Experimental Investigation and Parametric Optimization of FSW for the 2024-O Aluminum Alloy Joints

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Abstract. The effect of welding parameters on mechanical properties of aluminum alloy AA 2024-O Friction stir-welded (FSW) joints was investigated in the present study. Taguchi method was used to evaluate the optimum value of process parameters from tensile tests using nine experiments designed according to the matrix proposed by the scientist Taguchi for the design of experiments (L9) using two parameters (welding speed and rotation speed). Two different process parameters have been selected: rotational speeds of 1300,1500 and 1700 rpm and feed speeds of 20,40 and 60 mm/min. The design of experiments (DOE) is performed by L9 (3^2) orthogonal array (9 experiments, two variables, three levels). Also, the signal-to-noise (S/N) ratio larger is better has been performed for analyzing the results (σu for FSW &FSP) by the statistical software (MINITAB® 16). The best results of the weld gained at the parameter 40 mm/min travel speed and 1300 rpm rotation speed. The efficiency obtained was 95% respect to the ultimate tensile strength (UTS) of the base metal. In addition, the analysis of variance (ANOVA) techniques has also been performed by the statistical software (DOE Pro XL) to identify the essential factors that are affecting the ultimate tensile strength (UTS) for FSW.

Keywords. FSW (friction stir welding), Ultimate tensile strength UTS, AA 2024-O, ANOVA.

1. Introduction

For the purpose of welding butt and overlapping joints, especially those that are difficult to weld by traditional methods, such as some aluminum alloys, friction stir welding is used, which is one of the methods of solid-state welding. FSW is a technology that was invented in 1991 by TWI (The Welding Institute). This technology is used in welding aluminum alloys of 2000 and 6000 series and the rest and other aluminum alloys and welding other metals and other alloys, including steels. Because the welding area is not melting and re-embedding the metal, the distortion is low, and the welding is porous [1]. Friction stir welding (FSW) is an advanced and very important technique that has created a solid phase bond. In this method, a rotating tool is used to generate friction heat on the surface that softens the component material below the surface during mixing without reaching the melting temperature and allows the tool to move along the welding line. The plasticized material is transferred from the leading edge to the back edge of the tool probe, leaving a solid phase bond between the two parts [2]. FSW is a solid-state bonding process in which a non-expendable rotating tool is forced into immersion at the joining line.
between the workpieces to be joined and moved along the contact lines shown in Figure 1. The tool with axial force generates frictional heat on the surface of the piece and below the surface, thus working on softening the material around the tool pin. The diluent is forced to move from the front of the pin and behind the pin, resulting in solid welding. The maximum temperature observed in the FSW process is much lower than the melting temperature of the parent material and may reach more than half the melting temperature at times resulting in reduced residual deformation, absence of cracks, and softening induces in the microstructures as described by Zhu and Chao. The FSW joint is made up of four different regions, which are the unaffected base minerals, the heat-affected region, the thermomechanically heat affected regions, and the solid block proposed by TWI. It was found that the critical welding variables in this way are tool rotation speed, welding speed, axial force, and pin profile or that control welding efficiency [3]. The friction stir welding was investigated by many researchers based on various parameters, such as the effect of temperature on the fatigue behavior for friction stir welding [4], the effect of rotation speed on the friction stir welding [5], investigation of fracture and fatigue on friction stir welding [6], studying the mechanical properties for friction stir welding [7], and finally, investigation the microstructure and mechanical properties of friction stir welding [8]. Variables of this technology (for example, tool design, tool rotation, travel speed, the direction of rotation, countersunk depth of tool shoulder, (z) and (x) axis forces, tool tilt angle, weld gap, and thickness mismatch) affect the quality of the weld area by affecting the material flow and then the consolidation in the welding zone. In this paper, the mechanical properties (tensile strength, hardness) of the 2024 O welded aluminium alloy were studied to determine the best rotation speed and travel speed values. Moreover, make a comparison between the friction stir welding (FSW) and the base metal. Also, determine the optimum parameters by using one of the optimized methods to ensure optimum welding efficiency based on the tensile strength, the examination of the obtained optimum parameters for mechanical properties and efficiency, applying experiment design (DOE) technique and developing models could support designers and engineers to achieve outstanding welding properties. ANOVA techniques have been used to identify significant factors affecting the ultimate tensile strength (UTS).

