IJESRT: 7(12), December, 2018 ISSN: 2277-9655

International Journal of Engineering Sciences & Research Technology

(A Peer Reviewed Online Journal)
Impact Factor: 5.164

IJESRT

Website:www.ijesrt.com Mail: editor@ijesrt.com

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

IJESRT
INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

MATHEMATICAL ANALYSIS OF CENTRAL COMPOSITE DESIGN ON TENSILE STRENGTH OF FRICTION STIR WELDED ALUMINUM ALLOY JOINTS

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DOI: 10.5281/zenodo.2526233

ABSTRACT

Aluminum alloy 6061 is a medium to high strength heat-treatable alloy. It has very good corrosion resistance and very good weld ability although reduced strength in the weld zone. It has medium fatigue strength. It has good cold formability in the temper T4, but limited formability in T6 temper. It is typically used for heavy duty structures in Rail coaches, Truck frames, Ship building, Bridges and Military bridges, Aerospace applications including helicopter rotor, skins, Tube, Pylons and Towers, Transport, Motorboats, Rivets. The structural application of aluminum alloy involves welding and joining, which are difficult to weld using conventional welding processes. In 1991 a solid state joining process named Friction Stir Welding was developed and this technique has attracted considerable interest from the aerospace and automotive industries, since it is able to produce defect free joints particularly for light metals i.e. aluminum alloy and magnesium alloy. This process uses a non-consumable tool to generate frictional heat in the abutting surfaces. The welding parameters such as tool rotational speed, welding speed and tool shoulder diameter play a major role in deciding the weld quality. In this research work an attempt has been made to understand the effect of tool rotational speed, welding speed and tool shoulder diameter on friction stir welding of AA6061 aluminum alloy. Statistical tools such as design of experiments, analysis of variance, and regression analysis are used to develop the relationships. The mathematical model has been developed to predict mechanical properties of friction stir welded aluminum alloy joints at the 95% confidence level.

KEYWORDS: Aluminum Alloy; Friction Stir Welding; Mathematical Model; Design of Experiment

1. INTRODUCTION

In today`s modern world there are different welding techniques to joint metals. They range from the conventional oxyacetylene torch welding to laser welding. The two types of welding can be divided as fusion welding and pressure welding. The fusion welding process involves bonding of the metal in the molten stage and may need a filler material if required such as a consumable electrode or a spool of wire. Some processes may also need an inert ambience in order to avoid oxidation of the molten metal. A flux material or an inert gas shield in the weld zone protects weld pool to avoid defects. Examples of fusion welding are metal inert gas welding (MIG), tungsten inert gas welding (TIG) and laser welding. There are many disadvantages in the welding techniques where the metal is heated to its melting temperatures and let it solidify to form the joint. The melting and solidification causes the mechanical properties of the weld in some cases to deteriorate such as low tensile strength, fatigue strength and ductility. The disadvantages also include porosity, oxidation, micro segregation, hot cracking and other micro structural defects in the joint. The process also limits the combination of the metals that can be joined because of the different thermal coefficients of expansion. The solid state welding is the process where coalescence is produced at temperatures below the melting temperatures of the base metal without any need for the filler material or any inert ambience in many cases. Examples of solid state welding are friction welding, explosion welding, forge welding, hot pressure welding and ultrasonic welding. The three important parameters time, temperature and pressure individually or in combinations produce the joint in the base metal. As the metal in solid state welding does not reach its melting temperatures, there are fewer defects caused due to the melting and solidification of the metal. In solid state welding the metals being joined retain their original properties as melting does not occur in the joint and the heat affected zone (HAZ) is also very small compared to fusion welding techniques where most of the deterioration of the strength and ductility begins. Dissimilar metals can be joined with ease compared to fusion welding. Friction stir welding (FSW) is

an advanced friction welding process. The conventional friction welding is done by moving the parts to be joined relative to each other along a common interface also applying compressive forces across the joint. The frictional heat generated at the interface due to rubbing softens the metal and the soft metal gets extruded due to the compressive forces and the joint forms in the clear material, the relative motion is stopped and compressive forces are increased to form a sound weld before the weld is allowed to cool. Friction stir welding is also a solid state welding processes; this remarkable upgradation of friction welding was invented in 1991 in The Welding Institute (TWI). The process starts with clamping the plates to be welded to a backing plate so that the plates do not fly away during the welding process. A rotating wear resistant tool is plunged on the interface between the plates to a predetermined depth and moves forward in the interface between the plates to form the weld. The advantages of FSW technique is that it is environment friendly, energy efficient, there is no necessity for gas shielding for welding aluminium. Mechanical properties as proven by fatigue, tensile tests are excellent. There is no fume, no porosity, no spatter and low shrinkage of the metal. Joining dissimilar and previously unweldable metals can be attempted by this unique process.

