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Design and Development of Manufacturing Facilities for Friction Stir Welding Process using Conventional Milling Machine

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Abstract. Friction stir welding (FSW) is a solid-state joining process that has many advantages including the ability to join high strength alloy as well as dissimilar metals which are hard to be joined by conventional fusion techniques. This welding process involves the penetration of rotating tool which consist of shoulder and prolonged by a pin into a metal plate. The process is followed by advancing speed to weld the metal plate. However, it requires a specialized machine to perform the joining process. A new FSW system including its tools may be costly and thus becomes the main barrier to the development of this FSW process in industry. One of the possible solutions is by adapting the current conventional milling machine with additional rotating and feeding principles to suit the FSW process requirement. In this work, suitable tools, jigs and fixtures for FSW process using conventional milling machine were designed. The design of the tool, jigs and fixtures were fabricated and tested by joining two similar plates of A6061 aluminium alloys. The investigation shows promising results with defect-free welds, good strength and smooth surface finish without gap creation between the welded plates.

1. Introduction

Friction stir welding (FSW) is a joining process of similar or dissimilar work pieces which takes place in a solid phase [1]. FSW was firstly discovered in 1991 by The Welding Institute (TWI) in UK, which was first introduced in joining of aluminium alloy [2]. The application of FSW has expended in wide variety of industries such as automotive, maritime, aerospace, and railways [2]. FSW eliminates the problems that associate with material melting and solidification during the welding process such as residuals stress, cracks and distortion of the weldment [1]. FSW has many advantages as compared to other welding processes. FSW can weld metal alloys which is hard or impossible to weld by other fusion welding method. It does not require any filler materials or shielding gas in order to perform the welding process. Besides, fumes, arc flash, spatter and pollution are reduced in this process which can minimize the environmental pollution [3].

FSW process involves a penetration of rotating tool which consists of a shoulder and prolonged by a pin into a metal plate, followed by advancing speed to weld the metal plate [4]. The friction between tool shoulder and metal plates will generate heat and soften the metal plate under the melting point of the metal [5,6]. Thus, the materials can easily flow between the two similar or dissimilar metals. There are many variables that must be considered in this welding such as the tool rotation speed, welding



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speed, plunged depth, tilt angles, sideways tilt angles, shoulder geometry, shoulder features (scrolls), pin geometry, pin features (threads, flutes, flats) and suitable jigs and fixtures [7,8]. Figure 1 illustrates the process of FSW.

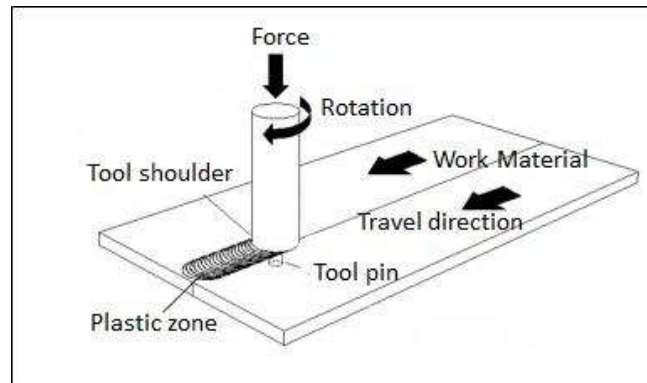


Figure 1. Illustration of FSW process

The application of this type of welding are easy automation, lower residual stress, less distortion and performing good mechanical properties in the weldment region. However, it requires a specialized machine to perform the joining process. There are many types of FSW machinery available in the markets. In fact, purchasing of this machinery may contribute to higher manufacturing cost and this seems to be the main barriers to extend this process among related industries. One of the possible solutions is by adapting current available in conventional machining with rotating and feeding principles such as milling machine. However, implementation of FSW using milling machine requires some adjustments and modifications on the machine facilities. The modification requires designing a suitable jig and fixture and a suitable tool in order to perform the FSW process using the milling machine. Hence, suitable tools, jigs and fixtures for FSW process using conventional milling machine are designed in this study. The design of the tool, jigs and fixtures was fabricated and tested by joining two similar plates of A6061 aluminum alloys at various rotational speeds and welding speeds.

