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Optimizing Process Parameter of Friction Stir Welding on Aluminium Using Response Surface Methodology

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Abstract: Friction stir welding (FSW) has been widely experimented on manufacturing industry due to its broad engineering applications. FSW technique results in the material having low distortion and high joint strength as compared with other joining techniques. The purpose of this study is to analyse the effect of various process parameters such as rotational speed, welding speed and tool geometries on the joining process of aluminium alloy then determine the optimum process parameter. Every year, friction stir welding techniques advances and revolutionises the process. Owing to its excellent weld strength compared to other welding techniques, it is utilised to weld aluminium alloys in a variety of industries. However, FSW on aluminium alloys frequently results in substantial complications in the setting of welding parameters due to the constraints of joining the material. Hence, the need to determine the optimum process parameters is critical. The optimization of process parameter is done after completing the welding procedure by using design of experiment (DOE) concept which is response surface methodology in Minitab software. In this study, central composite design technique and mathematical model was developed by response surface methodology with three process parameters and 20 runs, was used to develop the relationship between the FSW parameters and the responses, tensile strength were established. The results show that the triangular welding tool pin, 1200 rpm rotational speed and 60 mm/min welding have the highest tensile strength which is 169 MPa. The optimum parameter of the FSW process evaluated by the response optimizer are 1200 rpm rotational speed, 30 mm/min welding speed and triangular tool pin geometry.

Keywords: Friction Stir Welding, Response Surface Methodology , Aluminium Alloy 6061, Optimization

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1. Introduction

Friction stir welding (FSW) is a solid-state welding technology developed by The Welding Institute (TWI) in 1991. This recent technology is eco-friendly and energy-saving which may be used to join high-strength aluminum alloys and other metallic materials that are difficult to fuse using conventional fusion welding methods [1]. FSW process takes place below the melting point of the weld material. The surface modification of aluminum by FSW is studied using a non-consumable rotating tool with shoulder and pin profile that is plunged into the weld joint and forced to travel along the joint line by heating the components and generating internal friction, thus producing a weld joint by stirring action of the tool at the junction of two work pieces [2]. The rotation of tool inside the work pieces deforms the material plastically, resulting in a strong joint.

The friction stir welding (FSW) process is clearly effective for welding divergent aluminum alloys. Weld distortion is not a concern because these processes do not entail the melting phase. Similarly, in combination welding of aluminum composites, the FSW technique addresses a variety of difficulties such as porosity, distortion, heat affected zones, and cracking [3].

In this study, friction stir welding (FSW) process is performed to join aluminum 6061. The response surface methodology (RSM) is applied for optimizing the process parameters. The mechanical properties and macrostructure of the weld joints are also identified on visual inspection while as for the weld strength, it is discussed by undergoing the tensile test. Materials with a high strength-to-weight ratio, strong ductility, outstanding corrosion resistance, and relatively low cost are constantly sought by manufacturing sectors, particularly the automotive and aerospace industries [4].

There are situations when several types of aluminum alloys must be welded together due to the demands of various service conditions. This is because, aluminum alloys possess good strength and ductility even though it is light in weight. The selection of appropriate joining method becomes crucial in the performance of these materials in actual service conditions. As a result, it makes the material eligible to be used in a wide range of industrial situations [5].

Aluminum 6061 has good mechanical properties such as light weight, moderate strength, high corrosion resistance, workability, proven weldability, and good electrical and thermal conductivity. Hence, it is commonly utilized in a broad range of engineering applications such as transportation, building, aircraft, and other structural applications that require strength and weldability [6]. However, there is always the potential or propensity of mending defective components during the production or use of these structures, which often necessitates welding. Conventional fusion welding has been observed to generate poor quality weld joints when joining aluminum alloys [7]. As a result of these problems, friction stir welding (FSW) was developed to address these potential issues [8].

