Friction Stir Welding and its Applications: A Review

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Abstract

Friction stir welding (FSW) is a solid-state joining technique in which coalescence occurs due to thermo mechanical deformation of work pieces as the resulting temperature exceeds the solidus temperature of work pieces. A defining characteristic of FSW is that the joint is created by a cylindrical rotating tool, mechanically traversed through the materials. Frictional heat is generated between the wear-resistant welding tool shoulder and pin, and the material of the work-pieces. The process was initially used for mostly low melting materials, such as Al, Mg and Cu alloys. But, with recent developments in technology of friction stir welding, the applications have been extended to the welding of high melting point materials such as various types of steels, Ti alloys, Ni-based super alloys and dissimilar welding of various types of steels with alloys of aluminum, magnesium, copper, titanium and also other alloy. In this review article, the present state of art and development of the friction stir welding is addressed. Emphasis has been given to process parameters that influence the quality of the weld, microstructural analysis within the thermo-mechanical regions, Properties of the weld joints, Materials being involved in the friction stir welding, so far, industrial applications of friction stir welding, process variants of friction stir welding and their contribution beyond the conventional frictional stir welding process and, future work on friction stir welding.

Keywords: *Microstructure Evolution, Mechanical Properties, Residual Stress, Sticking Torque.*

1. Introduction

1.1 Historical Background

Friction stir welding (FSW) was developed and patented at The Welding Institute (TWI), Cambridge of UK in 1991 as a solid-state joining technique, and it was first used for materials having low melting point, such as Al, Mg and Cu alloys [1,3,7,9, 25]. With recent developments in technology of friction stir welding, the applications have been extended to the welding of high melting point materials such as various types of steels, Ti alloys, Ni-based super alloys and dissimilar welding of various types of steels with alloys of aluminum, magnesium, copper, titanium and also other alloy [3]. However, the market demands more on the improvement of performance of the welding tool to effectively join high temperature alloys.

1.2 Principles of Operation

Friction stir welding (FSW) is a solid-state joining technique in which coalescence occurs due to thermo mechanical deformation of workpieces as the resulting temperature exceeds the solidus temperature of workpieces [1]. A defining characteristic of FSW is that the joint is created by a cylindrical rotating tool, mechanically traversed through the materials. Frictional heat is generated between the wear-resistant welding tool shoulder and pin, and the material of the work-pieces [3].

The process, as shown in figure 1 below, uses a non-consumable cylindrical tool consisting of a shoulder, and a smaller diameter profiled pin, protruding from the tool shoulder. It is a new innovative solid state process in which material is welded below its melting temperature and hence, eliminates welding defects that were unpleasant phenomenon in conventional fusion welding processes.

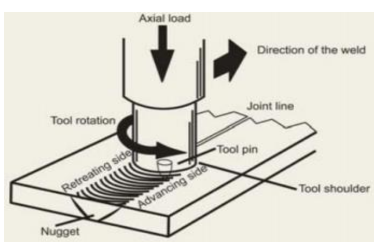


Fig. 1 Friction Stir Welding [3]

1.3 Benefits of Friction Stir Welding

In order to justify the use of the friction stir welding process over other conventional techniques, it becomes logical to compare friction stir welding process with other conventional welding processes. The unique and favorable characteristics of friction stir welding are to be considered as possible sources of technical justification for the comparison between frictions stir welding and arc welding processes [4].

2. Process Parameters

Friction stir welding (FSW) is an energy efficient, environment friendly, and versatile process whose principal advantages are low distortion, absence of melt related defects and high joint strength. Shoulder and pin are important part of the FSW tool designed to serve three functions: (i) generate the frictional and deformational heat to softens the work material around and ahead of the pin, (ii) control the material flow to produce a defect-free joint, and (iii) confine the hot material under the shoulder. Parameters shown in table 1 play an important role in FSW for quality of the welded joint. These parameters are tool design and material, rotational and welding speed of the tool, and axial force [1, 3, 4, 7, 11]. Location of base materials being located either on leading or retreating side, and preheating of the base materials to be joined, are important parameters that should be considered for successful joint strength, in FSW.

Table 1: Main FSW process variables [4]

Tool design variables	Machine variables	Other variables
Shoulder and pin material	Welding speed	Anvil material
Shoulder diameter	Spindle speed	Anvil size
Pin diameter	Plunge force or depth	Work piece size
Pin length	Tool tilt angle	Work piece properties
Thread pitch		
Feature geometry		

2.1 Tool Geometry

Tool geometry shown in figure 2 affects the heat generation rate, traverse force, torque and the thermo-mechanical environment experienced by the tool. The flow of plasticized material in the work piece is affected by the tool geometry as well as the linear and rotational motion of the tool. Important factors are shoulder diameter, shoulder surface angle, pin geometry including its shape and size and the nature of tool surfaces [29].