2. Methodology

2.1 Design of Jig and Fixture

Clamping system, movement and flexibility are the most important criteria in designing jig and fixture [9]. Conceptual designs had been done to determine the appropriate design for the jigs and fixtures. The selection of the design is based on decision based method having five design considerations; ability of heat dissipation, movement and vibration stability, manufacturability and minimum cost. Figure 2 shows the assembly drawing and exploded view of the jig and fixture design. The dimension of the fixture is 375 x 200 x 20 mm.

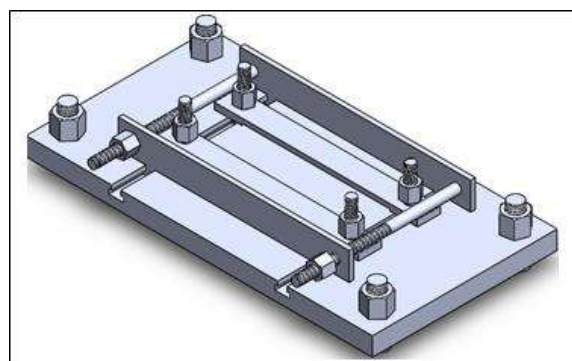


Figure 2. Assembly view of Jig and fixture

Figure 3 shows the three parts of the designed jig and fixture; back plate (fixture), pressure bar and clamp. As recommended by Kamble et al. [9] the back plate should have sufficient thickness in comparison with the thickness of the plates to be joined. The list and specification of parts used in fabrication of jig and fixtures are listed in Table 1. Mild steel is used to fabricate these parts.

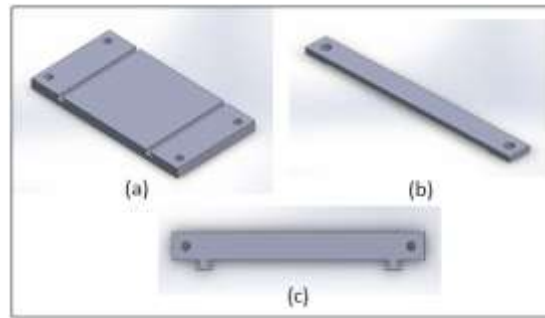


Figure 3. (a) Fixture (Back plate) (b) Pressure bar (c) Clamp

Table 1. Parts in Jig and Fixtures

Part	Quantity	Specification
Back Plate	1	L(200mm), W(200mm), t(20mm)
T-Clamp	2	L(250mm), W(30mm), t(5mm)
Pressure Bar	2	L(220mm), W(25mm), t(7mm)
Bolt M16	4	Standard part
Nut M16	6	Standard part
Nut M10	4	Standard part

2.2 Fabrication of jig and fixture

Fabrication of jig and fixture involved cutting, machining drilling and finishing process. The machining was conducted using EDM and milling process. The mild steel plate was first cut to appropriate size for each part as listed in Table 1. The T-slots on the back plate were cut using milling machine whereas the pressure bar was fabricated using end milling process. The holes with various diameters for bolts and nuts were fabricated using drilling machine and milling machine. Bolts and nuts are used to hold the fixture which was attached to the worktable of milling machine. Finally, all parts were polished with filer and sand paper to remove sharp burs at the side of the parts.

2.3 Design and Fabrication of Tool

The main components of FSW tool are pin and shoulder. The function of the pin is to deform the work material around the tool and to generate heat due to friction. Thus, a suitable tool is required to be designed and fabricated. In this work, a tool made of H13 steel was designed and used. The tool material is selected based on its melting point which should be higher than the work material. The shoulder diameter of the tool is 20 mm having 8° concave and pin was tapered with 15° from 4.55 mm diameter on the base. Shoulder is the primary means of generating heat as it is in contact with the top surface of the joint while in the motion and it also prevents softening work material to come out from the weld pool. Besides, shoulder assists work material movement around the tool. The length of the pin from the shoulder is 2.7 mm with 0.3 mm clearance to avoid the joining of the work materials with the back plate. The tool design is shown in Figure 4. The tool is fabricated using CNC machine.

**Figure 4.** Tool Design

2.4 Work Material preparation

Aluminium alloy, AA6061-T6 with dimension of 125 x 50 x 4 mm was welded to test the performance of the designed jig and fixture. Four samples are prepared at various welded parameters as tabulated in Table 2.

Table 2. Welding parameters for samples

Sample	Rotational Speed (rpm)	Welding Speed (mm/min)
A	1000	218
B	1000	249
C	1270	218
D	1270	249

Rotational speed and welding speed is an important factor in heat generation. Rotational speed affects the heat generation and balances the work material movement. High rotational speed will increase the heat generated. The welding speed affects the input heat per unit time and the work material consolidation behind the tool pin. Increasing the travel speed will reduce the heat generated [10].

