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Friction stir welding of dissimilar aluminum alloys AA7075 to AA2014: Optimization of process parameters using Taguchi technique

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***Abstract*---**The joining of dissimilar Al-Cu alloy AA2014-T651 and Al-Zn alloy AA7075-T651 plates was carried out using friction stir welding (FSW) technique and the process parameters were optimized using Taguchi L9 orthogonal design of experiments. The rotational speed, transverse speed, and axial load were the parameters taken into consideration. The optimum process parameters were determined with reference to tensile strength of the joint. The predicted optimal value of tensile strength was confirmed by conducting the confirmation run using optimum parameters. This study shows that defect free, high efficiency welded joints can be produced using a wide range of process parameters and recommends parameters for producing best joint tensile properties. Analysis of variance showed that the axial load is the most dominant factor in deciding the joint soundness while rotational speed and welding speed also played significant roles.

***Keywords*---**non-ferros metals, alloys, welding, microstructure.

Introduction

Fusion welding of dissimilar aluminum alloys is very challenging mainly due to the formation of low melting eutectics by the constituent elements resulting in weld solidification cracking (hot cracking). Solidification cracking in aluminum

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alloys is extremely sensitive to weld metal composition, which depends on the composition of the filler metal, composition of the base metal, and amount of dilution. Therefore, one must carefully choose the filler composition and/or welding parameters such that the resultant weld composition is not susceptible to solidification cracking. This can be done without much problem in the case of fusion welding of similar aluminum alloys. Guidelines for selection of filler metals exist for different classes and types of aluminum alloys. However, when it comes to fusion welding of dissimilar aluminum alloys, solidification cracking is not easy to deal with. For many dissimilar aluminum alloy combinations, there exist no filler metals that can produce crack-free welds. Even in cases where there is a reasonable filler metal option, one cannot achieve satisfactory joint efficiency. For these reasons, fusion welding of dissimilar aluminum alloys is generally avoided in the industry.

Solid-state welding processes are ideally suited for welding of dissimilar aluminum alloys. Because these processes do not involve melting, the issue of weld solidification cracking does not arise. Similarly, solid-state welding processes overcome a variety of other problems in fusion welding of aluminum alloys such as porosity, segregation, brittle intermetallic formation, and heat-affected zone liquation cracking. Among the solid-state welding processes, friction stir welding is very attractive for welding of dissimilar aluminum alloys as it is suitable for producing welds in a variety of joint configurations, including butt joints. FSW of dissimilar alloys/metals has attracted extensive research interest due to potential engineering importance and problems associated with conventional welding.

Several different dissimilar aluminum alloy combinations have been successfully friction stir welded with excellent joint efficiencies [1-6]. In most of these investigations, significant mechanical mixing of the two alloys was noticed in the stir zone or weld nugget with complex vortex, whorl, and swirl features characteristic of chaotic-dynamic mixing. Also, it has been shown that the locations of two dissimilar alloys exerted a significant effect on material flow pattern and the resultant weld quality [7].Many investigators reported that it is beneficial to place the stronger of the two materials on the advancing side [1, 8]. In their studies on FSW of cast aluminum alloy A356 to wrought aluminum alloy AA6061, Lee et al. [9] found that the stir zone predominantly consisted of the material that was placed on the retreating side. Whereas, Priya et al. [6], working on friction stir welding of AA2219 to AA6061, observed that the material placed on the advancing side dominated the stir zone. However, most of these studies focused on material flow visualization [7, 8, 11, and 12] and no optimum FSW parameters and tool geometry were identified in these systems.

FSW Parameters

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 joint. The tool serves two primary functions: (a) heating of work piece, and (b) moving the material to produce the joint. The heating is accomplished by friction between the tool and the work piece and plastic deformation of work piece. The localized heating softens the material around the pin and the combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. As a result of this process, a joint is produced in solid state. Because of various geometrical features of the tool, the material movement around the pin can be quite complex [13]. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains [9-15]. The fine microstructure in friction stir welds produces good mechanical properties.

The tool geometry, welding parameters, joint designs are the significant parameters affecting the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of the material [16]. The detailed list of FSW process parameters are given below.

1. Rotational speed of the tool (rpm)
2. Welding speed or transverse speed (mm/min)
3. Tool geometry
   (a) Pin profile
   (b) Tool shoulder diameter D (mm) (c) Pin diameter, d (mm)
   (d) D/d ratio of tool
   (e) Pin length (mm)
   (f) Tool inclination angle (◦)
4. Axial load.

