Application of Taguchi Technique to Study the Mechanical Behaviour of Friction Stir Welded Aluminum Alloy AA8011

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Abstract **-Friction Stir Welding is a solid state joining technique which is widely being used for aerospace, marine, automotive and other applications for joining similar and dissimilar metals. Compared to other welding techniques FSW produces better mechanical properties in the weld zone. The main objective of this article is to investigate the similar joints of AA8011 alloy mechanical behavior with different process parameters. Three major factors at three levels namely tool angle, rotational speed and weld speed are considered for the present study. The uncontrollable factors include ultimate tensile strength, percentage of elongation which can be converted to signal-to noise ratios, by using Taguchi method used to optimize the factors. The ultimate tensile strength and percentage of elongation values for different combinations are noted from the response table and we get the optimum rank for the process parameters. Hence the prediction of the optimum process parameters using Taguchi technique is investigated.**

Index Terms **-Friction Stir Welding, Methodology, Taguchi method, Aluminium AA8011, means, S/N ratio.**

I. INTRODUCTION

Friction stir welding was invented in 1991 at the welding institute of UK. It is a solid state joining process which is widely being used for aerospace, marine, automotive and other applications for joining similar and dissimilar metals [12]. Compared to other welding techniques FSW produces better mechanical properties in the weld zone [8]. And it was initially applied to aluminium and copper alloys. In which a non consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of front.

The work piece is placed on a backup plate and clamped rigidly by a fixture to prevent lateral movement during FSW. A specially designed frustum shaped tool with a pin extending from the shoulder is rotated with a speed of several hundred rpm and slowly plunged into the joint line. The pin usually has a diameter one-third of the shoulder and typically has a length slight less than the thickness of the work piece. The pin is forced into the work piece at the joint until the shoulder contact the surface of the work piece. As the tool descends further, its surface friction with work piece createsadditional heat and plasticizes a cylindrical metal column around the inserted pin and the immediate material under the shoulder.

The work piece to be joined and the tool are moved relative to each other such that the tool tracks along the weld interface. The rotating tool provides the 'stir' action, plasticizing metal within a narrow zone while transporting metal from the leading face of the pin to the trailing edges [4]. As the tool passes, the weld cools, thereby joining the two plates together. On tool extraction a hole is left as the tool is withdrawn from the work piece. The process is well suited to butt and lap joints [5].

N. Bhanodaya Kiran Babu, this paper discuss about the friction stir welding of joining heat treatable aluminium alloys for the aerospace and automobile industries. These welded joints have higher tensile strength to weight ratio and finer micro structure. FSW of aluminium alloys have the potential to hold good mechanical and metallurgical properties. The aim of this study was to investigate the effect of process parameters on the tensile strength of the welded joints.

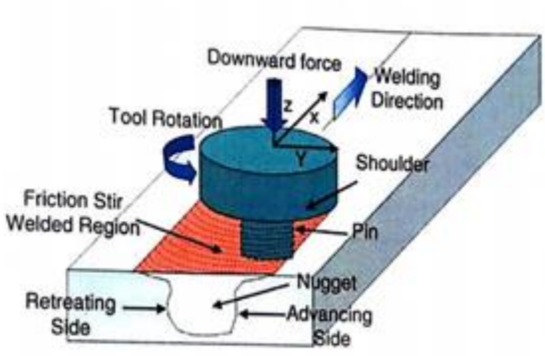

Fig.1. Principle of operation

Material details

The Similar material aluminum alloy AA8011 was used in this investigation. Chemical compositions of the alloy material are given in the Table.1. Mechanical properties of aluminum alloy were given in Table.2. The Similar aluminum alloy used in this investigation was welded using Friction stir welding technique.

Table 1. Chemical composition of AA 8011 aluminum alloys

Cu%	Mg%	Si%	Mn%	Fe%	Zn%	Cr%	Ti%	Al%
0.033	0.033	0.614	0.066	0.68	0.012	0.003	0.030	98.50

Table 2. Mechanical properties of AA 8011 aluminum alloys

Tensile Strength (MPa)	Density (Kg/m3)	Thermal conductivity (W/m-k)	Melting point C	Hardness (HRB)
110	2689	237	660.2	60

II. METHODOLOGY

Experimental design

The parameters identified for investigation are tool angle, tool rotation speed, welding speed [11]. The selected process parameter and their levels are shown in table 3.This is the design of experiment by which the works are done [1].