![Figure1](image.png)

**Figure1.** The principle of friction stir welding process[1].

2. Experimental work
The experimental technique can calculate the agreement results for friction stir welding with various parameters effect with or without comparison the results calculated by analytical or numerical technique. The experimental work included presenting the properties for materials used and then presenting the details samples test, and finally, information is given for test machine and test steps used. Many researchers in different fields have used some structural elements manufactured and assembled by using FSW and proved its effectiveness in testing and in calculating the stresses and deformations [9-27].
2.1. Materials used

For the purpose of the FSW process, two aluminium sheets used for this work, 2024-O Aluminium alloys, from which O stands for Annealed—Material undergoing annealing treatment at approximately 327°C, O means Temper (Annealing)—To soften the alloy from a heat-treated condition. The standard mechanical properties and chemical composition of AA 2024-O are given in Table 1 and Table 2.

**Table 1. Mechanical properties of AA 2024-O.**

|        | Ultimate strength (MPa) | Elongation (%) | Youngs Modulus (GPa) |
|--------|-------------------------|----------------|----------------------|
| Standard | 186                     | 12             | 73.1                 |
| Measured | 190.944                 | 10             | 73.70                |

**Table 2. Chemical composition of AA 2024-O alloy.**

| Element | Si     | Fe     | Cu     | Mn     | Mg     | Cr     | Ni     | Zn     | Ti     | Ga     | V     |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|
| Standard | 0.5    | 0.5max | 3.8min | 0.3min | 1.2min | 0.10   | 0.25   | 0.15   |        |        |       |
| Measured | 0.087  | 0.193  | 5.57   | 0.535  | 1.25   | 0.008  | 0.003  | 0.103  | 0.014  | 0.007  | 0.008 |

The two aluminium sheets used for FSW were with a thickness of 3 mm, a length of 100 mm, and a width of 200 mm are attached to the butt of Figure 2. The welding process requires fixing the pieces to be welded to a metal plate to preserve heat from the bottom and prevent its leakage, and the alignment of the two pieces is done to ensure that the movement of the tool is along the straight seam.

**Figure 2. Plate dimension and schematic of friction stir welding (FSW).**

The welding protection is done by using a tool, as shown in Figure 3. The length of the pin was less than the required welding depth by 2.9 mm.

**Figure 3. Friction stir welding (FSW) tool.**
The tool was manufactured from X38 tool steel with an 18 mm shoulder diameter. The chemical composition of the tool material is shown in Table 3.

|   | C     | Si     | Mn    | P     | Cr      | Ni     | Mo    | Co    | Fe     |
|---|-------|--------|-------|-------|---------|--------|-------|-------|--------|
|   | 0.88-0.96 | 0.16  | 0.40  | 0.03  | -       | 4.7-2.0 | 4.5-5.0 | Balance |

3. Taguchi’s technique

Taguchi method was used to evaluate the optimum value of process parameters from tensile tests by using nine experiments designed according to the matrix proposed by the scientist Taguchi for the design of experiments (L9) using two variables are welding speed and rotation speed at three levels. The Taguchi method is applied for solving several complex problems in manufacturing industries and to determine the most influential parameters in the overall performance. Three different process parameters have been selected: rotational speed of 1300, 1500 and 1700 rpm and feed speed of 20, 40 & 60 mm/min. The design of experiments is performed by L9 (3^2) orthogonal array (9 experiments, two variables, three levels) that suggested by Taguchi. Many works have been conducted and designed their experiments according to Taguchi’s to optimize the number of experiments [28-31].

| Parameters | Level 1 | Level 2 | Level 3 |
|------------|---------|---------|---------|
| Rotation speed [r/min] | 1300 | 1500 | 1700 |
| Welding speed [mm/min] | 20 | 40 | 60 |

3.1. Signal-to-noise ratio (S/N ratio)

The Taguchi method uses the S/N ratio as one method for measuring a quality characteristic that deviates from the desired values. The method for modelling the S/N ratio depends on whether the quality characteristic is the largest-best, smallest-best, or nominal-best. The S/N ratio is calculated using the largest is the best criterion for tensile testing, as shown in Equation 1.

$$\text{(S/N)Ratio} = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} \left( \frac{1}{y_{ij}} \right) \right)$$  (1)

Where; $y_{ij}$: The total results of trials, n: number of trials, i: Trial number and j: Experiment number.

The effects of each factor can be obtained at different levels, from the used orthogonal matrix. For example, the average S / N ratio for a given factor, such as A at three levels (1, 2, and 3), can be obtained by computing the average S / N ratio. Similarly, the average S / N ratio is calculated for each level of all factors. The orthogonal matrix L9 is used in experimental investigations. The results for the corresponding S / N ratio are calculated using Equation 1. Inputs to Design Expert and Minitab 16 are shown in Table 5 that illustrates the design of the experiment. Regardless of the class of performance characteristics, the greater the algebraic value of the S / N ratio corresponds to the better performance characteristics. Hence, the level with the highest S / N ratio is the optimal level of the parameter.
Table 5. Orthogonal experimental results for tensile test and S/N ratio of FSW for AA 2024-O.

