Monte Carlo simulation based prediction model for ultimate tensile strength of Friction Stir Welded AA6063-ETP copper joint

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Abstract. In the present study, Al–6063 and ETP Cu were lap welded using friction stir welding wherein the aluminum alloy sheet was placed on top of the Copper sheet. The process parameters, namely, tool rotational speed, tool traverse speed, and thickness of zinc inter-filler material, were optimized using Taguchi L9 orthogonal design of experiments. The optimum process parameters were determined with respect to the ultimate tensile strength of the weld. The predicted optimal value of ultimate tensile strength was confirmed through confirmation run using the optimum parameters. The analysis of variance showed that tool traverse speed and the zinc foil thickness were the most dominant factors contributing to the weld strength. The most critical parameters were found by using the full factorial analysis. Using full factorial analysis, tool traverse speed, zinc foil thickness, and their interactive effect, were found to be the most critical parameters. The Anderson-Darling test indicates that the ultimate tensile strength tends to follow a normal distribution.

1. Introduction
Aluminium and copper joining have applications in industries such as automotive, HVAC, and refrigeration [1], [2]. These industries prefer substituting the comparatively costly copper parts with aluminium, either partially or entirely [3], [4]. Entire substitution of copper with aluminium is impractical as it unfavourably affects the system efficiency. Hence, it is crucial to join copper to aluminium. The usual methods used to join copper to aluminium are friction welding [5], [6], ultrasonic welding [7], and laser welding [8]. The dissimilar physical properties of aluminium and copper make them difficult to lap weld. Intermetallic compounds (IMCs) are formed during the welding process. Thick layers of intermetallic layers comprises microcracks, which decrease the strength of the joint. It is hard to control the thickness of the intermetallic compound layers [9], [10]. Friction Stir Welding (FSW) is newly used technique to join aluminium and copper feasibly. FSW was developed by W.M. Thomas et al. at The Welding Institute (TWI) in Cambridge, UK, in 1991 [11]. This process has been widely used for joining aluminium and aluminium alloys [12]. In some studies, an intermediate layer such as zinc is used, which is compatible with aluminium as well as copper [13], [14]. From the present literature [15]–[18], the FSW process parameters, namely tool traverse speed and tool rotational speed, have significantly effect on the quality of the weld. Further, few studies pertaining to dissimilar metal welding, an inter-filler material was found to significantly affect the weld quality [13], [19].
Taguchi method is a technique for robust design and performance improvement of product, process, and system with significantly reduced time and cost of experimentation, which helps in the production of a low-cost good quality product. It provides a systematic approach to optimize the design for performance, cost, and quality. Taguchi has established Orthogonal arrays (OA) to depict a large number of experimental situations. However, it seems that the optimization of dissimilar (Al-Cu) FSW process parameters when an inter-filler layer is employed has not been reported using Taguchi technique.

2. Materials And Methodology
AA6063 and ETP copper sheets, both with 3 mm thickness, 130 mm length, and 90 mm width, were chosen for producing lap joints. 0.2 mm and 0.4 mm thick foils of zinc were used as an intermediate layer. Heat-treated H13 steel tools were used. Four distinct tools with pin lengths of 4.4 mm, 4.6 mm, 4.8 mm, and 4.94 mm were used to achieve 50% penetration in the bottom copper material. The tool pin profile was inverse conical with top and bottom diameters 5.4 mm and 6 mm, respectively. A flat shouldered tool of 24 mm diameter was used, and the shoulder penetration of 0.1 mm was used for producing adequate frictional heat for welding. The work pieces were placed on a mild steel base plate and firmly clamped.

Preliminary experiments were performed to set the operational range of process parameters, namely, tool rotational and traverse speeds. Accordingly, the tool rotational speed used was 1000, 1200, 1400 rpm; and the tool traverse speed used was 5, 10, and 15 mm/min; and the thickness of zinc inter-filler (ZFT) used was 0.2 mm and 0.4 mm. Taguchi L9 OA is used in the present study. The level-wise process parameters are shown in Table 1. The chemical composition and mechanical properties of the base materials are presented in Table 2. and Table 3., respectively. For testing the mechanical properties, tensile shear tests were conducted. The tensile shear test specimens 20 mm wide and 130 mm long were cut from the weld portion.