2. PROBLEM FORMULATION

It was found that previous researchers have studied the effect of welding parameters on desired response using conventional method of varying one parameter at a time, though popular, does not give any information about interaction amongst the parameters. The effort has been made to investigate the individual and combined effect of welding parameters on mechanical and metallurgical properties of the friction stir welded joints of the aluminum alloy using response surface methodology (Central composite design).

3. EXPERIMENTATION

Principles of experimental design:

1. Randomization:

Random assignment is the process of assigning individuals at random to groups or to different groups in an experiment. The random assignment of individuals to groups (or conditions within a group) distinguishes a rigorous, "true" experiment from an adequate, but less-than-rigorous, "quasi-experiment". There is an extensive body of mathematical theory that explores the consequences of making the allocation of units to treatments by means of some random mechanism such as tables of random numbers, or the use of randomization devices such as playing cards or dice. Provided the sample size is adequate, the risks associated with random allocation (such as failing to obtain a representative sample in a survey, or having a serious imbalance in a key characteristic between a treatment group and a control group) are calculable and hence can be managed down to an acceptable level. Random doesn’t mean haphazard, and great care must be taken that appropriate random methods are used.

2 Replication:

Measurements are usually subject to variation and uncertainty. Measurements are repeated and full experiments are replicated to help identify the sources of variation, to better estimate the true effects of treatments, to further strengthen the experiment's reliability and validity, and to add to the existing knowledge of the topic. However, certain conditions must be met before the replication of the experiment is commenced: the original research question has been published in a peer-reviewed journal or widely cited, the researcher is independent of the original experiment, the researcher must first try to replicate the original findings using the original data, and the write-up should state that the study conducted is a replication study that tried to follow the original study as strictly as possible.

3. Blocking:

Blocking is the arrangement of experimental units into groups (blocks/lots) consisting of units that are similar to one another. Blocking reduces known but irrelevant sources of variation between units and thus allows greater precision in the estimation of the source of variation under study.

Material Selection:

The material selected for the study aluminium alloy 6061 which have a better strength to weight ratio than that of high strength steel. Chemical composition and mechanical properties of base material of the original alloy have been presented in Table 3.1 and 3.2 respectively. Problems caused by the conventional fusion welding can be dispelled by FSW, which can significantly widen the applications of aluminium alloys. Varieties of aluminium alloys have been successfully welded by FSW.

Ta#ble 3.1 chemical composition of base material

Si	Fe	Cu	Mn	Mg	Al
0.57	0.35	0.22	0.12	1.1	Bal

Table 3.2 mechanical properties of base material

Ultimate tensile strength (MPa)	Elongation	Hardness Hv
280	20	100

Experimentation has been divided into two stages .i.e. Trial experimentation and Final Experimentation.

Final Experimentation:

The final experiment was performed as per design matrix as presented in Table 3.5. The material used in this investigation was 100 mm×100 mm x 6 mm in size. But the appropriate size for welding was 200 mm x 100 mm for friction stir welding. The plates were prepared using power hacksaw. Thirty six plates of size 100 mm x 100 mm were cut to obtain eighteen friction stir welded joint with different parameters. Then cut edges are finished with filling operation so that interfaces can be properly matched. For welding process vertical milling machine was used as shown in Figure 3.1. All the specifications and standards for machine used are provided in the table 3.6. Fixture was first fixed on the machine bed with help of clamps. Fixture was properly held and then plates were held on the fixture.

Table 3.5 Central composite rotatable experimental design (in coded and actual levels of four factors and five levels)

Experiment No.	Coded Factors			Actual factors		
	N (rpm)	S (mm/min)	D (mm)	N (rpm)	S (mm/min)	D (mm)
1	-1	-1	-1	800	40	16
2	+1	-1	-1	1200	40	16
3	-1	+1	-1	800	80	16
4	+1	+1	-1	1200	80	16
5	-1	-1	+1	800	40	20
6	+1	-1	+1	1200	40	20
7	-1	+1	+1	800	80	20
8	+1	+1	+1	1200	80	20

9	-1	0	0	800	60	18
10	+1	0	0	1200	60	18
11	0	-1	0	1000	40	18
12	0	+1	0	1000	80	18
13	0	0	-1	1000	60	16
14	0	0	+1	1000	60	20
15	0	0	0	1000	60	18
16	0	0	0	1000	60	18
17	0	0	0	1000	60	18
18	0	0	0	1000	60	18

