

Optimization of Process Parameters in Friction Stir welding of dissimilar aluminium alloys (AA5083 and AA6061) Using Taguchi Technique

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ABSTRACT: Taguchi method was applied to find the most significant control factors which will yield higher tensile strength of the joints of friction stir welded dissimilar AA5083 and AA6061 aluminium alloy. In order to optimise the process parameters such as tool rotational speed, weld travel speed and tool tilt angle on tensile strength of friction stir welded dissimilar AA5083 and AA6061 aluminium alloy, Taguchi Design of Experiment (DOE) and optimization method was used. The optimum levels of process parameters were identified by using the Taguchi parametric design concept. The results shows that the rotational speed, welding speed and tool tilt angle are the important parameters in deciding the ultimate tensile strength of the weld joint. The predicted optimal value of ultimate tensile strength of friction stir welded dissimilar AA5083 and AA6061 aluminium alloy is 295Mpa. The results were confirmed by further experiments.

KEYWORDS: Friction stir welding; aluminium alloy; Taguchi design; Process parameters; Tensile strength.

I. INTRODUCTION

Friction stir welding(FSW) has emerged as a technology of widespread interest due to its numerous advantages, most important of which is its ability to weld generally unweldable alloys[1]. Compared with number of the fusion welding processes that are routinely utilized for joining structural alloys, FSW is a solid state joining technique in which the material that is being welded below its melting point[2]. Defect free welds with high mechanical properties have been made in a various aluminium alloys, even those previously thought to be not weldable. Porosity, hot cracking and alloy segregation defects will not get in the friction stir welding process. FSW produces good surface finish and need not required post weld cleaning [3]. There have been a number of efforts to understand the effect of process parameters on microstructure formation and material flow behaviour, hence mechanical properties of friction stir welded joints. The impact of some parameters such as rotational speed, traverse speed and tool tilt angle on weld properties is major topics for investigators[4-6]. Taguchi design of experiment (DOE) is a powerful tool to find significant factor from many by conducting relatively few number of experiments, in any case, this design basically does not account for the interaction among processing parameters. In view of time and cost saving, occasionally these interactions are ignored. If compulsory, the missing interactions can be found by further conducting the required experiments.

In this research work , applying Taguchi techniques on fusion welding processes and casting methods have been reported in literatures[7-8], it shows that the optimization of FSW process parameters of AA5083 and AA6061 aluminium alloy using Taguchi technique has not been reported effectively yet. Considering the above truths, the Taguchi L9 Orthogonal array is used to find the influence of each processing parameters (i.e. rotational speed, traverse speed and tool tilt angle) for optimum tensile strength of friction stir welded joints of AA5083 and AA6061 aluminium alloy.

II. LITERATURE REVIEW

Shige Matsu et. al. (2003) [9] managed Joining of 5083 and 6061 aluminum alloys by friction stir welding. He found that in this procedure, a rotating tool goes down the length of contacting metal plates, and produces a highly plastically deformed zone through the related stirring action. Localized heating zone is developed by friction between the plate top surface and the tool shoulder as well as plastic deformation of the material in contact with the tool.

N. T. Kumbhar et. al. 2008[10] managed Friction Stir Welding of Al 6061 Alloy. States that during the friction stir welding, high deformation is observed at the nugget zone and the developed microstructure strongly influences the mechanical properties of the joint. FSW trials were done utilizing a vertical milling machine on Al 6061 alloy.

Morteza Ghaffarpour, et. al. 2013[11] In his Review of Dissimilar Welds of 5083-H12 and 6061-T6 performed by Friction Stir Welding, describes that as the conventional fusion welding is undesirable for welding aluminum alloys, there are numerous works performed on the aluminum alloys by FSW. These works are considering to the effects of FSW parameters on sheet formability, weld quality after FSW, and optimization of the FSW process.

S. Jannet et. al. 2013[12] managed Comparative research of friction stir welding and fusion welding of 6061-T6 and 5083-O aluminum alloy in view of microstructure and mechanical properties states. In this study, the mechanical properties of welded joints of 6061-T6 and 5083-O aluminum alloy determined utilizing friction stir welding (FSW) with four rotational speeds (450, 560, 710 and 900 rpm) and conventional fusion welding are investigated.

