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INFLUENCE OF PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF ALUMINIUM ALLOY AA 6063 DURING FRICTION STIR WELDING

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ABSTRACT

Friction stir welding (FSW) is a novel solid state welding process for joining metallic alloys and has been employed in several industries such as aerospace and automotive for joining aluminum, magnesium and copper alloys. The various parameters such as rotational speed, welding speed, and plunge depth etc. play vital role in FSW process in order to analyze the weld quality.

The aim of this study is to investigate the effect of rotational speed, welding speed, and plunge depth on weld quality. Friction stir welds find use for structural and other fabrication industries. This experimentation work explains the effect of welding speed, rotational speed and plunge depth on the mechanical properties of welding joints in AA6063 material of 6 mm thickness.

KEYWORDS: Aluminium alloy AA6063, Friction Stir Welding, Process parameters, Mechanical Properties, Taguchi Method

I. INTRODUCTION

Friction stir welding which is also named as FSW was invented and experimentally proved by Thomas in 1991 and a team at The Welding Institute, Cambridge, UK. This technique is derived from the conventional friction welding. This process is mainly suited for aluminium and its alloys **[1-3],** and mainly for large pieces, which cannot be easily heat treated to recover temper characteristics. The process is most suitable for components, which are flat and long like plates and sheets, but can also be adapted for pipes and hollow sections **[6]**. The welds are produced by the combined action of frictional heating and mechanical deformation due to a rotating tool.

During this process the process parameters such as rpm, tool tilt angle, welding speed, plunge depth, Axial Force, cutting tool geometry etc. plays an important role in affecting the mechanical properties of welding joints Many researchers have done various experiments on Friction Stir Welding process parameters which makes effect on mechanical properties. Ouyang et al**.[4]** performed the study over the same and dissimilar alloys using the tool grade steel tool over the following configuration 6061-6061 & 6061-2024 alloy with the parameters 151-914 rpm & 57-330 mm/min with threaded tool. Liu et al., **[5]** investigated the tensile properties and fracture locations in FSW of AA6060-T6 alloy of dimensions 30 mm X 80 mm X 5 mm taking rpm, weld speed, revolutionary pitch as 1000-1500 rpm, 100-1000mm/min, 0.07-1.0 mm/r respectively. Gerlich et al., **[7]** studied the tool penetration in friction stir spot welding of Al and Mg alloys. 1.5 mm thick AZ91D, Al6061-T6 and Al5754-H12 and 1.3 mm thick Al6111-T4 Minton et al., **[8]** demonstrated conventional milling machine has been capable of performing FSW and producing reasonable welds using a relatively stout tool to join 6.3 mm thick 6082-T6 aluminium. Moreira et al., **[9]** studied Fatigue crack growth in friction stir welds of 6082-T6 and 6061- T6 aluminium alloys. Elangovan et al., **[10]** developed a mathematical model to predict tensile strength of the friction stir welded AA6061 aluminium alloy by incorporating FSW process parameters. Karthikeyan et al., **[11]** conducted a study on relationship between process parameters and mechanical properties of friction stir processed AA6063-T6 aluminum alloy with 200 mm X 50 mm X 10 mm as work piece dimensions. Jayaraman et al., **[12]** studied the surface roughness (R_a), roundness (Ø) and material removal rate (MRR) of AA6063 T6.

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Elanchezhian et al.,**[13]** studied taguchi method to obtain optimal condition for Friction Stir Welding of AA8011-6062 aluminium composite and concluded results with ANOVA experiment. Bayazid et al**.,[14]** Study shows, the effect of rotational speed, travel speed and plates positions on strength of dissimilar 6063-7075 joint which was investigated by using Taguchi method and ANOVA analysis. Fu et al., **[15]** performed FSW over dissimilar 6061-T6aluminum alloy to AZ31B magnesium alloy using 800 rpm & 50 mm/min by H13 Quenched & Tempered to 50 HRC tool. Dinaharan et al**.,[16]** studied AA6082 using the novel solid state method known as FSW. Empirical relationships were estimated to predict the influence of FSP parameters on the properties of AA6082.Abraham et al., **[17]** said that AA6063 Quartz AMCs can be effectively developed using FSP. The microstructure, micro hardness and sliding wear behaviour were studied using optical, scanning and transmission electron. Sharma et al**.,[18]** studied friction stir welding of circular butt weld joint between Aluminium alloy AA6061 and Magnesium alloy AZ31. Hema et al., **[19]** study develops Tensile strength, Impact strength and hardness models with Tool Rotational speed, Welding Speed and Axial Force for FSW process with AA 2014 and 6061 weld pieces using Response Surface Methodology

Objective of the Study

After a literature survey, it is concluded that a number of gaps have been observed in friction stir welding of aluminium alloys. Few parameters were studied with limited number of parameters. So, a comprehensive study is planned to investigate combined, main and interaction effects of tool rotational speed, welding speed, and plunge depth and other parameters on mechanical properties of friction stir welded aluminium alloy. The objective of study is to determine the combined effect of process parameters on mechanical properties of friction stir welded aluminium alloy 6063 by design of experiments for examples Taguchi Method .