Table 3.6 Experimental Results

Experiment No.	Run No.	N	S	D	Tensile strength (MPa)
1	1	-1	-1	-1	164
2	2	1	-1	-1	180
3	10	-1	1	-1	183
4	14	1	1	-1	179
5	16	-1	-1	1	192
6	8	1	-1	1	194
7	6	-1	1	1	191
8	11	1	1	1	200
9	4	-1.68179	0	0	186
10	7	1.68179	0	0	205
11	17	0	-1.68179	0	185
12	13	0	1.68179	0	198
13	5	0	0	-1.68179	190
14	9	0	0	1.68179	201
15	15	0	0	0	221
16	3	0	0	0	225
17	12	0	0	0	226
18	18	0	0	0	220

E. Testing procedures:

In present study testing two types of testing, first was visual inspection performed for all welded specimens. Second mechanical testing consisting of two tests i.e. tensile test, Impact test of welded specimens and micro hardness tests for the welded specimens.

F. Visual Inspection:

Visual inspection was performed for all welded samples in order to verify the presence of macroscopic external defects such as surface irregularities, excessive flash, lack of penetration, voids and surface open tunnel defects. For the purpose of visual inspection cutting of welded specimen from cross section was taken to inspect the presence of any large tunnel defects which were visible to naked eye. It was observed in the visual inspection of the welded specimens that, no macro defects were present in all the specimens.

G. Tensile test:

Tensile test specimens were prepared from each weld in accordance with ASTM specifications, E-8M-08, having specimen of 70 mm gauge length and 12.5 mm width.

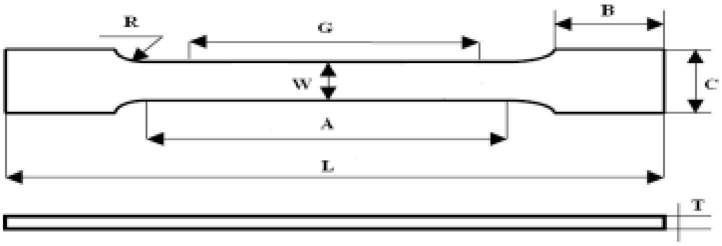

Fig 3.3 Tensile tested specimen dimensions

L= 200{Overall Length (mm)}
B= 50{Length of Grip Section (mm)}
G= 70{Gauge Length (mm)}
R=12 {Radius of Fillet (mm)}
A= 80{Length of Reduced Section (mm)}
C= 25 {Width of Grip (mm)}
W= 12.5{Width (mm)}
T=6{Thickness of Material (mm)}

Taking the above shown dimensions 72 specimens were taken from welded joints three from the each weld and 2 specimens from base material. Some tensile test specimen were shown in Fig 3.4. To test the tensile strength Servo Control Universal testing machine was used shown in Fig 3.5

Fig 3.4 Tensile test specimen before tensile test

Tensile test was carried out at a constant speed of 3 mm/min and 20 KN load. The load was applied until the necking was there and specimen failed. The same procedure was followed for the remaining specimens and values of the tensile strengths and % elongation were directly noted from the automatic computer display.

4. RESULT & DISCUSSION

It investigates an understanding about the relationship of various FSW process parameters selected for study and their effect on weld characteristics. Response Surface Methodology (RSM) was used to develop second order regression equation relating response characteristics and process parameters.

A. Development of design matrix

To design the experiments, the central composite rotatable design was adopted. Three parameters as tool rotational speed (N), welding speed and shoulder diameter (D) were selected and varied up to three levels.

B. Selection of mathematical model

The response function (Y) of friction stir welded joints are function of tool rotational speed (N), welding speed (S), and shoulder diameter (D) and it can be expressed as

$Y = f(N, S, D)$

The second order polynomial (regression equation) used to represent the response surface for K factors is given by

$Y = bo + \Sigma\, b_i X_i + \Sigma b_{ij} X_i X_{j.} + \Sigma b_{ii} X_i^2 + e$

where ‘b_o’is the free term of the regression equation and provides a mean value of the response factor, ‘b_i’ is the linear term, ‘bij’ is the interaction term, ‘bii’ is the quadratic term of the polynomial and ‘e’ is the residual error. The coefficients b_o, b_i, b_{ij} and b_{ii} are the least square estimates of true polynomial, representing the response surface. These coefficients represent the strength of the respective process parameters and their interactions. These are also called the parameters of the response function. The experiments were designed using software, Design Expert version 6.0 (State Ease). The same software was used for statistical analysis of the experiments data. For four factors, the selected polynomial can be expressed as given below:-

$$Y = \mathrm{bo} + \mathrm{b}_1(\mathrm{N}) + \mathrm{b}_2(\mathrm{S}) + \mathrm{b}_3(\mathrm{D}) + \mathrm{b}_{12}(\mathrm{NS}) + \mathrm{b}_{13}(\mathrm{ND}) + \mathrm{b}_{23}(\mathrm{SD}) + \mathrm{b}_{11}(\mathrm{N}^2) + \mathrm{b}_{22}(\mathrm{S}) + \mathrm{b}_{33}(\mathrm{D}^2)$$

