International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-4, November 2019

Optimal FSW Process Parameters to Improve the Strength of Dissimilar AA6061-T6 to Cu Welds with Zn Interlayer

V Shanmukha Prasad, Mooli Harish, M B S Sreekara Reddy, Koora Rajanikanth, B Nageswara Rao

Abstract**:** ***Dissimilar welding of Al-Cu has many potential applications in electric power, electronic and piping industries due to high corrosion resistance, heat and conducting properties. Weld joints through friction stir welding (FSW) process are free from melting- and solidification-related defects. Compared to the recently used Box–Behnken design of response surface methodology, a simple and reliable modified Taguchi design of experiments is utilized for the dissimilar welding of AA6061-T6 to Cu with Zn interlayer to obtain the optimal FSW process parameters and the expected range of strength properties. Empirical relation for the tensile strength is developed in terms of FSW process parameters (viz., tool rotation speed, tool travel speed and tool pin offset) and validated through test results. Most of the test data are within the expected range.***

Keywords : AA6061-T6; Copper; Friction stir welding; Modified Taguchi approach; Tensile strength; Tool pin offset; Tool rotation speed; Tool travel speed; ZN interlayer.

I. INTRODUCTION

Due to high corrosion resistance, heat and conducting properties, dissimilar welding of Al-Cu has many potential applications in electric power, electronic and piping industries. Friction stir welding (FSW) process makes the weld joints free from melting- and solidification-related defects, and formed the subject by large number of investigations in the past decade [1–10]. Pandya and [11] have developed mathematical models for tensile properties of dissimilar AA6061-T6 to Cu welds adopting FSW process with Zn interlayer (to minimize intermetallics formation at weld interfaces). They have conducted 15 test runs as per Box–Behnken design of response surface methodology with three factors and three levels. In fact, Taguchi approach [45] recommends selection of an appropriate orthogonal array for performing few experiments to acquire complete information useful in identifying optimal process parameters and check their adequacy through additional testing (if necessary). This approach has been used extensively in solving several optimization problems such as minimization of drilling induced damages in composites [12–15], significance of parameters in the stage and satellite separation processes [16, 17], and on the performance of heat exchangers [18] and other manufacturing problems [19–25]. Design and manufacturing group of authors contributed a lot relevant to the development of materials [26–33], fabrication aspects [34–36], and industrial/engineering optimization problems [37–44] for the benefit of the readers of the journal.

Industries prefer simple and reliable procedures to handle optimization problems. Compared to the recently used Box–Behnken design of response surface methodology [11], a simple and modified Taguchi design of experiments is used for the dissimilar welding of AA6061-T6 to Cu with Zn interlayer to obtain the optimal FSW process parameters and the expected range of strength properties. Empirical relation is developed for the tensile strength in terms of FSW process parameters and validated through test results.

II. TEST DATA ACQUISITION

Pandya and Menghani [11] have generated tensile strength properties of dissimilar AA6061-T6 to Cu welds adopting FSW process with Zn interlayer for minimizing intermetallics formation at weld interfaces. They have conducted 15 test runs as per Box–Behnken design of response surface methodology with three FSW process parameters (viz., tool travel speed, tool rotation speed and tool offset) and three levels. Table-I gives the chemical composition (wt%) of base metals (AA6061-T6 and Cu) and their mechanical properties are presented in Table-II. Pure Cu and AA6061-T6 sheets (having $150 \times 50 \times 3$ mm) are joined by FSW process along longitudinal direction after coating Cu sheets with $\approx 15 \mu m$ thick Zn coating. Specimens are cut across the weld as per ASTM-E08- 2004 for tensile testing at a speed of 1 mm/min.

Manuscript published on November 30, 2019.

* Correspondence Author

V Shnmukha Prasad*, Assistant Professor, Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Deemed to be University, Green Fields, Vaddeswaram, Guntur-522 502, India.

Mooli Harish, Assistant Professor, Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Deemed to be University, Green Fields, Vaddeswaram, Guntur-522 502, India.

M B S Sreekara Reddy, Assistant Professor, Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Deemed to be University, Green Fields, Vaddeswaram, Guntur-522 502, India.

Koora Rajanikanth, Assistant Professor, Department of Mechanical Engineering, CMR Technical Campus, Kandlykoya, Medchal, Hyderabad-501 401, India.