III. MATERIALS AND METHODS

Taguchi method

Taguchi method is an powerful problem solving tool, which can improve the performance of the process, product, design and system with a significant slash in experimental cost and time[13]. This technique that combines the experimental design theory and quality loss function concept has been applied for carrying out strong design of processes and products and solving many critical problems in manufacturing industries. Further, this method finds the most influential parameters in the entire performance. The optimum weld parameters found from the Taguchi concept are insensitive to the change in environmental condition and other noise factors[14]. In DOE number of trials increases when the number of process parameters increase. To solve this difficulty, the Taguchi technique utilizes a special design of orthogonal array to find the overall process parameter space with a few number of experiments only. Taguchi has developed three important signals to noise ratios (S/N) (i.e. the nominal-the-better, lower-the-better and the larger-the-better) depending on the of the quality characteristics. The S/N ratio for each of process parameter is calculated based on S/N analysis. Regardless of the classification of the quality characteristics, a larger S/N ratio relates to better quality characteristics. Therefore, the largest S/N ratio indicates to the optimal level of process parameter. Statistical analysis of variance (ANOVA) can be performed to find the significant process parameter. A confirmation test is conducted to validate the predicted optimal levels found out from the analysis.

FSW process parameters

An Ishikawa figure (cause and effect diagram)[15] was developed as shown in Fig.1 to identify the FSW process parameters that may impact the quality of FSW joints. Fig 2 shows the dynamics in friction stir welding process

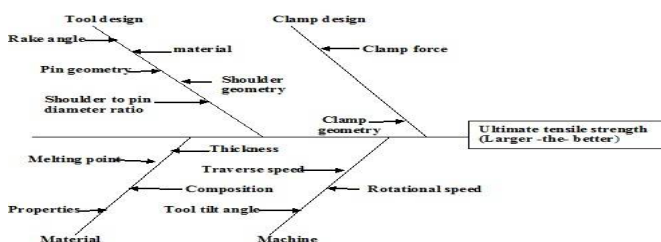


Figure 1. Cause and effect diagram

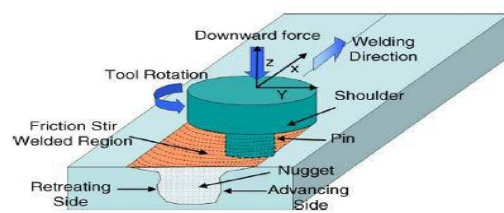


Figure 2. Frictions stir welding set up

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From Fig.1, the welding process parameters such as tool rotational speed, traverse speed, tool tilt angle, play a big role in deciding the weld quality. In the present research, three level process parameters, i.e. rotational speed(RPM), weld travel speed(WS) and tool tilt angle (TTA) were considered. Trial experiments were done using 5 mm thick plates of AA5083 and AA6061 Aluminium alloys to set the working range of FSW process parameters. The chemical composition and mechanical properties of the base metals (AA5083 and AA6061) used as a part of this investigation are given in Table 1 and 2 respectively.

Table1: Chemical composition of parent materials (mass fraction, %)

Alloy	Mg	Mn	Cu	Cr	Si	Fe	Al
AA6061-T6	1.046	0.101	0.259	0.195	0.533	0.262	Bal
AA5083-H321	4.0	0.548	0.065	0.10	0.145	0.238	Bal

The table 1 shows that AA5083 has more magnesium and manganese when compared with AA6061

Table2: Mechanical properties of parent materials

Alloy	Yield strength/Mpa	Ultimate tensile strength/Mpa	% Elongation mm	Average hardness at 0.5kg load (VHN)	Impact strength (J)
AA6061-T6	283	353	18	120	8
AA5083-H321	238	311	20	96	16

from table 2 It can be observed that AA6061 has superior mechanical properties among the two dissimilar materials considered.

When the tool rotational speed is lower than 560 rpm, worm hole defect is found it may be due to insufficient heat generation and inadequate metal depositing whereas a tunnel defect was found due to excessive heat generation when the rotational speed is higher than 1800 rpm. The FSW process parameters along with their ranges used in current investigations are given in Table 3.

Table 3 Process parameters with their range and values at three levels

Level	Rotational speed RPM (r min ⁻¹)	Weld travel speed WS (mm min ⁻¹)	Tool tilt angle TTA (degrees)
Range	560 - 1800	40-100	0 - 2
Level 1	560	40	0
Level 2	1120	70	1
Level 3	1800	100	2

When the traverse speed is lower than 40 mm/min, pin holes are observed because of excessive heat generation and a tunnel defect is observed due to insufficient heat input caused by insufficient metal flow, when the traverse speed is more than 100 mm/min. Defect free surface was found, for a tool tilt angle of 0 to 2°. Based on the above trials, the range of process parameters was selected as 560-1800 rpm for rotational speed, 40-100 mm/min for weld travel speed and 0-2° for tool tilt angle.