Table 3. Process parameter and their levels

Parameters/levels	Tool angle (deg)	Tool rotational speed (RPM)	Weld speed(mm/min)
1	0	560	25
2	1	900	35
3	2	1400	45

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 number of experiment is reduced to 9. The total degree of freedom must be calculated to choose the correct orthogonal array. The degree of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. So, L9 orthogonal array was selected which has a degree of freedom of 8. Nine experimental runs were conducted as per Taguchi L9 orthogonal array [2].

ANOVA analysis

Analysis of Variance (ANOVA) is a statistical method which is used to discuss the relative importance of the entire control factor. They are also used to find the contribution of each parameter. F-test proposed by Fisher is used as an auxiliary tool of inspection. Thus, the larger the value of f-test the more dominant the parameters are [7].

S/N ratio

Taguchi also recommended to analyse the valued using S/N ratio [2]. It involves conceptual approach which graphs the effect and identifies the significant values.

III. EXPERIMENTAL PROCEDURE

Process Involved the following processes of operations were adopted while carrying out the Friction Stir Welding [10].

1. Cutting,
2. Job Preparation,
3. Welding.

Cutting

The base metal sheets (AA8011) of dimensions 100 mm*50mm were cut by using shearing machine.

Job Preparation

Edges of sheared faces were grinded to get good finish and checked and ensured for perpendicularity. The initial joint configuration is securing the plates in position using mechanical clamps.

Welding

The direction of welding is normal to the rolling direction. Single pass welding procedures are used to fabricate the joints. Non-Consumable cylindrical tool is made up of high carbon steel. It is used to fabricate the joints. A non-consumable rotating tool is specially designed by pin and shoulder to insert into the abutting edges of sheets or plates to be joined and traversed along the line of the joint.

The primary functions of the tools are,

1. Heating the work piece.
2. Movement of material to form joints.

Plastic deformation of the work piece is achieved by the friction produced between the tool and the work piece [6]. The high heat which is produce softens the material around the pin. The combined effect of tool rotation and translation leads to movement of materials from front to the back of the pin. Thus a “solid state” join is formed [3]. During the friction stir welding process the material undergoes a plastic deformation at high temperature which results in generation of fine and equalled re-crystallized grains. Good mechanical properties of the work piece are due to the fine microstructure achieved through friction stir welding process [9]. Since FSW has good energy efficiency, versatility and environmental friendliness thus they are considered to be a GREEN technology. The experimental setup of FSW is shown in **Fig. 2.**

Fig.2. Friction stir weld on aluminium metal alloy

The stirring and mixing of materials around the rotating pin is done by the rotation of tools thus stirrers material from the front to the back of the pin and finishes the welding process. Since the tool rotates at high speed it generates high temperature because of higher friction heating and result in more intense stirring and mixing of material. Thus increases in heat are directly proportional with the tool rotation rate is not expected as the coefficient of friction at interface will change with increasing tool rotation rate.

IV. RESULT AND DISCUSSION

Analysis for ultimate tensile strength:

Table 4. S/N ratio of ultimate tensile strength

Ex.no	**Tool angle(degrees)**	**Tool rotational speed(RPM)**	**Weld speed(mm/min)**	**Ultimate tensile strength**	**S/N ratio of UTS**
1	0	560	25	136.278	42.6885
2	0	900	35	138.487	42.8282
3	0	1400	45	124.436	41.8989
4	1	560	35	129.455	42.2424
5	1	900	45	134.897	42.6000
6	1	1400	25	134.434	42.5702
7	2	560	45	125.419	41.9673
8	2	900	25	131.223	42.3602
9	2	1400	35	132.898	42.4704

Table 5. Response table for ultimate tensile strength

Level	**Tool angle(degrees)**	**Tool rotational speed(RPM)**	**Weld speed(mm/min)**
1	**42.47**	42.30	**42.54**
2	42.47	**42.60**	42.51
3	42.27	42.31	42.16
Delta	0.21	0.30	0.38
Rank	3	2	1

Based on the above response table the delta value is high at welding speed, the larger value is better for optimal solution.

