

Influence of tool geometry and processing parameters on welding defects and mechanical properties for friction stir welding of 6061 Aluminium alloy

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Abstract. Friction stir welding (FSW) is a form of solid state welding process for joining metals, alloys, and selective composites. Over the years, FSW development has provided an improved way of producing welding joints, and consequently got accepted in numerous industries such as aerospace, automotive, rail and marine etc. In FSW, the base metal properties control the material's plastic flow under the influence of a rotating tool whereas, the process and tool parameters play a vital role in the quality of weld. In the current investigation, an array of square butt joints of 6061 Aluminum alloy was to be welded under varying FSW process and tool geometry related parameters, after which the resulting weld was evaluated for the corresponding mechanical properties and welding defects. The study incorporates FSW process and tool parameters such as welding speed, pin height and pin thread pitch as input parameters. However, the weld quality related defects and mechanical properties were treated as output parameters. The experimentation paves way to investigate the correlation between the inputs and the outputs. The correlation between inputs and outputs were used as tool to predict the optimized FSW process and tool parameters for a desired weld output of the base metals under investigation. The study also provides reflection on the effect of said parameters on a welding defect such as wormhole.

Keywords Friction Stir Welding, FSW, Aluminium alloys, 6061

1. Introduction

Welding operation is the most commonly used metal joining process in the industrial sectors such as automotive, aeronautic, ship building, medical, nuclear, electronic, oil and gas etc. Welding is performed by generating localized coalescence of two materials under the action of heat, pressure or both [1]. Friction stir welding (FSW) is a solid state welding process developed by The Welding Institute (TWI) in 1991[2]. The process is widely used for the joining of different aluminium alloys ranging from all 2xxx – 7xxx series [3]. Most commonly it is utilized to join difficult-to-weld and high strength aluminium alloys. The FSW process has several advantages over the conventional fusion based welding processes such as lower input energy requirements and less exposure of microstructural changes. Due to the absence of metal melting phase in the FSW solid state welding process the phase transformation also remains in the solid state resulting in several advantages over the fusion welding processes [4]. Moreover, FSW results in low solidification porosity and distortions. The AA 6061 aluminium alloy is a medium strength alloy of aluminium mainly utilized in the automotive applications [5]. It also offers good corrosion resistance making it suitable for marine applications [6].



Several studies have been executed to understand the plastic deformation and frictional heat at the interface of two parts being joined together. Elangovan and Balasubramanian [7] performed FSW on AA 6061 aluminium alloy to investigate the role of pin profile and tool shoulder diameter. The study has incorporated five dissimilar FSW tool pin profiles namely straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square with three different FSW tool shoulder diameters. The study observed friction stir processed (FSP) zone and correlated the information with mechanical strength of the joints. The study revealed that square pin profile provided defect free FSP zone and reasonably good tensile strength. Lima et al. [8] performed FSW process on AA 6013 alloy. The study was aimed to investigate the relationship between texture, microstructure and residual stresses with respect to the FSW processing parameters. The residual stress curves revealed that HAZ contain worst mechanical properties. Bazayid et al. [9] investigated the friction stir welding process of 7075-T6 aluminium alloys in butt joint configuration using three different types of pin profiles namely cylindrical, square and triangle geometry. The study revealed that tunnel hole was smaller for triangular pin as compared to the cylindrical pin. The study also revealed that microstructure was refined for the square pin profile as compared to the other profiles. The study reported the defects of tunnel hole, kissing bond and zigzag line in case of cylindrical pin profiles. Severe plastic deformation with cracks were found with the triangular pin profiles.