Selection of orthogonal array(OA)

The optimal process parameters were calculated by analysing the characteristics obtained by using orthogonal arrays (OA). The number of degrees of freedom requires to be calculated to select a suitable orthogonal array for the experiments. Taguchi develops number of standard orthogonal arrays and corresponding linear graphs were developed by Taguchi for this purpose. In this research three factors were selected, i.e., Friction stir welding process parameters for the three factors and three levels Taguchi suggested some standard array. Hence an L9 OA (3³) was selected for this research. This array requires nine trial runs and has three columns.

IV. EXPERIMENTAL WORK

In this research for base material used for the friction stir welding experiments were cut into 5 X 75 X 200 mm size from AA5083 and AA6061 aluminium alloys plates. Two plates of base metal (AA5083 and AA6061) were friction stir welded (FSW) in the butt configuration by using the vertical milling machine. The two plates located side by side and clamped rigidly to stop abutting joint faces from being forced apart. The length of the tool pin is slightly shorter than work piece thickness. In this research single pass welding method was used to produce the joints. The frictional heat generated between the tool shoulder surface and the base material of work piece surfaces due to rotating of weld tool. The heat developed by mechanical mixing method due to the stirred materials to soften below the melting point. As tool pin is travelled in the direction of welding the front face of the tool pin, with the help of special tool pin profile, forces plasticized material to the back of the pin while applying a sufficient forging force to solidify the weld metal. The weld metal was facilitated by intense plastic deformation in solid state involving dynamic recrystallization of base material. The welded joints sliced by using with an EDM wire cutting machine to required dimensions, according to ASTM E8M-04 guidelines should be followed for preparing test samples. The welded joints were cut as shown in Fig. 3.

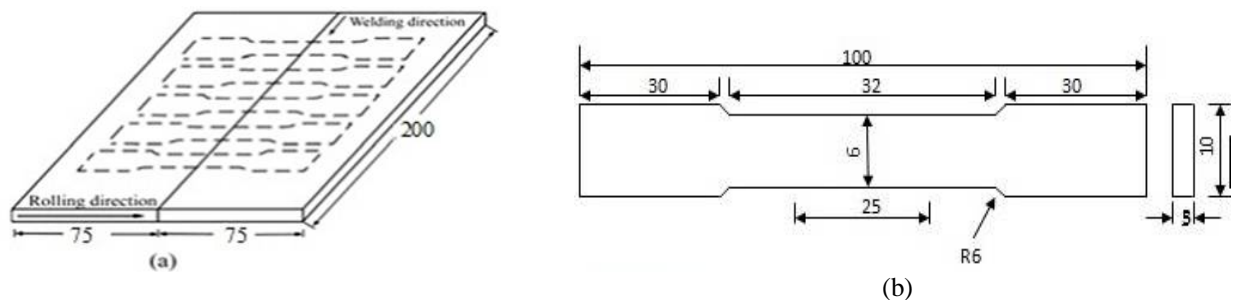


Figure 3. (a) Scheme of welding with respect to rolling direction and extraction of tensile specimen (b) dimensions of flat tensile specimen (ASTM E8M-04)

The tensile samples were prepared to evaluate ultimate tensile strength. At every experimental level three samples were prepared to reduce the noise factor. Tensile test was conducted in 40 ton, electromechanical controlled universal testing machine at room temperature.

Tool design: Tool geometry assumes an important part in material flow in the joint. FSW tool has two fundamental functions localized heating and material flow. The tool used in present work is shown in figure 4.



Figure 4: (a) & (b) weld tool, (c) Probe Dimensions

The tool ought to play out the accompanying capacities [Mishra RS et.al (2005)] are decrease the welding force, empower simpler stream of plasticized material, encourage the downward force impact, and expand the interface between the pin and the plasticized material, thereby increase the frictional heat production. In this work Concave shoulder with scrolling on shoulder surface and cylindrical taper treaded pin /probe was used. Shoulder diameter = 18mm, Root diameter = 6mm, Probe diameter = 4mm, Probe length= 4.7mm. Tool material = H13 tool steel is used.