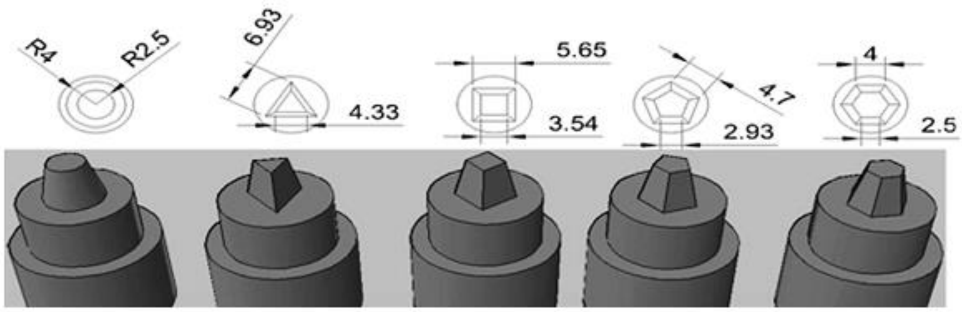


Fig. 2 Geometry of tool profiles [11]

2.1.1 Shoulder Diameter

Experimental studies have shown that the shoulder diameter is found to be the critical parameters that strongly affects downward or forging force and tensile strength of welds [1]. Properly designed shoulder diameter will causes the material of the workpieces to be properly plasticized due to heating by frictional contact of the tool shoulder and the work piece when the rotating pin (tool) is pushed into the material until shoulder meets the work piece surface [3]. Majority of the deformation and frictional heat generation between the workpieces and the tool is caused by the tool shoulder. Due to its large surface area, friction increases, which in turn increases the amount of heat generated [4, 25, 29].

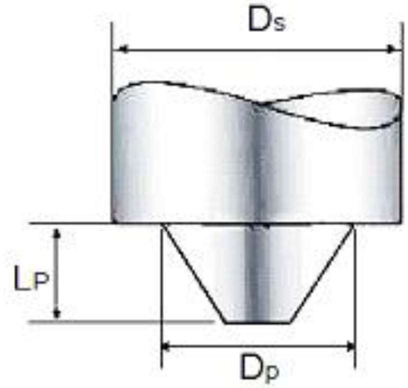


Fig. 3 Tool Geometry [4]

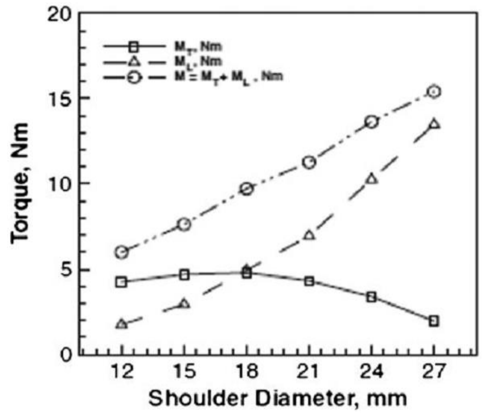


Fig. 4 Variation of Sliding, Sticking and Total Torque with Shoulder Diameter [29]

Researchers who have considered various parameters in their studies have found that the ratio of tool shoulder diameter to the pin diameter has the most significant effect on the joint properties [9]. This ratio of the diameter of the tool shoulder to the diameter of the tool pin (D_s/D_p), shown in figure 3 are chosen based on the literature survey [4, 29].

Due to the larger tool/workpiece interfacial area during friction stir welding of aluminum alloy AA6061, the sliding torque continuously increases with shoulder diameter as shown in the figure 4. With increase in temperature, the flow stress σ decreases when the area increases with shoulder diameter. The product of these two opposing factors leads to a maximum in the sticking torque versus shoulder diameter plot which indicates the maximum grip of the shoulder on the plasticized material. The optimum shoulder diameter should correspond to the maximum sticking torque for a given set of welding parameters and workpiece material. The grip of the tool shoulder on the plasticized materials largely establishes the material flow. Even though both sliding and sticking generate heat, material flow is caused only from sticking. So, for a good FSW practice, the material should be adequately softened for flow, the tool should have adequate grip on the plasticized material and the total torque and traverse force should not be excessive [29]. Similarly, for successful material flow, the location of base materials being located either on leading or retreating side has been overlooked by Prof. Bharat Raj Singh in his conclusion.

2.1.2 Shoulder Surface

The nature of the tool shoulder surface is an important aspect of tool design. Several studies has been carried out on flat, convex and concave tool shoulders, and cylindrical, tapered, inverse tapered and triangular pin geometries. According to these studies, triangular pins with concave shoulders have shown high performance in high strength spot welds. Other researchers have examined the role of geometric parameters of convex shoulder step spiral (CS4) tools and identified the radius of curvature of the tool shoulder and pitch of the step spiral as important geometric parameters [29].

2.1.3 Pin (Probe) Geometry

Good tool can improve both quality of the weld and the maximum possible welding speed. So it is desirable that the tool material is sufficiently strong, tough, and wearing resistance at the welding temperature along with good oxidation resistance and low thermal conductivity. More advanced tool materials are necessary for more demanding applications such as highly abrasive metal matrix composites or higher melting point materials such as steel or titanium [1].

The geometry of the pin tool along with the process parameters plays an important role in dictating the path that the material takes. The tool geometry, figure 5, was carefully chosen and fabricated to have a nearly flat welded interface pin profile [4]. The shape of the tool pin (or probe) influences the flow of plasticized material and affects weld properties. Studies suggested that while the tool shoulder facilitated bulk material flow, the pin aided a layer by layer material flow [29].

