Optimization of FSW Process Parameters to Yield Maximum Shear Fracture Load of AA2024 Aluminum Alloy Joints

A Rajesh¹*, C Bhaveshkumar¹, L Aswin¹, S Aravind Nachiappan¹, R Ashwin¹

¹Department of Mechanical Engineering, Sri Krishna College of Engineering and Technology, Coimbatore, India-641008.

*rajesh@skcet.ac.in

Abstract. AA2024 Aluminum alloy has predominantly been used for making aircraft engine parts and frames. The normal welding process does not apply to join aluminum alloy. Because Al and its alloy have a low melting point and high thermal conductivity, which can easily lead to porosity and partially melting; as a result, Friction Stir Welding (FSW) has been employed to solve these issues. This work focused on the parameter’s optimization to the conceived maximum strength of AA2024 aluminum alloy. Four major parameters viz., tilt angle, shoulder diameter, welding speed, and rotational speed were selected. The formulation of empirical relationship was made using statistical tool design of experiment, and analysis of variance has been used to check the developed model’s adequacy. Furthermore, the response surface graphs were used to identify the maximum strength and its corresponding FSW parameters. The joint obtained the full power from the experimental results at a tilt angle of 1.5 deg., traverse speed of 15 mm/ min, speed of tool 1100 rpm, and diameter of shoulder 24 mm.

Keywords: FSW, Al-Cu alloy, lap joint.

1. Introduction

Aluminum alloy is essential in structural fabrication industries such as aircraft and automobile industries due to its strength ratio, corrosion resistance, and formability. The joining of this alloy is tedious by high thermal conductivity, partial melted zone, alloy segregation, etc. [1,2]. A solid-state welding technique has been widely used in recent years. TWI was invented the FSW process in UK, 1998 and used on Al alloys. However, a thorough understanding of this joining process alters metallurgical properties under a solid-state. Is still required for widespread use of this welding procedure in the industry [3]. The effectiveness of the produced joint is, in fact, substantially influenced by several operating parameters [4]. First, tool geometry had a significant impact on material mixing and heat development due to rubbing load [5]. Second, process parameters viz., welding speed, rotational speed, and tilt angle must be chosen to improve the integrity of the nugget. Which leads to strength, microstructure, and fatigue strength of the joint [6]. The heat generated by the friction tool, which is made up of two major portions: probe and shoulder. The shoulder is the primary heat generation source and holds the plasticized material contained in the weld area. The pin stirs the materials between abutting faces [7]. This helps to produce sound joints. Canvas et al. [8] optimized FSW process parameters on marine grade aluminum alloy by RSM. The maximum strength of the joint was observed at the rotational speed of 600 rpm, transverse momentum of 65 mm/min, and tilt angle of 1.5 deg. Kanakangi et al. [9] chosen RSM to optimize FSW and tool parameters to maximize the joint strength. In this study, five types of tools were used; hexagonal pin profile yielded higher
strength than the other tool. Farzad et al. [10] optimized the FSW parameter range using RSM. Five level central rotatable design matrix was used. The joint yielded maximum strength of 85% at the rotational speed of 500 rpm and shoulder diameter of 16 mm. Chanakya et al. [11] investigated the influence of friction stir processing parameter of AA6082 using RSM. The capability of the developed model was analyzed using analysis of variance. Goyal et al. [12] developed a mathematical model to study the tensile behavior of AA5086 alloy joints. This model was used to study individual and interaction effects on strength and flexibility. From the previous work [1-12], it is understood that a lot of research work has been carried out on FSW butt joints of aluminum alloy. Hence an attempt has been planned to optimize FSW parameters for lap welded joints of AA2024 aluminum alloy to get maximum shear strength. However, the FSW procedure for lap welded joints was developed, and the optimization of process parameters was carried out using response surface methodology.

2. Experimental work

AA2024-T6 rolled plate with 4 mm thickness was the base material (BM) in this work. Using a Do-all machine, the sheet was cut to the desired size of 125 mm length and 60mm breadth, then ground to eliminate the burrs. This alloy has 4.7 wt% Cu and 0.87 wt% Mn as the primary alloying elements. Tables 1-2 show the BM chemical composition and mechanical characteristics.

| Sl. No | Parameters       | Notation | Unit  | Levels | Levels |
|-------|------------------|----------|-------|--------|--------|
| 1     | Welding speed    | S        | mm/min| -2     | -1     |
| 2     | Rotational speed | N        | rpm   | 0      | +1     |
| 3     | Tilt angle       | Q        | deg   | 0      | +2     |
| 4     | Shoulder diameter| D        | mm    | 0      | +2     |

The rotating tool craved from high-strength alloy steel. Here, the tool was threaded tapered pin profile with a concave shoulder of 0.8 and tool shoulder diameters of 16mm,20mm,24mm,28mm, and 32mm. A CNC-controlled FSW machine-made lap joints. Many trials have been performed to fix the operating range of each process parameter (Table 3).
ASTM standard until the faying surface specimen was broken and recorded. For each condition, three samples were tested and presented in Table 4.