| No. | (RS) (A) | (FS) (B) | UTS1 (Mpa) | UTS2 (Mpa) | Mean (Mpa) | S/N ratio |
|-----|----------|----------|------------|------------|------------|-----------|
| 1   | 1300     | 20       | 171        | 89.822     | 130.411    | 41.0197   |
| 2   | 1300     | 40       | 183.833    | 180.5      | 182.166    | 45.2083   |
| 3   | 1300     | 60       | 114.772    | 144.889    | 129.831    | 42.0919   |
| 4   | 1500     | 20       | 180.111    | 183.778    | 181.945    | 45.1975   |
| 5   | 1500     | 40       | 182.333    | 179.778    | 181.055    | 45.1556   |
| 6   | 1500     | 60       | 180.222    | 179.667    | 179.945    | 45.1027   |
| 7   | 1700     | 20       | 177.722    | 175.444    | 176.583    | 44.9384   |
| 8   | 1700     | 40       | 126.489    | 177.556    | 152.023    | 43.2688   |
| 9   | 1700     | 60       | 179.278    | 180.389    | 179.834    | 45.0973   |

RS Rotational speed  
FS Feed speed  
UTS Ultimate tensile

In the Taguchi method, ANOM can determine the optimal parameters, as shown in Table 6. ANOM is a statistical approach for estimating the average S / N ratios for each parameter and for each of its levels. However, levels of the optimal parameters are more precisely determined using analysis of variance [ANOVA], when there are significant interactions between factors, and by looking at interaction plots. Analysis of variance (ANOVA) is performed to find out which process parameters are statistically significant. The optimal combination of process parameters can be predicted using S/N, and ANOVA analyzes.

Table 6. The main effects table of means and (S/N) ratios for UTS for FSW.

| Levels  | A | B | Levels  | A | B |
|---------|---|---|---------|---|---|
| 1       | 147.5 | 163.0 | 1 | 42.77 | 43.72 |
| 2       | **181.0** | 171.7 | 2 | 45.15 | **44.54** |
| 3       | 169.5 | 163.2 | 3 | 44.43 | 44.10 |
| Delta   | 33.5 | 8.8 | Delta | 2.38 | 0.83 |
| Rank    | 1 | 2 | Rank | 1 | 2 |

The experimental results calculated are agreement results that can be utilized to investigate the friction stir welding with various parameters effect with comparison by analytical technique, numerical technique, or other results publication, or can be depending on the experimental results calculated without comparison with other results. Similar approaches for comparing the experimental results with the numerical and/or numerical were presented in many previous studies [32-45].

4. Results and discussions

The steps involved in the Taguchi improvement method can be summarized as follows: Getting every S / N ratio of notes according to the bigger formula is better. Determine the factors that have a significant influence on the S / N ratio by analyzing the variance (ANOVA) of the S / N ratios. Table 5 shows the average tensile value for each trial point, and also from Equation 1, the S / N ratios are calculated. Figure
4 a and b the significant effect depicted for the S/N, is shown. Delta values are calculated from Table 6. Hence, the maximum parameter tension is \( A_2 B_2 \), as shown in Table 7.

| Table 7. Mean and (S/N) ratio at optimum condition for UTS for FSW. |
|-------------------------------------------------|
| Ultimate Tensile Strength (Mean) | Ultimate Tensile Strength (S/N)Ratio |
| A | B | A | B |
| 2 | 2 | 2 | 2 |
| Mean | S/N Ratio | Mean | S/N Ratio |
| 186.7527 | 45.57614 | 186.7527 | 45.57614 |

![Figure 4. (a). Main effects plot of means for UTS for FSW.](image)

![Figure 4. (b). Main effects plot of (S/N) ratio for UTS for FSW.](image)

The optimum condition was at spin speed (A) 1500 rpm, feed speed (B) = 40 mm / min based on the highest ratio (S / N). The factor effect is determined by estimating the variation between the lowest and highest value of the S / N for each factor. In this case, the most important factor which affects on rotational speed (a) and then the feeding speed (b) = 40 mm / min as shown in (rank), it should be noted that the optimal state (a2 and b2) is not done. It is found among the nine experiments that were performed, since (OA) represents only a small fraction (9 trials) of all possibilities ((3^2) = 9 trials). Therefore, the resistance to extreme stress is determined in the optimal state (A2 and B2). Figure 5 shows the values of the maximum tensile strength of the welded samples for two welded alloys (from both rotational speed and feed velocity) and the final tensile strength of base metals for AA 2024-O for FSW. Similar presentations of the results using the bar charts to give a direct indication of the values of the ultimate tensile strength for different applications [46-59], Table 8.
4.1. Analysis of variance technique

Table 8. ANOVA table for UTS for FSW tensile strength (mean).