II. MATERIAL AND EXPERIMENTATION

Material and preparations of specimens

The chemical composition of the base material and mechanical properties are presented in Table 1 and Table 2 respectively.

Table 1 Chemical composition of AA6063 aluminium alloy

Element	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Cr**	**Al**
Wt %	0.3	0.35	0.1	0.1	0.45	0.1	0.1	0.1	Bal

Table 2 Mechanical properties of AA6063 material

Property	**Ultimate Tensile Strength**	**Impact Strength**	**Hardness**
Value	215 MPa	23 J	83Hv

Taguchi's method

Taguchi's method is a tool for design of a high quality system. This method is a systematic approach for performance and quality optimization. By this method the numbers of experimentation runs are 16. The total degree of freedom must be calculated to choose the correct orthogonal array.. So, 4*3 design array was selected Sixteen experimental runs were conducted as per Taguchi L16 orthogonal array.

ANOVA analysis

Analysis of Variance (ANOVA) is a statistical method which is used to discuss the relative importance of the entire control factor. This is also used to find the contribution of each parameter. F-test proposed is used as an auxiliary tool of inspection. Thus, the larger the value of f-test the more dominant the parameters are.

S/N ratio

Taguchi method analyse the values using S/N ratio. It involves conceptual approach which graphs the effect and identifies the significant values.

Experimental Design

Welding process parameters such as tool rotational speed, welding speed, and plunge depth have significant effect on the weld characteristics. The minimum and maximum range of the tool rotational speed, welding

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speed and plunge depth was found by many trials. Various parameters along with their range were selected and presented according to Taguchi analysis in the Table 3.

Table 3. Selected welding parameters and levels

Process Parameter	Symbol	Units	Levels			
			1	2	3	4
Tool Rotational Speed	RPM	rpm	600	800	1000	1200
Welding Speed	WS	mm/min.	30	50	70	90
Plunge Depth	PD	mm	0.00	0.04	0.08	0.12

Specimens Prepared

Two aluminum alloy plates of thickness 6 mm and dimension of 300 x 100 mm were fixed on the table of welding machine using special fixture to form the square butt joint configuration of 300 x 200 mm. The FSW is done. The samples with solid state weld were formed behind the tool.

Friction Stir Welding Tool

The tool was prepared from high carbon high chromium material, as it was desirable, that the tool should be hard, wear resistant, tough and strong. The tool was machined having pin diameters 8mm, Shoulder Diameter 20 mm, Shoulder Height 25 mm and height of Pin as 4.7 mm and taper 14^0..

Tensile Test

The specimens for finding tensile characterstics were prepared as per American Society for Testing of Material Ultimate tensile property of the FS welded joints were evaluated using computerized universal testing machine . The Weld joints were cut and then machined to the required dimensions to prepare tensile specimens The observed values for tensile strength were tabulated in Table 4.

Impact Test

Charpy impact test was done to determine the impact energy of FS weld at a sudden load by using pendulum on un-notched specimen. This impact energy is a measure of a given material's toughness. The specimens for impact test were prepared and tested .The energy absorbed by each specimen was noted down. The observed values for impact strength were tabulated in Table 4.

Hardness test

This test is performed to measure the hardness at different zones of material. The samples were polished with emery papers. Then these samples were fine polished on surface polishing machine. The alumina powder paste and then diamond paste were used to get a mirror like surface. The readings were taken across the processed material each 15 mm apart under 0.5kg load for 20 seconds. The average observed values for hardness are shown in Table 4.