B Nageswara Rao, Professor, Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Deemed to be University, Green Fields, Vaddeswaram, Guntur-522 502, India.

III. DEVELOPMENT OF EMPIRICAL RELATIONS BASED ON THE TAGUCHI'S DESIGN OF EXPERIMENTS

As per the Taguchi design of experiments, the relation between the number of experiments ($N_{Taguchi}$), and the factors or input parameters (n_p) with their assigned levels (n_l) is [45]

$$N_{Taguchi} = 1 + n_p \times (n_l - 1) \qquad (1)$$

For $n_p = 4$ and $n_l = 3$, $n_l^{n_p} = 3^4 = 81$ tests are to be conducted for full factorial design of experiments, whereas equation (1) indicates only $N_{Taguchi} = 9$ experiments and hence Taguchi's L_9 orthogonal array will be more appropriate for the three FSW process parameters (viz., tool rotation speed, tool travel speed and tool offset) with three levels.

A. *Analysis of Variance (ANOVA)*

For easy of reference, the 3 FSW process parameters (viz., tool rotation speed, tool travel speed and tool offset) are designated by A, B and C respectively. The evaluated strength of dissimilar welds, viz., tensile strength, σ_{ult} (MPa), yield strength, σ_{ys} (MPa) and % elongation from the mathematical models [11] as per L_9 orthogonal array are presented in Table-3.

When $N_{Taguchi} = 9$ and number of levels $n_l = 3$, equation (1) gives four number of factors that can be accommodated. As in [22], a fictitious factor (fourth factor) D is also introduced in Table-III. To examine the sensitiveness of the change in the level of setting, the sum of the squares (SOS) of deviation of each of the mean value from the overall mean is determined. %Contribution is obtained by dividing the sum of the squares of each process parameter with the total sum of the squares. Analysis of variance (ANOVA) is thus performed to identify the optimal FSW process parameters to achieve high tensile strength. Regarding the individual contribution of FSW parameters on the tensile strength, it is noted from the ANOVA results of Table-4 that tool rotation speed (A) has maximum effect on the ultimate tensile strength with 57.6% contribution and other parameters like tool travel speed (B) and tool offset (C) on the tensile strength are 26.8 and 2.6% respectively. Similarly, tool rotation speed (A) has maximum effect on the yield strength with 57.9% contribution and other parameters like tool travel speed (B) and tool offset (C) on the yield strength are 19.5 and 9.9% respectively. In case of %Elongation, contributions of FSW parameters (A, B and C) are 50.4, 30.3 and 7.8% respectively. Sum of the %Contributions including the fictitious parameter (D) in the ANOVA results of Table-4 for the ultimate strength, yield strength and %Elongation is 100. Hence, Error (%) with inclusion of the fictitious parameter (D) is zero, whereas with exclusion of D, the Error (%) is equal to that of the %Contribution of D.

B. *Expected range of the output response*

To account the scatter in repeated experiments, it is preferable to have the expected range of the output responses. From the ANOVA results of Table-IV, the estimated ultimate strength, yield strength and %Elongation for the assigned levels of FSW process parameters in Table-III are presented in Table-V. The additive law [45] in Equation (2) is used for estimation of the output response (ϕ) for each test run.

$$\widehat{\phi} = \phi_{mean} + \sum_{i=1}^{n_p} \left(\phi_i - \phi_{mean}\right) \qquad (2)$$

Here $\widehat{\phi}$ is the estimated output response; ϕ_{mean} is the overall mean of ϕ; ϕ_i is the mean of ϕ at the specified level for the process parameters (i); and n_p is the number of process parameters. The estimated output responses in Table-V for the 9 test runs are found to be reasonably in good agreement with test results. It should be noted that $n_p = 3$ in equation (2) corresponds to the estimates of the output response with exclusion of fictitious parameter (D), whereas $n_p = 4$ corresponds to the estimates of the output response with inclusion of fictitious parameter (D). With inclusion of fictitious parameter (D), the estimates of output responses in Table-V are very close to the test results. Considering the levels of lowest and highest mean values of ϕ for the fictitious parameter (D) the expected range for the output responses is arrived. The test results in Table-V are found to be within the expected range of the output responses. Taguchi design of experiments suggests only nine experiments for the present case study having three process parameters with three levels. The additive law [45] of Taguchi approach given in Equation (2) provides the estimates of output responses for all possible 27 combinations of input variables. Tables VI to VIII give estimates of the tensile strength of welds for the full factorial design of experiments. Most of the test data is within the expected range.