2.5 Analysis

After the samples had been successfully welded, external visual inspection, welding strength, surface roughness of the welded surface and the percentage of material losses was investigated. Welding strength test was measured using Universal Testing Machine whereas the roughness of the welding zoom was measured using Mitutoyo surface roughness tester (SURFTEST SJ-210). The percentage of weight losses were calculated using Equation 1.

$$\% \text{ of losses} = \frac{mass_a}{mass_i} \times 100\% \quad (1)$$

where $mass_a$ is the mass of sample after welded and $mass_i$ is the initial mass of the sample.

3. Results and Discussion

3.1 External visual inspection

Figure 5 shows the appearance of the welding for the samples. External inspection on the welded zone shows all samples are perfectly welded using conventional milling machine with special design of jig and fixture and tool. The results reveals that FSW process can be performed using conventional milling machine. It is also notified that a metal residual are formed along the size of welded zone on all samples. The sample C which was welded at rotational speed of 1270 rpm and welding speed of 218 mm/min shows smoothest welded profile with minimum residual. Sample A and sample D are

found to exhibit higher residual. At low rotational speed, low heat is generated and lead to low plasticity region. This cause the welding surface rough and high residual occurs. As for sample D, high rotational speed with higher welding speed formed high plasticity region of the material and subsequently splashed the work material. No welding crack and internal crack were observed on all samples.



Figure 5. Welding appearance. a) Sample A b) Sample B c) Sample C d) Sample D

3.2 Welding strength

Table 3 summarizes the welding strength of the samples. The highest welding strength is exhibited by sample C which is welded using process parameter of 1270 rpm of rotating speed and 218 mm/min of welding speed. The result is reasonable because more heat are generated at higher rotational speed. This will lead to the increasing of the plasticity region which consequently increases the strength of the welded zone. In addition, lower welding speed will provide appropriate time for the heat to dissipate through the welding zone and cause the welding strength decreases. On the other hand, the lowest welding strength was observed on Sample A. At low rotational speed and welding speed, low heat is generated which cause insufficient softening of the work material. Consequently, inefficient consolidation and inadequate mixing occurred. The results are correlated with the findings reported by Khan et al. [10]. In addition, as reported by Salih et al. [11] the maximum strength was achieved at rotational speed of 1000 rpm to 1200 rpm depending on the grade of aluminium alloy.

Table 3. Welding Strength

Sample	UTS (MPa)
A	114
B	151
C	189
D	182

3.3 Surface roughness

As known, a smooth surface finish is important in the welding process as less finishing process need to be done to the specimens and it provides a good surface finish to the specimens. Figure 4 shows the surface roughness of the samples. Based on the results, sample C has the lowest surface roughness compared to the other specimens. This is due to the rotating speed that was used during the welding process is able to form appropriate heat and plasticity region for friction welding process.

Table 4. Surface roughness

Sample	Surface Roughness (μm)
A	5.657
B	8.198
C	2.090
D	3.497

Although similar speed was used for sample D, the surface finish for specimen C is smoother compared to the specimen D. This proved that higher welding speed causes welding surface to be rougher. The sample A and sample B exhibit rough surface finish on the welding zone. At rotational speed of 1000 rpm, less heat is generated that causes the welding zone less plasticity and hardly to be welded. Thus, the surface roughness is increased.

3.4 Weight loss

The weight of the samples was measured before and after performing FSW process. Based on the pre and post weight, the weight loss is calculated. The weight loss for the samples is shown in Table 5. The percentage of losses for each sample is approximately equal to 0.67%, which is indeed very small. The losses were due to the penetration of the pin to the specimen surface.

Table 5. Weight loss of the samples

Sample	Percentage of weight loss (%)
A	0.67
B	0.67
C	0.67
D	0.67

4. Conclusions

Based on the finding, the following remarks could be drawn:

- With special jig/features and tool designed, the FSW process is able to be conducted using conventional milling machine.
- Higher rotational speed will lead to higher heat generation and cause the work material to be more plasticity. Thus, effective FSW process could be achieved.
- Higher welding speed will deteriorate the quality of the welded surface.
- The optimum rotating speed and welding speed suggested in this design were 1270 rpm and 218 mm/min, respectively.

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