material than a cylindrical tool of same root diameter. The design characteristics of Whorl and MX Triflute are: (a) to reduce welding force (b) facilitate easier flow of plasticized material (c) increase the interface between the pin and the plasticized material, as a result increasing heat generation. For lap welding, two new pin geometries – Flared-Triflute and A skew has developed by The Welding Institute (TWI). Thomas and Dolby [18] suggested that both Flared-Triflute and A skew pins are suitable for lap, T, and similar welds joining.

2.1.2. Welding Parameters

After reviewing the available literature, it is well known that, tool rotation (rpm, either in clockwise or counter clockwise direction) and traverse speed (mm/min) along the joint interface in the desired direction are the most important welding parameters in FSW process. As discussed earlier in this paper that the secondary function of the tool is to “stir” and “move” the material. If the tool rotates at a higher rotation rate, it will generate higher temperature because of higher frictional heating and as a result more intense stirring and mixing of material take place. The combination of rotation and translation of the tool transfers the stirred material from the leading edge to the trailing edge of the tool and finishes welding process [20]. In addition to tool rotation and traverse speed, other process parameters are plunge depth (target depth or insertion depth) and tool tilt or angle of spindle with respect to the workpiece surface. The plunge depth, sometimes also called as target depth or insertion depth is associated with the pin height and is important for producing sound welds with smooth tool shoulder. If plunge depth is either too deep or too shallow, sound welds cannot be obtained. Because in case of too deep plunge, the shoulder of the tool that plunges into the workpiece create excessive flash. When the plunge is too shallow, the shoulder of the tool does not contact the upper workpiece surface and in this case the rotating tool shoulder cannot move the softened material efficiently from the front to the back of the pin. In case of too shallow plunge, the plasticized material can also move away from the surface of material as the tool shoulder prevents the plasticized material from flowing out from the weld surface. A suitable tool tilt towards the trailing direction is required so that the shoulder of the tool holds the plasticized material by threaded pin and moves the material efficiently from the front to the back of the pin [10, 15].

3. JOINT CONFIGURATIONS

3.1. Butt joint

Butt joint is the most common joint configuration used due to its stress distribution and easy set-up. A schematic representation of simple butt joint is shown in Fig. 3. In this configuration, two plates or sheets which are to be joined are placed together on a backing plate and clamped firmly on a specially designed fixture to ensure that the plates joint interface do not separate [10]. The major advantage of this joint configuration is that two metal plates can easily be welded together without any major concern about the surface condition of the plates [23].

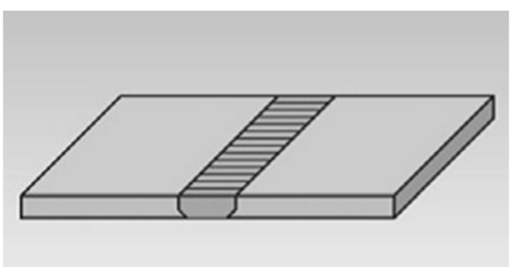

Fig. 3: Butt joint configuration by FSW. (Gibson et al. [23])

While performing butt welding, Ana et al. [2] described that in order to obtain high ultimate tensile strength (UTS) by FSW, an optimum process parameter of 1000 rpm, 290 mm/min, a shoulder diameter of 12 mm or 15 mm and a plunge depth of 2.85 mm should be used. As in FSW, heat generation is much influenced by the shoulder diameter which in turn affect the joint strength and they found that the use of a larger diameter degraded the UTS drastically. Yoo et al. [22] investigated the effect of process parameters on mechanical properties and macro structure of Al-Li alloy on friction stir butt welded joint. They considered rotation speed and traverse speed as main process parameters, material used for the experiment was A12195-T8 of thickness 7.4mm. The range for rotational speed was 300-800 rpm and 120-420 mm/min for traverse speed. They stated that the high strength is observed in the range of 400~600 rpm and 240~300 mm/min. Liu et al. [25] discussed the FSW ability of 2017-T351 aluminium alloy during butt welding and described the relation between optimum process parameters and mechanical properties of the joints. They stated that the maximum ultimate strength of the joint equivalent to 82% of the base metal was found when revolutionary pitch is 0.07mm/rev corresponding to the tool rotation of 1500 rpm and tool traverse speed 100mm/min.