| Source    | DOF | S(SS) | V(MS) | F ratio | P Contributed% |
|-----------|-----|-------|-------|---------|----------------|
| A(RS)     | 2   | 1739.8| 869.9 | 1.64    | 21.67%         |
| B(FS)     | 2   | 150   | 75.0  | 0.14    | 1.87%          |
| Error     | 4   | 2120.47| 530.117| 76.46% |
| Total     | 8   | 4010.24|       |         |                |

**DOF** Degree of freedom,
**SS** Sum of square,
**MS** Pure mean for sum of square,
**F** Fisher ratio
**P%** Percentage contribution

4.2. Calculation

4.2.1. **DOF(Degree of freedom) = (n-1)**

DOF(participant N) = (3-1) = 2
DOF(participant S) = (3-1) = 2
DOF(total) = (9-1) = 8
DOF(Error) = DOF(total) - DOF(participant (RS) - DOF(participant (FS)) = (8-2-2) = 4.

4.2.2. **SS(Sum of square) = n1(x1 - X)² + n2(x2 - X)² + n3(x3 - X)²**

Where X = (x1+ x2 + x3) / 3 and x1, x2 and x3 are mean of parameter as per level.
(a) SS (for mean)

X(participant N) = (147.5+181+169.5)/3 = 166 Mpa
X(participant S) = (163 + 171.7 + 163.2) / 3 = 166 Mpa
SS(participant N) =\[\sum_{i=1}^{9}(\text{mean})^2 + \sum_{i=1}^{9}(\text{mean})^2 + \sum_{i=1}^{9}(\text{mean})^2\] = 1739.8 Mpa
SS(participant S) =\[\sum_{i=1}^{9}(\text{mean})^2 + \sum_{i=1}^{9}(\text{mean})^2 + \sum_{i=1}^{9}(\text{mean})^2\] = 150 Mpa
SS(Total) =\[\sum_{i=1}^{9}(\text{mean})^2 + \sum_{i=1}^{9}(\text{mean})^2 + \sum_{i=1}^{9}(\text{mean})^2\] = 4010.2 Mpa
SS(Error) = SS(Total) - SS(participant N) - SS(participant S) = 2120.5 Mpa

4.2.3. Where \(X = (x_1 + x_2 + x_3) / 3\) and \(x_1, x_2\) and \(x_3\) are mean of parameter as per level.
MS = SS / DOF
MS(participant N) = 1739.8 / 2 = 869 Mpa
MS(participant S) = 150 / 2 = 75 Mpa
MS(Total) = SS(Total) = 4010.2 Mpa
MS(Error) = MS(Total) - MS(participant N) - MS(participant S) = 530.1 Mpa

4.2.4. \(F = \frac{MS\text{(participant N)}}{MS\text{(Error)}} = \frac{869}{530.1} = 1.64\) Mpa.
MS(participant N) / MS (Error) = 75 / 530.1 = 0.14 Mpa.

4.2.5. \(P\% \text{ (Percentage contribution)} = \frac{MS\text{ of participant}}{MS\text{ of total}}\)
P \(\%\) (participant N) = 869.9 / 4010.2 = 21.67 Mpa
P \(\%\) (participant S) = 75 / 4010.2 = 1.87 Mpa
P \(\%\) (Error) = 100 – 21.67 – 1.87 = 76.46 Mpa.

For performing the F test, from Table 5 the \((f_1, f_2) = (2, 4)\), the F table at 0.1 level of important (90% confidence or 10% risk) is \(F = 1.64\) Mpa. The estimated values of different ratios F for factor A less than the determined value obtained from the table. However, FA and FB are less than the F table. Thus, there is no significant different ultimate tensile strength by factors A and B within the confidence level of 90%. The percentage of the contribution of process factors A and B for ultimate tensile strength is shown in Figure 6.

![Figure 6](image-url)
5. Conclusions
1. Based on the S/N ratio results for UTS for FSW, for the given set of parameters, the optimum parameters were found at rotation speed = 1300rpm, feed rate 40 mm/min to get the higher ultimate tensile strength predicated = 186.7527 MPa, UTS (mean) actual = 182.166 MPa for the welded parts. In addition, the main factor affected the ultimate tensile strength of joints parts is rotational speed (A) followed by feed rate (B).
2. The design of the tool was suitable to avoid tool breakage.
3. From the ANOVA results for UTS for FSW, there is no significant difference in the UTS by factor. The percentage of contribution of significant factors (PA= 21.67 %, and PB = 1.87%).
4. The best result of joining efficiency was 40 mm/min travel speed and 1300 rpm rotation speed with (95 %) joint efficiency.

6. Acknowledgments
The authors are grateful to laboratories in Al-Nahrain University, and special thanks to university of Baghdad and all workers in it

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