2. Materials and Methods

2.1 Materials

In this experiment, the material of work pieces used is aluminum 6061. Aluminum 6061 metals are widely utilized among the 6000 series aluminum alloys, with higher weld strength compared to other heat-treatable alloys and it is one of the most popular and versatile extrusion alloy. For projects where weld ability is key, it is worth considering. The aluminum 6061, on the other hand, has outstanding corrosion resistance, machinability, and formability.

Table 1 : Mechanical and Physical Properties of Aluminum 6061 [9]

Material	Melting Point (˚C)	Solidus Temperature (˚C)	Thermal Conductivity (W/m-K)	Tensile Strength (MPa)	Hardness Vickers (HV)	Impact Energy (Joule)
AA6061	652	582	167	310	96	0.96

2.2 Equipment and welding tool preparation

The welding tool used in this experiment is fabricated using a lathe machine and milling machine. The material of welding tool is mild steel because it has high tensile strength and impact strength and able to prevent the welding tool to be worn. Mishra and Ma state that mild steel is also chosen as the material of the tool pin because the FSW tool must be tougher than the soldered material. In this experiment, there will be three types of welding tool with different pin geometry which are triangular pin, squared pin and cylindrical pin.

Table 2 : Characteristics of Tool Pin [10]

Geometry of welding tool	Material	Dimensions (mm)
Square	Mild steel	Pin height : 2.5 3 mm sq
Cylindrical	Mild steel	Pin height : 2.5 Pin diameter : 3
Triangular	Mild steel	Pin height : 2.5

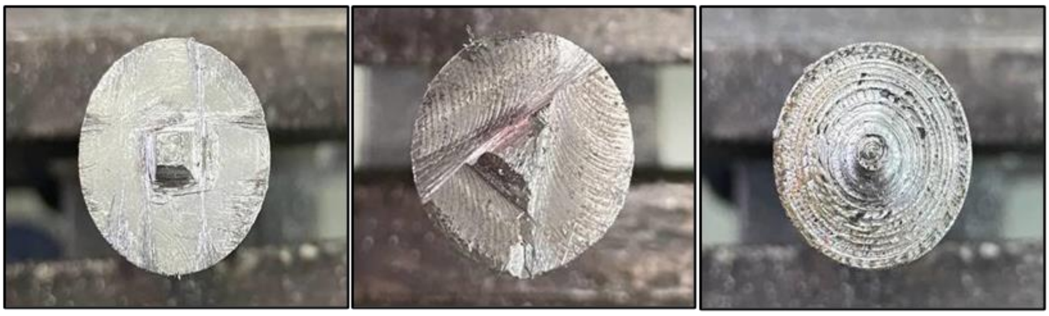


Figure 1: Geometry of tool pin

2.3 Welding Process

Friction stir welding is performed on a conventional milling machine. The machine has an anvil sized 1524 mm x 305 mm and may be tilted in x, y and z direction. Other than that, the motor of the conventional milling machine has a horsepower of 3 and rotates at speeds ranging from 0 to 3600 rpm.

Figure 2 Conventional milling machine

In the beginning of the weld process, the equipment and material are set up accordingly. The three parameters which are rotational speed, welding speed and geometry of the welding tool are set up on the conventional milling machine according to the number of run. The welding tool is set to be at the centre of the work pieces. The axle is then lowered and started pre- pivoting until the welding tool touches the work pieces. After finished setting up the equipment and work pieces, the process is started.

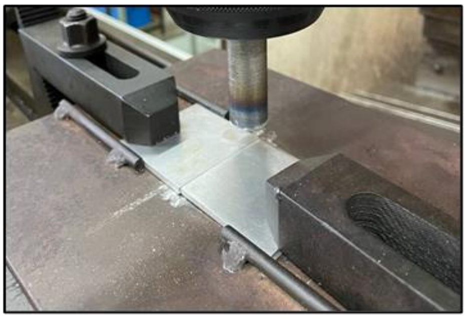


Figure 3 : Specimens are Clamped onto The Jig

Figure 4 During FSW Process

During the FSW process, a sound of pinging is created due to the work between the work pieces and the welding tool. It can also be seen that the work pieces started to melt and influencing joint formation caused by the frictional heat created by the tool and work pieces which allows plastic deformation to happen.