From the available literatures [16-20] the friction stir welding process parameters such as tool rotational speed, transverse speed, tool geometry and axial load significantly influence the process and play a major role in deciding the quality of the weld. It is reported that defect free weld in dissimilar materials of AA5052 to AA2017 are obtained when the transverse speed and rotational speed are at 60mm/min and 1000 rpm respectively. Further, the rotational speed or welding speed increases the tensile strength to a maximum value and then decreases due the occurrence of void defect [21-26]. The fracture is observed in weld nugget zone at lower welding speed due to significant softening associated with these regions, and the presence of occasional, irregularly-shaped voids near the boundary between base metal and weld zone on advancing side. Moreover for high rotational speed weld defects are mostly observed.

W.A. Baeslack III et al. [27], in their studies on friction stir welding of AA8009, found that for the high rotational speed of 1200 rpm the tensile strength value was 60 – 70% of the base metal and for the lower rotational speed of 428 rpm it was found to be 90%. Park et al. [28], investigated that the proper mixing of material in the nugget region was observed when the stronger base material was placed on the advancing side. In contrast, a thinner weld nugget and inadequate mixing occurred with weaker material on the advancing side. From the foregoing, the success in dissimilar friction stir welding requires careful judgment with respect to material placement, tool designing and process parameters depending on the properties of the materials to be joined.

Al-Zn alloy AA7075 and Al-Cu alloy AA2014 are two widely used aluminum alloys especially in the aerospace industry. Fusion welding of these alloys is not possible as Cu and Zn brought together in liquid state would result in low melting eutectic and solidification cracking. A number of researchers have explored friction stir welding for welding of dissimilar metals and alloys. Several different dissimilar aluminium alloy combinations have been successfully friction stir welded with reasonably good joint efficiencies. Practically no information is available in open literature on friction stir welding of this particular material combination. Therefore, an attempt is made here to investigate friction stir welding of AA7075 to AA2014. In this investigation the three parameters such as rotational speed, transverse speed and axial load are taken into consideration, the values and their symbols and levels are listed in Table 1.

Taguchi method

Taguchi addresses quality in two main areas: off-line and on-line quality control [30]. The most important difference between a classical experimental design and a Taguchi-method-based robust design technique is that the former tends to focus solely on the mean of the quality characteristic while the later considers the minimization of the variance of the characteristic of interest. Although, the Taguchi method has drawn much criticism due to several major limitations, it has been able to solve single response problems effectively. The Taguchi method attempts to optimize a process or product design consists of three stages, as follows:

1. Concept design or system design
2. Parameter design
3. Tolerance design.

The following are the steps to be followed for process parameter optimization [31].

Step 1: Determine the quality characteristic to be optimized
Step 2: Identify the noise factors and test conditions
Step 3: Identify the control factors and their alternative levels
Step 4: Design the matrix experiment and define the data analysis procedure
Step 5: Conduct the matrix experiment Step 6: Analyze the data and determine optimum levels for control factors
Step 7: Predict the performance at these levels.

Selection of orthogonal array (OA)

The selection of which orthogonal array to use predominately depends on these items in order of priority:

1. The number of factors and interactions of interest
2. The number of levels for the factors of interest
3. The desired experimental resolution or cost limitations

As three levels and three factors are taken into consideration, L9 OA is used in this investigation. Only the main factor effects are taken into consideration and not the interactions. The degrees of freedom (DoF) for each factor is 2 (No.of levels -1, i.e. 3-1=2) and therefore the total degrees of freedom will be 3×2=6.Generally the DoF of the OA should be greater than the total DoF of the factors. As the DoF of L9 is 8, it can be suitable for the study.

Table 1: Process parameters values and their levels

Level	Rotational speed (rpm)	Transverse speed (mm/min)	Axial load (kN)
Level 1	800	15	10
Level 2	1000	30	15
Level 3	1200	45	20

Table 2: Chemical composition of the plate AA 2014 –T651, wt%

Elements	Si	Fe	Cu	Mn
Specified values	0.5-1.2	0.7 Max	3.7-5.0	0.4-1.2
Wt%	0.683	0.166	1.362	0.685

Table 3:Mechanical properties of the base plate AA2014-T651

Mg	Cr	Zn	Ti	Al
0.2-0.8	0.10 Max	0.25 Max	0.15 Max	Remainder
0.743	<.001	0.100	0.020	93.22

Table 4: Chemical composition of the plate AA 7075 –T651, wt%

Elements	Si	Fe	Cu	Mn
Specified values	0.40 Max	0.50 Max	1.2-2.00	0.30 Max
Wt%	0.055	0.116	0.142	0.035