From the mean values of the tensile strength, σ_{ult} (MPa), yield strength, σ_{ys} (MPa) and % elongation, empirical relations developed in terms of the FSW process parameters (viz., tool rotation speed (A), tool travel speed (B) and tool offset (C) are

$$\sigma_{ult} = 140.69 - 1.74\xi_1 - 36\xi_1^2 - 9.14\xi_2 - 18.9\xi_2^2 + 2.14\xi_3 - 6.72\xi_3^2 \qquad (3)$$

$$\sigma_{ys} = 95.553 + 0.875\xi_1 - 20.705\xi_1^2 + 0.4\xi_2 - 12.03\xi_2^2 + 2.525\xi_3 - 7.375\xi_3^2 \qquad (4)$$

$$\%Elongation = 6.5678 - 0.26167\xi_1 - 1.65833\xi_1^2 - 0.40833\xi_2 - 1.12833\xi_2^2 - 0.29833\xi_3 - 0.43833\xi_3^2 \qquad (5)$$

Here, $A = 1000 + 345\xi_1 + 55\xi_1^2$; $B = 56 + 26\xi_2 - 2\xi_2^2$;

$C = 1 + 0.5\xi_3$; and $-1 \le \xi_i \le 1, \quad for\ i = 1, 2, 3$.

The lower bound values of σ_{ult} , σ_{ys} and % elongation, are obtained by applying corrections –9.86, -4.083 and -0.4898 to the results of equations (3) to (5). Similarly, the upper bound values of σ_{ult} , σ_{ys} and % elongation, are obtained by applying corrections 9.92, 6.417 and 0.4589 to the results of equations (3) to (5). The test results in Tables 6 to 8 are also within the expected range using the developed empirical relations (3) to (5) for the tensile strength, σ_{ult} (MPa), yield strength, σ_{ys} (MPa) and % elongation.

Cross-terms of can appear in empirical relations in a truly quadratic model of the RSM (response surface methodology), while fitting the output response in terms of process parameters. In the present study, empirical relations (3) to (5) are obtained from the three mean values of the output response and corresponding value of the process parameter level. Mean value plots confirm the quadratic nature of the output responses. Equations (3) to (5) provide the results same as those obtained from the additive law [45] given in equation (2).

From the ANOVA Table-IV, the maximum values of σ_{ult} , σ_{ys} and % elongation, are obtained for a set of FSW process parameters $A_2 B_2 C_2$. Subscript denotes the level of the process parameter. The increasing-decreasing nature of the mean values of output responses in Table-IV are found to be similar and hence optimal solution is obtained from a set of FSW process parameters for the output responses. Otherwise, one has to perform multi-objective optimization as in [19], [20]. The expected range of output responses (σ_{ult} , σ_{ys} and % elongation) for the optimum friction stir welding process parameters (Tool rotation speed, $A_2 = 1000\ rpm$; Tool travel speed, $B_2 = 56\ mm/\min$. ; and Tool offset, $C_2 = +1\ mm$) from Tables VI to VIII (see S.No.14) are: Ultimate tensile strength (MPa), $\sigma_{ult} \in [130.83, 150.61]$; Yield strength (MPa), $\sigma_{ys} \in [91.47, 101.97]$; and %Elongation, $\%El \in [6.0801, 7.027]$. These are in good agreement with three tests [11]. XRD analysis [11] indicates elimination of intermetallics of Al–Cu system at the weld interface using Zn interlayer coupled with tool offset of +1.0 and +1.5 mm, which improves dissimilar weld quality.