Kishta and Darras [10] performed an experimental investigation to friction stir weld marine grade 5083 aluminium alloy under dry air and under water environments. The study was focused to study the influence of submersion, rotational speed and translational speeds. The study measured welding temperature histories, void fraction, microhardness behaviour, power consumption and tensile characteristics. The study revealed good results for the tensile test and less void fraction in case of the submerged welding process. In another study, Basil and Kishta [11] studied the submerged welding of AZ31 Magnesium alloy under dry, hot water and cold water submersion. The study investigated the role of heating and cooling rates with respect to the microstructure and associated mechanical characteristics. The study revealed that hot water friction stir welding processing resulted in very high percentage elongation or improved formability. Rajakumar et al. [12] investigated the strength of AA7075-T6 aluminium alloy using friction stir welding process. The study investigated the influence of tool parameters with respect to their influence on the mechanical properties. The study revealed that refined grain structure and uniformly dispersed $MgZn_2$ particles provided the higher tensile strength. In another study, Rajakumar and Balasubramanian [13] studied the process parameters for six different grades of aluminium alloys. The study incorporated Response Surface Methodology (RSM) to attain the optimized processing parameters for gaining maximum strength. Lakshminarayanan et al. [14] investigated the friction stir welding of AA6061 and compared it with conventional gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) processes. The study revealed that friction stir processed samples provided better mechanical properties when compared to the conventional gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) processes.

Subramaniam et al. [15] utilized friction stir welding process to weld AA6063-T6 flat plates using triangular, cylindrical and square pin profiles. The study incorporated an acoustic emission monitoring technique to examine the influence of tool pin profile at mechanical tensile properties. Acoustic emission based parameters were correlated with the tensile properties of the welded samples, and study revealed good potential of acoustic emission based technique to use it as in-processing monitoring method. Wang et al. [16] performed stir friction processing on AZ31 magnesium alloys. The study analysed the effect of tool rotational rates on the temperature histories, microstructure and mechanical characteristics. Five various levels of tool rotations ranging from 800 – 1600 rpm were investigated. The study utilized uniaxial tensile testing and Charpy V-notch impact testing methods on the welded samples. Finite element based numerical model was also developed to predict the temperature field during the FSW process. The study revealed that 1200 rpm welding condition outperformed other rotational speeds. Dobriyal et al. [17] conducted stir friction butt welding on AE42 magnesium alloy. The study observed dynamic recrystallization in the welding region. At the same time reduction in the precipitate size was observed in the stir zone as compared to the thermo-mechanical affected zone (TMAZ) and the base material.

In this paper, the influence of different tool geometric and processing parameters was examined in reference to the resulting mechanical properties. The study incorporated friction stir welding process on 6061 aluminium alloy. Mechanical properties were analysed using uniaxial tensile test, and welding defects were monitored using optical light microscope.

2. Experimental Methods

The experimentation was executed using conventional milling machining in vertical arrangement. Specially design workpiece were utilized to facilitate the clamping and different combinations of feeding mechanisms were utilized for the experimentation. Figure 1 shows the experimental setup utilized during experimentation. Figure 2 illustrates the friction stir welding process and tensile test coupon preparation from the welded samples.

