Developments of mathematical models for prediction of tensile properties of dissimilar AA6061-T6 to Cu welds prepared by friction stir welding process using Zn interlayer

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Abstract. Amount of intermetallics formed at the weld interface in dissimilar friction stir welding may be reduced by use of suitable interlayer materials such as Zn. In the present investigation, mathematical models have been developed for prediction of tensile properties of dissimilar AA6061-T6 to pure Cu welds prepared by friction stir welding process with Zn interlayer. Experiments were planned as per Box–Behnken design of response surface methodology. Three-factor, three-level Box–Behnken design with 15 runs was employed. Three process parameters: tool rotation speed (710, 1000 and 1400 rpm), tool travel speed (28, 56 and 80 mm/min) and tool pin offset (+0.5, +1.0 and +1.5 mm towards AA6061-T6 sheet) were considered. Lacks of fit for the developed models were assessed using analysis of variance (ANOVA). Validities of the developed models were checked by conducting confirmation runs. Predicted and experimental results of confirmation runs were found in reasonable agreements. Microstructural characterization revealed typical microstructure composed of intercalation of base metals. It was observed by X-ray diffraction analysis that use of Zn interlayer coupled with tool offset of +1.0 and +1.5 resulted in elimination of intermetallics of Al–Cu system at the weld interface, improving dissimilar weld quality.

Keywords. Friction stir welding; dissimilar; response surface methodology; interlayer; tensile strength.

1. Introduction

Friction stir welding process is a solid-state joining technique [1] invented at The Welding Institute (TWI), London, in 1991. The process has been successfully applied for joining similar metal joints of many ferrous and non-ferrous metals [2, 3] as well as dissimilar metal joints [4]. In the friction stir welding process, the welded joint is formed with typically wrought microstructure [1] by heating and stirring of softened base metal sheets beneath a rotating non-consumable tool. Heating takes place due to plastic deformation and frictional contact between the rotating tool and base metal sheets. Subsequently, the weld is formed by stirring and mixing of base materials by the rotating tool pin.

Joining of dissimilar metals is required in numerous engineering applications. Pure Cu is widely utilized in engineering applications because of its higher electrical and thermal conductivity [5]. Aluminium alloys are utilized for numerous applications because of their higher strength to weight ratio [6]. Therefore, there are many potential applications of dissimilar Al–Cu welds. Use of fusion

welding processes for joining dissimilar materials is normally not desirable due to several melting- and solidification-related issues [7] such as differences in melting points and thermal conductivities of base metals, differences in coefficients of thermal expansion of base metals, higher residual stresses, formation of brittle intermetallics, etc. Friction stir welding process is a better technique for welding dissimilar metals. Due to solid-state nature of the friction stir welding process, welded joints prepared using the process are free from melting- and solidification-related defects.

Microstructure and mechanical properties of Al–Cu dissimilar welds prepared by friction stir welding have been a matter of research interest in the last decade. Formation of brittle intermetallics is one of the common observations in microstructure of dissimilar Al–Cu friction stir welds. Muthu and Jayabalan [8] investigated effects of tool travel speed on 6-mm-thick dissimilar AA1100-H14 to pure Cu butt joints prepared by friction stir welding process. They reported formation of Al_2Cu , $AlCu$ and Al_4Cu_9 intermetallics. The higher tensile strength of the strongest weld was attributed to thin and continuous nano-sized intermetallic layer and strengthening due to dispersion of Cu particles within Al matrix in stir zone. Xue *et al* [9] also

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reported strengthening due to formation of composite-type structure along with formation of thin interlayer ($\sim 1 \mu\text{m}$) for dissimilar AA1060 to commercially pure Cu welds. Genevois *et al* [10] also attributed formation of defect-free dissimilar Al–Cu joints to formation of very thin interlayer composed of intermetallics – Al_2Cu and Al_4Cu_9 . Bisadi *et al* [11] investigated effects of tool travel speed and tool rotation speed on dissimilar AA5083 to pure Cu sheets in lap configuration. They observed low strength with fracture location for lap shear testing specimen on advancing side. The lower strength of the weld was attributed to hooking defects and formation of brittle intermetallics – Al_2Cu and Al_4Cu_9 . Mehta and Badheka [12] observed highly brittle welds of dissimilar AA6061-T651 to pure Cu sheets prepared by friction stir welding process. They attributed brittleness of the weld to the presence of hard intermetallics of Al–Cu system. Geometry of friction stir welding tool pin also affects formation of Al–Cu intermetallics. Muthu and Jayabalan [13] investigated effects of three different types of tool pin profiles on microstructure and mechanical properties of dissimilar Al–Cu friction stir welds. It was observed that pin profiles with threads and whorls on peripheral surface result into pulsating material flow, increasing transfer of higher Cu content in stir zone. Higher Cu content increases chances of formation of brittle intermetallics. Higher strength was observed for the weld prepared using plain taper profile as compared with strengths of welds prepared using tool pin with whorls and threads on peripheral surface. It is observed that when there is formation of thick intermetallic intermediate layer at the Al–Cu interface, the joint strength of dissimilar Al–Cu welds is low. However, stronger welds are produced when there is a thin intermetallic intermediate layer. Thus, nature, form and amount of intermetallics formed at the Al–Cu interface affect the tensile strength of the Al–Cu dissimilar friction stir welds.

It is necessary to control the amount of these intermetallics to enhance the tensile properties of the dissimilar Al–Cu welds. Ouyang *et al* [14] suggested insertion of any type of interlayer material between base metal sheets to minimize amount of brittle intermetallics. Use of interlayer to control growth of intermetallics in dissimilar metal welding has been reported in the literature for many fusion [15–17] and non-fusion welding [18, 19] processes. For dissimilar friction stir welding of Al–Cu welds, Kuang *et al* [20] used 0.2-mm-thick Zn foil as interlayer material for joining of 2-mm-thick sheets in lap configuration. Sahu *et al* [21] investigated effects of Ni, Ti and Zn foil as interlayer on dissimilar AA1050 to pure Cu sheets welded by friction stir welding in butt configuration. It was observed that use of Ti and Zn as interlayer improved tensile strengths of dissimilar Al–Cu welds as compared with welds prepared without any type of interlayer. Use of tool pin offset is another approach to control the growth of intermetallics. Okamura and Aota [4] reported that plunging tool pin completely in Al sheet (using full tool pin

offset) eliminates formation of brittle intermetallics in friction stir welding of dissimilar Al–Cu welds. Sahu *et al* [22] varied tool pin offset and observed that sound AA1050 to pure Cu welds are obtained when tool pin offset is set to $+1.5 \text{ mm}$. If the tool is set offset towards retreating side (RS) sheet, then tool pin offset is denoted with a $+ve$ sign, while if the tool pin offset is set towards advancing side material then it is denoted with a $-ve$ sign as per common convention. Improvement in tensile properties of dissimilar Al–Cu welds due to use of tool pin offset in friction stir welding is also reported by Yaduwanshi *et al* [23], Galvao *et al* [24] and Xue *et al* [25].