III. RESULTS AND DISCUSSIONS

Experimental Results

As per the design matrix, According to Taguchi analysis 16 experiments were conducted, with their three process parameters and four levels. After experimentation, Mechanical investigations Experimental results for tensile strength, impact Strength, hardness are given in Table 4

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Table 4 Experimental results for tensile strength, impact toughness, hardness

Run	RPM	WS	PD	Tensile Strength (Mpa)	Impact strength (J)	Hardness (Hv)
1.	1	1	1	161	17	68
2.	1	2	2	166	20	76
3.	1	3	3	163	18	70
4.	1	4	4	165	19	72
5.	2	1	2	158	20	77
6.	2	2	1	165	23	79
7.	2	3	4	168	19	80
8.	2	4	3	166	22	83
9.	3	1	3	159	21	74
10.	3	2	4	156	19	73
11.	3	3	1	165	20	78
12.	3	4	2	169	19	75
13.	4	1	4	153	16	65
14.	4	2	3	157	19	68
15.	4	3	2	165	20	69
16.	4	4	1	159	16	63

Analysis of variance (ANOVA) for Tensile Strength

. The ANOVA table for tensile strength is calculated and listed in table 5. The high F value indicates that the factor is highly significant in affecting the response of the process. Minitab is used to assigns ranks based on delta values in descending order; the highest delta value has rank 1 and rank 2 is assigned to the second highest, and so on. In our investigation, for the material AA 6063 the welding speed is a highly significant factor and plays a major role in affecting the tensile strength of the weld.

Table 5 Analysis of Variance for Tensile Strength

Analysis of Variance for means						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
A-RPM	3	81.19	81.19	27.06	2.52	0.154
B-WS	3	148.19	148.19	49.40	4.60	0.053
C-PD	3	36.69	36.69	12.23	1.14	0.406
Residual Error	6	64.37	64.37	10.73		
Total	15	330.44				

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Response Table for Means

Level	RPM	WS	PD
1	163.8	157.8	162.5
2	164.3	161.0	164.5
3	162.3	165.3	161.3
4	158.5	164.8	160.5
Delta	5.8	7.5	4.0
Rank	2	1	3

Response Table for Signal to Noise Ratios

Level	RPM	WS	PD
1	44.28	43.96	44.22
2	44.31	44.13	44.32
3	44.20	44.36	44.15
4	44.00	44.33	44.10
Delta	0.31	0.40	0.22
Rank	2	1	3

Larger Value is better (ANOVA Experiment)

Effect of tool rotational speed, Welding Speed and Plunge Depth on tensile strength

Figure 1 shows the effect of tool rotational speed, Welding Speed and Plunge Depth on tensile strength of friction stir welded AA6063 aluminum alloy.

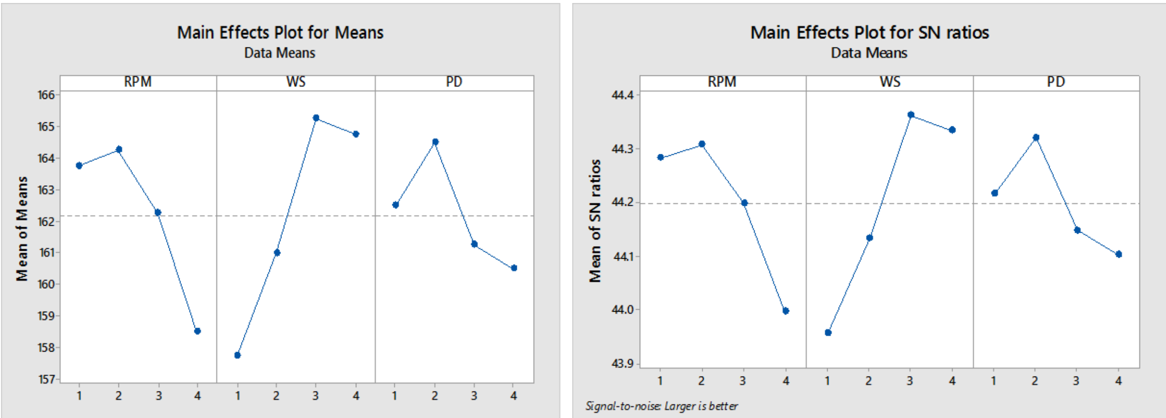

Figure 1 Effect of tool rotational speed, Welding Speed and Plunge Depth on tensile strength

Analysis of variance for Impact Strength

The ANOVA table for impact strength is calculated and listed in table 6. In our investigation, for the material AA 6063 the rotational speed is a highly significant factor and plays a major role in affecting the impact strength of the weld.