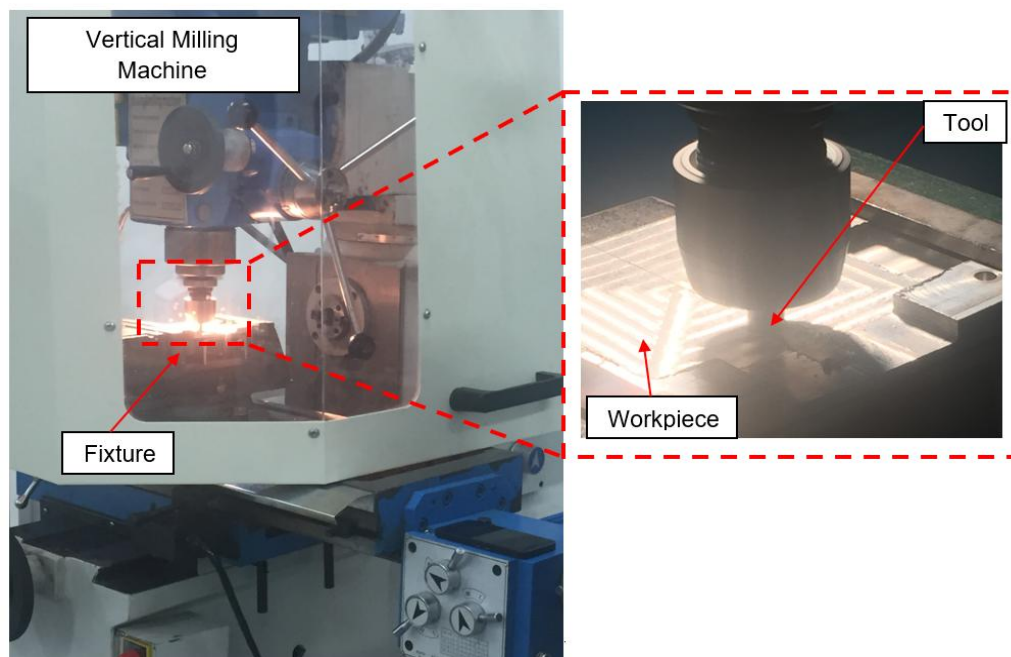


Figure 1: Experimental setup of friction stir welding (FSW) process and close-up view

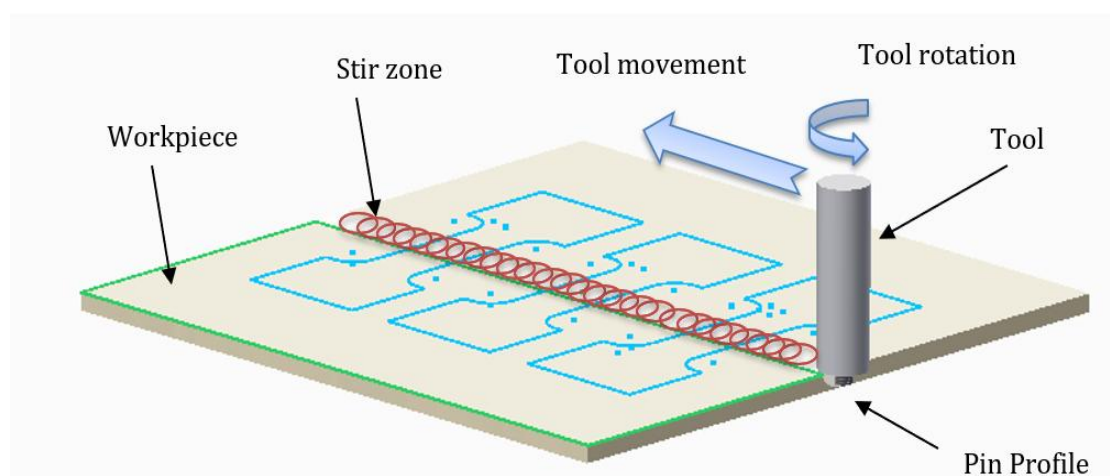


Figure 2: Schematic illustration of the friction stir welding (FSW) process

In the presented study, AA 6061 aluminium alloy was investigated in the form of 4 mm thick flat plates under butt welding configuration. The chemical composition of AA 6061 (6061-O temper)

aluminum alloy has been presented in Table 1. Similarly, the mechanical properties of AA 6061 (6061-O temper) aluminum alloy has been presented in Table 2.

Table 1. Nominal composition of AA6061 (6061-O temper) alloy (Wt.%) [18]

Element	%	Element	%
Si	0.4-0.8	Cr	0.04-0.35
Fe	0.7	Zi	0.25
Cu	0.15-0.40	Ti	0.15
Mn	0.15	Al	Remaining
Mg	0.8-1.2		

Table 2. Mechanical properties of AA6061 (6061-O temper) alloy [18]

Ultimate tensile strength (MPa)	0.2% Proof Stress (MPa)	Brinell Hardness Number (BHN)	Elongation (%)
110-152	65-110	30-33	14-16

The different welding parameters and conditions utilized during the experimentation are reported in the Table 3. The study incorporated three various levels of welding speed ranging from 6 – 12 mm/min. Two levels of pin length were also investigated. The pin profile was cylindrical throughout experimentation; however, two different thread pitch values were also employed in the current study. The tool rotation was restricted to 1750 rpm. Shoulder and pin diameters were 25 mm and 5 mm respectively. To produce a butt welding joint single pass welding method has been utilized. Welding tools were fabricated using stainless steel material, and then each tool was utilized to support each welding condition. The study prepared 12 different weld joints.