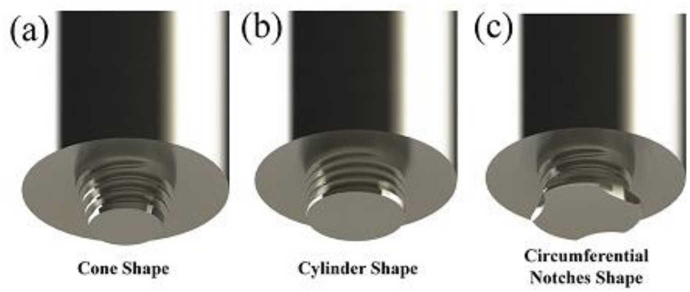


Fig. 5 Illustration of three designed probe geometries: (a) cone shape, (b) cylinder shape & (c) circumferential notches shape

2.2 Welding Parameters

The two process parameters, tool rotation and traverse speeds have considerable importance and must be chosen with care to ensure a successful and efficient weld. According to Sushil et al. (2017) increasing the rotation speed or decreasing the traverse speed will result in a hotter weld for good weld quality. The material surrounding the tool should be hot enough to enable the extensive plastic flow required and minimize the forces acting on the tool leading to tool breakage. However, unless the extent of this high heat input is controlled, it may be detrimental to the quality of the weld [1]. Karwande et al.(2016) have observed that input parameters like tool rotational speed, welding speed, tool angle and tool pin profiles have some significant effect on the tensile strength of dissimilar materials [3]. Piyush et al. (2017) in their experimental study have obtained different FSW butt welds by varying the process parameters within the range and the optimal values are drawn based on the trend of the values. Process parameters like tool design, tool rotational speed, welding speed and materials are found to be the main parameters to produce the effective butt joint by friction stir welding [4]. The process parameters optimization result of Devaiah et al. (2018) indicated that tool rotational speed (RPM), and welding speed (WS) are the most significant factors, followed by tool tilt angle (TTA) in deciding the mechanical properties of friction stir welding [7]. The tool material with their forging temperature is as shown in the table 2.

Table 2: Tool material with their forging temperature [3]

S. No	Material Alloys	Tool Material	Forging Temperature in ^{0}C
1	Aluminum Alloys	Tool steel, WC-Co	440-550
2	Magnesium Alloys	Tool steel, WC	250-350
3	Copper and Copper Alloys	Nickel alloys, PCBN(a), Tungsten alloys, Tool steel	600-900
4	Titanium Alloys	Tungsten alloys	700-950
5	Stainless Steels	PCBN, Tungsten Alloys	860-1020
6	Low-alloy Steel	WC, PCBN	650-800

Wentao et al. (2018) designed and used a novel stirring tool with dual-pin structure, figure 6 shown below, to perform welding AA2024 to AA6061 aluminum alloy plates with butt configuration to improve the degree of materials mixing in dissimilar Friction Stir Welded joints and mechanical properties. Microstructure and mechanical properties of the joints comparisons were made between the newly designed dual pin tool and single pin tool. The study has shown that the tool pin structure is another significant parameter to be considered and the highest ultimate tensile strength (UTS) of 242MPa was obtained with the dual-pin tool at welding speed of 150 mm/min, when compared to the highest ultimate tensile strength of 173MPa of single-pin tool at welding speed of 90 mm/ min [9]. But, what has not been considered in this comparison is the cost incurred to produce the complex dual-pin tool when compared with easily manufactured single pin tool.

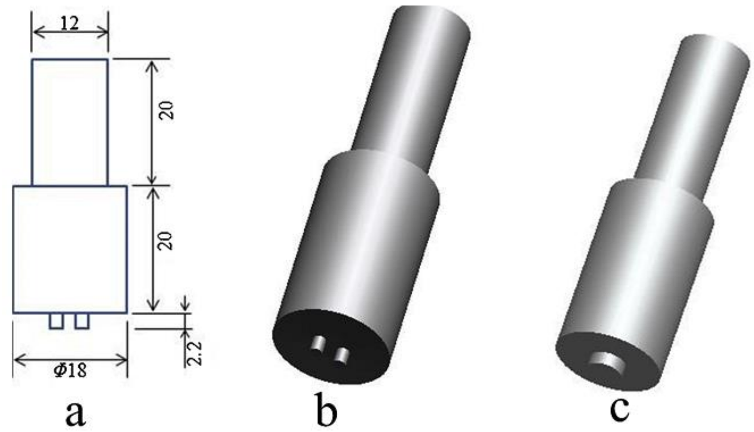


Fig. 6 Geometry and dimension of applied tools: (a –b) dual-pin tool, (c) single-pin tool [9].

Zhou et al. (2018) showed how the welding process parameter, pin profile, has greater influence on heat production and material flow in friction stir welding. According to this study, microstructure evolution and mechanical properties of the welded joint has been greatly affected by the pin profile that were designed to join aluminum and copper by friction stir welding [10]. In another study, Rambabu et al. (2015) have developed a mathematical model to predict the corrosion resistance of friction stir welded AA2219 aluminum alloy by incorporating FSW process parameters, such as tool pin profile, rotational speed, welding speed and axial force. According to this mathematical model, the response function corrosion resistance (CR) of the joints is a function of the tool profile (P), rotational speed (N), welding speed (S) and axial force (F) and is expressed as:

$$CR = f(P, N, S, F)$$ [11].

3. Microstructures Analysis

Friction stir processing (FSP), developed on the principles of friction stir welding (FSW), is an emergent technique for micro-structural refinement of metallic materials [26]. Murshid et al. (2015), in the study of controlling the microstructural evolution during the friction stir welding of medium carbon low alloy S45C steel sheets, they have shown that microstructural evolution in steels during FSW is a more complex process than that in aluminum alloys due to the occurrence of phase transformations. Even though several factors such as tool design, tool rotational speed (ω), welding speed (V), axial load, tool tilt angle, and plunge depth are used to control the heat generation, other parameters such as material flow, and resultant thermo-mechanical cycle during the FSW process are to be regarded as crucial parameters in the analysis. So, the study claims peak temperature and cooling rate as the dominant parameters of thermal cycle that affect the micro-structural evolution [18].