There have been very few studies reported on friction stir butt welding of dissimilar Al–Cu welds using design of experiments (DOE). Recently, Sahu *et al* [26] optimized friction stir welding process parameters for welding of dissimilar Al–Cu sheets using systematic experiments as per the Taguchi method of DOE. DOE is a good technique to collect and analyse experimental data. DOE is also helpful for optimization of process parameters [27]. Response surface methodology is a type of DOE technique. If the objective of the experimental study is to investigate individual, interaction and quadratic effects of process parameters on the response variable, response surface methodology is a good method. Response surface methodology is useful to develop and verify the mathematical model correlating one or more than one response variables and experimental process parameters [28]. For development of mathematical model, initially the experimental data are collected by conducting experiments as per response surface methodology. Thereafter, a first- or second-order regression equation is developed [29].

Box and Behnken [30] developed Box–Behnken DOE, which is a sub-type of response surface methodology. Box–Behnken designs are rotatable through design space. The Box–Behnken design for three factors is divided into three blocks. In each block, one factor is held fixed at intermediate level (coded value: 0) while other two factors are varied in all possible combinations of their high (coded value: $+1$) and low (coded value: -1) levels. Thus, they make $3 \times 4 = 12$ runs. Including three repeat runs for the central points (for which all factors are kept at their intermediate levels; coded value: 0) makes a total of 15 runs [31]. Applications of response surface methodology for investigating effects of friction stir welding process parameters on tensile properties or other responses have been reported in the literature [32–35]. Ghetiya and Patel [32] developed a mathematical model for prediction of tensile strength of AA2014-T4 immersed friction stir welds using Box–Behnken design. Genetic algorithm was applied to optimize friction stir welding process parameters. Mohamed *et al* [33] developed the first-order regression model to predict mechanical properties as a function of friction stir welding process parameters – tool travel speed and tool rotation speed for similar AA6061 T651 welds in butt configuration. Ghaffarpour *et al* [34] optimized the

friction stir welding parameters for joining the dissimilar AA5083-H12 to 6061-T6 welds using Box–Behnken design with four friction stir welding process parameters. Mastanaiah *et al* [35] derived a mathematical model for prediction of sound welds of aluminium alloys AA5083 and AA2219, considering three factors – tool travel speed, tool rotation speed and tool offset.

It can be concluded that experimentation based on response surface methodology has been successfully applied for development of mathematical model for friction stir welding of similar metals and dissimilar Al alloys; however, there is no systematic study involving experimentation based on response surface methodology for dissimilar Al–Cu welds. Similarly, two experimental investigations [20, 21] have been reported related to effects of Zn interlayer on structure and properties of Al–Cu dissimilar friction stir welds. Out of these two investigations, one is for lap joint configuration [20] while the other one is for butt joint configuration [21]. A mathematical model for tensile strength of dissimilar Al–Cu butt friction stir welds prepared with Zn coating interlayer is lacking. The present investigation is an attempt to fulfil the research gap by developing a mathematical model for the same. For experimentation, Box–Behnken design of response surface methodology is followed.

2. Experimental procedure

Experiments were planned as per Box–Behnken design of response surface methodology. Three friction stir welding process parameters – tool travel speed, tool rotation speed and tool offset – were considered. The process parameters considered, their symbols and levels are listed in table 1.

Selection of levels of process parameters was done based on prior trial runs conducted. Ranges of tool travel speed and tool rotation speed were selected in a manner such that defect-free welded joints can be obtained. Levels for tool offset have been selected based on practical feasible limits. Lower feasible limit for tool offset is 0 mm, which is the case of dissimilar friction stir welding without tool offset. However, it is well known that at 0 mm tool offset (no offset), very high amount of brittle intermetallics is formed [9]; therefore, a lower limit of +0.5 mm was considered. The upper feasible limit of tool offset would be equal to tool pin radius. In the present investigation, tool pin diameter is 4.0 mm; hence the maximum feasible tool offset would be +2.0 mm. At this maximum level of tool offset, tool pin just touches Cu sheet tangentially at the sheet interface and remains within the Al sheet completely. Although formation of intermetallics could be suppressed using the highest level of tool offset equal to tool radius, welded joints are formed purely by diffusion and normally strong and sound welds could not be produced [4]. Therefore, for the present study, the upper limit of tool offset is kept up to only +1.5 mm. It is important to consider that in dissimilar friction stir welding process without using interlayer when tool pin offset is varied within feasible range, proportion of volumes of both base metals (here Al and Cu) swept by tool pin is also varied (figure 1a). Similarly, in dissimilar friction stir welding with interlayer, when tool pin offset is changed from lower (here +0.5 mm) to higher (here +1.5 mm) level, proportions of volumes of base metal Cu and Zn interlayer swept by tool pin are

Table 1. Process parameters and their levels.

Parameter	A	B	C
Coded level	Tool rotation speed (rpm)	Tool travel speed (mm/min)	Tool offset (mm)
–1	710	28	+0.5
0	1000	56	+1.0
+1	1400	80	+1.5

Figure 1. Effect of tool pin offset on proportion of swept volumes of base metals by tool pin.

Table 2. Chemical composition of base metals (wt%).

Base metal	Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
AA6061-T6	0.88	0.48	0.29	0.26	0.12	0.11	0.11	0.01	Bal.
Pure copper	–	–	–	> 99.9	–	–	–	–	–

Table 3. Mechanical properties of base metals.

Base metal	Ultimate strength (MPa)	Yield strength (MPa)	Elongation (%)	HV0.2
AA6061-T6	261	187	24	87.8
Pure copper	239	175	43	91.2

decreased while proportion of volume of base metal Al gets increased in total swept volume of stir zone (figure 1b). Thus, as the tool pin offset is varied with constant Zn interlayer thickness, a variation in amount of Zn in stir zone by volume is also achieved.

Pure Cu and AA6061-T6 sheets having 150 mm × 50 mm × 3 mm size were joined along the longitudinal direction by friction stir welding process. Chemical composition and mechanical properties of both base metals are given in tables 2 and 3, respectively.

Prior to welding, all Cu sheets were coated with a pure Zn coating having thickness of ~15 µm on abutting edge (figure 2) by electroplating. Before electroplating, the pure

Cu sheets were cleaned by pickling in dilute sulphuric acid solution (10% by volume) at 50°C. After pickling, all surfaces of pure Cu sheets were masked using masking tapes except abutting edges. Thereafter, electroplating of Zn was carried out as per alkaline cyanide plating procedure. Plating of Zn interlayer is done with a view to minimize amount of brittle intermetallics of Al–Cu system. Zn interlayer may act as a barrier between Al and Cu particles mixed within stir zone.

