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The Effect of Rotation and Welding Speeds on Toughness and Microstructure of FSW Al Plates

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Abstract. Friction stir welding (FSW) is a solid-state welding process that is used for fabricating high-quality aluminum weldments. In this study, FSW is used to weld aluminum alloy AA6063 plates. Different combinations of FSW conditions were used, and the generated welds were tested for toughness and microstructural grain size, in addition to macrostructure evaluation. Factorial design of experiment approach was used to investigate the significance of the FSW factors on the material properties of the joints. Moreover, response surface methodology (RSM) was used to optimize the toughness and grain size response and the optimal FSW conditions were determined. The results revealed that both tool rotational and traverse speeds as well as experiment factors have a great influence on the material properties. All interactions between experiments factors are significant except for the welding speed and temperature interaction in impact test.

Keywords:Friction Stir Spot Welding, Aluminum Alloys, Impact test, Microstructural and Macrostructural analysis, Response Surface Methodology.

1. INTRODUCTION

The vast advantages of the neoteric friction stir welding (FSW) necessitates more research on its effects on mechanical and microstructural properties of the welded material. While FSW is based on the principle of joining materials in the solid-state, the process depends on the heat generation in the gap between the two joined parts that is produced due to stirring movement of a rotating tool. FSW is superior compared to other fusion-based techniques as it avoids problems such as weld porosity defects, which are common in welding aluminum alloys using these techniques. FSW is mainly used for joining light metals such as aluminum, magnesium and titanium alloys [1-3]. The tool rotational and welding speeds are the most influential FSW

process parameters that affect the mechanical performance of the welded joints [4].

There are massive research focusing on the microstructural and mechanical characteristics of the produced joints. In particular, the welding process affects the grain size of the welded material as C. Sharma, D. K. Dwivedi, P. Kumar[5] highlighted that the FSW joints showed larger grains in heat affected zones than in the base metal. K.V. Jata, K.K. Sankaran, and J.J. Ruschau [6]found that the resulted dynamically recrystallized zone contains fine (1.5 µm) grains. Sizova Olga *et al.* [7] concluded that the weld has fine-grained microstructure. Additionally, some research investigate the effect of the process on material toughness. Sudhir Kumar and Pardeep Kumar [8] assess the FSW parameters on aluminum 6063 alloy toughness using Izod Charpy test. They evaluate the effect of rotational speed, tool feed, and tool diameter, and conclude that tool diameter is the most significant followed by tool fees, and then rotational speed. Devaiah .D et al. [9] evaluate the resultant impact strength of joining the dissimilar aluminum alloys AA5083 and AA6061. They assess the parameters tool rotation, tool tilt angle, and traverse speed, and find out that rotational speed has more influence than tilt angle and traverse speed, which is less influential. Abdasalam Eramah et al. [10] introduce a study of the impact fracture as response to the FSW of Al-Mg alloy, and concludes that stir zone imperfections are highly effective on the fast fracture stage. Finally, A. K. Lakshminarayanan et al. [11] discuss the effect of FSW on several tungsten based alloy properties. They use one rotational speed and one welding speed in their analysis, and find that toughness of the welded material decreased in comparison to base metal. Moreover, they perform an assessment of the microstructure of the welded material, and report finer grain size in the whole welded area except for the outer HAZ, which has similar structure to the base metal.

The aim of the present investigation is to study the effect of FSW process parameters, typically, the tool rotational and traverse speeds on the toughness and microstructure of AA6063 butt joints. Full factorial design of experiments approach has been employed to examine the effects of the aforementioned FSW process parameters on the welded material properties. Moreover, optimization of such FSW parameters carried out using response surface methodology (RSM).

2.EXPERIMENTAL WORK

2.1. Materials

Plates of the AA6063 wrought aluminum alloys were joined using FSW. The plates have dimensions of 12 mm (thickness) × 300 mm (length) × 50 mm (width). The chemical compositions of alloys are listed in Table 1.

Table 1. Chemical composition of the AA6063 aluminum alloy (wt.-%).

Alloy	Elements (wt.-%)							
	Cu	Fe	Mn	Mg	Si	Zn	Cr	Al
AA6063	0.01	0.36	0.01	0.36	0.35	0.06	0.01	Bal.