Friction stir welding is a thermo-mechanical processes whose microstructure can be divided into four regions, namely base material (BM), weld nugget zone (WNZ), thermo-mechanical affected zone (TMAZ), and heat affected zone (HAZ) [1, 6, 9, 24].

3.1 Base Material Region (BM)

The base material region (BM) is one of micro-structural regions which is not affected by heat as it is far away from the recrystallized zone and hence micro- structural and mechanical properties of this region remains unaltered [1, 2].

3.2 Weld Nugget (Stir) Zone (WNZ)

Weld Nugget or stir zone or fully recrystallized zone is located next to thermo-mechanically affected zone in which tool pin rotates and produces frictional heat; results in severe plastic deformation [1]. The Weld Nugget Zone (WNZ) located in the center of the weld area, consists of recrystallized micro-structure of very fine grains due to the severe plastic deformation and high temperature formed where the tool pin penetrates the joint as shown in the figure 7. Several studies have postulated that rotation of the tool during FSW process results in extrusion of semi-cylinder layers of material, resembles the familiar 'onion ring' structure when it is viewed from a sliced cross-section [11]. Sadeesh et al. (2014) in their microstructural analysis showed how the nugget region is dominated by the material placed on the advancing side [2].

Huabing et al. (2017) have suggested on their result that the grain structure evolution in weld nugget zone or stir zone (SZ) is dominated by continuous dynamic recrystallization (CDRX) and the grain refinement is highly affected by the strain rate [27].

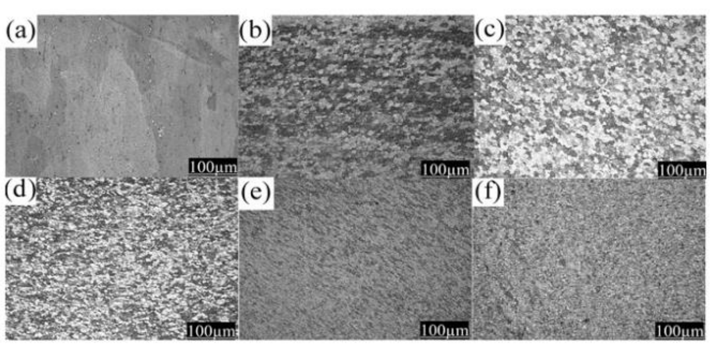


Fig. 7 Optical micrographs of AA2219 FS Welds of Nugget Zone (a) Base metal (b) Conical tool (c) Triangle tool (d) Square tool (e) Pentagon tool and (f) Hexagon tool [11].

3.3 Heat Affected Zone (HAZ)

Heat-affected zone (HAZ) is located next to base material region. Though the region is affected by heat input to cause mechanical and micro-structural properties changes, no plastic deformation takes place [1]. Pradeep et al. (2013) observed two typically distinct heat affected zones, figure 8, with variation in the micro-structure of the specimens in a metallurgical analysis using optimum process parameter. All zones are found to be defect free. HAZ 1 has coarse grains while HAZ 2 has fine grains as shown in figure 8 [6]. This seems to contradict the real situation happening in the thermo-mechanical regions. Mehmet et al. (2012) studied the effect of tool rotational and traverse speed on friction stir weldability of AISI 430 ferritic stainless steels. The study revealed that the grain size becomes smaller from base metal to welding zone with an average values 6.5 µm in stirring zone, 15µm in HAZ and 30µm in Base Material [8].

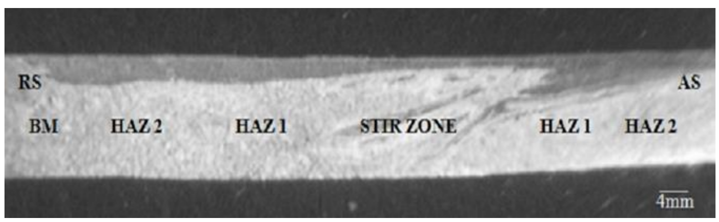


Fig.8 Transverse cross-section of a typical low alloy steel butt welded plate exhibiting various regions.

In the study of micro-structure evolution and mechanical properties of friction stir welding, Wentao et al. (2018) showed that HAZ does not have positive strengthening mechanism such as grain refinement which makes it the weakest region in the joints. The extent of precipitate coarsening in HAZ is determined by the heat input. Lower heat input generate less severe precipitate coarsening to cause higher minimum hardness value in HAZ as illustrated in figure 9[9].

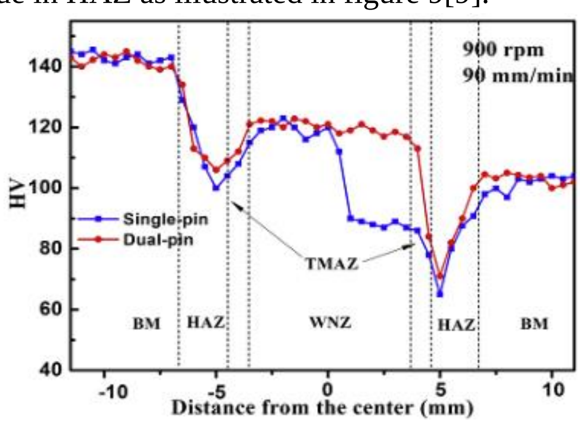


Fig. 9 Vicker's micro-hardness profiles of the cross-section of dissimilar joints produced by single-pin and dual-pin tool [9].