Table 6. ANOVA table for UTS

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**% of Contribution**
Tool angle	2	19.89	19.89	9.94	0.32	0.760	10.86

Tool rotational speed(RPM)	2	38.47	38.47	19.24	0.61	0.621	21.01
Weld speed(mm/min)	2	61.70	61.70	30.85	0.98	0.505	33.69
Error	2	63.03	63.03	31.51			
Total	8	183.09					

Referring to the sum of squares in Table 6 , the factor Weld Speed makes the largest contribution to the total sum of the squares ((61.70/183.09)*100=33.69%).The factor Tool rotational speed makes the next largest contribution(21.01%) to the total sum of squares, whereas the factor tool angle make only (10.86%) contribution. The larger contribution of a particular factor to the total sum of squares, the larger ability is of the factor to influence ultimate tensile strength. Moreover, the larger the F- value, the larger will be the factor effect in comparison to the error mean square or the error variance [2].

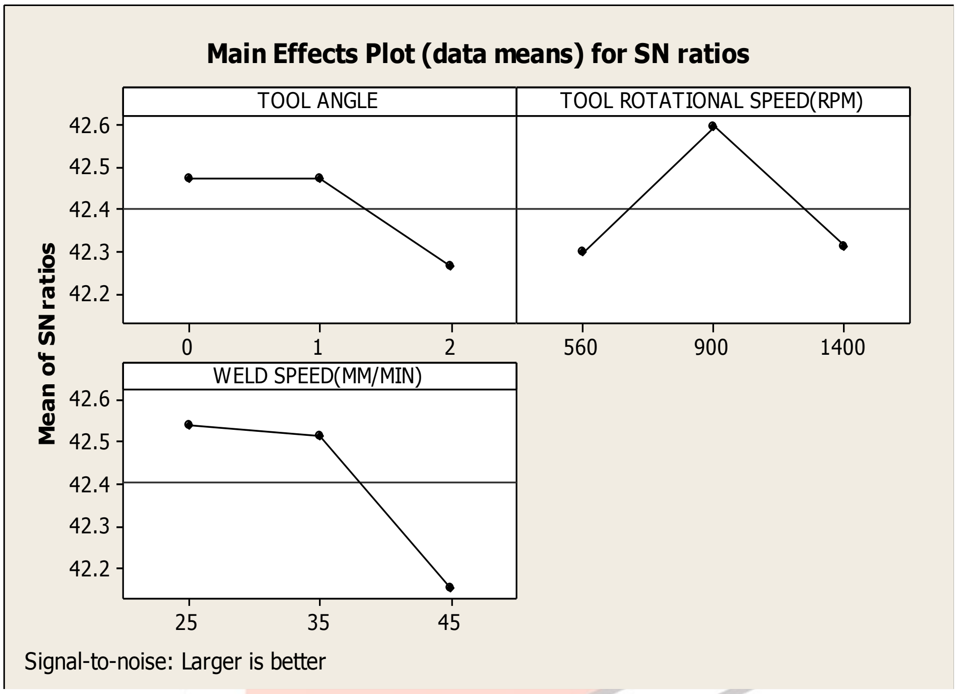

Fig.3. Main Effects Plot (data means) for SN ratios

The **figure.3** shows the main effects plot for S/N ratios. It is observed that the factor welding speed the delta value is high. Now taken the larger the better value for optimal solution.

