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A Statistical approach on the mechanical property evaluation of friction stir welding of Al 6351 alloy with addition of reinforcement

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Abstract
A statistical approach on the mechanical property evaluation of friction stir welding of Al 6351 alloy with addition of reinforcement in the weld zone was attempted. In this study, the mathematical model for predicting the tensile strength, hardness and impact strength of the weldment were developed. Friction stir welding experiment were carried out using mixed level orthogonal array of Taguchi's technique. The process parameters such as axial load, rotational speed, welding speed were taken at 3 levels and weight percentage of SiC particles was taken at 2 levels. The properties were evaluated for two sets of condition namely as-weld and annealed conditions and were optimized using S/N ratios. Taguchi's quality loss function "Larger-the-Better" criterion was selected for achieving optimum levels of process parameters. The optimum levels were found to be at a 1.5 wt % of SiC particles, tool rotational speed of 1000 rpm, axial load of 2 KN and welding speed of 29 mm/min.

Key words: Friction stir welding, Taguchi's loss function, Minitab 16, S/N ratios

1. Introduction

Friction stir welding has proved its reliability in the welding of aluminium and other light weight alloys [1]. Though there were numerous advancements in the conventional joining processes, friction stir welding stand alone owing to its unique advantages [2-5] like environment friendly and overcoming other difficulties encountered while joining by the conventional techniques. Taguchi method involves reducing the variation in a process through robust design of experiments. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they varies. Instead of having to test all possible combinations like in the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affects the product quality with a minimum number of experimentation, thus saving time and resources [6, 7].

2. Experimental details

Aluminium alloy of grade 6351 were used in this study. The Mechanical properties of the aluminium alloy 6351 are given in table 1. The square tool pin profile is used as friction stir welding tool with a ratio of 3. (i.e.) Ratio of tool shoulder diameter to the tool pin diameter. The specifications of the tool profile were taken with reference to the previous works [8-12]. The friction stir welding parameter [13-16] ranges were taken by considering the machine specification and with trial experiments which resulted in a defect free welding by visual inspection. The parameter ranges and levels chosen for the experiments are given in the table 2.

Table 1: Mechanical Properties of Al 6351 alloy

Properties	Metric
Tensile strength	250 MPa
Yield strength	150 MPa
Shear strength	200 MPa
Fatigue strength	90 MPa
Elastic modulus	70-80 GPa
Poisson's ratio	0.033
Elongation	20%

Table 2: Parameter levels and ranges

Parameter	Units	-1	0	1
SiC	Wt %	1	1.5	-
L	KN	1.5	2	2.5
S	RPM	710	1000	1400
F	MM/min	14	21	29

The novelty of this reinforced friction stir welding is that the SiC particles were added evenly in the surface of the butt joint area prior to the welding. Then the plates were placed in the fixture and the friction stir welding was performed. The added SiC particles in the joint region get mixed with the material while stirring

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action takes place in the weld zone. This method of addition of SiC particles avoids the problem of porosity, solidification cracking etc, which is usually caused during the casting process of composites. Taguchi's L18 mixed level orthogonal array was used to perform the experiments. The reinforced friction stir welded plates of 6351 aluminium alloy using this technique were evaluated in two conditions, namely as-weld and annealed condition. The responses like Tensile strength, Brinell hardness and Impact strength were evaluated in two conditions. The samples of the test were prepared by following ASTM B557 for tensile strength, ASTM E10-12 for Brinell hardness and ASTM D256 for impact strength. Optimization was done using Taguchi's quality loss function "Larger-the-Better" criteria using Minitab 16 statistical software.

3. Results and discussions

The responses such as Tensile strength, Brinell hardness and impact strength were evaluated for the as-weld and annealed conditions and are shown in table 3 and table 4 respectively.

Table 3: Responses welded Al 6351 alloy plates in as-weld condition

Exp.no.	SiC wt %	L (KN)	S (RPM)	F (mm/min)	Responses		
					UTS MPa	Hardness HB	Impact Kgm
1.	1	1.5	710	14	135.5	60	0.84
2.	1	1.5	1000	21	141.67	63	0.84
3.	1	1.5	1400	29	178.57	62	0.98
4.	1	2	710	14	137.5	53	0.84
5.	1	2	1000	21	154.47	61	0.84
6.	1	2	1400	29	185.8	64	0.84
7.	1	2.5	710	21	144	62	0.84
8.	1	2.5	1000	29	138.44	63	0.98
9.	1	2.5	1400	14	134.72	54.5	0.98
10.	1.5	1.5	710	29	141.67	60	0.84
11.	1.5	1.5	1000	14	138.21	52	0.7
12.	1.5	1.5	1400	21	175	58.5	0.84
13.	1.5	2	710	21	147.22	56.5	0.98
14.	1.5	2	1000	29	138.89	64.5	1.26
15.	1.5	2	1400	14	131.19	59.5	0.84
16.	1.5	2.5	710	29	163.89	60	0.84
17.	1.5	2.5	1000	14	133.33	54	1.12
18.	1.5	2.5	1400	21	129.78	51.5	0.84