Table- I: The chemical composition (wt %) of base metals (AA6061-T6 and Cu)

Element	**Weight (%)**	
	Al6061-T6	***Cu***
Mg	0.88	-
Si	0.48	-
Fe	0.29	-
Cu	0.26	>99.9
Cr	0.12	-
Mn	0.11	-
Zn	0.11	-
Ti	0.01	-
Al	Balance	-

Table- II: Tensile strength properties of base metals (AA6061-T6 and Cu)

Property	***Al6061-T6***	***Cu***
Ultimate strength, σ_{ult} (MPa)	261	239
Yield strength, σ_{ys} (MPa)	187	175
% elongation	24	43
HV0.2	87.8	91.2

Table- III: FSW process parameters and tensile properties of dissimilar welds as per Taguchi's L_9 orthogonal array

a) Assigned levels of FSW process parameters

FSW process parameters	**Designation**	**Level-1**	**Level-2**	**Level-3**
Tool rotation speed (rpm)	A	710	1000	1400
Tool travel speed (mm/min)	B	28	56	80
Tool offset (mm)	C	+0.5	+1	+1.5
Fictitious	D	d_1	d_2	d_3

Table- III: FSW process parameters and tensile properties of dissimilar welds as per Taguchi's L_9 orthogonal array

b) Tensile properties of dissimilar A6061-T6 to Cu welds

Test Run	Levels of input parameters				Tensile properties[22]		
	A	B	C	D	σ_{ult} (MPa)	σ_{ys} (MPa)	%elongation
1	1	1	1	1	97.73	58.06	4.77
2	1	2	2	2	106.37	71.64	5.20
3	1	3	3	3	63.95	53.41	2.41
4	2	1	2	3	121.07	79.04	5.36
5	2	2	3	1	146.03	97.12	6.29
6	2	3	1	2	103.73	71.69	4.92
7	3	1	3	2	88.55	56.11	3.22
8	3	2	1	3	84.23	61.74	4.02

9	3	3	2	1	84.83	70.51	3.57
Overall Mean					**99.61**	**68.81**	**4.42**

Table-IV: Analysis of variance (ANOVA) on the tensile properties of dissimilar welds.

Parameters	**1-Mean**	**2-Mean**	**3-Mean**	**Sum of squares**	**% contribution**
Tensile strength, σ_{ult} (MPa)					
A	89.35	123.61	85.87	2610.17	57.6
B	102.45	112.21	84.17	1215.66	26.8
C	95.23	104.09	99.51	117.79	2.6
D	109.53	99.55	89.75	586.89	13.0
Yield strength, σ_{ys} (MPa)					
A	61.04	82.62	62.79	861.99	57.9
B	64.40	76.83	65.20	290.40	19.5
C	63.83	73.73	68.88	147.04	9.9
D	75.23	66.48	64.73	189.88	12.7
% Elongation					
A	4.13	5.52	3.60	5.9110	50.4
B	4.45	5.17	3.63	3.5467	30.3
C	4.57	4.71	3.97	0.9183	7.8
D	4.88	4.45	3.93	1.3480	11.5

Table-V: Estimates of tensile strength, σ_{ult} (MPa), yield strength, σ_{ys} (MPa) and % elongation of dissimilar AA6061-T6 to Cu welds, and comparison with test data [11].

Test Run	**Levels of FSW process parameters**				**Test [11]**	**Estimate Eq. (2)**			**Expected range**	
	A	**B**	**C**	**D**		$n_p = 3$	**R.E. (%)**	$n_p = 4$	**Lower bound**	**Upper bound**
Tensile strength, σ_{ult} (MPa)										
1	1	1	1	1	97.73	87.81	10.2	97.73	77.95	97.73
2	1	2	2	2	106.37	106.43	-0.1	106.37	96.57	116.35
3	1	3	3	3	63.95	73.81	-15.4	63.95	63.95	83.73
4	2	1	2	3	121.07	130.93	-8.1	121.07	121.07	140.85
5	2	2	3	1	146.03	136.11	6.8	146.03	126.25	146.03
6	2	3	1	2	103.73	103.79	-0.1	103.73	93.93	113.71
7	3	1	3	2	88.55	88.61	-0.1	88.55	78.75	98.53
8	3	2	1	3	84.23	94.09	-11.7	84.23	84.23	104.01
9	3	3	2	1	84.83	74.91	11.7	84.83	65.05	84.83
Yield strength, σ_{ys} (MPa)										
1	1	1	1	1	58.06	51.643	11.1	58.06	47.56	58.06
2	1	2	2	2	71.64	73.973	-3.3	71.64	69.89	80.39
3	1	3	3	3	53.41	57.493	-7.6	53.41	53.41	63.91
4	2	1	2	3	79.04	83.123	-5.2	79.04	79.04	89.54
5	2	2	3	1	97.12	90.703	6.6	97.12	86.62	97.12
6	2	3	1	2	71.69	74.023	-3.3	71.69	69.94	80.44
7	3	1	3	2	56.11	58.443	-4.2	56.11	54.36	64.86
8	3	2	1	3	61.74	65.823	-6.6	61.74	61.74	72.24
9	3	3	2	1	70.51	64.093	9.1	70.51	60.01	70.51
% Elongation										
1	1	1	1	1	4.77	4.3111	9.6	4.77	3.8234	4.77
2	1	2	2	2	5.2	5.1711	0.6	5.2	4.6834	5.63
3	1	3	3	3	2.41	2.8978	-20.2	2.41	2.4101	3.357