Friction stir welding was performed using a conventional milling machine. Cu sheets were positioned on advancing side while AA6061-T6 sheets were placed on RS as it is reported in the literature [9] that positioning harder material (here Cu) on advancing side results in defect-free joints. Plunge depth and tool tilt angle were kept constant at 0.1 mm and 2°, respectively. The friction stir welding tool had a 16 mm diameter concave shoulder, and standard straight cylindrical tool pin having 4 mm diameter and 2.9 mm length. The tool was made of AISI H13 tool steel. A load cell of 80 kN capacity was used for load measurement. Four k-type thermocouples having a tip diameter of 1.75 mm were inserted from the top surface in holes of 2.0 mm diameter for temperature measurement. Thermocouples were inserted at distances of 12 and 15 mm from weld interface in transverse direction and longitudinally at 45 mm and 60 mm from start point of weld (figure 3) on both advancing side and RS. For all runs, welding was started at a distance of 15 mm along the longitudinal direction from the edge of the sheet while welding runs were finished by leaving 15 mm at the end. Welded sheets were examined visually before mechanical testing.

Figure 2. Scanning electron micrograph (SEM) indicating size of Zn interlayer thickness. **Figure 3.** Arrangement for temperature measurement: all dimensions are in mm.

Figure 4. Photograph of prepared tensile testing specimens.

For tensile testing, standard sub-size specimens were cut across the weld from each welded sheet as per ASTM-E08-2004 (figure 4). Average of two tests was reported for analysis. A KIPL-make tensometer was used for tensile testing. Tensile testing was done at a speed of 1 mm/min. Vickers' microhardness measurements were carried out at mid-depth of the cross-sectional surface of welds. The measurements were performed as per ASTM E-384:11a using the load of 200 g and the dwell time of 15 s. Indentations were made at the weld interface and at intervals of 1 mm from weld interface on both advancing side and retreating side up to 15 mm. For microstructural characterization, samples were prepared as per the standard metallographic procedure. Finely polished specimens were etched. For Al side regions, solution of 4 ml HF into 100 ml H₂O was applied as etchant. Pure Cu side was etched with a mixture of 0.1 l H₂O, 4 ml saturated NaCl solution, 2 g potassium dichromate and 8 ml H₂SO₄. X-ray diffraction (XRD) analysis was carried out using a Rigaku-make Miniflex X-ray diffractometer. For XRD analysis, 20 mm × 20 mm size square pieces incorporating weld interface were cut from welded sheets and tested.

3. Results and discussion

3.1 Friction stir welding

A photograph of welded sheets is shown in figure 5. Top seam appearances of all welds are shown in figure 6. It is observed that top surface of all weld seams appears smooth and defect free in general.

3.2 Tensile testing

Results of tensile testing are tabulated in table 4, along with results of temperature measurement. During friction stir

Figure 5. FS-welded sheets for all 15 runs.

welding process, average axial load measured was ~ 3 kN. The highest tensile strength (UTS: 143.7 MPa) has been observed for standard-order weld run 13 (randomized weld run order no. 11) conducted at 56 mm/min, 1000 rpm and +1.0 tool pin offset. Similar results are observed for yield strength (YS) and percentage elongation also. The highest UTS observed (143.7 MPa – table 4) is very low as compared with that of pure Cu (239 MPa), which has lower strength of the two base metals.

3.3 Analysis of experiment results

3.3a Mathematical model: Experiments were performed as per 3-factor, 3-level Box–Behnken design of response surface methodology with total 15 runs including 3 centre points. Analysis of data was done using DESIGN EXPERT software.

A second-order (quadratic) mathematical model can be developed for prediction of response variable:

$$Y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

where Y is the response variable, while x_i are factors or process variables. In Eq. (1), terms in x_i are linear, terms in x_i^2 are quadratic and terms in $x_i x_j$ are product terms; β_0 , β_i , β_{ii} and β_{ij} are constant coefficients while ε is residual random error.

Model for UTS

Here, UTS of dissimilar welds is the response variable. Tool rotation speed (N), tool travel speed (V) and tool pin offset (O) are factors or process variables. Therefore, Eq. (1) can be expressed as follows:

Figure 6. Top seam appearance of FS welds.

Table 4. Tensile properties and peak temperature of dissimilar welds.

Std. weld run no.	Randomized run order no.	Tool rotation speed (rpm)	Tool travel speed (mm/min)	Tool pin offset (mm)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Peak temp. at TC-1 (°C)
1	15	710	28	1.0	97.04	63.20	4.84	192
2	1	1400	28	1.0	68.98	55.43	2.32	248
3	6	710	80	1.0	69.50	54.86	3.19	200
4	13	1400	80	1.0	87.77	64.88	3.86	201
5	3	710	56	0.5	103.50	66.90	4.65	194
6	14	1400	56	0.5	81.85	53.69	3.50	248
7	7	710	56	1.5	107.59	73.18	5.63	161
8	12	1400	56	1.5	118.66	84.21	5.08	188
9	9	1000	28	0.5	115.83	68.67	5.71	287
10	10	1000	80	0.5	103.22	73.20	5.16	231
11	4	1000	28	1.5	130.24	84.94	5.55	200
12	8	1000	80	1.5	111.20	82.41	3.54	193
13	11	1000	56	1.0	143.67	95.95	6.10	221
14	2	1000	56	1.0	132.04	78.35	6.54	243
15	5	1000	56	1.0	141.31	100.20	6.06	239

tensile strength (UTS)

$$= \beta_0 + \beta_1 N + \beta_2 V + \beta_3 O + \beta_{12} NV + \beta_{13} NO + \beta_{23} VO + \beta_{11} N^2 + \beta_{22} V^2 + \beta_{33} O^2 \quad (2)$$

Applying regression analysis on the friction stir welding process parameters and response variables, the following second-order polynomial equation is obtained:

$$\begin{aligned}
 \text{tensile strength (UTS)} &= -173.72350 + 0.49950(N) + 2.24316(V) \\
 &\quad -20.22124(O) + 1.29041 \times 10^{-3}(N)(V) \\
 &\quad + 0.04754(N)(O) - 0.12308(V)(O) \\
 &\quad -2.95771 \times 10^{-4}(N)^2 - 0.03403(V)^2 - 3.71667(O)^2.
 \end{aligned} \quad (3)$$

Equation (3) is a mathematical model for prediction of UTS of dissimilar welds with Zn-electroplated interlayer in uncoded form.