2.1. FSW Process

The two plates of AA6063 aluminum alloys are joined in a butt configuration. The FSW was conducted using a tool has a tapered cylindrical pin profile and a plate shoulder. The tool is made from K110 tool steel. The shoulder diameter was 40 mm while the smaller and larger diameters of the tapered pin were 8 mm and 13.5 mm, respectively. The tilt angle and plunging depth were kept constant at 3^o and 0.1 mm, respectively. FSW was conducted using different four rotational speeds and three traverse (welding) speeds. The experiment design resulted had 12 runs (4×3) and the FSW process parameter values were set as shown in Table 2.

Table 2. The FSW parameters and their levels.

FSW Parameter	Level			
	Level 1	Level 2	Level 3	Level 4
Rotational speed (rpm)	470	590	740	900
Traverse speed (mm/min.)	16	31.5	50	-

2.3 Toughness measurement

The impact test is performed to investigate the effect of welding parameters on the toughness of the experimental aluminum alloy AA6063. The test is conducted in three different specimen temperatures as in table 4.x. Test specimens are prepared with 2mm v-notches.

2.4 ANOVA and RSM analyses

A full factorial experiment is designed for 4 rotational speeds, 3 welding speeds, and 3 temperature levels with 3 replicates for each factor’s combination. A total of 108 experiments are conducted. The designed experiment is shown in table 3.

Table 3. Impact test experiment design

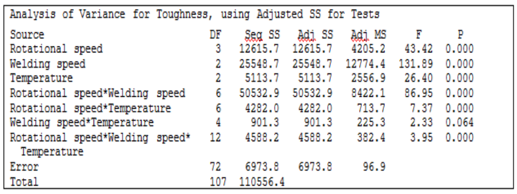
No.	Rotational speed (rpm)	Welding speed (mm/min)	Temp. (°C)
1	470	16	37 (room)
2	590	31.5	-20
3	740	50	-40
4	900	---	---

2.1. Results and analysis

The analysis of variance (ANOVA) of the conducted experiments reveal that all factors affect the reponse toughness as their p-values are less than the significant level of 0.05 as in fig. 1.

Moreover, all factors combinations are significant infuncers on toughness except the change of welding speed and temerature, which is proved to have no effect on the material toughness with p-value > .05.

The main effects of the 3 factors are plotted in fig. 2, which implicates that toughness tend to decrease with the increase of the welding speed. However, toughness increases with the decrease of specimen temperature. The contour plot of the RSM analysis is shown in fig. 3.



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Analysis of Variance for Toughness, using Adjusted SS for Tests

Source                          DF    Seq SS    Adj SS    Adj MS       F      P
Rotational speed                 3   12615.7   12615.7    4205.2   43.42  0.000
Welding speed                    2   25548.7   25548.7   12774.4  131.89  0.000
Temperature                      2    5113.7    5113.7    2556.9   26.40  0.000
Rotational speed*Welding speed   6   50532.9   50532.9    8422.1   86.95  0.000
Rotational speed*Temperature     6    4282.0    4282.0     713.7    7.37  0.000
Welding speed*Temperature        4     901.3     901.3     225.3    2.33  0.064
Rotational speed*Welding speed* 12    4588.2    4588.2     382.4    3.95  0.000
  Temperature
Error                           72    6973.8    6973.8      96.9
Total                          107  110556.4
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Fig .1: ANOVA for the impact test

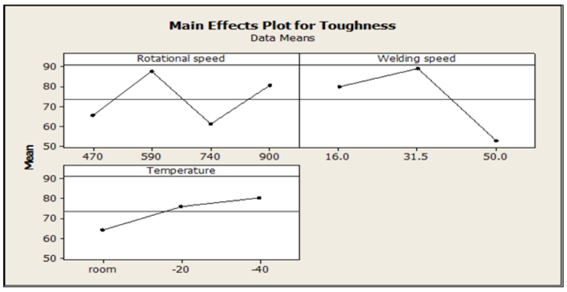


Fig. 1: Toughness main effects

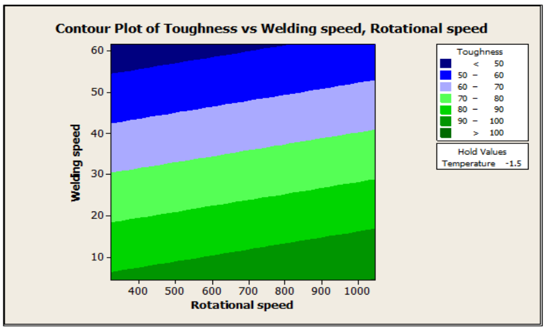


Fig. 2: toughness contour plot for RSM

2.2. Microstructure test

2.6.1. Microstructure examination

Examination of the microstructure of the welded AA6063 specimens provides information about the change of material grains sizes due to different welding conditions. This information can be used to define if the structure remains in the acceptable range or conforms to certain specification.