3.4 Thermo-mechanically Affected Zone (TMAZ)

Thermo mechanically affected zone (TMAZ) is a region, very near to weld nugget zone in which materials are plastically deformed without recrystallization, by means of a rotating tool [1].

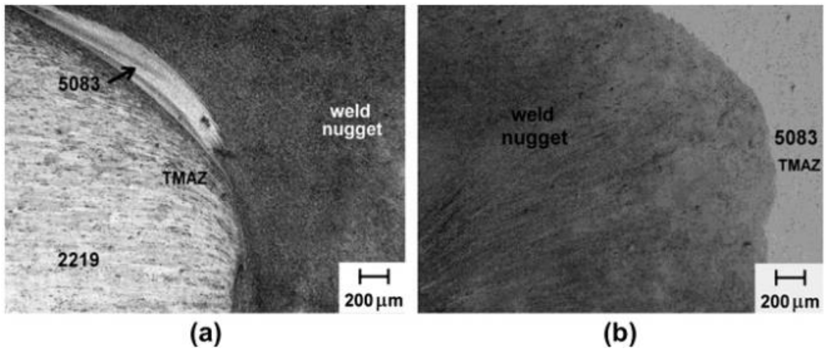


Fig. 10 TMAZ microstructures: (a) advancing, & (b) retreating side [5].

Sadeesh et al. (2014), on the studies on FSW of AA2024 and AA6061 dissimilar metals, there is a growth of boundaries which could be due to the plastic deformation and the less heat developed during the process. The study has clearly shown a distinct grain boundary that separates the recrystallized zone of weld nugget zone from the deformed zones of the TMAZ [2]. Koilraj et al. (2012) differentiated the micro-structure of the weld on advancing and retreating side of the base metal of friction stir welding. According to this study, the TMAZ on the advancing side showed highly deformed grains, with a clearly observable SZ/TMAZ and TMAZ/HAZ boundaries (Fig. 10a). However, on the retreating side, these interfaces were rather diffused, especially the latter (Fig. 10b) [5].

4. Properties

4.1 Residual stress

Residual stresses are generally known to be low in friction stir welds due to low temperature solid-state process of FSW. But, the rigid clamp used to securely fix the parts in friction stir welding exerts a much higher restraint on the welded plates. It arrests the contraction of the weld nugget and heat-affected zone during cooling in both longitudinal and transverse directions, figure 11, thereby resulting in generation of longitudinal and transverse stresses which affect post weld mechanical properties of weld [32]. Ghosh et al. (2010) investigated that low residual stress level within weld nugget improves the bond strength when A356 and 6061 aluminum alloys were friction stir welded. The typical tool rotational speed and traversing speed for this investigation were1000 –1400rpm and of 80 –240mm/min respectively, keeping other parameters same. The low level residual stress exhibits substantial improvement in bond strength (~ 98% of that of 6061 alloy) when friction stir welding is performed with lowest possible tool rotational and traversing speed [22]. Similarly, Huang et al. (2015) summarized the study on FSW of high strength 7XXX aluminum using four process variants, residual stress increases with increasing welding speed [31]. Xiaocong et al. (2014) showed how residual stresses generated during the friction stir welding process degrade the structural integrity and performance of components. In this numerical analysis, the maximum and the minimum residual stresses are found to be located in the heat affecting zone and on the advancing side beyond the weld zone [23].

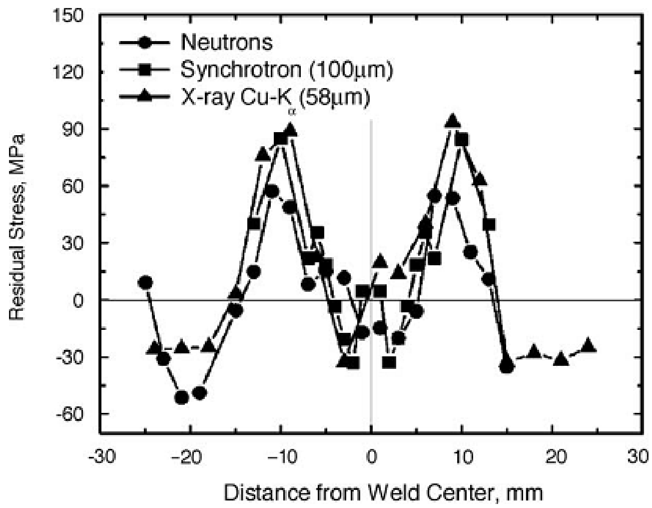


Fig. 11 Longitudinal residual stress distribution in FSW 6013Al-T4 welds determined by different measurement methods (tool rotation rate: 2500 rpm, traverse speed: 1000 mm/min tool shoulder diameter: 15 mm) [32]

4.2 Mechanical Properties

Wentao et al. (2018) on the study of dissimilar friction stir welding of aluminum alloys adopting a novel dual-pin tool, pointed out the role of material arrangement on mechanical properties of weld. According to this study, the composition of the material placed at the retreating side determines the weld strength [9].

Several investigation have been carried out to observe the effect of pin profile on the microstructure and mechanical properties of FSW joints, such as aluminum alloys [10]. The investigation was supported by using optical microscope (OM), scanning electron microscope (SEM), micros hardness tester and tensile testing machine. The result of the findings approves the weld joint variation as a result of using various pin profiled tools. And some others focus their studies on the banded structure (BS) zone of intermetallic compounds and claimed it to be one of the critical/weak zones in the weld and were responsible for most of the joint failures [12].