The same equation can be written in coded form as follows:

$$\begin{aligned}
 \text{tensile strength (UTS)} &= 139.03 - 2.54(N) - 5.04(V) \\
 &\quad + 7.93(O) + 11.58(N)(V) + 8.20(N)(O) - 1.60(V)(O) \\
 &\quad - 35.20(N)^2 - 23.00(V)^2 - 0.93(O)^2.
 \end{aligned} \quad (3)$$

Model for YS

Similarly, the mathematical model for prediction of YS of dissimilar weld can be expressed in uncoded form as follows:

$$\begin{aligned}
 \text{YS} &= -112.8248 + 0.2897(N) + 1.5491(V) + 2.8844(O) \\
 &\quad + 4.96 \times 10^{-4}(N)(V) + 3.507 \times 10^{-2}(N)(O) \\
 &\quad - 0.134615(V)(O) - 1.6710^{-4}(N)^2 - 1.7810^{-2}(V)^2 \\
 &\quad - 8.53333(O)^2.
 \end{aligned} \quad (5)$$

Equation (5) can be expressed in coded form as follows:

$$\begin{aligned}
 \text{YS} &= 91.47 + 0.4(V) + 7.775(O) + 4.45(N)(V) + 6.05(N) \\
 &\quad (O) - 1.75(V)(O) - 19.83(N)^2 - 12.03(V)^2 - 2.13(O)^2.
 \end{aligned} \quad (6)$$

Model for percentage elongation

Similarly, mathematical model for prediction of percentage elongation of dissimilar weld can be expressed in uncoded form as follows:

$$\begin{aligned}
 \% \text{ elongation} &= -6.61608 + 0.019243(N) + 0.113625(V) \\
 &\quad + 1.11710(O) + 8.89 \times 10^{-5} + 8.70 \\
 &\quad \times 10^{-4}(N)(O) - 0.02808(V)(O) \\
 &\quad - 1.2417 \times 10^{-5}(N)^2 - 1.779 \times 10^{-3}(V)^2 \\
 &\quad - 0.161667(O)^2.
 \end{aligned} \quad (7)$$

Equation (7) can be expressed in coded form as follows:

$$\begin{aligned}
 \% \text{ elongation} &= 6.23 - 0.4438(N) - 0.3338(V) + 0.0975(O) \\
 &\quad + 0.7975(N)(V) + 0.15(N)(O) \\
 &\quad - 0.365(V)(O) - 1.478(N)^2 - 1.20(V)^2 \\
 &\quad - 0.0404(O)^2.
 \end{aligned} \quad (8)$$

3.3b Analysis of variance (ANOVA): The significance of fits of the developed mathematical models was tested using analysis of variance (ANOVA). Results of ANOVA are presented in tables 5, 6, 7.

A regression model/parameter is assessed for its significance using *F*-test. As per *F*-test, a regression model/parameter can be considered to be significant when the following two conditions are satisfied: (i) *F*-value (Fisher's ratio) for the model/parameter must be higher than *F*-statistic (also known as *F* critical value) of respective model/parameter and (ii) *p*-value (prob > *F*) must be lower than α (alpha level); α indicates critical probability, which can be obtained by subtracting confidence interval from 100%. In ANOVA (tables 5, 6, 7), *p*-value (prob > *F*) is the conditional probability of getting a test statistic (*F* - statistic) as extreme or more extreme than the calculated test statistic (*F*-value for model/parameter), given that the null hypothesis is true. *F*-value for a model/parameter is calculated as ratio of mean sum of squares for a model/parameter to mean sum of squares of residuals. *F*-statistic can be obtained depending on α , degrees of freedom (dof) of regression model/parameter and dof of residuals using *F* -statistic table for probability distribution for *F*-statistic. The most commonly used confidence interval is 95%, and α level for the same is 0.05.

ANOVA for UTS model

F-value for the developed mathematical model for UTS is 23.31, while *F*-statistic is 4.7725 (dof of model: 9 and dof of residuals: 5 with α : 0.05). Here, *p*-value is 0.0015 (table 5), which is less than 0.05 (α level for 95% confidence interval); hence, null hypothesis can be rejected. This indicates that the regression model is significant. For a parameter (term) to be considered significant, *p*-value for the parameter must be lower than α level considered. For the 95% confidence interval, applicable α value is 0.05. Hence, significant model terms are the terms for which *p*-value is less than 0.050. Thus, terms *O*, *NV*, *NO*, *N*² and *V*² are significant in the developed mathematical model for UTS. Tool rotation speed (*N*) and tool travel speed (*V*) are insignificant terms in the model; however, square of tool rotation speed (*N*²) and square of tool travel speed (*V*²) are significant terms. This indicates that effects of tool rotation speed and tool travel speed on UTS of dissimilar weld are non-linear. For 'lack of fit,' *F*-value is 0.97 and *p*-value is 0.5443. This means the 'lack of fit' is non-significant.

Table 5. ANOVA for UTS full regression model.

Source	Sum of squares	dof	Mean square	F value	p-value (prob > F)	Coefficient of determination (R^2)	Remark
Model	7717.05	9	857.45	23.31	0.0015	0.9767	Significant
N	51.51	1	51.51	1.40	0.2898		
V	203.01	1	203.01	5.52	0.0656		
O	502.44	1	502.44	13.66	0.0141		
NV	535.92	1	535.92	14.57	0.0124		
NO	268.96	1	268.96	7.31	0.0426		
VO	10.24	1	10.24	0.28	0.6203		
N^2	4576.00	1	4576.00	124.43	0.0001		
V^2	1953.94	1	1953.94	53.13	0.0008		
O^2	3.19	1	3.19	0.087	0.7803		
Residual	183.88	5	36.78				Not significant
Lack of fit	108.90	3	36.30	0.97	0.5443		
Pure error	74.99	2	37.49				
Cor. total	7900.93	14					

Table 6. ANOVA for yield strength full regression model.

Source	Sum of squares	dof	Mean square	F value	p-value (prob > F)	Coefficient of determination (R^2)	Remark
Model	2585.34	9	287.26	4.99	0.0458	0.8998	Significant
N	0.0000	1	0.0000	0.0000	1.0000		
V	1.28	1	1.28	0.0222	0.8873		
O	483.61	1	483.61	8.39	0.0339		
NV	79.21	1	79.21	1.38	0.2938		
NO	146.41	1	146.41	2.54	0.1718		
VO	12.25	1	12.25	0.2127	0.6641		
N^2	1452.41	1	1452.41	25.21	0.0040		
V^2	534.65	1	534.65	9.28	0.0285		
O^2	16.80	1	16.80	0.2917	0.6123		
Residual	288.03	5	57.61				Not significant
Lack of fit	18.74	3	6.25	0.0464	0.9834		
Pure error	269.29	2	134.64				
Cor. total	2873.37	14					

Table 7. ANOVA for percentage elongation full regression model.

Source	Sum of squares	dof	Mean square	F value	p-value (prob > F)	Coefficient of determination (R^2)	Remark
Model	18.27	9	2.03	3.12	0.1114	0.8490	Not significant
N	1.58	1	1.58	2.42	0.1802		
V	0.8911	1	0.8911	1.37	0.2944		
O	0.0761	1	0.0761	0.1170	0.7462		
NV	2.54	1	2.54	3.91	0.1048		
NO	0.0900	1	0.0900	0.1385	0.7250		
VO	0.5329	1	0.5329	0.8200	0.4067		
N^2	8.06	1	8.06	12.41	0.0169		
V^2	5.34	1	5.34	8.22	0.0351		
O^2	0.0060	1	0.0060	0.0093	0.9270		
Residual	3.25	5	0.6499				Not significant
Lack of fit	3.11	3	1.04	14.60	0.0648		
Pure error	0.1419	2	0.0709				
Cor. total	21.52	14					

Non-significant ‘lack of fit’ is preferred to fit the model. Determination coefficient (R^2) of any model indicates its goodness of fit. For this model, determination coefficient (R^2) is 0.9767 while adjusted determination coefficient (adjusted R^2) is 0.9348. This indicates good correlation between experimental and predicted results.