Mg	Cr	Zn	Ti	Al
2.1-2.9	0.18-0.28	5.1-6.1	0.20 Max	Remainder
2.303	0.193	5.332	0.073	90.46

Table 5:Mechanical properties of the base plate AA7075-T651

AA 7075 -T651	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	% Elongation
Base Metal	479.13	539.10	17.00

Experimental procedure

The materials used in this study are 6 mm thick sheets of Al-Zn alloy AA7075-T651 and Al-Cu alloy AA2014-T651. The rolled plates were cut and machined into rectangular coupons (100 mm long and 50 mm wide) for friction stir welding. Welding was carried out in butt joint configuration using friction stir welding machine. The butt joints were fabricated normal to the rolling direction. The experiments were conducted using parameters of the designed L9 OA. The process parameters are tool rotational speeds, tool transverse speeds, and axial load. The tools made of H13 grade tool steel (pin length 5.7 mm and pin diameter 6 mm) of hardness 50 -55 VHN was employed for friction stir welding. The pin was positioned at the centre of the joint line.

Transverse tensile specimens with a gage length of 25 mm and a width of 6 mm (overall length: 100 mm) were prepared from the weld coupons in as-welded condition. Room-temperature tensile tests were conducted on three samples as per ASTM E8 [32] on a universal tensile testing machine. The wire cut EDM was used to cut the smooth profile tensile specimens. To minimize the machining error (noise) three specimens were prepared at each levels of the designed matrix. The dimensions of tensile specimen are shown in Fig. 1. The prepared tensile specimens were subjected to tensile test and their ultimate tensile strengths were evaluated. The following Table 6 gives the values of designed experimental layout.

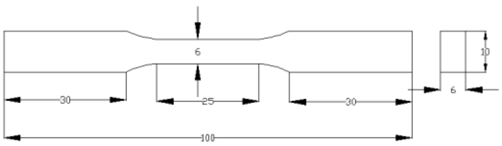

Fig.1: Dimensions of tensile specimen.

Results and Discussion

SI. No	Mean value Mpa	S/N Ratio
1	265.65	48.08382
2	301.63	49.92469
3	304.75	49.74625
4	284.07	49.13589
5	290.44	48.85875
6	241.58	47.99641
7	273.36	49.06989
8	252.39	48.10885
9	333.07	50.04842

Table 6: Experimental layout – L9 orthogonal array, mean value and SN ratio value

AA2014-T651	Yield Strength (MPa)	Ultimate Tensile Strength	% Elongation

		(MPa)	
Base Metal	440.30	470.62	15.50

Table 7: Response table for tensile strength signal to noise ratio

Level	RS	TS	AL
1	49.25	48.76	48.06
2	48.66	48.96	49.70
3	49.08	49.26	49.22
Delta	0.59	0.50	1.64
Rank	3	2	1

The optimal setting is $RS_1TS_3AL_2$ based on S/N ratio.

SI. No	Input Parameter	Response				
	RS Rpm	TS mm/ min	AL kN	T1 Mpa	T2 Mpa	T3 Mpa
1	800	15	10	237.33	266.61	293.01
2	800	30	15	303.55	286.44	314.90
3	800	45	20	277.58	336.56	300.13
4	1000	15	15	284.01	286.17	282.05
5	1000	30	20	318.38	291.46	261.48
6	1000	45	10	307.64	249.68	167.42
7	1200	15	20	256.61	291.99	270.48
8	1200	30	10	274.27	268.08	214.84
9	1200	45	15	315.89	351.07	332.26

Table 8: Response table for tensile strength mean

Level	RS	TS	AL
1	290.7	274.4	253.2
2	272.0	281.5	306.3
3	286.3	293.1	289.5
Delta	18.6	18.8	53.0
Rank	3	2	1

The optimal setting is $RS_1 TS_3 AL_2$ based on Mean

Table 9: Analysis of variance for tensile strength means]

Source	DoF	Seq SS	Adj SS
RS	2	570.0	570.0
TS	2	538.9	538.9

AL	2	4412.9	4412.9
Residual error	2	908.4	908.4
Total	0	6430.2	

Adj MS	F	% Contribution
285.0	0.63	8.8644
269.4	0.59	8.3807
2206.5	4.86	68.627
454.2		14.127
		100

Table 10: Analysis of variance for tensile strength S/N ratio

Source	DoF	Seq SS	Adj SS
RS	2	0.5463	0.5463
TS	2	0.3806	0.3806
AL	2	4.2680	4.2680
Residual error	2	0.8363	0.8363
Total	8	6.0313	

Adj MS	F	% Contribution
0.2732	0.65	9.057
0.1903	0.46	6.310
2.1340	5.10	70.764
0.4182		13.865
		100

DoF -Degree of freedom, Seq SS-sequential sum of squares, Adj SS-Adjusted sum of square, Adj MS- Adjusted mean square, SS'- Pure sum of squares, F- Fisher ratio.