Confirmation Test

Furthermore, the confirmation test is conducted to verify the improvement of results and to predict the optimum performance at the selected levels (since all factors have a confident level more than 90%) of significant parameters such as A1, C1, B2 . The most optimal set of combination of parameter is found out. The predicted mean(M) expressed as,

M = (A1-T) + (B2-T) + (C1-T) + T, (1)

where ,T= current grand average of S/N ratio

Table 7. The comparison between actual and predicted results of ultimate tensile strength

	Estimation	**Experimental**	**Difference**
Level	A1B2C1	A1 B2 C1	
Ultimate tensile strength	138.458	138.487	0.029
S/N Ratio in Db	42.81	42.82	0.01

Mean, (M)= (42.47-42.40) + (42.60-42.40) + (42.54-42.40) + 42.40 = 42.81Db

$$C.I = \left[\sqrt{(F\alpha(1,fe) * Ve\left(\frac{1}{Nf}+\frac{1}{R}\right)}\right]$$

The comparison between experimental and predicted results of ultimate tensile strength within range for the given confidence level.

Table 8. The optimal set of parameters for ultimateTensile strength test

Parameter	Optimum setting
Tool angle	0
Tool rotational speed	900
Welding speed	35

Analysis for % of Elongation:

Table 9 .S/N ratios of % Elongation

Ex.no	Tool angle (degrees)	Tool rotational speed(RPM)	Weld speed(mm/min)	% of Elongation	S/N ratios of % of Elongation
1	0	560	25	3.88	11.7766
2	0	900	35	5.12	14.1854
3	0	1400	45	7.06	16.9761
4	1	560	35	9	19.0849
5	1	900	45	12.54	21.9660
6	1	1400	25	12	21.5836
7	2	560	45	7.4	17.3846
8	2	900	25	8.36	18.4441
9	2	1400	35	4.94	13.8745

Table 10. Response table for % of Elongation

Level	Tool angle(degrees)	Tool rotational speed(RPM)	Weld speed(mm/min)
1	14.31	16.08	17.27
2	**20.88**	**18.20**	15.71
3	16.57	17.48	**18.78**
Delta	6.57	2.12	3.06
Rank	1	3	2

Based on the above response table the delta value is high at tool angle, the larger value is better for optimal solution.

Table 11. ANOVA table for % of Elongation

Source	Df	Seq ss	Adj ss	Adj ms	F	P	% of contribution
Tool angle	2	54.661	54.661	27.330	25.41	0.038	74.57
Tool Rotational Speed (RPM)	2	5.652	5.652	2.826	2.63	0.276	07.71
Weld Speed(mm/min)	2	10.833	10.833	5.416	5.04	0.166	14.78
Error	2	2.151	2.151	1.076			
Total	8	73.296					

The major inferences from the ANOVA table are discussed [2]. Refering to the sum of the squares in Table 11, the factor Tool angle makes the largest contribution to the total sum of the squares ((54.661/73.296)*100 =74.57%). The factor Weld speed makes the next largest contribution(14.78%) to the total sum of the squares, where as the factor tool rotational speed make only(07.71%) contribution. The larger contribution of a particular factor to the total sum of squares, the larger ability is of the factor to influence % of elongation. Moreover, the larger the F- value, the larger will be the factor effect in comparison to the error mean square or the error variance.