Post Taguchi analysis, further analysis was carried out using the full factorial DOE to find the most critical parameters from selected parameters. Monte Carlo simulation is used to predict the ultimate tensile strength. The normality of the response variable ‘ultimate tensile strength (UTS)’ is assessed by the Anderson-Darling test.

| Table 1. Process parameter values and their levels |
|---|---|---|---|
| Level | A Rotational speed (rpm) | B Traverse speed (mm/min) | C Thickness of zinc foil (mm) |
| Level 1 | 1000 | 5 | 0 |
| Level 2 | 1200 | 10 | 0.2 |
| Level 3 | 1400 | 15 | 0.4 |

| Table 2. Main chemical compositions of the base materials |
|---|---|---|---|---|---|
| Sheet Metal | Al | Cu | Mg | Mn | Zn |
| Al 6063 | Base | 0.08 | 4.8 | 0.8 | 0.1 |
| ETP Cu | 0.02 | Base | – | – | 4.7 |
Table 3. Mechanical properties of the base materials

| Sheet Metal | Ultimate Tensile strength (MPa) | Microhardness (HV) |
|-------------|---------------------------------|-------------------|
| Al6063      | 160                             | 80-85             |
| ETP Cu      | 263                             | 85–90             |

3. Results And Discussion

3.1. Taguchi Method

3.1.1 Signal to noise ratio

Taguchi technique uses the S/N ratio to assess the deviation of the quality characteristic from the desired value. The S/N ratio characteristics can be separated into three modes: the nominal is best, the smaller is better, and the larger is better. In the present work, the objective is to maximize the ultimate tensile strength through optimum FSW process parameters, and larger is better characteristic is used. The SN ratio is calculated using the following formula:

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

where $y_i$ is the value of ultimate tensile strength for the $i^{th}$ test, $n$ is the number of tests, and $N$ is the total number of data points.

The ultimate tensile strength of the welded joints is analyzed to understand the effect of the FSW process parameters. The analysis is done using the MINITAB 18 software. Table 4. shows the mean S/N ratio for each level of the welding parameters. The higher S/N ratio corresponds to better quality characteristics. On the basis of S/N ratio values, the optimal level setting was achieved at the rotational speed of 1000 rpm (A1), traverse speed of 10 mm/min (B2), and zinc foil thickness of 0.2 mm (C2). The response table for mean effect and S/N ratio are given in Table 5. and Table 6., respectively. The main effects plot for means and S/N ratios are given in figure 1. and figure 2., respectively.

Table 4. S/N response for the weld strength

| Sr. No. | Rotational Speed (rpm) | Traverse Speed (mm/min) | Zinc foil Thickness (mm) | Mean Ultimate Tensile Strength (MPa) | Signal to noise ratio (S/N) |
|--------|------------------------|-------------------------|--------------------------|-------------------------------------|----------------------------|
| 1      | 1000                   | 5                       | 0                        | 65.65                               | 36.3447                    |
| 2      | 1000                   | 10                      | 0.2                      | 106.1                               | 40.5143                    |
| 3      | 1000                   | 15                      | 0.4                      | 43.5                                | 32.7698                    |
| 4      | 1200                   | 5                       | 0.2                      | 79.67                               | 38.0259                    |
| 5      | 1200                   | 10                      | 0.4                      | 61.89                               | 35.8324                    |
| 6      | 1200                   | 15                      | 0                        | 48.97                               | 33.7986                    |
| 7      | 1400                   | 5                       | 0.4                      | 43.99                               | 32.8671                    |
| 8      | 1400                   | 10                      | 0                        | 69.8                                | 36.8771                    |
| 9      | 1400                   | 15                      | 0.2                      | 63.14                               | 36.0061                    |
Table 5. Response Table for Means

| Level | A   | B   | C   |
|-------|-----|-----|-----|
| 1     | 71.75 | 63.1 | 61.47 |
| 2     | 63.51 | 79.26 | 82.97 |
| 3     | 58.98 | 51.87 | 49.79 |
| Delta | 12.77 | 27.39 | 33.18 |
| Rank  | 3    | 2    | 1    |