4	2	1	2	3	5.36	5.8478	-9.1	5.36	5.3601	6.307
5	2	2	3	1	6.29	5.8311	7.3	6.29	5.3434	6.29
6	2	3	1	2	4.92	4.8911	0.6	4.92	4.4034	5.35
7	3	1	3	2	3.22	3.1911	0.9	3.22	2.7034	3.65
8	3	2	1	3	4.02	4.5078	-12.1	4.02	4.0201	4.967
9	3	3	2	1	3.57	3.1111	12.9	3.57	2.6234	3.57

Table-VI: Estimates of tensile strength, σ_{ult} (MPa) for the full factorial design of experiments.

S. No.	FSW process parameters						Tensile strength, σ_{ult} (MPa)		
	Levels			Tool rotation speed, A (rpm)	Tool travel speed, B (mm/min.)	Tool offset, C (mm)	Lower bound	Upper bound	Test [11]
	A	B	C						
1	1	1	1	710	28	0.5	77.95	97.73	
2	1	1	2	710	28	1	86.81	106.59	97.04
3	1	1	3	710	28	1.5	82.23	102.01	
4	1	2	1	710	56	0.5	87.71	107.49	103.5
5	1	2	2	710	56	1	96.57	116.35	
6	1	2	3	710	56	1.5	91.99	111.77	107.59
7	1	3	1	710	80	0.5	59.67	79.45	
8	1	3	2	710	80	1	68.53	88.31	69.50
9	1	3	3	710	80	1.5	63.95	83.73	
10	2	1	1	1000	28	0.5	112.21	131.99	115.83
11	2	1	2	1000	28	1	121.07	140.85	121.49
12	2	1	3	1000	28	1.5	116.49	136.27	130.24
13	2	2	1	1000	56	0.5	121.97	141.75	
14	2	2	2	1000	56	1	130.83	150.61	143.67 132.04 141.31
15	2	2	3	1000	56	1.5	126.25	146.03	140.8
16	2	3	1	1000	80	0.5	93.93	113.71	103.22
17	2	3	2	1000	80	1	102.79	122.57	
18	2	3	3	1000	80	1.5	98.21	117.99	111.2
19	3	1	1	1400	28	0.5	74.47	94.25	
20	3	1	2	1400	28	1	83.33	103.11	68.98
21	3	1	3	1400	28	1.5	78.75	98.53	
22	3	2	1	1400	56	0.5	84.23	104.01	81.85
23	3	2	2	1400	56	1	93.09	112.87	
24	3	2	3	1400	56	1.5	88.51	108.29	118.66 118.74
25	3	3	1	1400	80	0.5	56.19	75.97	
26	3	3	2	1400	80	1	65.05	84.83	87.77
27	3	3	3	1400	80	1.5	60.47	80.25	

Table-VII: Estimates of yield strength, σ_{ys} (MPa) for the full factorial design of experiments.

.S. No.	FSW process parameters						Yield strength, σ_{ys} (MPa)		
	Levels			Tool rotation speed, A (rpm)	Tool travel speed, B (mm/min.)	Tool offset, C (mm)	Lower bound	Upper bound	Test [11]
	A	B	C						
1	1	1	1	710	28	0.5	47.56	58.06	
2	1	1	2	710	28	1	57.46	67.96	63.2
3	1	1	3	710	28	1.5	52.61	63.11	
4	1	2	1	710	56	0.5	59.99	70.49	66.9
5	1	2	2	710	56	1	69.89	80.39	
6	1	2	3	710	56	1.5	65.04	75.54	73.18
7	1	3	1	710	80	0.5	48.36	58.86	
8	1	3	2	710	80	1	58.26	68.76	54.86
9	1	3	3	710	80	1.5	53.41	63.91	
10	2	1	1	1000	28	0.5	69.14	79.64	68.67
11	2	1	2	1000	28	1	79.04	89.54	80.1