Microstructural examination is performed using a CETI Optical Metallurgical Microscope shown in Fig. 4.x to magnify the grain size in order to be able to measure it.

All specimens are prepared by grinding under water using Metasery Grinder 2000 rotating disc shown in Fig. 4.x. discs are of the carbide abrasive type with increasing fineness scale, starting from 100, 120 up to 2500 grit. The specimens are then polished using 10 µm alumina paste. Afterwards, specimens are subjected to etching process using a killer solution (1 ml HF 40% concentration + 4 ml HCl + 2 ml NHO_3 70% concentration + 93 ml of H_2O) for 5.5 min at ambient temperature. During the 5.5 minutes the specimen is checked every10 seconds if grains are revealed. Revealed grains are measured using JMicroVision software, and 40 grains are assessed with 20x magnification.

2.6.2. ANOVA and RSM analyses

A full factorial experiment is designed for 4 rotational speeds, and 3 welding speeds, with 40 replicates for each factor's combination. A total of 480 experiments are conducted. The designed experiment is shown in table 4.

Table 4: Microstructure examination experiment design

Samples Code		
	Rotational speed (rpm)	**Welding speed (mm/min.)**
A	470	16
B	590	
C	740	
D	900	
E	470	31.5
F	590	
G	740	
H	900	
I	470	50
J	590	
K	740	
L	900	

2.6.3 Results and analysis

Optical images of the microstructural examination are shown in fig. 4. and average grain size for each welding condition is shown in table 5.

The analysis of variance (ANOVA) of the conducted experiments reveal that the 2 factors affect the reponse grain size as their p-values are less than the significant level of 0.05 as in fig. 5. Moreover, the 2 factors combination significantly influence the grain size of the welded material in the weld zone.

The main effects of the 2 factors are plotted in fig. 6, which implicates that grain size tend to increase with the increase of the welding speed. However, variable grain sizes are obtained with different rotational speeds. The contour plot of the RSM analysis is shown in fig. 7.

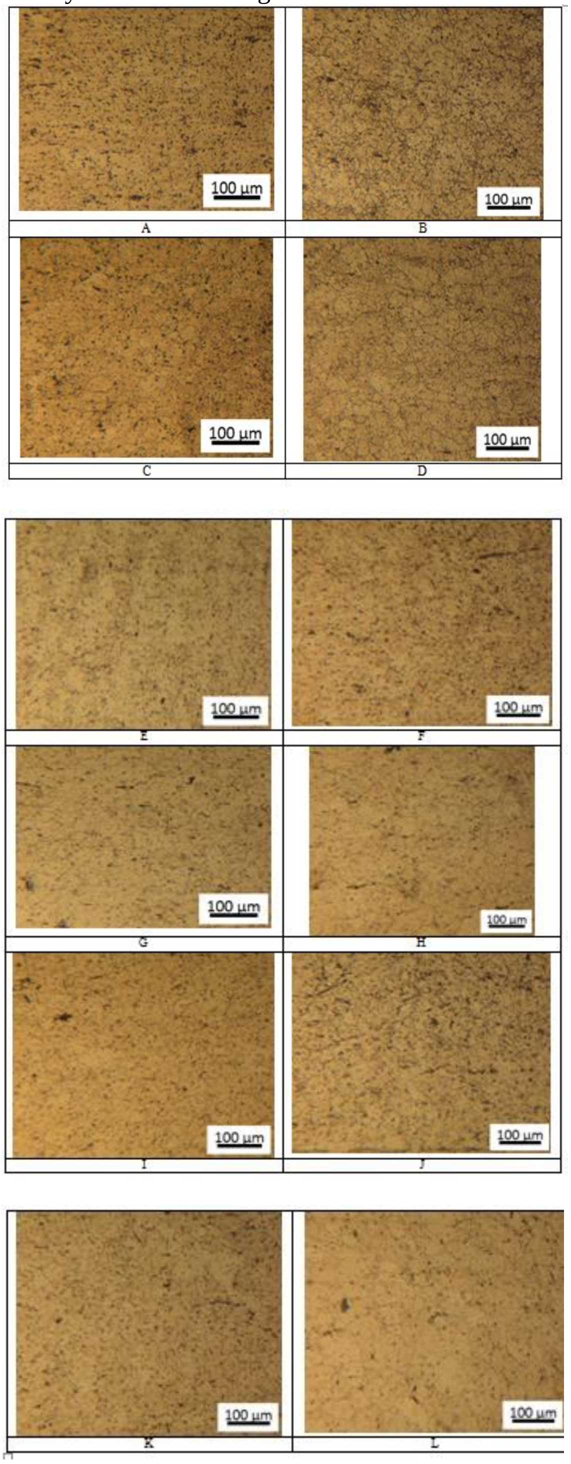
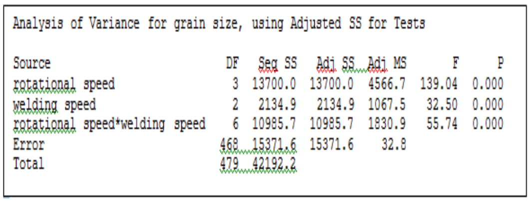