ANOVA for YS model

F -value for the developed mathematical model for YS is 4.99, while F -statistic is 4.7725 (dof of model: 9 and dof of residuals: 5 with α : 0.05). For the developed model of YS, p -value is 0.0458 (table 6); hence, null hypothesis can be rejected for 95% confidence interval, and the regression model is significant. Model terms O , N^2 and V^2 are significant in the developed mathematical model for YS. Tool rotation speed (N) and tool travel speed (V) are insignificant terms in the model; however, square of tool rotation speed (N^2) and square of tool travel speed (V^2) are significant terms. This indicates that effects of tool rotation speed and tool travel speed on YS of dissimilar weld are non-linear. For ‘lack of fit,’ F -value is 0.0464 and p -value is 0.9834. This means the ‘lack of fit’ is non-significant. Non-significant ‘lack of fit’ is preferred to fit the model. For model of YS, determination coefficient (R^2) is 0.8998 while adjusted determination coefficient (adjusted R^2) is 0.7193.

ANOVA for percentage elongation model

F -value for the developed mathematical model for percentage elongation is 3.12, while F -statistic is 4.7725 (dof of model: 9 and dof of residuals: 5 with α : 0.05). For the developed model for percentage elongation, p -value is 0.1114 (table 7); hence, null hypothesis cannot be rejected and the regression model cannot be considered significant. In the developed mathematical model for percentage elongation, only terms N^2 and V^2 are significant. This indicates that effects of tool rotation speed and tool travel speed on percentage elongation of dissimilar weld are non-linear. For ‘lack of fit,’ F -value is 14.60. ‘Lack of fit’ is non-significant as p -value for ‘lack of fit’ is 0.0648. Although ‘lack of fit’ is not significant, p -value for ‘lack of fit’ is relatively low, which is not good. For model of percentage elongation, determination coefficient (R^2) is 0.8490 while adjusted determination coefficient (adjusted R^2) is 0.5771. This full model for percentage elongation is non-significant and has many non-significant terms; further improvement of the model is possible by excluding non-significant terms.

3.3c Model reduction: From ANOVA for full models for prediction of all three response variables (section 3.3b), it is observed that there are many non-significant terms in all full models, and the full model for prediction of percentage elongation is not significant. Therefore, improvement of models by excluding non-significant terms is required. In this section, reduced models for all three response variables are presented. The reduced model is derived by excluding non-significant terms of the full model (except those non-

significant terms that are required to maintain hierarchy of terms in the model).

Reduced model for UTS

Reduced model for prediction of UTS can be expressed in uncoded form as follows:

$$\begin{aligned} UTS = & -162.96 + 0.4982(N) + 2.10867(V) - 34.30(O) \\ & + 1.29 \times 10^{-3}(N)(V) + 4.75 \times 10^{-2}(N)(O) \\ & - 2.95 \times 10^{-4}(N)^2 - 3.39 \times 10^{-2}(V)^2. \end{aligned} \quad (9)$$

Equation (9) is the final reduced mathematical model for prediction of UTS of dissimilar welds with Zn electroplated interlayer in uncoded form. It can be expressed in coded form as follows:

$$\begin{aligned} UTS = & 138.46 - 2.54(N) - 5.04(V) + 7.93(O) + 11.58(N)(V) \\ & + 8.20(N)(O) - 35.13(N)^2 - 22.93(V)^2. \end{aligned} \quad (10)$$

Reduced model for YS

The final reduced mathematical model for prediction of YS of dissimilar weld can be expressed in uncoded form as follows:

$$\begin{aligned} YS = & -161.3568 + 0.348684(N) + 1.91165(V) \\ & + 15.55(O) - 1.65 \times 10^{-4}(N)^2 - 1.756 \times 10^{-2}(V)^2. \end{aligned} \quad (11)$$

Equation (11) can be expressed in coded form as follows:

$$\begin{aligned} YS = & 90.15 + 0.0000(N) + 0.4(V) \\ & + 7.78(O) - 19.67(N)^2 - 11.87(V)^2. \end{aligned} \quad (12)$$

Reduced model for percentage elongation

The final reduced mathematical model for prediction of percentage elongation of dissimilar weld can be expressed in uncoded form as follows:

$$\begin{aligned} \% \text{ elongation} = & -5.64304 + 2.00 \times 10^{-2}(N) + 8.505 \\ & \times 10^{-2}(V) + 8.891 \times 10^{-5}(N)(V) \\ & - 1.239 \times 10^{-5}(N) - 1.775 \times 10^{-3}(V)^2. \end{aligned} \quad (13)$$

Equation (13) can be expressed in coded form as follows:

$$\begin{aligned} \% \text{ elongation} = & 6.21 - 0.4438(N) - 0.3338(V) \\ & + 0.7975(N)(V) - 1.4748(N)^2 + 1.20(V)^2. \end{aligned} \quad (14)$$

3.3d ANOVA for reduced models: Results of ANOVA for reduced models of all three response variables are presented in tables 8, 9, 10.

Table 8. ANOVA for UTS final reduced regression model.

Source	Sum of squares	dof	Mean square	F value	p-value (prob > F)	Coefficient of determination (R^2)	Remark
Model	7703.62	7	1100.52	39.04	< 0.0001	0.9750	Significant
N	51.51	1	51.51	1.83	0.2185		
V	203.01	1	203.01	7.20	0.0314		
O	502.44	1	502.44	17.83	0.0039		
NV	535.92	1	535.92	19.01	0.0033		
NO	268.96	1	268.96	9.54	0.0176		
N^2	4584.57	1	4584.57	162.65	< 0.0001		
V^2	1953.37	1	1953.37	69.30	< 0.0001		
Residual	197.31	7	28.19				
Lack of fit	122.33	5	24.47	0.6525	0.6974		Not significant
Pure error	74.99	2	37.49				
Cor. total	7900.93	14					

Table 9. ANOVA for yield strength final reduced regression model

Source	Sum of squares	dof	Mean square	F value	p-value (prob > F)	Coefficient of determination (R^2)	Remark
Model	2330.67	5	466.13	7.73	0.0045	0.8111	Significant
N	4.547E-13	1	4.547E-13	7.541E-15	1.0000		
V	1.28	1	1.28	0.0212	0.8874		
O	483.60	1	483.60	8.02	0.0197		
N^2	1436.98	1	1436.98	23.83	0.0009		
V^2	523.26	1	523.26	8.68	0.0163		
Residual	542.71	9	60.30				
Lack of fit	273.42	7	39.06	0.2901	0.9092		Not significant
Pure error	269.29	2	134.64				
Cor. total	2873.37	14					

Table 10. ANOVA for percentage elongation final reduced regression model.