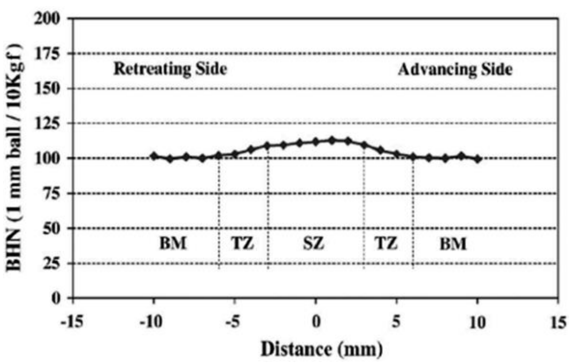
Hamed et al. (2018) studied the relationship between the friction stir welding processing parameters and mechanical properties of the weld joint such as tensile strength, bending strength, material flow and hardness to attain defect-free joints with proper mechanical strength. According to this study, joint strength of the weld is highly controlled by rotational speed of the tool [14].

One of the challenging task remained for friction stir welding was joining of dissimilar materials such as aluminum and copper. Najib et al. (2019) used a new ultrasonic vibration assisted friction stir welding (UVaFSW) system to successfully join AA6061-T6 aluminum alloy and C10100 pure copper plates. The study has employed the effect of ultrasonic vibration on the joint formation, macro-structural features, microstructure and mechanical properties of the joints. This novel process of UVaFSW has successfully enhanced the formation mechanism and mechanical properties of the joint. The fracture location of the Al-Cu joint was found to be shifted to the heat affected zone in the Al side of the joint to have a ductile fracture mode due to the influence of ultrasonic vibration. The joints with no effect of ultrasonic vibration, fracture has occurred mainly at the thermo-mechanically affected zone in the Cu side of the joints, and the fracture surface showed a mixture of brittle and ductile fracture mode [19].

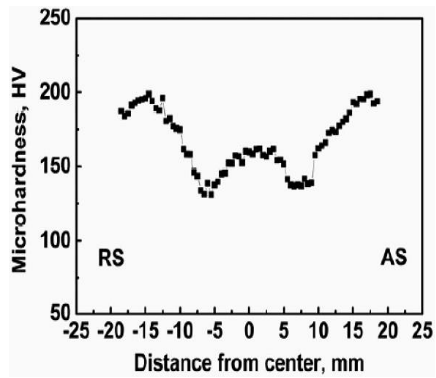
Several studies made on Friction stir welding (FSW) have shown the relationship between process parameters of FSW and microstructural evolution and mechanical properties of the joints. Zhou et al. (2010) investigated the effect of tool rotation speed on microstructure and mechanical properties of friction stir welded joints for Ti–6Al–4V titanium alloy. According to this investigation, rotation speeds ranging from 400 to 600 rpm at a constant welding speed of 75 mm/min were used to produce Joints. The result has concluded that rotation speed has a significant impact on micro-structure and mechanical properties of the joints. No influence has been shown in the micro-structure of heat affected zone by the rotational speed used. The hardness in the weld zone was found to be lower than that in the base material and continued decreasing with increasing rotation speed. Transverse tensile test carried out on the same sample exhibited lower tensile strength of the joint than the base material and continued to decrease with increasing rotation speed of the welding tool [20]. Coelho et al. (2012) studied the influence of the distinct HSS base material on the joint efficiency. Two different grades of high strength steel (HSS), with different microstructures and strengths of AA6181-T4 Al alloy were successfully joined by FSW without any defects. Both joints have possessed similar strength and micro-structure developments through microstructure investigations regardless of their differences in the size and amount of detached steel particles in the aluminum alloy with in both heat and thermo-mechanical affected zone. The final conclusion of this study showed that the mechanical properties of the heat and the thermo-mechanical affected zone of the aluminum alloy is highly responsible for the joint efficiency [21].

4.3 Micro-hardness

Hardness of the weld joint in friction stir welding is measured perpendicular to the welding direction. Changes in the hardness of various zones can be easily obtained along this direction. Parikh et al. (2011) showed two types of thermo-mechanical hardness profiles. In the first hardness profile, figure 12(a), the highest hardness value (115 HV) was recorded in the nugget zone. According to this study, the hardness decreases in the transmission zone and reduces until the hardness of base composite [34].



(a)



(b)

Figure 12 Micro hardness profile reinforced with SiC particles for (a) A356 and (b) AA2009 [34]

In this type of profile, base composites will have the highest hardness, which decreases through TMAZ up to HAZ and then increases again in the nugget zone. ‘W’ shaped profile, figure 10(b), is the second types of hardness profile being common and reported in several findings of the studies. This hardnesss profile is characterized by highest value of hardness on base composite which decreases through TMAZ up to HAZ and then increases again in the nugget zone [34].

4.4 Corrosion behavior of FSW

The first study carried out on FSW 5454 aluminum alloy have investigated pitting and stress corrosion cracking (SCC). The findings were compared with base alloy samples joined by GTAW. The resulting observations is that in FSW samples, pits have been observed in the HAZ whereas in GTAW samples the pits have been formed in the large dendritic region just inside the fusion zone. The other observation is that FSW welds showed a pitting resistance higher than those of base alloy and GTAW welds [32].

5. Materials

The rapid development and its successful implementation into commercial applications of FSW in aluminum alloys have prompted its application to other ferrous and non-ferrous materials [32].