Table 3. Welding condition and parameters with their associated levels

Parameters	Symbol	Levels
Welding speed (mm/min)	WS	6, 9, 12
Tool rotational speed (rpm)	RS	1750
Tool shoulder diameter (mm)	SD	25
Pin diameter (mm)	PD	5
Pin length (mm)	PL	3, 3.5
Tool pin profile	PP	Cylindrical
Right Hand (RH) Thread	TP	M5-Pitch 0.8, M5 - Pitch 0.9

3. Results and discussion

In this current study, butt welded samples were examined in terms of their tensile strength and welding defects using universal testing machine and optical microscope respectively.

3.1 Tensile Strength Analysis

The welded samples were taken to the CNC milling machine where tensile test coupons were precisely generated. After the preparation, tensile coupons were taken to the universal testing machine and stress strain behaviour of each welded sample was recorded and examined with reference to the unprocessed material as shown in Figures 3a and 3b. The unprocessed stress strain behaviour of material was found in agreement with the available literature as mentioned in the Table 2.

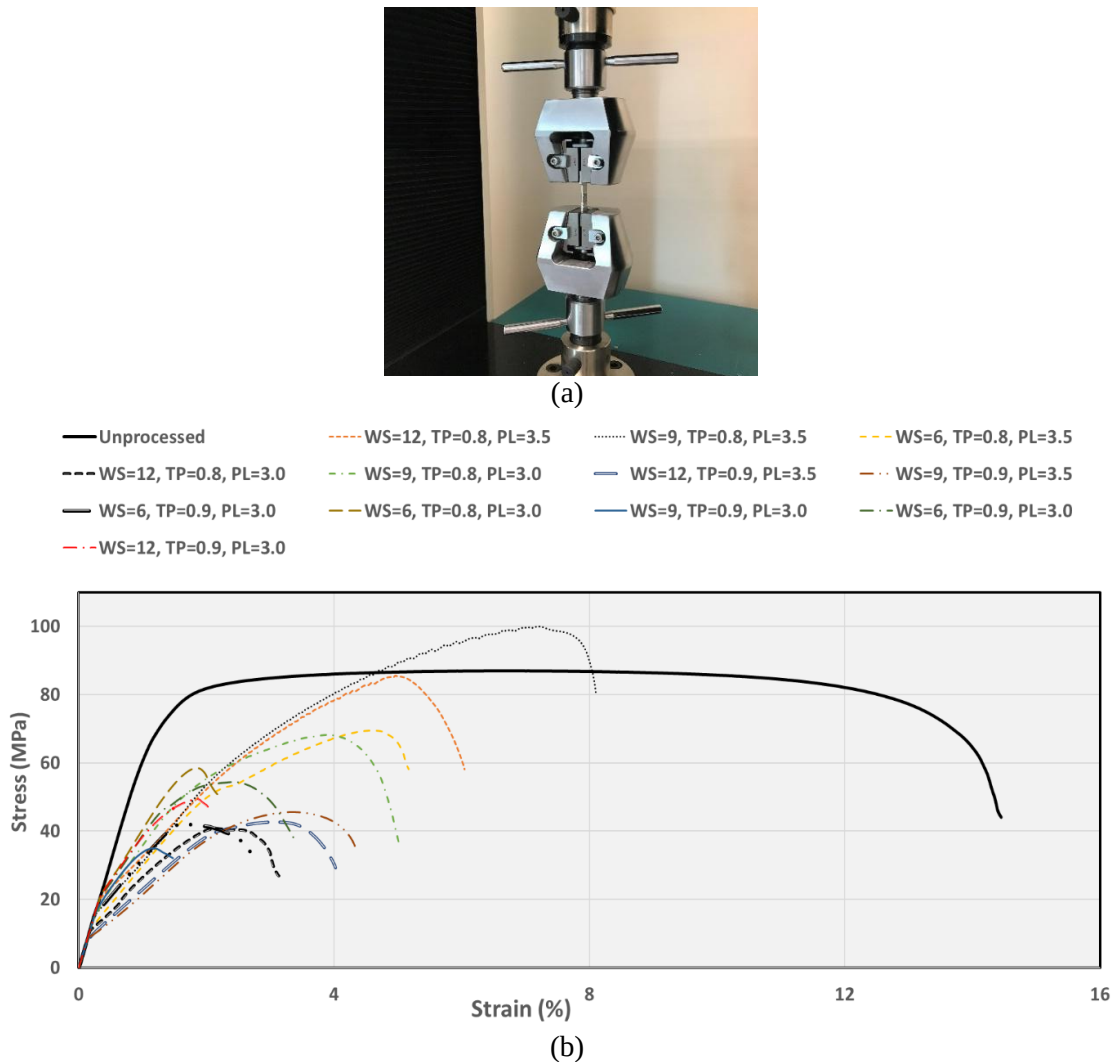


Figure 3: (a) Experimental setup of tensile test conducted in the lab (b) Stress – Strain curves of unprocessed and all 12 welded samples

It has been observed that lower value, 3mm, of pin length did not performed well as compared to the pin length of 3.5 mm. The ultimate tensile strength was found better than the unprocessed materials for the welding condition of welding speed = 9 mm/min, pin length = 3.5 mm and thread pitch of 0.8 mm. For the unprocessed sample the yield point, ultimate tensile strength and elongation came to be 80 MPa, 86.94 MPa and 14.2% as shown in Figure 3b. For all welding samples, the tensile strength, yield strength and elongation came to be lower than the unprocessed sample, except only one condition where welding speed, thread pitch and pin length were 9 mm/min, 0.8 mm and 3.5 mm respectively. Only this condition revealed an exceptional defect free interface when examined from the sectional side direction.

3.2 Macrostructure defects analysis

The macrostructure examination was conducted using an optical microscope with an imaging processing software. FSW is a type of solid state welding method, it involves an excessive plastic flow of material and joining is facilitated through the stirring action. FSW is free from conventional welding defects such as porosity, inclusions and slag formation etc. However, it has its own type of defects such as work hole (tunnel like voids), cracks and kissing bond etc. Tables 4 and 5 represents macrostructural observations in the welded samples.

Table 4. Macrostructure based observations for the pin length (PL) of 3mm for all welding conditions