Table 6. Response Table for Signal to Noise Ratios: Larger is better

| Level | A   | B   | C   |
|-------|-----|-----|-----|
| 1     | 36.54 | 35.75 | 35.67 |
| 2     | 35.89 | 37.74 | 38.18 |
| 3     | 35.25 | 34.19 | 33.82 |
| Delta | 1.29  | 3.55  | 4.36  |
| Rank  | 3    | 2    | 1    |

Figure 1. Main effects plot for Means
3.1.2 Signal to noise ratio

The analysis of variance is used to evaluate the effect of process parameters on ultimate tensile strength. The results from ANOVA of means and ANOVA of signal to noise ratios are shown in Table 7. and Table 8., respectively. In this investigation, the tool traverse speed and the zinc foil thickness were found to be the most significant factors contributing to the weld strength.

**Table 7. Analysis of Variance for Means**

| Source | DF | Seq SS | Adj MS | F    | P    | % Contribution |
|--------|----|--------|--------|------|------|----------------|
| A      | 2  | 251.61 | 125.803| 20.12| 0.047| 8.114          |
| B      | 2  | 1137.73| 568.864| 90.97| 0.011| 36.688         |
| C      | 2  | 1699.22| 849.61 | 135.87| 0.007| 54.795         |
| Residual Error | 2 | 12.51  | 6.253  |      |      | 0.4            |
| Total  | 8  | 3101.06|        |      |      | 100            |

**Table 8. Analysis of Variance for signal to noise ratios**

| Source | DF | Seq SS | Adj MS | F    | P    | % Contribution |
|--------|----|--------|--------|------|------|----------------|
| A      | 2  | 2.5074 | 1.2537 | 14.95| 0.063| 4.976          |
| B      | 2  | 18.999 | 9.4993 | 113.25| 0.009| 37.702         |
| C      | 2  | 28.718 | 14.359 | 171.19| 0.006| 56.989         |
| Residual Error | 2 | 0.1678 | 0.0839 |      |      | 0.333          |
| Total  | 8  | 50.392 |        |      |      | 100            |

\(a\) Dof – degrees of freedom, Seq SS – sequential sum of squares, Adj MS – adjusted mean square, F – fisher ratio
3.1.3 **Determination of the maximum ultimate tensile shear strength**

From the experiments, the optimum level setting is $A_1B_2C_2$. The average values of the factors at their levels are taken from Table 5, and the predicted value of the ultimate tensile strength is given below

$$\text{Ultimate tensile strength} = A_1 + B_2 + C_2 - 2T$$

$$= 71.75 + 79.26 + 82.97 - 2 \times 64.74 = 104.5 \text{ MPa}$$

where $A_1$ is the mean value of tool rotational speed at $1^{st}$ level, $B_2$ is mean value of tool traverse speed at $2^{nd}$ level, and $C_2$ is mean value of thickness of zinc inter-filler material at $2^{nd}$ level.

3.1.4 **Confirmation test**

The improvement of the quality characteristic is verified using the optimal level of the design parameters. The tool rotational speed, tool traverse speed, zinc foil thickness were set at 1000 rpm, 10 mm/min, and 0.2 mm, respectively. The average ultimate tensile strength value of the friction stir welded AA6063 and ETP copper joint was 106.1 MPa.

3.2. **Full factorial analysis**

Further analysis was carried out using the full factorial DOE to find the most critical parameter from selected parameters. The full factorial DOE suggested eight combinations for the three parameters. The ultimate tensile strength for the different combination is computed and analyzed using a normal plot of effect, main effect plot, Pareto chart, and interaction plot. The normal effect plot shows that the tool traverse speed, the zinc foil thickness, and their interaction have a significant effect on ultimate tensile strength at 95% confidence interval, which is also evident from the Pareto chart. The normal effect plot, the main plot of the effects, and the Pareto chart of the effects are shown in figure 3., figure 4., and figure 5., respectively. The main effect plot identified that a high ultimate tensile strength is obtained at higher values of tool traverse speed and zinc foil thickness. Variation in tool rotational speed had an insignificant effect on ultimate tensile strength.