5.1 Copper Alloys

Copper due to its high thermal diffusivity (10-100 times steel and nickel alloys), it has been difficult to work with conventional fusion welding techniques [32].

5.2 Titanium Alloys

Post weld heat treatment of titanium alloys is additional process step that increases production costs by GTAW. To avoid the post weld heat treatment, FSW is becoming a better emerging welding technology [32].

5.3 Magnesium Alloys

Due to poor formability, sheet material of magnesium alloys is made commercially by casting or die casting processes. And the magnesium alloys made from casting cannot be joined by conventional fusion welding due to the porosity formation in the weld. Relatively large coefficient of expansion of magnesium alloy is another reason to causes large deformation/ distortion of the weld. Therefore, solid-state welding technique such as FSW should be the optimum choice for joining cast magnesium alloy sheets [32].

5.4 Metal Matrix Composite

Yahya Bozkurt studied the weldability of AA2124 containing 25% of SiC particles with T4 heat treated aluminum Metal Matrix Composite (MMC) plates by FSW process at low welding parameters. To evaluate the weld nugget characteristics of friction stir welded MMC plates, microstructure, ultimate tensile strength, surface roughness and micro-hardness of samples was tested and determined without post-weld heat treatment. After microstructural modification was made, micro-hardness improvement was observed on stir zone with ultimate tensile strength efficiency of 73% when compared to the base composite [35].

5.5 Steels

Friction stir welding uses lower heat input relative to fusion welding processes. This low heat input process produce less metallurgical changes in the HAZ to minimize distortion and residual stresses in steels especially for thick-section components, such as in the shipbuilding and heavy manufacturing industries. Welding fumes are eliminated in friction stir welding to comply with OSHA standards. FSW parameters and tool materials for FSW of steels is given in the table3 [32].

Table 3: FSW parameters and tool materials for FSW of steels [32]

Material to be welded	Plate thickness (mm)	Tool rotation rate (mm)	Tool traverse speed (mm/min)	Tool materials
12% Cr steel	12	-	240	-
Low carbon steel	12, 15	-	102	-
AISI 1010	6.4	450-650	25-102	Mo and W-based alloys
304L	3.2, 6.4	300, 500	102	W alloy
304	6.0	550	78	Polycrystalline cubic boron
304L, 316L	5, 10	300-700	150, 180	-
Al 6XN	6.4, 12.7	-	102	W alloy
HSLA-65	6.4, 12.7	400-450	99-120	W
DH-36	6.4	-	102-457	W alloy
C-Mn	6.4	-	-	Polycrystalline cubic boron nitride

5.6 Dissimilar Alloys and Metals

With recent developments in technology, friction stir welding (FSW) is now possible to carry out dissimilar welding of various types of steels with alloys of aluminum, magnesium, copper, titanium and also other alloys [3]. Table 4 summarizes the materials and FSW parameters for FSW of dissimilar alloys/metals [32].

Table 4: A summary of dissimilar alloys/metals FSW [32]

Materials	Plate thickness (mm)	Rotation rate (rpm)	Traverse speed (mm/min)
2024Al to 6061Al	6.0	400-1200	60
6061Al to 2024Al	12.7	637	133
2024Al to 1100Al	0.65	650	60
5052Al to 2017Al	~5.3, 3	1000, 1250	60
7075Al to 2017Al	~5.3, 3	1000, 1250	60
7x1xAl (Sc) to 7x5xAl (Sc)	~5.3	1000	60
7075Al to 2017Al	3	1250	60
7075Al to 1100Al	3	1250	60
5083Al to 6082Al	5.0	-	170-500
2024Al to D357	-	-	-
6061Al to A356	4	1600	87-267
2024Al to 7075Al	25.4	150-200	76.2-127
20 vol.% Al_2O_3/6061 Al to 10 vol.% SiC/A339	6.5	800	60
20 vol.% Al_2O_3/2014 Al to 2024 Al	4	1120	120
6061 Al to Copper	6.0	400-1200	60-180
2024 Al to Copper	6.5	650	60
2024 Al to Silver	6.0	650	60
Copper to brass	6.2	1000	60
1050 Al to AZ31	6	2450	75
6061 Al to AZ31 B		800	75
6061 Al to AZ91 D		800	75
AZ91 D to AM60B		2000	75
5083 Al to mild steel	2	100-1250	25
6061 Al to AISI 1018	6	914	140

6. Friction Stir Welding Process Variants

Almigdad et al. (2018) studied the friction stir diffusion cladding (FSDC); a new version of solid-state welding process based on friction stir welding. The process was employed for cladding ASTM 516-70 steel with Al5052-H32 alloy. The effects of tool rotation and traveling speeds on microstructural and mechanical properties of the cladded system were investigated. The cladding was employed for ASTM 516-70 steel with Al5052-H32 alloy and tool rotation speeds of 250, 500 and 1000rpm and traveling speeds of 50, 100 and 150 mm/min were selected. The investigation as the result of the study shows that optimum properties were obtained at a combination rotation and travel speeds of 500rpm and 50mm/min respectively. These optimum process parameters were able to achieve specific fracture load of about 430N/mm^2 [15].

Joaquín et al. (2017) studied the effect of the tool geometry and its penetration depth during Friction Stir Spot welding (FSSW), of hybrid structure of aluminum Alloy AA5052 and low carbon steel joints. Axial load and the corresponding electrical current consumed were recorded in this investigation to understand the relationship between penetration depth, the fracture loads and tool geometry. According to this study, when the depth of penetration of the tool is increasing, the fracture loads and tool geometry optimization is also increasing [16]. Friction stir spot welding system and clamping device is as shown in figure 13.The conclusion seems to agree with the real scenario. Tool geometry optimization is required to improve the tool life either through avoiding catastrophic failure or reducing normal tool wear.