Source	Sum of squares	dof	Mean square	F value	p-value (prob > F)	Coefficient of determination (R^2)	Remark
Model	17.56	5	3.51	7.99	0.0040	0.8162	Significant
N	1.58	1	1.58	3.59	0.0908		
V	0.8911	1	0.8911	2.03	0.1881		
NV	2.54	1	2.54	5.79	0.0395		
N^2	8.08	1	8.08	18.39	0.0020		
V^2	5.35	1	5.35	12.17	0.0068		
Residual	3.95	9	0.4394				
Lack of fit	3.81	7	0.5447	7.68	0.1200		Not significant
Pure error	0.1419	2	0.0709				
Cor. total	21.52	14					

ANOVA for reduced model of UTS

F -value for the developed final reduced mathematical model for UTS is 39.04, while F -statistic is 3.787 (for dof of model: 7 and dof of residuals: 7 with α : 0.05). For the developed model of UTS, p -value is less than 0.0001 (table 8), which indicates that the regression model is significant. Model terms V , O , NV , NO , N^2 and V^2 are significant in the developed final reduced mathematical model

for UTS. Even though tool rotation speed (N) is not a significant term, significant square of tool rotation speed (N^2) and square of tool travel speed (V^2) terms in the model indicate that effects of tool rotation speed and tool travel speed on UTS of dissimilar weld are non-linear. For 'lack of fit,' F -value is 0.6525 and p -value is 0.6974. This means the 'lack of fit' is non-significant. For this reduced model for UTS, determination coefficient (R^2) is 0.9750 while

adjusted determination coefficient (adjusted R^2) is 0.9501. This indicates good correlation between experimental and predicted results. Hence the model is sufficient to describe the relationship between UTS and process variables – tool rotation speed, tool travel speed and tool offset.

ANOVA for reduced model of YS

F -value for the developed final reduced mathematical model for YS is 7.73, while F -statistic is 3.4817 (dof of the reduced model: 5 and dof of residuals: 9 with α : 0.05). For the developed reduced model of YS, p -value is 0.0045; therefore the regression model can be considered to be significant. Terms O , N^2 and V^2 are significant terms in the developed reduced mathematical model for YS. Effects of tool rotation speed and tool travel speed on YS of dissimilar weld are non-linear as square of tool rotation speed (N^2) and square of tool travel speed (V^2) are significant terms, while tool rotation speed (N) and tool travel speed (V) are non-significant terms in the mathematical model for prediction of YS. For ‘lack of fit,’ F -value is 0.2901 and p -value for “prob > F -value” is 0.9092, which indicate that the ‘lack of fit’ is non-significant. For the reduced model of YS, determination coefficient (R^2) is 0.8111 and adjusted determination coefficient (adjusted R^2) is 0.7062. This indicates good correlation between experimental and predicted results.

ANOVA for reduced model of percentage elongation

F -value for the developed final reduced mathematical model for percentage elongation is 7.99, while F -statistic is 3.4817 (dof of model: 5 and dof of residuals: 9 with α : 0.05). For the reduced model for percentage elongation, p -value is 0.0040 (table 10), which is less than 0.05; therefore, null hypothesis can be rejected. This indicates that the reduced regression model for percentage elongation is significant. In the model for percentage elongation model terms, NV , N^2 and V^2 are significant. Significant second-order terms in the model indicate that effects of tool rotation speed and tool travel speed on percentage elongation of dissimilar weld are non-linear. Parameter tool pin offset has very little effect on percentage elongation. For ‘lack of fit,’ F -value is 7.68 and p -value is 0.1200. This means that ‘lack of fit’ is non-significant. Determination coefficient (R^2) value of 0.8162 and adjusted determination coefficient (adjusted R^2) value of 0.7141 indicate good correlation between experimental and predicted results for the reduced model of percentage elongation.

3.3e Response surface and effects of process parameters:

Effect of process parameters on 3-D response surface of response UTS is shown in figures 7, 8, 9. As discussed earlier, effects of tool rotation speed (N) and tool travel speed (V) on UTS are non-linear. The same is reflected in response surfaces as curvature along axes of these two parameters. 3-D response surface indicating effect of tool travel speed and tool rotation speed on UTS of dissimilar welds is shown in figure 7. Peak value of UTS is observed

Figure 7. Response surface for effect of tool travel speed and tool rotation speed on UTS.

Figure 8. Response surface for effect of tool pin offset and tool rotation speed on UTS.

Figure 9. Response surface for effect of tool pin offset and tool travel speed on UTS.

in the central region of the plot. At low tool rotation speed of 710 rpm, reduced UTS is observed due to insufficient heat input. Insufficient heat input results in lack of

Figure 10. Response surface for effect of tool travel speed and tool rotation speed on YS.

Figure 12. Response surface for effect of tool pin offset and tool travel speed on YS.

Figure 11. Response surface for effect of tool pin offset and tool rotation speed on YS.

Figure 13. Response surface for effect of tool rotation speed and tool travel speed on YS.

plasticization of both base materials, leading to improper material flow. Improper material flow results in weak welds. At intermediate tool rotation speed of 1000 rpm there is sufficient heat input, leading to proper plasticization and mixing of materials from both sides, resulting in strong welded joints. However, increasing tool rotation speed to 1400 rpm resulted in weaker joints due to very high heat input. High heat input results in growth of thick intermetallic layers of Al–Cu system at the Al–Cu interface. Commonly formed intermetallics are CuAl_2 and Cu_9Al_4 . These intermetallics are very hard and brittle. With a view to minimize formation of intermetallics of Al–Cu system, a thin layer ($\sim 15 \mu\text{m}$) of pure Zn was electroplated on abutting edge of pure Cu sheets prior to welding. Even then, formation of intermetallics could not be prevented at very high heat input. Presence of these hard and brittle intermetallics decreases the UTS of dissimilar Al–Cu joints. Effect of tool travel speed could be understood again based on heat input. Lower tool travel speed (28 mm/min)

increases heat input, leading to formation of intermetallics and reduced UTS. Higher tool travel speed of 80 mm/min results in insufficient heat input and improper material flow. Hence, high tool travel speed leads to reduction in UTS. The effect of tool travel speed and tool rotation speed on heat input can be verified from the measured values of peak temperature at thermocouple-1 (TC-1) tabulated in table 4. However, effect of change of levels of tool offset on heat generation and heat input should be considered.