Fig. 3: Microstructure examination optical images

Table 5: Average grain size for microstructure examination

	Sample No.	Average Grain Size (µm)
1	A	28
2	B	23
3	C	29
4	D	26
5	E	39
6	F	18
7	G	21
8	H	39
9	I	37
10	J	21
11	K	38
12	L	31



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Analysis of Variance for grain size, using Adjusted SS for Tests

Source                           DF   Seq SS   Adj SS  Adj MS       F      P
rotational speed                  3  13700.0  13700.0  4566.7  139.04  0.000
welding speed                     2   2134.9   2134.9  1067.5   32.50  0.000
rotational speed*welding speed    6  10985.7  10985.7  1830.9   55.74  0.000
Error                           468  15371.6  15371.6    32.8
Total                           479  42192.2
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Fig. 4: ANOVA for microstructure examination

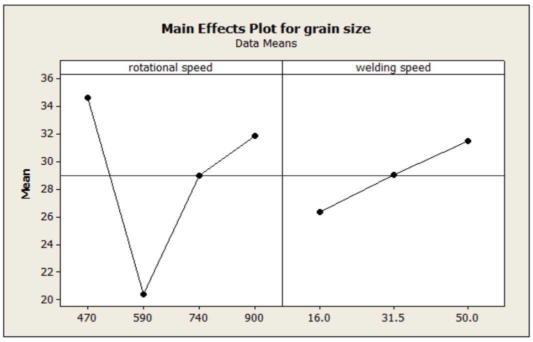

Fig. 4: Main effects for microstructure examination

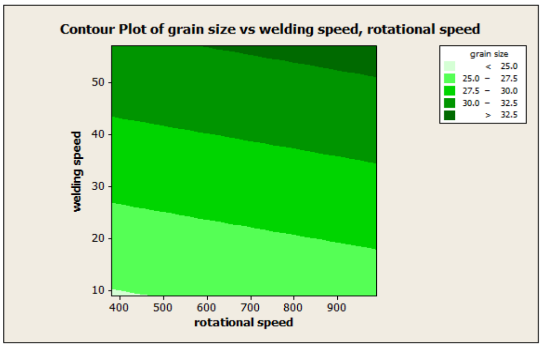

Fig. 5: microstructure examination contour plot for RSM

2.6.4 Macrostructure test

The etching process for the macrostructure evaluation was executed using a chemical solution, which consists of 4 ml HF, and 100 ml H2O for 8 to 12 min at ambient temperature. Fig. 8 shows the images of the macrostructure evaluation.

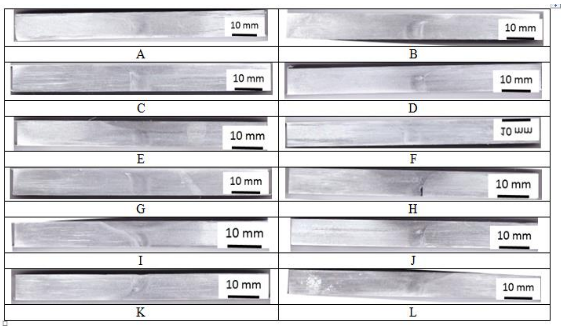

Fig. 6: Macrostructure evaluation images

3.Conclusions

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