The values of the coefficients of the polynomials were calculated with the help of the statistical software Design-expert 6.0. All the co-efficient were tested for their significance at 95% confidence level applying F-test using design expert software. To test the goodness of the fit and validation of the developed models, adequacy was determined by the analysis of variance technique (ANOVA).

C. Effect of process parameter on tensile strength

The Model F-value of 10.22 implies the model is significant. There is only a 0.16% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case N,S, D, N^2, S^2, D^2 , NS are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 8.82 implies there is a 5.15% chance that a "Lack of Fit F- value" this large could occur due to noise. Lack of fit is bad -- we want the model to fit. This relatively low probability (<10%) is troubling. After dropping the insignificant co-efficient the final model is given below.

Tensile Strength =223 +4.02N+3.29S+6.55D-11.25N^2-12.66 S^2 -11.25 D^2 -1.62 NS

Table 4.1 ANOVA for Response Surface Quadratic model tensile strength

Source	**Sum of Squares**	**Degree of freedom**	**Mean Square**	**F Value**	**p-value Prob > F**	**Significant**
Model	4691.79	9	521.31	10.22	0.0016	Yes
Tool rotational speed	221.13	1	221.13	4.33	0.0709	Yes
Welding speed	147.38	1	147.38	2.89	0.0012	Yes
tool shoulder diameter	586.53	1	586.53	11.49	0.0095	Yes
NS	21.13	1	21.13	0.41	0.0053	Yes
ND	0.13	1	0.13	2.450E-003	0.9617	No
SD	21.13	1	21.13	0.41	0.5379	No
N^2	1600.22	1	1600.22	31.36	0.0005	Yes
S^2	2027.93	1	2027.93	39.74	0.0002	Yes

D^2	1600.22	1	1600.22	31.36	0.0005	Yes
Residual	408.21	8	51.03			
Lack of Fit	382.21	5	76.44	8.82	0.0515	not significant
Pure Error	26.00	3	8.67			
Cor Total	5100.00	17				

The "Pred R-Squared" of 0.3950 is not as close to the "Adj R-Squared" of 0.8299 as one might normally expect; i.e. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 9.841 indicates an adequate signal. This model can be used to navigate the design space. Considering these criteria, following response model was selected after dropping insignificant coefficients for representing the variation of tensile strength for the further analysis.

Scatter diagrams, which show the predicted and the observed values of responses, were also drawn so as to test the validity of these models. A good agreement was found to exist between the actual and the predicted responses of tensile strength as shown in Fig. 4.1 and Fig 4.2 respectively.

Table 4.2 Summary statistics of the model for tensile strength

Std. Dev.	7.14	R-Squared	0.9200
Mean	196.67	Adj R-Squared	0.8299
C.V. %	3.63	Pred R-Squared	0.3950
PRESS	3085.45	Adeq Precision	9.841

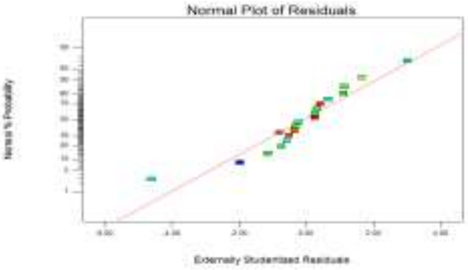

Fig 4.1 Normal plot of residuals for Tensile strength (MPa)

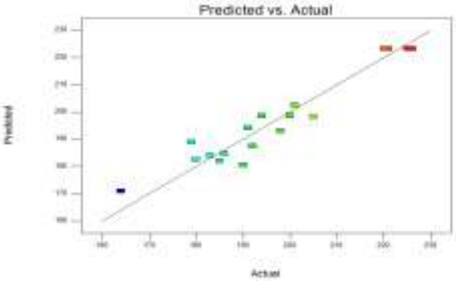

Fig.4.2 Predicted v/s actual plot for Tensile strength (MPa)

D. Direct Effect of tool rotational speed on tensile strength

The tensile strength of the joint increases as the tool rotational speed increases but it shows the decreasing trend as the tool rotational speed increases beyond that certain limit as shown in Fig 4.3. At tool rotational speed of 800 rpm, the tensile strength was lower but as tool rotational speed was increased upto 1000 rpm the tensile strength of the joint was improved. But as the tool rotational speed was further increased, the tensile strength of the weld joint decreased. At the lower tool rotational speed of 800 rpm, heat input was low. When the tool rotational speed increased from 800 rpm to 1000 rpm, there was increase in the heat input. Further increase in the tool rotational speed, from 1000 rpm to 1200 rpm, heat input increases, and slow cooling rate.