![Figure 3. Normal plot of the effects](image-url)
Figure 4. Main plot of the effects

Figure 5. Pareto chart of the effects
Interaction plot, as shown in figure 6, shows the interaction between any two selected parameters with respect to ultimate tensile strength. Negligible interaction is observed between rotational speed and traverse speed. Moderate interaction is observed between rotational speed and zinc foil thickness. Strong positive interaction is observed between traverse speed and zinc foil thickness. A functional equation is developed and shown below to predict the ultimate tensile strength.

$$\text{Ultimate tensile strength} = 63.07 - 0.0154 \times \text{Rotational speed} + 4.026 \times \text{Traverse speed} - 41.1 \times \text{Zinc foil thickness} - 0.00044 \times \text{Rotational speed} \times \text{Traverse speed} + 0.00525 \times \text{Rotational speed} \times \text{Zinc foil thickness} - 15.78 \times \text{Traverse speed} \times \text{Zinc foil thickness} + 0.03065 \times \text{Rotational speed} \times \text{Traverse speed} \times \text{Zinc foil thickness}$$

3.3. Monte Carlo simulation
Monte Carlo simulation is applied to predict the ultimate tensile strength by using the equation developed from the full factorial analysis. The random data was generated with about 10,000 data points for the three parameters using the normal distribution. The simulation was performed to compute the performance using the equation for ultimate tensile strength. The mean ultimate tensile strength is 119.65, based on about 10,000 samples. The minimum and maximum ultimate tensile strength, are 112.54 and 127.26, respectively, with a standard deviation of 1.92. The probability plot and the summary report of ultimate tensile strength are shown in figure 7. and figure 8, respectively. The Anderson-Darling test is used to check the normality of UTS. The p-value of 0.073 indicates that UTS tends to follow the normal distribution.
Figure 7. Probability plot of Ultimate tensile strength

Summary Report for Ultimate tensile strength

| Anderson-Darling Normality Test |   |   |
|---------------------------------|---|---|
| A-Squared                       | 0.69 |
| P-Value                         | 0.073 |

| Statistics           |   |   |
|----------------------|---|---|
| Mean                 | 119.65 |
| StDev                | 1.92 |
| Variance             | 3.69 |
| Skewness             | 0.0410428 |
| Kurtosis             | -0.0321641 |
| N                    | 10010 |

| Quartiles           |   |   |
|---------------------|---|---|
| Minimum             | 112.54 |
| 1st Quartile        | 118.34 |
| Median              | 119.64 |
| 3rd Quartile        | 120.96 |
| Maximum             | 127.26 |

| Confidence Intervals |   |   |
|----------------------|---|---|
| 95% Confidence Interval for Mean | 119.62 | 119.69 |
| 95% Confidence Interval for Median | 119.59 | 119.69 |
| 95% Confidence Interval for StDev | 1.89 | 1.95 |

Figure 8. Probability plot of Ultimate tensile strength
4. Conclusion
Friction-stir welding experiments were conducted to lap weld the AA6063 and ETP copper sheets. The following conclusions were reached:
1. The optimum levels of tool rotational speed, tool traverse speed, and thickness of zinc inter-filler material are 1000 rpm, 10 mm/min, and 0.2 mm, respectively.
2. It is found that the tool rotational speed, tool traverse speed, and thickness of zinc inter-filler contribute 8.11%, 36.69%, and 54.80%, respectively, to the ultimate tensile strength of welded joints.
3. The error between the predicted and the experimental value of the ultimate tensile strength was 1.53%.
4. The factorial analysis shows that tool traverse speed, zinc foil thickness, and their interaction have the most dominant effect on ultimate tensile strength.
5. By Monte Carlo simulation, the range of ultimate tensile strength observed varies from 112.54 MPa to 127.26 MPa, with a mean value of 119.65 MPa.
6. The ultimate tensile strength tends to follow the normal distribution.

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