Fig. 13: Friction Stir Spot welding system and clamping device [16]

Jeon et al. (2011) examined the structural response of single-crystal austenitic stainless steel to friction stir spot welding, FSSW. The study investigated that there is a strong correlation between crystal rotations with simple shear deformation; and grain boundary development with texture evolution. The study also observed how structural evolution is dominated by recrystallization in which single crystal is broken down in to ultrafine-grained micro-structure with a mean grain size of ~ 0.2µm. However, the continuous recrystallization is followed by discontinuities as a result of shoulder-contacting during the FSSW cooling cycle and finally the grain structure is coarsened led to annealing [17].

Xueqi et al. (2018) carried out an investigation on the application of angularly exerted ultrasonic vibrations in friction stir welding for the joining of AA6061-T4 alloy to AZ31B at different tool rotation speeds. The result of investigation includes an increase of working temperature, wide material flow path, mechanically interlocked features at weld interfaces as a result of employing ultrasonic energy. The ultrasonic enhanced improvement in weld mechanical properties was intensified at very low rotation speeds but less substantial at higher rotation speeds [28]. Rahmi et al. (2017) investigated the modified version of friction stir welding techniques, friction stir vibration welding process (FSVW). In this investigation, two welding methods, FSW and FSVW have been employed to weld Al5052 alloy specimens. Microstructure evolutions and mechanical properties were compared. Metallographic analyses show that, during the application of FSVW, there was a decrease in grain size and an increase of hardness of the weld joint. FSVW also outsmarted FSW through the tensile test results. The weld joint specimens as a result of FSVW showed better strength and ductility due to more work hardening of plasticized material, and hence, to more generation and movement of dislocations. Another observation is that the mechanical properties of the weld improve as vibration frequency increases [33].

7. Applications of FSW

7.1 Marine Industry

Jonathan et al. (2015) describe the development and assessment of joining aluminum alloys using the Floating Bobbin Friction Stir Welding (FBFSW) technique. The technique allows the friction stir weld to be made with no vertical force. Thus, offers the capability to work with less expensive, smaller and portable friction stir welding equipment. The FBFSW technique has first been designed to be used on a mobile FSW system for use in a shipyard. Comparisons was made between the principles of FBFSW techniques and conventional welding techniques in terms of parameters such as welding forces, tool life, weld properties and panel distortion. As the result of comparison, it was concluded that the development and exploitation of FBFSW offers the potential for a low cost, reliable solid-phase joining technique and the possibility of mobile FSW equipment to be developed [31].

7.2 Armor Industry

Friction Stir Welding (FSW) is now became a sound substitution for conventional welding such as gas tungsten arc welding, GTAW and gas metal arc welding, GMAW in armor industry. One of the beneficiaries of FSW in armor industry is Advanced Amphibious Assault Vehicle (AAAV) that carries up to 18 fully out fitted combatants, at high speed, over land or sea to their destinations. This under development armored personnel carrier of AAAV was welded from aluminum structure successfully by solid-state process of FSW with superior as-welded mechanical properties [32].

7.3 Aerospace Industry

The emergence of friction stir welding (FSW) becomes a new revolution on traditional approach of producing lightweight assemblies for high-strength aluminum alloys such as 2XXX and 7XXX series. These alloys are widely used for aerospace structures such as fuselage, fins, wings, etc. Manufacturing complexity and cost of riveting for joining of aerospace structures has been significantly reduced by the application of FSW. Eclipse 500 aircraft & adoption of FSW by Boeing for its Delta rocket tanks and C17 internal structures are some of the examples to mention [32].

7.4 Automotive Industry

Friction Stir welding (FSW) have found to be the best choice in automotive industries. Components made of aluminum can easily be welded by FSW such as bumper beams, rear spoilers, crash boxes, suspension systems, rear axles, drive shafts, intake manifolds, water coolers, stiffening frames, cylinder heads, engine blocks, dash boards, rollover beams, pistons, engine and chassis cradles, wheel rims, attachments to hydro - formed tubes, tailor welded blanks (TWBs), etc. [3].

7.5 Railway Industries

Friction stir welded structures are now revolutionizing the way in which trains and trams are built. In Europe, suppliers to the railway rolling stock industry are exploiting the process for the prefabrication of large panels, which are made from aluminum extrusions. In Japan, complete trains are being assembled from hollow extrusions using the innovative process. Recent investigations into the crashworthiness of aluminum railcars have clearly demonstrated the benefits of using innovative joint and tool designs and optimized procedures for friction stir welding [36].

8. Conclusion

Friction stir welding will continue to make inroads into light metal fabrication for joints suitable for mechanized welding at the expense of MIG, TIG and Mechanical fastening. However, regardless of the progresses made in FSW, it is impossible to fully replace the conventional processes of joining. Laser welding of aluminum is becoming the promising competent in this regard to strengthen its market niche.

The author beliefs that the full potential of friction stir welding is unknown to claim for the maturity of technology. Research and development programs are carried out for significant improvements in tool design, tool materials, process control, etc. The other complement of the author is that the technology is not yet geared up to respond to the market demand for high temperature materials such as steels and nickel alloys [37]. Recent literatures have disclosed that promising progress started to be shown on high temperature materials by using FSW tool of an optimum tool profile.

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