Table 4: Responses welded Al 6351 alloy plates in annealed condition

Exp.no.	SiC wt %	L (KN)	S (RPM)	F (mm/min)	Responses		
					UTS MPa	Hardness HB	Impact Kgm
1.	1	1.5	710	14	111.1	41.2	0.7
2.	1	1.5	1000	21	104.2	47.5	0.84
3.	1	1.5	1400	29	128	46	0.7
4.	1	2	710	14	118.05	43.5	0.84
5.	1	2	1000	21	108.33	41.8	0.84
6.	1	2	1400	29	116.34	42.5	0.84
7.	1	2.5	710	21	127.78	43.5	0.84
8.	1	2.5	1000	29	129.17	46	0.7
9.	1	2.5	1400	14	133.33	42.5	0.98
10.	1.5	1.5	710	29	136.11	44.5	0.7
11.	1.5	1.5	1000	14	108.40	40.5	0.7
12.	1.5	1.5	1400	21	122.22	49.5	0.84
13.	1.5	2	710	21	138.9	43.5	0.84
14.	1.5	2	1000	29	127.78	44	0.98
15.	1.5	2	1400	14	129.17	46	0.7
16.	1.5	2.5	710	29	126	45	0.7
17.	1.5	2.5	1000	14	130.55	43.5	0.84
18.	1.5	2.5	1400	21	123	44.5	0.84

Results of both the as-weld and annealed condition show that the addition of SiC particles in the nugget zone has enhanced the weld strength. Even in case of annealed condition the properties tend to retain its characteristics because of the pinning action of the mixed SiC particles in the nugget zone. Normally, in annealed condition the material tends to lose its properties because of the effect of grain coarsening [18, 19]. To overcome this problem, few earlier researches [20-23] have suggested to add ceramic particles during casting of the alloy. However, this technique is highly susceptible to processing defects which may affect the quality of the weld. The present method of addition of ceramic particles in the nugget zone during welding has resulted in overcoming the above problem.

3.1 S/N ratio

Taguchi's quality loss function the "Larger-the-Better" has been chosen for the properties such as tensile strength and for hardness. In Taguchi's method the S/N ratio is used to determine the deviation of quality characteristics from the desired value. The S/N ratio can be expressed as in the equation (1).

$$SN_L = -10\log\left(\frac{\sum_{i=1}^{n} 1/y_i^2}{n}\right) \quad (1)$$

dd

These S/N ratio calculations were done using the Minitab 16 software. The identification of significant factors of as-weld condition and annealed condition are shown in the table 5 and table 6 respectively. In both the conditions the axial load is found to be the significant factor which influences the mechanical properties.

Table 5: Significant factor for the responses of as-welded plates with of SiC Particles (L18)

Level	SiC wt%	Axial load	Rotational speed	Welding speed
1	3.702	3.215	3.479	3.631
2	3.897	4.066	4.218	3.479
3	*	4.118	3.702	4.289
Delta	0.195	0.903	0.739	0.810
Rank	4	1	3	2

Table 6: Significant factor for the responses of annealed plates with of SiC Particles (L18)

Level	SiC wt%	Axial load	Rotational speed	Welding speed
1	2.876	2.200	2.463	2.686
2	2.700	3.214	2.950	3.255
3	*	2.950	2.950	2.423
Delta	0.176	1.015	0.487	0.832
Rank	4	1	3	2

3.2 Regression Modelling

Regression modelling was done using Minitab 16 software. Regression was done only for the samples which are welded with SiC particles in the weld region to predict the samples characteristics. The response function representing the properties can be expressed as a function of the SiC wt %, axial load, rotational speed and welding speed and for FSW operation as shown in equation (2)

$$Y = f(SiC, L, S, F) \quad (2)$$

For the second order relations, with 'k' number of factors, the model will be of the regression type given in the expression (3)