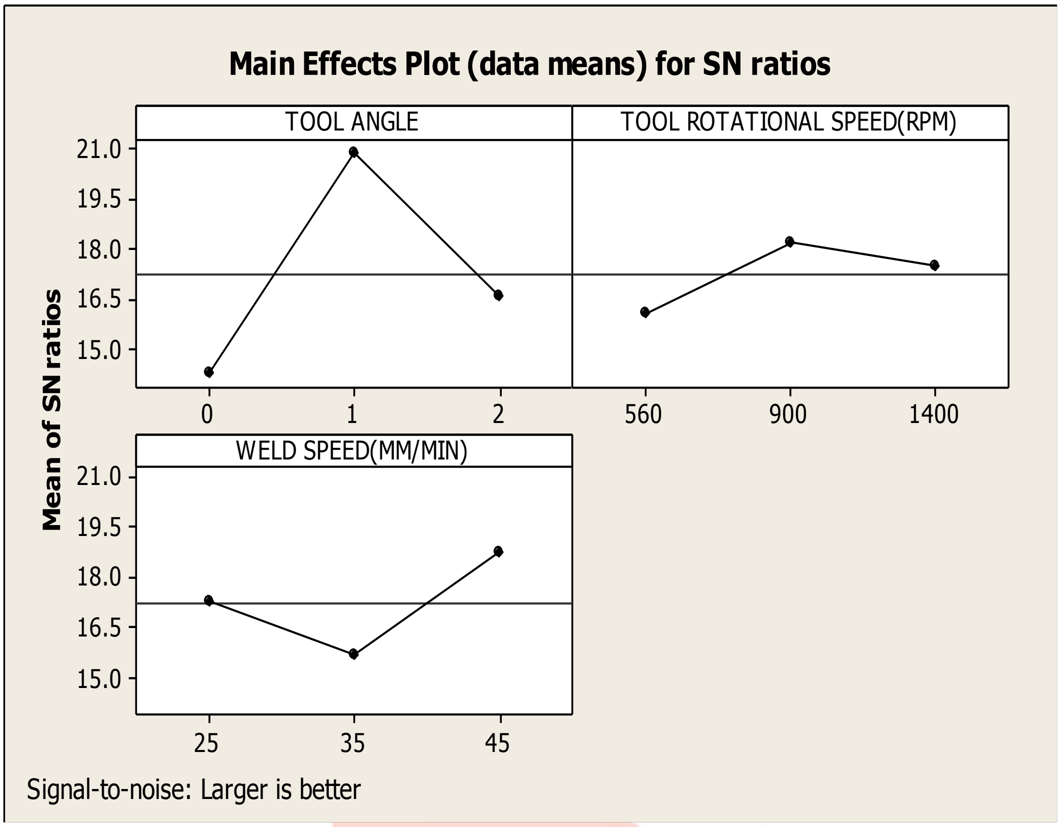

Fig.4. Main Effects Plot (data means) for SN ratios

The **figure.4** shows the main effects plot for S/N ratios [2]. It is observed that the factor tool angle the delta value is high. Now taken the larger the better value for optimal solution.

Confirmation Test

Furthermore, the confirmation test is conducted to verify the improvement of results and to predict the optimum performance at the selected levels (since all factors have a confident level more than 90%) of significant parameters such as A3, C3, B1 . The most optimal set of combination of parameter is found out. The predicted mean(M) expressed as,

$$M = (A3-T) + (B1-T) + (C3-T) + T, \qquad (2)$$

where ,T= current grand average of S/N ratio

Table 12. The comparison between actual and predicted results of % of elongation

Perticulars	Estimation	Experimental	Difference
Level	A3 B1 C3	A3 B1 C3	
% of Elongation	12.01	12.54	0.53
S/N Ratio in Db	21.06	21.96	0.9

Mean , (M)= (20.88-18.13) + (18.20-18.13) + (18.78-18.13) + 18.13 = 21.06dB

$$C.I = \left[\sqrt{(F\alpha(1,fe) * Ve\left(\frac{1}{Nf}+\frac{1}{R}\right)}\right]$$

The comparison between experimental and predicted results of % of Elongation within range for the given confidence level.

Table 13. The optimal set of parameters for % of elongation)

Parameter	Optimum setting
Tool angle	1
Tool rotational speed	900
Welding speed	45

V. CONCLUSIONS

AA8011 Aluminium alloy Plates of similar cross-section are joined using friction stir welding method and the main conclusions are as follows:

- The friction stir welding process is successfully employed to join the AA8011 plates.
- It is observed that the failure of tensile specimen is occurred at weld zone in all combinations of process parameters.

- Traverse tensile strength of the stir zone showed the highest value i.e 138.487Mpa in case of welding speed at 35mm/min with 900rpm.
- From taguchi analysis it is observed that tool angle is the most influencing parameter while considering % of elongation and Weld speed while considering UTS.
- ANOVA is performed to find the contribution of parameters and it is concluded that for % of elongation, Tool angle contributed 74.57% and weld speed contributed 14.78% while the other parameter tool rotational speed contributes only 7.71% which is less.
- It is observed that for Ultimate tensile strength, weld speed contributed 33.69% and tool rotational speed contributes 21.01% while the other parameter tool angle contributed 10.86% which is less compared to other parameters.
- The comparison between experimental and predicted results of ultimate tensile strength and % of elongation are within range for the given confidence level.

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