Watanabe et al. [26] investigated the effects of tool rotational speed and the position of the pin axis inserted on the joint interface on the tensile strength and microstructure evolution on butt welded joint. They butt-welded an aluminium alloy plate to a mild steel plate and claimed that the maximum tensile strength of the joint was about 86% of the parent metal. They also examined the behavior of the oxide film present on the faying surface of the steel during welding and revealed that a small amount of inter-metallic compounds was formed at the upper part of the aluminium-steel interface, while in the bottom and middle parts of the interface, no inter-metallic compounds were found. The regions where the inter-metallic compounds formed seemed to be fracture paths in the joint. Zhang et al. [27] investigated the effect of welding parameters on the microstructure and mechanical properties of friction stir butt welded joint of a super strength aluminium alloy with high concentration of Zn. They observed that the greatest ultimate tensile strength of 484 MPa was obtained at 350 rpm-100 mm/min and the largest elongation of 9.4 was obtained at 350 rpm-50 mm/min. They also found that, when rotation rate increased from 350 rpm to 950 rpm at a constant welding speed of 100 mm/min, the density of the strengthening precipitates has decreased and precipitates coarsened as a result of elevated temperature and severe stirring, and ultimately the ultimate tensile strength and elongation of the material decreased drastically. Macrostructure of butt welded joint is shown in Fig. 4.

Fig. 4: Macrostructure of butt welded FSW joint. (Joon et al. [22])

3.2. Lap joint

In a simple lap joint, two plates or sheets which is to be welded are lapped and clamped firmly on a backing plate. A specially designed rotating tool which is characterized by a shaped pin at its end is vertically plunged through the upper sheets or plates into the lower plate with a proper tilt angle and then traversed all along the joint interface, as shown in Fig. 5.

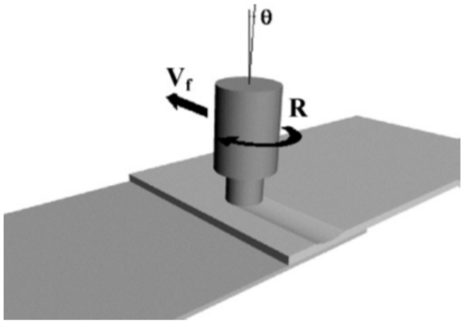

Fig. 5: Lap joint configuration by FSW (Buffa et al. [28])

Buffa et al. [28] performed an experiment on the lap joining of AA2198-T4 aluminium alloy blank by FSW. They investigated the joints strength and metallurgical properties by varying the joint configuration and the tool geometry and rotational speed, and revealed that the use of cylindrical-conical pin tools and proper sheet positioning increases the welded nugget extension and as a result improving the mechanical performances of the welded joints. Shirazi et al. [24] investigated the combined effect of tool rotation (rpm) and traverse speed (mm/min) on the macrostructure and defect formation i.e., hooking, kissing bond, and cavity during lap joining of AA5456 aluminium alloy by FSW. They claimed that the hooking height decreased as the welding speed increased and increased by increasing rotational speed. Cavity was created and the kissing bond was formed at higher welding speeds. Ana et al. [2] performed friction stir welding and claimed that the best mechanical properties were obtained at high rotational speed of 1500 rpm and also stated that the rotational speed and welding speed do not have a significant interaction between each other. Only the interaction between rotational speed and probe penetration shows relevance. Macrostructure of lap joint is shown in Fig. 6.

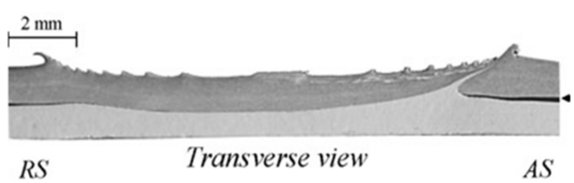

Fig. 6: Macrostructure view of lap joint configuration by FSW. (Costa et al. [33])

3.3. T-joint

Several studies may be found in the literature related to the FSW of different joint configurations, but most of them are mainly focused on butt and lap joints configuration. As par T joint is concerned, there is still a scarcity of studies regarding determination of a proper set of process parameters. T joint configuration is shown in Fig. 7.