At the end of the weld process, it can be observed that there is a weld joint formed on the work pieces. The macrostructure of the weld joint is varied according to the chosen process parameters which consist of rotational speed, welding speed and tool geometry. Each of the samples has different mechanical properties since the process parameters influence the mechanical properties of the weld joint.

Figure 5: Formation of Weld Joint

2.4 Tensile Test

Tensile test is a method of determining an overall strength of a material or object. Moreover, it is performed to determine the strength and ductility of a material. The object is placed in the middle and both of the object ends are gripped and progressively dragged apart until it breaks. On the other hand, this testing process is conducted to determine the tensile strength, yield strength or yield point, elastic modulus, percentage of elongation and decrease in area of a material or an object.

To carry out metallurgical experiments, specimens of the desired size were cut from the welded plate with a CNC milling machine to be machined to the required dimension accordance to the standard of ASTM D3039.

Figure 6: Tensile Test Sample

The tensile test is conducted on a computerized hydraulic testing machine. The specimen is loaded at the load speed of 2 mm/min as per standard specifications. When the specimen has finally failed, the load versus displacement data is recorded.

2.5 Response Surface Methodology

The empirical relationships is develop by using statistical technique of Response Surface Methodology (RSM). In this study, central composite design (CCD) technique and mathematical model are developed using RSM with three parameters and 20 runs to establish the relationship between the FSW parameters and the response which is tensile strength. The upper limit of a factor was coded as +1, and the lower limit was coded as –1. The “face-centered CCD” involves 20 experimental observations at three independent input variables. The experimental friction stir welding parameters and their levels in this study in the actual form is given in Table 3 below.

Table 3: Friction Stir Welding Parameters and Their Levels

Parameters	-1	0	1
Tool pin geometry	Squared (1)	Triangular (2)	Cylindrical (3)
Rotational speed (rpm)	800	1000	1200
Welding speed (mm/min)	30	60	90

3. Results and Discussion

3.1 Microstructure Analysis

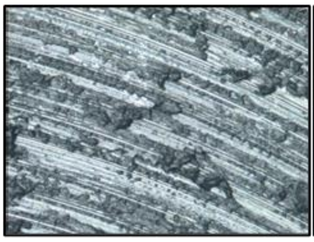


Figure 7

Figure 8

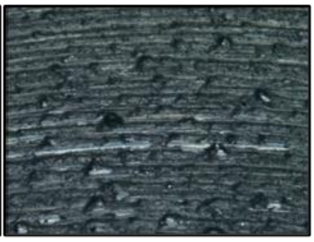


Figure 9

The analysis has been conducted at rotational speed of 1200 rpm with welding speed of 90 mm/min and 60 mm/min. Based on the tensile test result, figure 7 has highest tensile strength than figure 7 and 9. This is because, the rotational speed, welding speed and tool geometry influence the weld joint formation. When the rotational speed is high, there is sufficient heat generation hence, it creates proper material flow. As for the welding speed, higher welding speed creates insufficient heat input, it will result inadequate material flow. From this study, the base metal has a slightly lower maximum stress than the welded joint. This is due to the fact that the friction stir welding process causes the strengthening precipitates to accumulate in the TMAZ, HAZ, and weld nugget regions. As a result, the tensile strength of the friction stir welded joint of AA6061 is lower than the base metal.

3.2 Result of Tensile Test

Table 4: Result of Tensile Test

Experiment no.	Rotational speed (rpm)	Welding speed (mm/min)	Tool geometry	Tensile strength (MPa)
1	800	30	1	142
2	1200	30	1	155
3	800	90	1	128
4	1200	90	1	132
5	800	30	3	122
6	1200	30	3	160
7	800	90	3	118
8	1200	90	3	156
9	1000	60	2	154
10	1000	60	2	149
11	1000	60	2	151
12	1000	60	2	132
13	800	60	2	168
14	1200	60	2	169
15	1000	30	2	167
16	1000	90	2	140

17	1000	60	1	135
18	1000	60	3	148
19	1000	60	2	143
20	1000	60	2	155

3.3 Response Surface Methodology

This study is to develop the relationship between three process parameters and one response by utilizing response surface methodology. To demonstrate the relationship between process parameters and reactions, a scientific model was developed. The full quadratic model was applied and 95% level of confidence was used in this study. The significant values are less than 0.05 while if the values is greater than 0.05, it is insignificant. The adequacy of the developed empirical relationship for the response variables, tensile strength was tested using the analysis of variance (ANOVA) technique as shown in the table 5 below.