Table 6 Analysis of Variance for Impact Strength

Analysis of Variance						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
A-RPM	3	24.500	24.500	8.167	2.97	0.119
B-WS	3	6.500	6.500	2.167	0.79	0.543
C-PD	3	7.500	7.500	2.500	0.91	0.490
Residual Error	6	16.500	16.500	2.750		
Total	15	55.000				

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Response Table for Means

Level	RPM	WS	PD
1	18.50	18.50	19.00
2	21.00	20.25	19.75
3	19.75	19.25	20.00
4	17.75	19.00	18.25
Delta	3.25	1.75	1.75
Rank	1	2.5	2.5

Table for Signal to Noise Ratios

Level	RPM	WS	PD
1	25.33	25.29	25.49
2	26.42	26.10	25.91
3	25.90	25.68	25.99
4	24.94	25.52	25.20
Delta	1.48	0.81	0.79
Rank	1	2	3

Larger Value is better (ANOVA Experiment)

Effect of tool rotational speed, Welding Speed and Plunge Depth on impact strength

Figure 2 shows the effect of tool rotational speed, Welding Speed and Plunge Depth on impact strength of friction stir welded AA6063 aluminum alloy

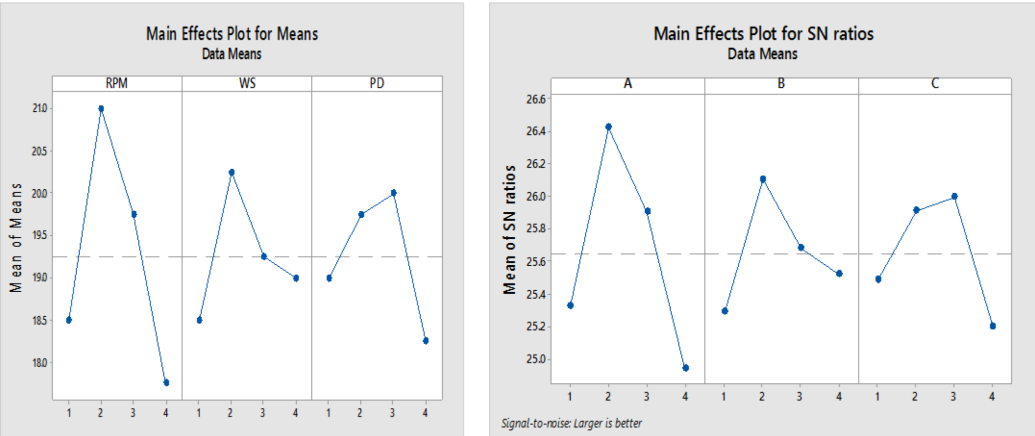


Figure 2 Effect of tool rotational speed, Welding Speed and Plunge Depth on impact strength

Analysis of variance for Hardness

The ANOVA table for S/N ratios for hardness is calculated and listed in Table 7. The F test is being carried out to study the significances of the process parameter. The high F value indicates that the factor is highly significant in affecting the response of the process. In our investigation, for the material AA 6063 the rotational speed is a highly significant factor and plays a major role in affecting the hardness of the weld.

Table 7 Analysis of Variance for Hardness

Analysis of Variance						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
A-RPM	3	402.69	402.69	134.229	14.29	0.004
B-WS	3	26.69	26.69	8.896	0.95	0.475
C-PD	3	14.69	14.69	4.896	0.52	0.683
Residual Error	6	56.38	56.38	9.396		
Total	15	500.44				

Response Table for Means

Level	RPM	WS	PD
1	71.50	71.00	72.00
2	80.00	74.00	74.25
3	75.00	74.25	74.00
4	66.25	73.50	72.50
Delta	13.75	3.25	2.25
Rank	1	2	3

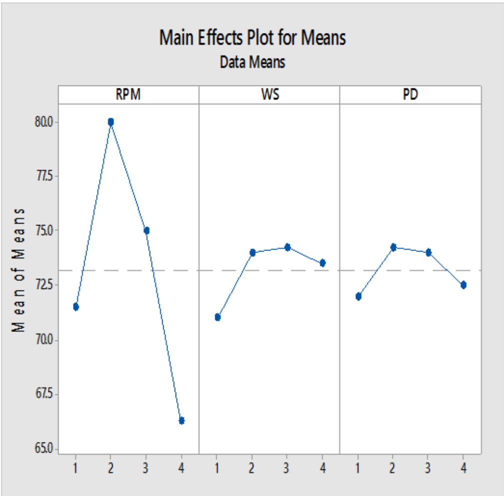
Table for Signal to Noise Ratios

Level	RPM	WS	PD
1	37.08	37.01	37.11
2	38.06	37.37	37.41
3	37.50	37.40	37.36
4	36.42	37.28	37.18
Delta	1.64	0.39	0.30
Rank	1	2	3

Larger Value is better (ANOVA Experiment)

Effect of tool rotational speed, Welding Speed and Plunge Depth on hardness

Figure 3 shows the effect of tool rotational speed, Welding Speed and Plunge Depth on hardness of friction stir welded AA6063 aluminum alloy.