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V. EXPERIMENTAL RESULTS AND DISCUSSION

1. Signal to noise ratio

Tensile strength is the main characteristic considered in this research describing the quality of FSW joints. So as to evaluate the impact of factors on the response, the Signal-to-Noise ratios (S/N) and means for every control factor can be calculated. The signals are indicators of the impact on average responses and the noises are measures of the impact on the deviations from the affectability of the experiment output to the noise factors. The suitable S/N ratio must be selected using past learning, skill, and understanding of the process. At the point when the objective is settled and there is trivial or absent signal factor (static design), it is possible to select the signal-to-noise (S/N) ratio depending on the target of the design [16]. In this study, the S/N ratio was chosen corresponding to the criterion of the larger-the-better, in order to maximize the response. In the Taguchi technique, the signal to noise ratio is utilized to determine the deviation of the quality characteristics from the desired value. The S/N ratio η_j (larger-the-better) in the j_{th} experiment can be communicated as

$$\eta_j = -10 \log_{10}((1/n) \sum (Y_{ijk})^2) \quad (1)$$

where n is the number of tests and Y_{ijk} is the experimental value of the i th quality characteristics in the j th experiment at the k th test.

Table 4 Orthogonal array for L9 with response (raw data and S/N ratio) replace the value

No	Input parameters			Response			Mean value	S/N ratio
	RPM	WS	TTA	T1	T2	T3		
1	560	40	0	188	198	189	191.702	45.6465
2	560	70	1	198	225	193	205.156	46.1849
3	560	100	2	280	189	183	217.389	46.2807
4	1120	40	1	259	259	214	243.951	47.6411
5	1120	70	2	296	299	290	295.36	49.4049
6	1120	100	0	240	229	220	229.703	47.2065
7	1800	40	2	200	199	199	199.112	45.9819
8	1800	70	0	173	280	173	208.964	45.7763
9	1800	100	1	188	200	188	191.672	45.6404

In the present study, the ultimate tensile strength data were analyzed to find the impact of FSW weld parameters. The trial results were then converted into means and signal-to-noise (S/N) ratio. In this work, 9 means and 9 S/N ratios were computed and the estimated tensile strength, means and signal-to-noise (S/N) ratio are given in Table 4.

Every experiment will give the analysis of mean for better combination of parameters levels that guarantees a high level of ultimate tensile strength according to the experimental set of data. The mean response indicates to the average value of execution characteristics for every parameter at various levels. The mean for one level was computed as the average of all responses that were found with that level. The mean response of crude information and S/N ratio of tensile strength for every parameter at level 1, 2 and 3 were computed and are shown in Table 5.

Table 5 Main effects of tensile strength (means and S/N ratio)

Level	for Means			for S/N Ratios		
	RPM	WS	TTA	RPM	WS	TTA
1	204.7	211.6	210.1	46.04	46.42	46.2
2	256.3	236.5	213.6	48.08	47.12	46.49
3	199.9	212.9	237.3	45.80	46.38	47.22
Delta	56.4	24.9	27.2	2.28	0.75	1.01
Rank	1	3	2	1	3	2

(RPM,WS,TTA are process parameters)

The means and S/N ratio of the different process parameters when they converted from the lower to higher levels are also shown in Table 5. It is clear that a larger S/N ratio with respect to better quality characteristics. Therefore, the optimal level of weld parameter is the level of highest S/N ratio [17]. The comparison of mean effect and S/N ratio are given in Fig.5(a & b).

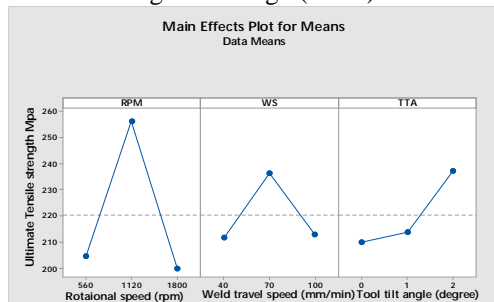


Figure:5 (a) F Main Effects Plot for Means of UTS

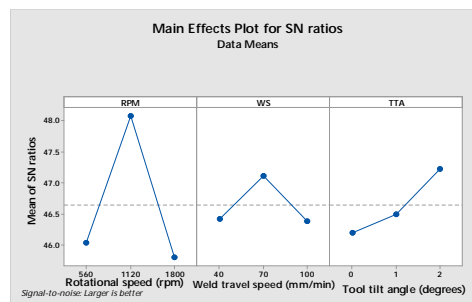


Figure:5 (b) Main Effects Plot for S/N ratio of UTS

The mean effect and S/N ratio for ultimate tensile strength were computed by statistical software [18], showing that the ultimate tensile strength was at highest when rotational speed, welding speed and tool tilt angle are at level 2, 2 and 3 i.e. rotational speed at 1120 r/min, welding speed at 70 mm/min and tool tilt angle at 2⁰ degrees.

2. Analysis of variance (ANOVA)

Analysis of variance (ANOVA) test was conducted to find the weld parameters that are statistically significant. The purpose of the ANOVA test is to research the importance of the process parameters which influence the tensile strength of FSW joints. The ANOVA results for tensile strength of means and S/N ratio are given in Table 6 (a, b).