Figure. 1 a) Photograph of fabricated tools, b) FSW joints, c) Tensile specimens and d) Fractured specimens

3. Developing empirical relationship

Response Surface Methodology (RSM) is a set of mathematical and statistical approaches for modeling and analyzing issues in which a response of one interest is impacted by several factors, to optimize that response [13-16]. RSM has utilized this study to minimize the number of experiments and create an empirical relationship between weld quality and welding parameters. The SFL of fabricated joints is a function of tilt angle (Q), traverse speed (S), the diameter of the shoulder (D), and rotational speed (N).

\[ SFL= f (Q, S, D, N) \]  
\[ SFL=bo+b1*(N)+b2*(S)+b3*(Q)+b4*(D)+b12*(S*N) +b13*(Q*N) +b14*(D*N) +b23*(Q*S) +b24*(D*S) +b11*(N^2) + b22*(S^2) +b33 * (Q^2) + b44 * (D^2) \text{ kN} \]  

The importance of each coefficient was measured using P values and student t-test. Model values are significant if the value of “Prob>F” is lower than 0.05. For this instance, the following terms are substantial: N, S, D, Q, NS, and Q2. The final empirical relationship to predict the SFL of the FSW joint has been framed using these essential terms.

\[ SFL= {186.26+0.26* N+1.05* S+1.1* D+21.6*Q -003* S *D-0.04* S * Q-0.03 * S2-0.01*D2-4.3*Q2} \text{ kN} \]
| Joint number | Parameters | SFL (kN) |
|-------------|------------|----------|
|             | N  S  D  Q |          |
| 1           | 1100 15 20 1.0 | 10.5    |
| 2           | 1300 15 20 1.0 | 11.32   |
| 3           | 1100 25 20 1.0 | 10.83   |
| 4           | 1300 25 20 1.0 | 12.41   |
| 5           | 1100 15 28 1.0 | 12.04   |
| 6           | 1300 15 28 1.0 | 12.4    |
| 7           | 1100 25 28 1.0 | 12.83   |
| 8           | 1300 25 28 1.0 | 13.95   |
| 9           | 1100 15 20 2.0 | 12.75   |
| 10          | 1300 15 20 2.0 | 13.04   |
| 11          | 1100 25 20 2.0 | 12.67   |
| 12          | 1300 25 20 2.0 | 13.75   |
| 13          | 1100 15 28 2.0 | 12.83   |
| 14          | 1300 15 28 2.0 | 12.82   |
| 15          | 1100 25 28 2.0 | 13.4    |
| 16          | 1300 25 28 2.0 | 13.9    |
| 17          | 1000 20 24 1.5 | 10.86   |
| 18          | 1400 20 24 1.5 | 12.12   |
| 19          | 1200 10 24 1.5 | 11.32   |
| 20          | 1200 30 24 1.5 | 12.71   |
| 21          | 1200 20 16 1.5 | 14.04   |
| 22          | 1200 20 32 1.5 | 15.79   |
| 23          | 1200 20 24 0.5 | 10.59   |
| 24          | 1200 20 24 2.5 | 12.34   |
| 25          | 1200 20 24 1.5 | 16.24   |
| 26          | 1200 20 24 1.5 | 15.87   |
| 27          | 1200 20 24 1.5 | 15.67   |
| 28          | 1200 20 24 1.5 | 15.54   |
| 29          | 1200 20 24 1.5 | 15.76   |
| 30          | 1200 20 24 1.5 | 15.82   |
Table 5 Macrograph of cross-section of welded lap joints.

ANOVA is employed to determine the model's suitability, and the test results are presented in Table 6. The required degree of confidence was set at 95%. The relationship may be regarded as adequate if the created relationship's computed F ratio and calculated R ratio both surpass the tabulated value of the R ratio for a desired level of confidence. The F (203.76) value for the model indicates that it is significant. The lack of fit was 0.31 and suggested that the lack of fit is negligible. There's only a 94.41 percent probability that a significant lack of fit F values is attributable to noise. Each calculated value is closely matched with the predicted value. The Fisher's F test, which has a low probability value, shows that the regression model has a very high significance. The determination coefficient checks the model's quality of fit (R²). The determination coefficient for the response was estimated to be 0.9948. R² should always be in the range of 0 to 1. The R² value of a model should be close to 1.0 if it is statistically sound. The corrected R²=0.9899 value is likewise high, indicating that the model is very significant. The expected R² value is 0.9838. The Adj. R² of 0.9899 is in reasonable accord with this. The variation in coefficient is as low as 1.33, indicating that there is little difference between experimental and anticipated values.
Table 6 ANOVA Results