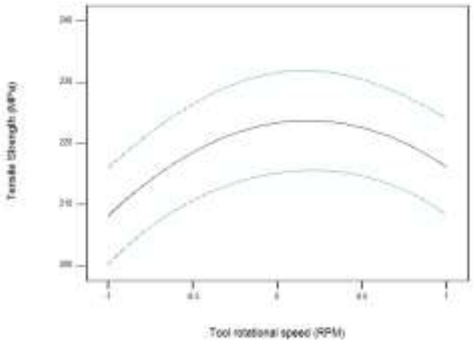

Figure 4.3. Effect of tool rotational speed on tensile strength

E. Direct Effect of welding speed on tensile strength

The tensile strength of the joint increases as the welding speed increases but the decreasing trend as the welding speed increases beyond that certain limit as shown in Figure 4.4. As the welding speed increased the tensile strength was increased. But at higher welding speed the tensile strength of the joint decreased. When the welding speed was lower 40 mm/min, heat input in the weld zone was high. These may be the reasons for lower tensile strength of the joint at lower welding speed. With the increase in the welding speed 60 mm/min, interaction between tool and work piece was improved and tensile strength was improved. But at the higher welding speed 80 mm/min interaction between the tool and workpiece reduced which may be the reason of lower tensile strength of the joint is lower.

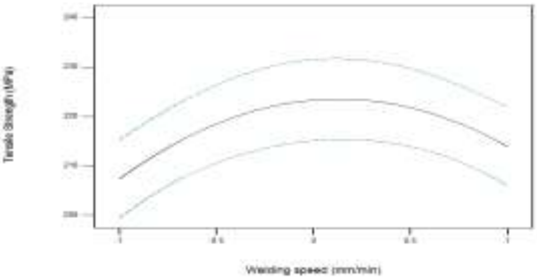

Fig.4.4 Effect of welding speed on tensile strength

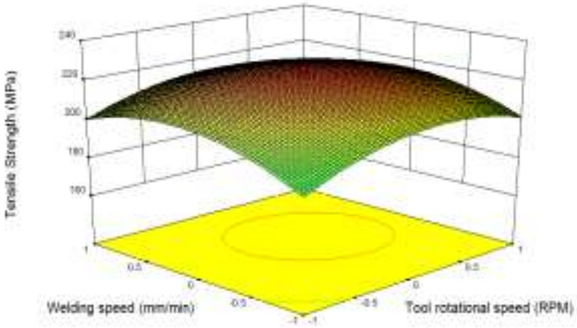

Fig.4.5 3D surface plots showing the effect of tool rotational speed and welding speed on tensile strength

5. CONCLUSION

- Empirical models alone are not able to completely optimize any welding process.
- Classical DOE methods must be modified due to the highly interactive and non-linear nature of welding.
- A five level four factor full factorial design matrix based on the central composite rotatable design technique could be effectively used for the development of mathematical models to predict the tensile strength.
- Response surface design was found to be an effective technique for developing mathematical models to accurately predict the main, quadratic and two-way interaction effects of various input parameters on different responses.

- Response surface methodology facilitated revealing of the effects of process parameters, over their working ranges, on desire response. The two-way interaction effects could be easily represented with the help of response surfaces along with the contour plots.
- All models developed showed either linear or quadratic relationship between input process.
- Tensile strength of the joint increases with increase in tool rotational speed but at higher value of tool rotational speed tensile strength of joint starts decreasing
- Tensile strength, percentage elongation, micro hardness, Impact toughness of joint increases with increase with increase in welding speed.

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CITE AN ARTICLE

Gill, A., Choudhary, V. S., & Chahal, G. S. (2018). MATHEMATICAL ANALYSIS OF CENTRAL COMPOSITE DESIGN ON TENSILE STRENGTH OF FRICTION STIR WELDED ALUMINUM ALLOY JOINTS. *INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY*, *7*(12), 400-409.