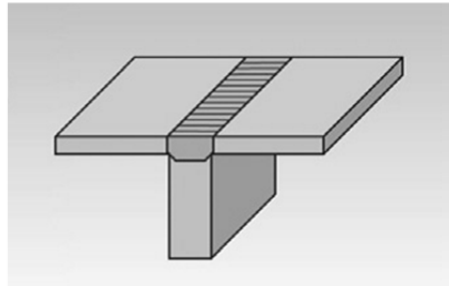

Fig. 7: T-joint configuration (Gibson et al. [23]).

There are many applications that require welding of base material in T-joint configuration, for example, supporting frames, bridge structures, buildings, etc. [34]. FSW of T-joint is difficult compare to butt and lap joints as clamping of workpiece T-joint is not so easy. Special fixture is required during FSW of T-joints. Only some studies related to FSW of T-joints are available due to the complexity of T-joint configuration. Erbsloh et al. [29] studied FSW of AA6013-T4 in T joint configuration and reported that T joints are highly sensitive to welding parameters and tool geometry, especially when a rounded fillet radius are required. Fratini et al. [30] investigated the influence of FSW parameters on the performance of the extruded AA6082-T6 in T-joint configuration and found that the best joint strength was obtained at optimum process parameter of 1000 rpm, 150 mm/min and 3^{o} of tilt angle. Ana et al. [2] performed FSW of AA6082-T6 aluminium alloy in T-joint configuration and provided a set of optimized process parameter in order to achieve higher UTS, and observed that higher UTS was obtained at a rotational speed of 1000 rpm, a shoulder diameter of 15 mm, a probe penetration of 3.90 mm and lower welding speeds (78–216 mm/min). Macrostructure of T joint is shown in Fig. 8.

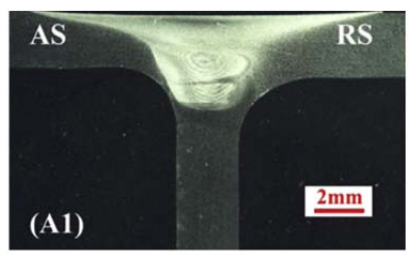

Fig. 8: Macrostructure view of T-joint configuration. (Yong Zhao et al. [32])

4. CONCLUSIONS

Joint configuration has great effect on the quality of welded joint during FSW. Welding parameters have different effect on different joint configurations. The shoulder diameter is one of the most important parameters that affect the heat input. The different effect of shoulder diameter during FSW of butt and T joint is justified by the different heat input demands. In T joints, the lower diameters should be avoided, and in butt joints the larger diameter should be avoided. Butt joints only require the heat of two parts, where T joints have a third component that must be heated. For that reason, in T joints, low shoulder diameters are undesirable due to insufficient heat generation. At low diameters of the tool, inadequate heat will be generated that results in poor joints. FSWed T joint require a larger amount of heat input due to the necessary forging action aimed at fulfilling the joint fillets. So, the use of large shoulder diameters is recommended. Different joint configurations present different heat and flux stirring requirements. In the case of T and lap joints, the material must flow upwards, while in butt joints, the required flux is only on the plain of the joint. The heat input required for each joint configuration depends on the joint configuration, due to different surface interfaces, increasing the thermal conductivity complexity and volume of the material to be heated. The selection of tool shoulder diameter depends on the joint configuration. Also plunge depth plays important role in T joints in order to confirm the penetration depth. Also rotational speed and welding speed should be carefully selected based on the type of joint configuration to obtain sound joints. It is important to emphasize that these conclusions are only valid in the conditions described, namely, using the same tool geometry and materials among other parameters that were kept constant. The main reason for the differences between the parameter values needed to perform welds with different joint configurations is the heating and material flux requirements in the entire zone to be mixed.

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