Table 6(a) ANOVA for tensile strength (for mean)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% of contribution
RPM	2	5868.2	2934.1	15.56	0.060	67.2
WS	2	1177.7	588.8	3.12	0.243	13.5
TTA	2	1311.3	655.7	3.48	0.223	15.0
Error	2	377.2	188.6			04.3
Total	8	8734.4				100.0

DF- Degrees of freedom, Adj SS-Adjusted of square, Adj MS-Adjusted mean square, F- Feisher ratio, P- Probability that exceeds the 95% confidence level.

Table 6(b) ANOVA for tensile strength (S/N ratio)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Of contribution
RPM	2	8.1670	4.0835	19.77	0.048	70.1
WS	2	1.4548	0.7274	3.52	0.221	12.5
TTA	2	1.6127	0.8063	3.90	0.204	13.8
Error	2	0.4132	0.2066			03.6
Total	8	11.6476				100.6

DF- Degrees of freedom, Adj SS-Adjusted of square, Adj MS-Adjusted mean square, F- Feisher ratio, P- Probability that exceeds the 95% confidence level.

Also, the F-test named after Fisher can also be utilized to find which process has a significantly affects on tensile strength. Generally, the change of the process parameter significantly affects the quality characteristics, when *F* is high. The results of ANOVA show that the considered weld parameters are highly significant factors

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affecting the tensile strength of FSW joints in the order of rotational speed, tool tilt angle weld travel speed.

3. Interpretation of experimental results

3.1. Percentage of contribution

The percentage of contribution is the part of the total variation observed in the experiment attributed to every significant factors and/or interaction which is shown. The percentage of contribution is a function of the sum of squares for each significant item; it shows the relative power of a factor to minimise the variation. If the factor levels are controlled precisely, then the total variation could be minimise by the amount represented by the percentage of contribution.

3.2. Estimation of optimum performance characteristics.

The methods explained in this process for tensile strength prediction and optimization can terminate the need for conducting experiments on the basis of the conventional hit and trial technique which is time consuming and financially not justifiable. The present study is aimed at to recognize the highest influencing significant parameter and percentage contribution of every parameter on tensile strength of friction stir welded dissimilar AA5083 and AA6061 aluminium joints by conducting least number of experiments using Taguchi orthogonal array. Based on the greatest values of the S/N ratio and mean levels (Fig.5) for the significant factors RPM, WS and TTA the entire optimum condition thus obtained were RPM₂, WS₂ and TTA₃. Once an experiment is performed and the optimum process condition within the experiment is found, one of two conceivable outcomes exists:

- 1) The recommended combination of factors level is identical to one of those in the experiment,
- 2) The recommended combination of factors level is excluded in the experiment.

The optimum value of tensile strength is predicted at the chosen levels of significant levels of significant parameters. the predicted UTS is taken from the literature (19) The estimated mean of the response characteristics (tensile strength) can be calculated as

$$\text{Ultimate Tensile Strength UTS (predicted)} = \text{RPM}_2 + \text{WS}_2 + \text{TTA}_3 - 2T \quad \dots\dots\dots(2)$$

where T is the overall mean of ultimate tensile strength in Mpa (Table 2),

RPM₂ = The average ultimate tensile strength second level of rotational speed, 1120r/min;

WS₂ = The average ultimate tensile strength at second level of welding speed 70 mm/min,

TTA₃ = The average tensile strength at third level of tool tilt angle 2⁰degrees. Substituting the values of various terms in Eqn (2), then

$$\text{Tensile strength} = 256.3 + 236.5 + 237.3 - 2 \times 220.32 = 289.5 \text{ Mpa.}$$

3.3. Confirmation test: The confirmation test was conducted for ultimate tensile strength (UTS) and it was found that predicted value (289.5 Mpa) for UTS was very close to the values obtained after actual test conditions on optimum levels (295.36 Mpa).

VI. CONCLUSION

- 1) AA5083 and AA6061 alloys were successfully friction stir welded under the following range of process Parameters: tool rotational speed of 560 -1800 rpm, weld travel speed of 40-100 mm/min, and the tool tilt angle of 0-2⁰.
- 2) The percentage contribution of FSW process parameters was evaluated. It is observed that the tool Rotational speed has 67.2% contribution, tool tilt angle 15% and traverse speed has 13.5 % contribution to Ultimate tensile, strength of welded joints.
- 3) The optimum value of process parameters like rotational speed, traverse speed and tool tilt angle are determined to be 1120 r/min, 70 mm/min and 2⁰ degrees respectively.

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