| Source | SS   | df | MS | F Value | p-value     | Status         |
|--------|------|----|----|---------|-------------|----------------|
| Model  | 87.66| 14 | 6.26| 203.76  | < 0.0001    | significant    |
| N      | 3.24 | 1  | 3.24| 105.48  | < 0.0001    | significant    |
| D      | 4.51 | 1  | 4.51| 146.66  | < 0.0001    | significant    |
| Q      | 6.39 | 1  | 6.39| 207.81  | < 0.0001    | significant    |
| N*S    | 0.50 | 1  | 0.50| 16.17   | 0.0011      | significant    |
| N*D    | 0.20 | 1  | 0.20| 6.59    | 0.0215      | significant    |
| N*Q    | 0.26 | 1  | 0.26| 8.30    | 0.0114      | significant    |
| S*D    | 0.24 | 1  | 0.24| 7.65    | 0.0544      | Not significant|
| S*Q    | 0.14 | 1  | 0.14| 4.46    | 0.0520      | Not significant|
| D*Q    | 1.84 | 1  | 1.84| 59.75   | < 0.0001    | significant    |
| N²     | 30.93| 1  | 30.93| 1006.46| < 0.0001    | significant    |
| S²     | 23.75| 1  | 23.75| 773.03 | < 0.0001    | significant    |
| D²     | 1.16 | 1  | 1.16| 37.74   | < 0.0001    | significant    |
| Q²     | 31.29| 1  | 31.29| 1018.34| < 0.0001    | significant    |
| Residual| 0.46| 15 | 0.031|         |             |                |
| Lack of Fit | 0.18| 10 | 0.018| 0.31    | 0.9441      | Not significant|
| Pure Error | 0.28| 5  | 0.057|         |             |                |
| Cor Total | 88.12| 29 | |         |             |                |
| Std. Dev. | 0.18|    | | R-Squ. | 0.9948      |                |
| Mean    | 13.20|    | | Adj R-Squ. | 0.9899      |                |
| C.V. %  | 1.33 |    | | Pred R-Squ. | 0.9838      |                |
| PRESS   | 1.43 |    | | Adeq Prec.  | 43.148       |                |

4. FSW parameters optimization

RSM is a collection of mathematical and statistical approaches for conducting tests, creating an empirical model, assessing the ideal set of the input variables, and visually showing the result [14,15]. The 2D and 3D plots, indicators of probable factor independence, were created for the suggested mathematical link by taking two factors in the center portion and two parameters in the X-axis and Y-axis into account, as given in Fig 2. Determine the inducing nature and optimum form of the process on SFL. These response contours may be used to anticipate the behavior of any zone in the design domain [16]. The province of the best factor assigning for second-level response is graphically depicted using a contour plot. After the stationary point has been observed, it is usually necessary to define the reaction surface in the immediate area. The most straightforward approach to do so is to use a contour plot to analyze it. Contour plots are pretty handy when looking at a response surface. It is apparent that when rotational tool speed, tilt angle, and welding speed rise, the SFL climbs to a particular point then drops. It's also been noticed that increasing the shoulder diameter first raises the SFL to a specific value, which expanding the shoulder diameter further increases the SFL remains constant. The highest possible SFL value is discovered to be 16.24 kN after evaluating the contour and response plots (Fig 2). Tool rotating speed of 1200 rpm, welding speed of 20 mm/min, tool shoulder of 24 mm, and tool tilt angle of 1.5 are the matching characteristics that give this maximum SFL value. For the range covered during this study, the F ratio value indicates that tool angle is the vital component in optimizing SFL, followed by welding speed, tool shoulder, and rotational speed. This figure depicts the change in SFL as each SFL parameter travels far away from
the aim of reference. At the same time, other parameters remain constant at the initial value. The default point of contact for the design of the experiment is within the middle of the planning space. The joint conceived a maximum SFL was due to the formation of the density distribution of precipitate in the aluminum matrix by the optimum heat input during the FSW cycle [18-21].

Figure 2 Response surface and contour plots
5. Confirmation test

Three validation tests were performed to validate the developed models, with welding conditions chosen randomly from the optimal results, and therefore the actual response was estimated. The values obtained, anticipated values, and percentage difference are summarized in Table 7. The validation findings showed that the generated models are fairly accurate because the percentage of prediction error was in good agreement.

| Sl. No | Rotational speed (rpm) | Tool tilt angle (deg) | Tool shoulder (mm) | Traverse speed (mm/min) | TSFL (kN) | Accuracy | % of Error |
|-------|------------------------|----------------------|-------------------|-------------------------|-----------|----------|-----------|
| 01    | 1212.77                | 1.53                 | 28                | 21.36                   | Act. 15.10| Pred. 15.53| 97.21     | 2.78         |
| 02    | 1199.00                | 1.55                 | 25.84             | 21.56                   | Act. 15.90| Pred. 16.13| 99.97     | 1.42         |

6. Conclusion

The precipitation hardening aluminum alloy (AA2024) was joined using solid state welding successfully.

i) Of the four process parameters, the tool tilt angle was the major factor to decide the quality of joint, followed by welding speed, shoulder diameter, and rotational speed.

ii) The maximum shear fracture load of 16.24 kN was observed at the rotational speed of 1100 rpm, the tilt angle of 1.5 deg., a diameter of 24, and the welding speed of 20 mm/min.

iii) From the ANOVA test result, the tilt angle has a greater influence than the other parameters.

iv) The deviation between predicted and estimated SFL load was lower. It shows each predicted value is well mapped with the calculated value.

v) The reason for the joint yielded a maximum strength may be the formation of the defect-free and optimum flow of material in the weld region.

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