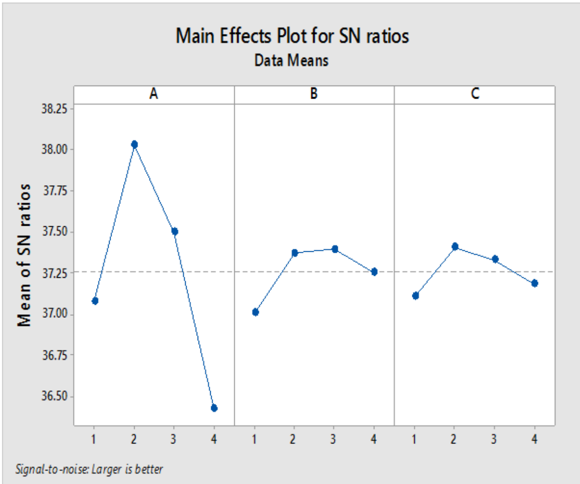


Figure 3 Effect of tool rotational speed, Welding Speed and Plunge Depth on hardness

Optimized Solution

Minitab 18 software was used to optimize the input process parameters using different criteria for obtaining optimum numerical solutions as per the conditions desired. The optimization module in Minitab 18 searches for a combination of factor levels that simultaneously satisfy the requirements placed (i.e. optimization criteria) on each of the responses and process factors (i.e. multiple responses optimization).

The one of objectives of the study was to find out the optimal welding parameters at which the desirable mechanical properties of the friction stir welded AA6063 could be achieved. Table 8 shows that desirable mechanical properties are set to maximization goal.

Table 8 Optimal Criteria Chosen

Response	Goal	Lower	Upper
Tensile Strength	Maximum	159	169
Impact Strength	Maximum	16	23
Hardness	Maximum	63	83

Table 9 presents the optimal welding process parameters and responses according to the criteria chosen

Table 9 The optimal welding process parameters and responses

Optimized Process Parameters	
RPM	2
WS	3
PD	2
Maximized Responses	
Tensile Strength	164.6 MPa
Impact Strength	20.41 J
Hardness	76.20 Hv

IV. CONCLUSION

Taguchi Method technique can be successfully applied for designing the experiments and to study the effects of various input parameters on different responses. Friction stir welding process of aluminum alloy AA6063 can be successfully achieved. There is a significant effect of process parameters of FSW on mechanical properties of AA6063.

- As tool rotational speed increased from 600rpm to 800rpm, the tensile strength increased from 163.8 Mpa to 164.3 Mpa ,the Impact Strength of the joint increased from 18.5 J to 21 J and hardness increased from 71.5 Hv to 80 Hv. But as the rpm was increased further the tensile strength, Impact Strength and hardness decreased drastically.
- When the welding speed was increased from 30 to 50 mm/min. there was a sharp rise in tensile strength. After the increase in welding speed to 70 mm/min., a decrease in tensile strength of welded joint was observed.
- At zero plunge depth, the tensile strength was 162.5 MPa. But at plunge depth 0.04 mm, there was increase in tensile strength to164.5 MPa. At other values of plunge depths, there was again decrease in tensile strength.
- At welding speed 30 mm/min the impact strength was low as 18 J. as welding speed was increased to 50 mm/min, the impact strength increased to 19.25 J, but after any increase in welding speed resulted into decrease in impact strength.
- At zero plunge depth, the impact strength was low. But at plunge depth 0.04 mm, and 0.08 mm there was increase in impact strength. After that, there was again decrease in impact strength.
- The hardness of the weld joints increases with increase in welding speed but at the higher welding speed micro hardness of the joint starts decreasing.
- At zero plunge depth, the hardness was low. But at plunge depth 0.04 mm, there was increase in hardness. After that, there was again decrease in hardness..
- For achieving maximum mean tensile strength 164.6 MPa, hardness 76.20 Hv and impact strength 20.41 J, the process parameters should be such as Tool rotation speed at **800 rpm**, Welding speed at **70 mm/min**, and plunge depth at **0.04 mm**.

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