12	2	1	3	1000	28	1.5	74.19	84.69	84.94
13	2	2	1	1000	56	0.5	81.57	92.07	
14	2	2	2	1000	56	1	91.47	101.97	95.95 78.35 100.2
15	2	2	3	1000	56	1.5	86.62	97.12	100.95
16	2	3	1	1000	80	0.5	69.94	80.44	73.20
17	2	3	2	1000	80	1	79.84	90.34	
18	2	3	3	1000	80	1.5	74.99	85.49	82.41
19	3	1	1	1400	28	0.5	49.31	59.81	
20	3	1	2	1400	28	1	59.21	69.71	55.43
21	3	1	3	1400	28	1.5	54.36	64.86	
22	3	2	1	1400	56	0.5	61.74	72.24	53.69
23	3	2	2	1400	56	1	71.64	82.14	
24	3	2	3	1400	56	1.5	66.79	77.29	84.21 76.42
25	3	3	1	1400	80	0.5	50.11	60.61	
26	3	3	2	1400	80	1	60.01	70.51	64.88
27	3	3	3	1400	80	1.5	55.16	65.66	

Table-VIII: Estimates of %Elongation for the full factorial design of experiments.

.S. No.	FSW process parameters						% Elongation		
	Levels			Tool rotation speed, A (rpm)	Tool travel speed, B (mm/min.)	Tool offset, C (mm)	Lower bound	Upper bound	Test [11]
	A	B	C						
1	1	1	1	710	28	0.5	3.8234	4.77	
2	1	1	2	710	28	1	3.9634	4.91	4.84
3	1	1	3	710	28	1.5	3.2267	4.173	
4	1	2	1	710	56	0.5	4.5434	5.49	4.65
5	1	2	2	710	56	1	4.6834	5.63	
6	1	2	3	710	56	1.5	3.9467	4.893	5.63
7	1	3	1	710	80	0.5	3.0067	3.953	
8	1	3	2	710	80	1	3.1467	4.093	3.19
9	1	3	3	710	80	1.5	2.4101	3.357	
10	2	1	1	1000	28	0.5	5.2201	6.167	5.71
11	2	1	2	1000	28	1	5.3601	6.307	5.26
12	2	1	3	1000	28	1.5	4.6234	5.57	5.55
13	2	2	1	1000	56	0.5	5.9401	6.887	
14	2	2	2	1000	56	1	6.0801	7.027	6.10 6.54 6.06
15	2	2	3	1000	56	1.5	5.3434	6.29	6.3
16	2	3	1	1000	80	0.5	4.4034	5.35	5.16
17	2	3	2	1000	80	1	4.5434	5.49	
18	2	3	3	1000	80	1.5	3.8067	4.753	3.54
19	3	1	1	1400	28	0.5	3.3001	4.247	
20	3	1	2	1400	28	1	3.4401	4.387	2.32
21	3	1	3	1400	28	1.5	2.7034	3.65	
22	3	2	1	1400	56	0.5	4.0201	4.967	3.5
23	3	2	2	1400	56	1	4.1601	5.107	
24	3	2	3	1400	56	1.5	3.4234	4.37	5.08 4.12
25	3	3	1	1400	80	0.5	2.4834	3.43	
26	3	3	2	1400	80	1	2.6234	3.57	3.86
27	3	3	3	1400	80	1.5	1.8867	2.833	

IV. CONCLUDING REMARKS

Dissimilar welding of Al-Cu has many potential applications due to high corrosion resistance, heat and conducting properties. Weld joints through friction stir welding (FSW) process are free from melting- and solidification-related defects.

Present work deals with the identification of FSW process parameters to achieve maximum tensile strength of AA6061-T6 to Cu welds with Zn interlayer. ANOVA analysis is performed to examine the significance of the FSW process parameters, viz. Tool rotation speed, Tool travel speed and Tool offset) on the output responses (viz., σ_{ult}, σ_{ys} and % elongation). One of the process parameters, viz. the tool offset is showing little negligible variation on the overall mean value of the output responses. From the ANOVA results, the developed empirical relations (3) to (5) for the output responses (viz., σ_{ult}, σ_{ys} and % elongation) in terms of FSW process parameters are reasonably in good agreement with test results.

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