The determination coefficient, R^2 indicates the goodness of fit for the model. In this study, the value of the determination coefficient, R^2 is 80.52%. it indicates that the total variability explained by the model after considering the significant factors is 80.52%. The models are not over fitted as indicated by the comparison between R^2 and R^2 – adjusted values. The difference between these two is 21.64% of the total variations which were not explained by the model. The value adjusted determination coefficient is R^2- adjusted is 58.88%.

Based on the table below, the rotational speed, welding speed and the square of tool geometry is significant as it has P- value lower than 0.005 which is 0.013, 0.042 and 0.031 respectively.

Table 5: Analysis of Variance (ANOVA)

Source	DF	Adj SS	Adj MS	F- Value	P- Value
Model	10	3439.19	343.92	3.72	0.030
Blocks	1	304.05	304.05	3.29	0.103
Linear	3	1416.40	472.13	5.11	0.025
Rotational speed	1	883.60	883.60	9.56	0.013
Welding speed	1	518.40	518.40	5.61	0.042
Tool geometry	1	14.40	14.40	0.16	0.702
Square	3	833.00	277.67	3.00	0.087
RS*RS	1	387.16	387.16	4.19	0.071
WS*WS	1	24.00	24.00	0.26	0.623
TG*TG	1	603.16	603.16	6.52	0.031
2- Way interaction	3	550.37	183.46	1.98	0.187
RS*WS	1	10.13	10.13	0.11	0.748
RS*TG	1	435.12	435.12	4.17	0.058
WS*TG	1	105.12	105.12	1.14	0.314

Error	9	832.01	92.45		
Lack-of-fit	5	467.01	93.40	1.02	0.505
Pure error	4	365.00	91.25		
Total	19	4217.20			
	S = 9.615	**R^2 = 80.52%**	**R^2 (adj) = 58.88%**		

3.4 Contour Plot and Surface Plot

According to figure 3.4 below, the tensile strength is in the range of 114 to 150 MPa at rotational speeds between 800 and 110 rpm and welding speeds between 50 and 90 mm/min. As can be shown, welding speed has less of an impact on the tensile strength of the weld joint than a change in rotational speed. Figure 7 above shows the tensile strength is between 160 to 170 MPa at tool geometry 2 and rotational speed of 1100 to 1200 rpm. The tensile strength is more sensitive to the change in rotational speed for a triangular tool pin geometry. From the contour plot shown in figure 8, it is inferred that the tensile strength is more sensitive to change in tool pin geometry than to the changes in welding speed when a triangular tool pin geometry is used. Of the three tool pin geometry used, the triangular tool pin geometry is more sensitive to tensile strength at an optimum welding speed and rotational speed. Interaction effects among the factors of rotational speed and welding speed, rotational speed and tool geometry and welding speed and tool geometry exist. The maximum tensile strength is obtained from the response surface and contour plots by using a triangular tool pin geometry with welding speed of 30 mm/min and a rotational speed of 1200 rpm.