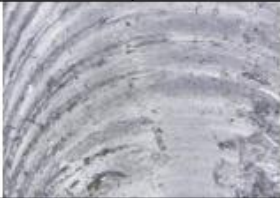
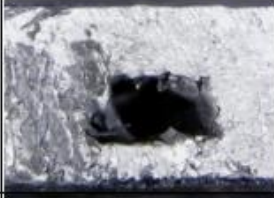
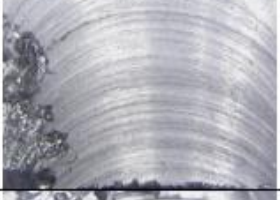
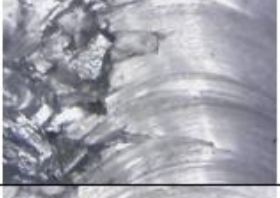
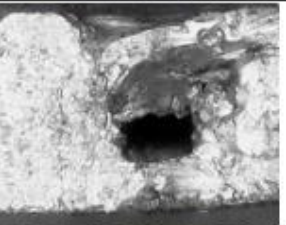
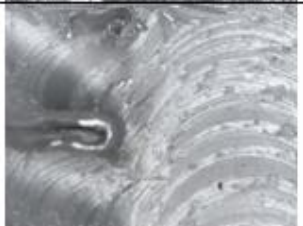
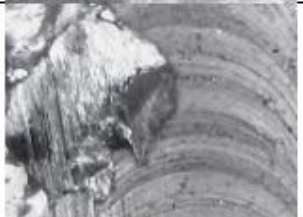
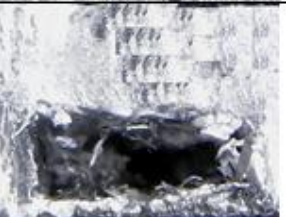
Sr. No.	Welding Conditions	FSW Stir Zone		Defect examination W = 1.9 mm H = 1.4 mm	Comments
		Retrieving Side	Advancing Side		
1	WS = 6 PL = 3 TP = 0.8			- Stir zone was clear on retrieving side - Worm hole defect was observed, it can be linked with the insufficient heat generation	
2	WS = 9 PL = 3 TP = 0.8			- Stir zone has material accumulated on the retrieving side - Worm hole defect was observed due to insufficient heat generation	
3	WS = 12 PL = 3 TP = 0.8			- Stir zone has material accumulated on the retrieving side - Comparatively larger worm hole was observed due to insufficient heat generation	
4	WS = 6 PL = 3 TP = 0.9			- Stir zone has material accumulated on the retrieving side - Worm hole was observed due to insufficient heat generation	
5	WS = 9 PL = 3 TP = 0.9			- Stir zone has excessive material accumulated on the retrieving side - Worm hole was observed due to insufficient heat generation	
6	WS = 12 PL = 3 TP = 0.9			- Stir zone has excessive material accumulated on the retrieving side - Comparatively larger worm hole was observed due to insufficient heat generation	

Table 5. Macrostructure based observations for the pin length (PL) of 3.5 mm for all welding conditions

Sr. No.	Welding Conditions	FSW Stir Zone		Defect examination	Comments
		Retrieving Side	Advancing Side		
1	WS = 6 PL = 3.5 TP = 0.8			- Stir zone was clear on retrieving side - Tunnelling defect was observed at the bottom middle portion due to insufficient heat generation	
2	WS = 9 PL = 3.5 TP = 0.8			- Stir zone was clear on retrieving side - Sufficient heat generation and material flow to produce good weld	
3	WS = 12 PL = 3.5 TP = 0.8			- Stir zone was clear on retrieving side - Sufficient heat generation and material flow to produce good weld	
4	WS = 6 PL = 3.5 TP = 0.9			- Stir zone has excessive material accumulated on the retrieving side - Tunnelling defect was observed due to insufficient heat generation	
5	WS = 9 PL = 3.5 TP = 0.9			- Stir zone has excessive material accumulated on the retrieving side - Tunnelling defect was observed due to insufficient heat generation	
6	WS = 12 PL = 3.5 TP = 0.9			- Stir zone has excessive material accumulated on the retrieving side - <u>Comparatively larger</u> worm hole was observed due to insufficient heat generation	

The study revealed that worm hole in different geometrics was present in almost all welded samples, except welding speeds of 9-12 mm/ min, pin length 3.5 mm and thread pitch of 0.8 as shown in Table 5. These two good quality welds provided reasonable ultimate tensile strength as shown in the Figure 3b.

4. Conclusions

The current study was focused on examining the FSW process using various levels of welding speeds, pin lengths and thread pitches. The study revealed that welding speed plays a key role towards the heat generation, and lead to the generation of worm hole in the welding nugget in case of wrong selection. The thread pitch has a controlling influence on the stirring action and it can contribute towards the material accumulation towards the retrieving side of the welding. Submersion of a pin length is also a crucial factor. Insufficient pin length can lead to the lack of penetration and pin hole generation.

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