Figure 8 displays the 3-D response surface showing effects of tool pin offset and tool rotation speed on UTS of dissimilar welds. Curvature is observed along the tool rotation speed axis. Effects of tool rotation speed can be explained based on heat input, proper material mixing and formation of intermetallics. An increment in UTS is observed as tool pin offset is increased from +0.5 to +1.5 mm. This rise is not so notable at tool rotation speed of 710 and 1000 rpm. However, it is notable and severe at higher rotation speed of 1400 rpm. Theoretically, as tool

Table 11. Results of confirmation runs.

Sr. no.	FSW process parameters			UTS (MPa)			YS (MPa)			Elongation (%)		
	N (rpm)	V (mm/min)	O (mm)	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)
1	1000	56	+1.5	140.80	143.93	+2.22	100.97	97.39	−3.55	6.30	6.20	−1.59
2	1400	56	+1.5	118.74	117.28	−1.23	76.42	78.22	+2.36	4.12	4.32	+4.85
3	1000	28	+1.0	121.49	121.9	+0.35	80.10	77.4	−3.40	5.26	5.51	+4.75

Figure 14. Optical micrograph of base metals.

pin offset is increased towards Al side, amount of Cu volume in stir zone (weld nugget) decreases. This decrement in volume of Cu within swept volume reduces amount of intermetallics formed [36]. Response surface indicates maxima at +1.5 mm. This is with the least intermetallic content and formation of a thin intermetallic layer at the Al–Cu interface is likely. If the tool pin offset range is set beyond +1.5 mm there might be maxima near +1.5 mm. These results are similar to observations of Sahu *et al* [22]. Sahu *et al* [22] varied tool pin offset at four levels (+0.5, +1.0, +1.5 and +2.0 mm) and observed that tool pin offset of +1.5 mm towards Al alloy sheet is optimum, resulting in the highest UTS of weld. Extreme value for tool pin offset could be 2.0 mm only as tool pin diameter is 4.0 mm. However, in this case, joint formation would be based on diffusion at base metal sheet interface [4] and a strong joint cannot be expected.

A curvature along tool travel speed axis is observed in 3-D response surface, indicating effects of tool pin offset and tool travel speed on UTS (figure 9). As tool pin offset is increased, tensile strength is also increased. However, effects in change of tool offset are not strong at high tool travel speed of 80 mm/min and intermediate tool travel speed of 56 mm/min. It is notable and severe at lower tool

travel speed of 28 mm/min. Notable impact of tool pin offset at high tool rotation speed of 1400 rpm (figure 8) and low tool travel speed of 28 mm/min (figure 9) may be attributed to growth of intermetallic layers at these conditions of high heat input. However, at lower and moderate heat input conditions, amount of formed intermetallics is reduced and gain available from use of tool pin offset for reduction of content of intermetallics becomes insignificant.

Similar trends are also observed for effects of process parameters on YS (figures 10, 11, 12) and percentage elongation (figure 13). As tool pin offset term (both linear O and non-linear O^2 form) is not included in the final reduced regression model for percentage elongation, only one response surface (figure 13) is generated for the model of percentage elongation.

3.3f Confirmation runs: Mathematical models presented were derived from quadratic regression fits. To check efficacy of the developed final reduced regression models, three confirmation runs were conducted (table 11). Parameter settings for confirmation run no. 2 were from plan of experiments. Confirmation run no. 2 was a repeat run from 15 runs conducted as a part of Box–Behnken DOE. Parameter settings for confirmation run nos. 1 and 3 were within defined

(a) Macrostructure **(b) Bottom region of stir zone** **(c) Stir zone - Cu fragment** **(d) Stir zone of AA6061** **(e) Thin interlayer between Cu & Al** **(f) composite structure with intercalated layers****Figure 15.** Microstructural characterization of the weld of confirmation run 1.

range of levels for all process variables. Predicted values and measured values of UTS, YS and percentage elongation are tabulated in table 11. From table 11, it may be noted that % error between experimentally measured and predicted values of UTS is within -1.23% to $+2.22\%$. For the reduced model of YS, % error between experimentally measured and

predicted values is within -3.55% to $+2.36\%$. For reduced model of percentage elongation, %error between experimentally measured and predicted values is within the range of -1.59% to $+4.85\%$. Error between predicted and experimentally measured tensile properties of dissimilar welds of confirmation runs is within -5% to $+5\%$. This indicates good

Figure 16. Microhardness distribution for confirmation weld 1 (1000 rpm, 56 mm/min, +1.5 mm offset).

Figure 17. XRD analysis for welds of confirmation runs 1 and 3.

level of correlation between experimental and predicted values.

4. Characterization of welds

4.1 Microstructural characterization

Optical micrographs of parent metals AA6061-T6 and pure Cu sheet are shown in figure 14. In the microstructure of AA6061-T6 (figure 14a), Mg_2Si precipitates dispersed in grains having random orientation are observed. AA6061 is in solution-treated and artificially age hardened temper condition. In the optical micrograph of parent metal pure Cu (figure 14b), comparatively fine grains as compared with grains of AA6061-T6 are observed. Typical annealing twins are also observed.

Optical micrographs of dissimilar friction stir weld of confirmation run 1 (1000 rpm, 56 mm/min, +1.5 mm tool offset) are shown in figure 15. In the bottom region of stir

zone (figure 15b), fine intercalated layers of base metals along with layers of Zn are observed. Along with base metal layers, agglomeration of blackish particles in bottom region of stir zone is observed, which are likely inter-metallic layers. This is because bottom region of stir zone is rapidly cooled due to contact with the backing plate of fixture. Intermetallics are formed due to generation of very high peak temperature, leading to high cooling rates. Higher intermetallic content deteriorates tensile properties of dissimilar welds. In figure 15c, notable variation in grain size of Cu from stir zone to thermo-mechanically affected zone (TMAZ) boundary to heat-affected zone (HAZ) is observed. Very fine grain structure near the weld interface in TMAZ on advancing side is observed. Thereafter, coarse grains are observed within HAZ. This may be attributed to grain coarsening due to annealing of Cu due to typical heating and cooling cycle during friction stir welding process. Within AA6061-T6 side of stir zone, very fine grain structure (figure 15d) is observed, which may be attributed to dynamic recrystallization. Figure 15e indicates that

growth of intermediate layer is not significant. In figure 15e, interface between Cu and AA6061 in bottom region of stir zone has been shown. A very thin and uniform intermediate layer between Al and Cu is observed. Use of Zn coating interlayer between Al and Cu is one of the reasons for formation of the very thin intermediate intermetallic layer. Notably higher UTS of weld of confirmation run 1 could be attributed to suppressed growth of intermetallic layer at the Al–Cu interface. Identification of phases within the thin intermediate layer may be performed using XRD analysis.

In the central part of stir zone (figure 15f), intercalated layers of base metals Al and Cu along with many entrapped particles of base metals are observed. Entrapped particles were also observed by Tohid *et al* [37]. Thus, use of Zn coating interlayer resulted in formation of a composite-like structure. However, intercalated layers are not uniform in terms of size. It may be concluded from the microstructural characterization that for confirmation weld 1, use of Zn coating interlayer suppressed growth of intermediate intermetallic layer notably and formed the composite-like structure.