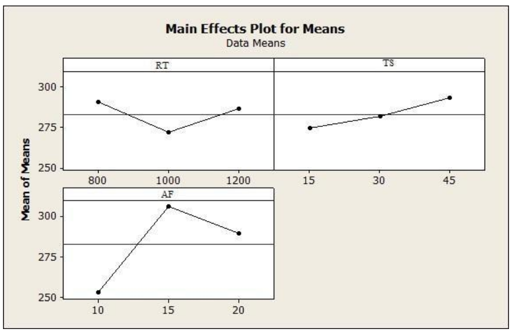

Figure 2: Main effects plot for tensile strength meane

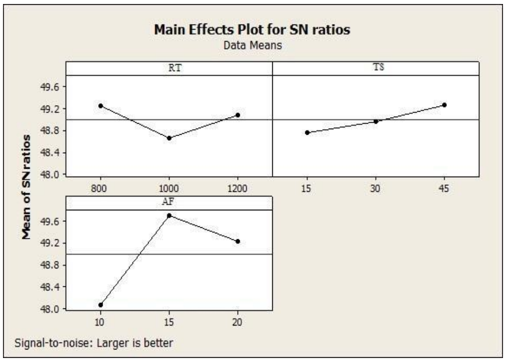

Figure 3: Main effects plot for tensile

Signal to noise ratio

$$\frac{S}{N}\, Ratio\ (\eta) = -10 \log_{10} \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}$$

The SN ratio is calculated based on the quality of the characteristics intended. The objective function described in this investigation is maximization of the tensile strength so; the larger the better SN ratio is to be calculated. The formula used for calculating the SN ratio is given below.

Larger the better

The tensile strength of the friction stir welding joints values is analyzed to study the effects of the FSW process parameters. The experimental data are converted into mean and SN ratio. The calculated mean and SN ratio values are tabulated in the Table 6. The average mean and SN ratio values of all levels are calculated and listed in the Tables 7 and 8. The larger SN Ratio corresponds to the better quality characteristics [18 -21]. Based on mean and SN ratio values the optimal level setting is $RS_1TS_3AL_2$.

Analysis of variance (ANOVA)

The purpose of ANOVA is to find the significant factor statistically. It gives a clear picture as to how far the process parameter affects the response and the level of significance of the factor considered. The ANOVA table for mean and signal to noise ratio are calculated and listed in the Tables 9 and 10. The main effects for mean and SN ratio are plotted in the Fig. 2 and 3. The F test is being carried out to study the significance 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, Axial load is a highly significant factor and plays a major role in affecting the tensile strength of the weld.

Predicted value of tensile strength

Based on the experiments, the optimum level settings is $RS_1TS_3AL_2$.The additive model to evaluate the predicted tensile strength is taken from the literature[24-

26,41].The average values of the factors at their levels are taken from the Table 8 and the predicted value of the response is given below.
Tensile strength (predicted)
= $RS_{1}+TS_{3}+AL_{2}$ -2T
= 290.7+293.1+306.3- 2(282.993)
= 324.1134 Mpa

Where,
RS1 - Average mean value of rotational speed at 1nd level
TS3 - Average mean value of transverse speed at 3st level
AL2 - Average mean value of axial force at 2nd level
T - Over all mean

Confirmation run

The confirmation experiments were carried out with cylindrically threaded pin profile and the other process parameters were set at their predicted optimum levels. The rotational speed, transverse speed, and axial load were set at 800 rpm, 45 mm/min and 15 KN respectively. The tensile specimen was subjected to tensile test and the value of the friction stir welded AA7075 and AA2014 was 320 MPa.

Conclusions

The friction stir welding process parameters were optimized with respect to tensile strength of the joint and the optimum level of settings were found out. The optimum levels of the rotational speed, Transverse speed, and axial load are 800 rpm, 45 mm/min and 15 KN respectively. The axial load plays a vital role and contributes 68.62% to the overall contribution. Friction stir welding can produce satisfactory butt welds between AA7075-T651and AA2014-T651 sheets with a joint efficiency of around 70% (based on alloy AA2014). For this specific material combination, failures occur in the heat-affected zone of alloy 2014.

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