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{ij=1}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i \ldots \quad (3)$$

With four factors, the polynomial equation is expressed as equation (4)

$$Y = b_0 + b_1 SiC + b_2 L + b_3 S + b_4 F \quad (4)$$

Where,
b_0 is constant
b_1, b_2, b_3 are coefficients of linear terms
S-rotational speed, F-welding speed, L-axial load,
SiC- Silicon carbide

The developed regression models are given below from equations (5) – (10)

As-weld plates of Al 6351 alloy with SiC particles

The regression equations for

Tensile strength = 134 - 11.4 SiC wt % - 11.1 Axial load + 0.0171 Rotational speed + 1.51Welding speed (5)

Hardness = 60.5 - 5.78 SiC wt % - 1.75 Axial load - 0.00053 Rotational speed + 0.450 welding speed (6)

Impact strength = 0.513 + 0.062 SiC wt % + 0.0933 Axial load + 0.000021 Rotational speed + 0.00483 Welding speed (7)

Annealed plates of Al 6351 alloy with SiC particles

The regression equations for
Tensile strength = 77.3 + 14.6 SiC wt % + 9.97 Axial load- 0.00022 Rotational speed + 0.375 Welding speed (8)

Hardness = 38.8 + 1.44 SiC wt % - 0.70 Axial load + 0.00242 Rotational speed + 0.116 welding speed (9)

Impact strength = 0.671 - 0.0311 SiC wt % + 0.0700 Axial load + 0.000064 Rotational speed - 0.00173 Welding speed (10)

3.3 Optimum parameters

The optimum parameters were found using the S/N ratios of the responses. Since the larger-the-better criterion was used, the parameter combination which produced a higher value in the responses is considered as optimal condition for the friction stir welding of Al 6351 alloy plates. The Figure 1 shows the optimal condition graphs for both as-weld and annealed conditions. The S/N ratio values in the graphs are the cumulative values of the responses in different condition that were found out using the appropriate formulae.

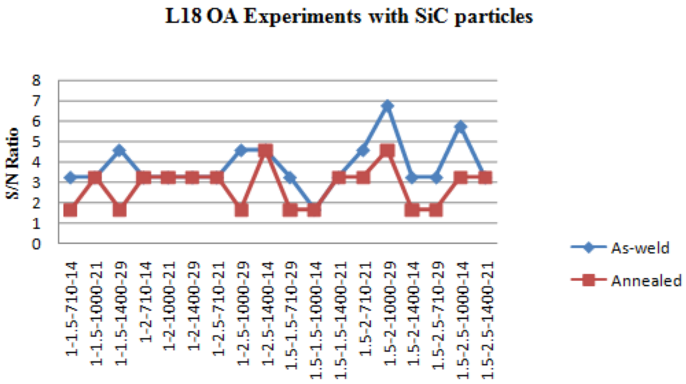

Fig.1. Optimum parameters graph for both As-weld and annealed condition

It is evident from the graph that in both conditions the responses had higher value when the parameters at the range of 1.5 wt % of Sic particles, axial load of 2 KN, tool rotational speed of 1000 RPM and a welding speed of 29 mm/min.

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3.4 Confirmation tests

The confirmation tests for the above conditions were conducted and the results are given below in table 7.

Table 7: L18 OA Experiments with SiC particles

Parameters/condition		As-weld	Annealed
SiC Particles, wt %		1.5	1.5
Rotational speed, RPM		1000	1000
Welding speed, mm/min		29	29
Axial load, KN		2	2
Tensile strength	Obtained value	141.46	128.11
	Predicted value	155.59	129.80
	Error %	9.9	1.3
Hardness	Obtained value	64	44.5
	Predicted value	60.85	45.344
	Error %	4.9	1.8
Impact strength	Obtained value	0.98	0.84
	Predicted value	0.954	0.78
	Error %	2.6	7.1

The results of the confirmation tests reveals that the predicted values and obtained values are reliable and the error percentages are within minimal range proving consistency of the predicted model.

4. Conclusions

1. The optimized welding parameters range for good quality friction stir welded joint of Al 6351 was found to be at 1.5 wt % of SiC particles, 2 KN of axial load, 1000 RPM of tool rotational speed and 29 mm/min of welding speed.
2. Among the chosen parameter, factor axial load is found to be the influencing factors in determining the mechanical properties.
3. Because of the pinning action of the added SiC Particles, the mechanical properties are improved in annealed condition too.

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