4.2 Microhardness distribution

Microhardness distribution for confirmation weld run 1 is plotted in figure 16. Here, microhardness indentation positions on advancing side are shown with a ‘negative (–)’ sign while the same on RS are shown with a positive (+) sign. The Al–Cu interface has been marked as ‘0’ (zero). Significant decrement in microhardness on advancing side is observed in comparison with microhardness of parent metal pure Cu (91.2 HV0.2). On the RS, an increment in microhardness above the microhardness of parent metal AA6061-T6 (87.8 HV0.2) is observed. On both sides, minor fluctuations in microhardness are observed. Increment in microhardness on AA6061-T6 side may be attributed to precipitation hardening because of precipitation of Mg_2Si particles due to heating and cooling cycle. Drop in microhardness on the advancing side (pure Cu) is because of softening of pure Cu sheet due to annealing. Heating due to friction stir welding and subsequent quenching by atmospheric air results in annealing of the pure Cu sheet. This is confirmed from results of optical microscopy. As per optical microscopy (figure 15c), in the advancing side HAZ, coarse grains are observed as compared with base metal Cu and stir zone due to annealing. At the Al–Cu interface, very high microhardness (137.0 HV0.2) is observed. Higher microhardness at the weld interface is typical of dissimilar Al–Cu welding. This may be attributed to formation of brittle intermetallics of Al–Cu and/or grain refinement due to dynamic recrystallization along with solid solution strengthening by dissolution of Zn atoms within stir zone material. As observed from optical micrographs of stir zone of Al (figure 15d), very fine grain

structure is observed. In addition, at the centre of stir zone (figure 15f), a composite-type structure composed of intercalated layers of base metals and several entrapped particles of base metals is observed. Higher hardness at the Al–Cu interface may be attributed to this composite type of structure (figure 15f) and intermetallic layer (figure 15e) formation. Akinlabi [38] also attributed higher microhardness at the Al–Cu interface to dissimilar FS weld, grain refinement and formation of intermetallic layer. However, this requires further investigation in terms of XRD analysis.

4.3 XRD analysis

XRD patterns for two confirmation runs with phase identifications are shown in figure 17. The presence of only Al and Cu peaks in XRD pattern indicates that no new phase has been formed. Apparently it appears that both patterns are different but they are nearly similar. Both patterns differ only in terms of peak intensity of Al; otherwise, positions of peaks are the same in both patterns. However, there is a notable difference in flex width (FWHM – full-width at half-maximum) of each peak in both patterns. FWHM for each peak for weld run 1 is higher than that of respective peak for weld run 3. Now it is well established that for a solid-phase material, grain size is inversely proportional to FWHM of XRD patterns of the same. Accordingly, it may be said that in weld of confirmation run 1, fine grains are formed as compared with weld of confirmation run 3. This is due to higher heat input for weld run 3. For weld run 3, net heat input is higher than the net heat input for weld run 1 because of higher welding speed in case of weld run 3. Due to high input there may have been grain growth for weld run 3. Low heat input coupled with dynamic recrystallization results in fine grain structure in case of weld run 1. It is also important to note the difference in levels of tool offsets used in both experiments. For confirmation weld run 1 the tool offset was +1.5 mm towards Al sheet, while for confirmation weld run 3 the tool offset was +1.0 mm. For the same tool rotation speed and tool travel speed, for the weld prepared at +1.5 mm tool offset, the heat generation is less in comparison with the weld made at +1.0 mm tool offset. Therefore it may be summarized that particle size of each phase detected by XRD (Al and Cu) is finer in case of confirmation run weld 1 as compared with confirmation run weld 3. In addition to effect on heat input, level of tool offset also affects amount and form of intermetallics in the manner where higher tool offset leads to better and sound weld with low amount of intermetallics. Therefore, weld of confirmation run 1 is stronger than the weld of confirmation run 3.

5. Conclusions

Following important conclusions may be drawn from the present investigation. (i) An experimental investigation has been conducted to investigate effects of friction stir

welding parameters – tool rotation speed, tool travel speed and tool pin offset – on tensile properties of dissimilar AA6061-T6 to pure Cu joints with Zn electroplated interlayer in butt configuration. (ii) Mathematical models have been developed for prediction of UTS, YS and percentage elongation of dissimilar friction stir welds using 3-level, 3-factor Box–Behnken design of response surface methodology. ANOVA indicated that the factor tool pin offset has significant effect on UTS and YS. However, the factor tool pin offset has little effect on percentage elongation of dissimilar weld. On the other side, squares of tool rotation speed and tool travel speed also have significant effects on UTS, YS and percentage elongation of dissimilar friction stir weld. Developed mathematical models were validated by conducting confirmation runs. Results of confirmation runs indicated that % errors between predicted and experimental values are within -3.55% to $+4.85\%$. Hence, a very good level of correlation between experimental and predicted values is observed. (iii) Microstructural characterization of weld of confirmation run 1 indicated formation of a very thin intermediate interlayer between Cu fragment and Al side stir zone. Along with typical dynamic recrystallization, a composite-type structure with dispersion of entrapped particles and intercalated layers of base metals is observed. (iv) Results of XRD analysis indicated that no new phase is observed other than base metals Al and Cu in two confirmation run welds (confirmation runs 1 and 3). However, in XRD pattern of the stronger weld of run 1, wider flex width is observed, indicating finer particle (grain) size. Thus, use of Zn interlayer essentially eliminated formation of thick intermetallic interlayer between AA6061-T6 and pure Cu. (v) Microhardness testing results of confirmation run weld 1 showed typically higher microhardness at the weld interface, indicating formation of harder composite-type stir zone and/or formation of intermetallics.

List of symbols

$\text{adj-}R^2$	adjusted determination coefficient for regression model
$\beta_0, \beta_i, \beta_{ii}$	constant coefficients in regression equation and β_{ij}
F -value	Fishers' ratio
HF	hydrofluoric acid
H ₂ O	water
H ₂ SO ₄	sulphuric acid
HV0.2	Vickers' microhardness with indentation load of 200 g
K ₂ Cr ₂ O ₇	potassium dichromate
MPa	10 ⁶ Pa (Pascal)
N	tool rotation speed
NaCl	sodium chloride
O	tool pin offset
p	probability

R^2	determination coefficient for regression model
V	tool travel speed
x_i	linear terms in regression equation
x_{ii}	quadratic terms in regression equation
$x_i x_j$	product terms in regression equation
Y	response variable in regression equation

Abbreviations

AISI	American Iron and Steel Institute
ANOVA	analysis of variance
AS	advancing side
ASTM	American Society of Testing Materials
DOE	design of experiments
FWHM	full-width at half-maximum
RS	retreating side
TMAZ	thermo-mechanically affected zone
TWI	The Welding Institute
UTS	ultimate tensile strength
XRD	X-ray diffraction
YS	yield strength

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