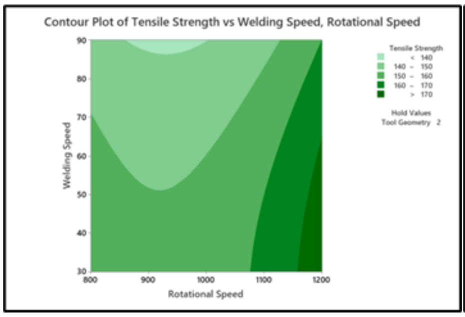


Figure 10

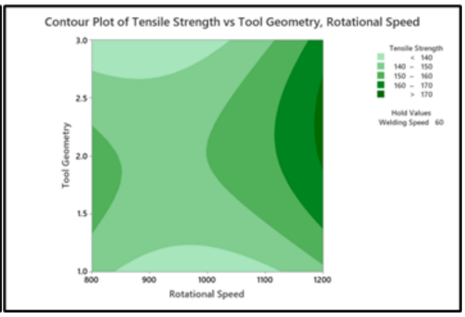


Figure 11

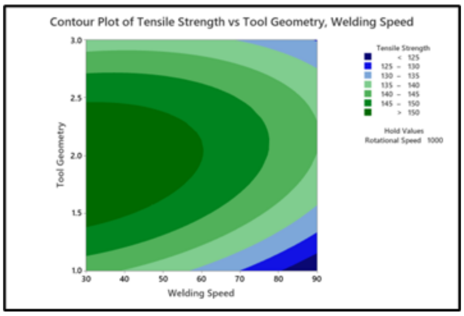
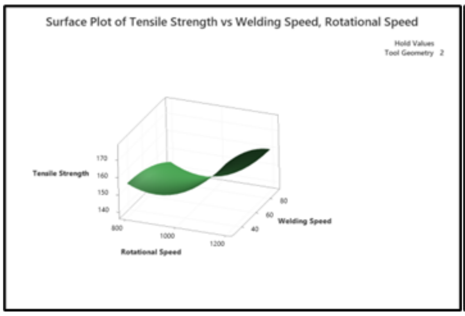
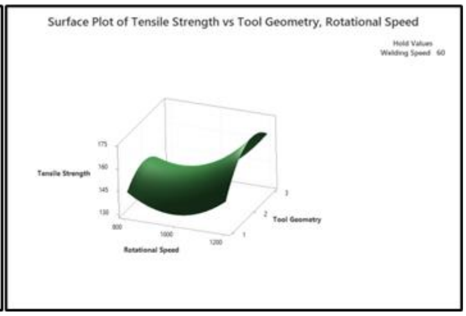


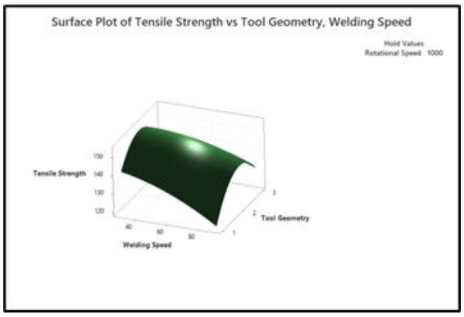
Figure 12

The three dimensional response surfaces were drawn. Response Surface plots clearly indicate the optimal response point. Figure 13 (a) - (c) shows the three dimensional response surface plots obtained from the regression model with various process parameters. The optimum tensile strength was exhibited by the apex of the response surface. From the response graphs, it can be observed that the higher tensile strength values were obtained for a triangular tool pin geometry. The optimum conditions identified from the response surface plots are triangular tool pin geometry, 1200 rpm rotational speed and 30 mm/min welding speed.





(a) (b)



(c)

Figure 13 (a), (b), (c) show the response of Rotational Speed, Welding Speed and Tool Geometry on Tensile Strength

4. Conclusion

In conclusion, the objective of this study has been achieved as the optimum process parameters of FSW is accomplished by using response surface methodology. The FSW process parameters are optimized to maximize tensile strength. The optimum levels of the rotational speed, welding speed and tool geometry are 1200 rpm, 68 mm/min and triangular geometry respectively.

The rotational speed and welding speed of the process are the most prominent parameters as the mechanical properties of the weld joints depend on it. A high rotational speed contributes to the sufficient material flow while low welding speed produces sufficient heat input that will give out sufficient material flow. Additionally, the geometry of the welding tool pin also influences the strength properties of the weld joints. When the tool rotates, it stirs and mixes the material, therefore, the speed of the FSW process is determined by the tool transfer, which moves the stirred material from the front to the back of the pin.

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