# Desirability function analysis based multi response optimization of process parameters during friction stir welding of AA6061-AA7075

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***Abstract:*** *The goal of this work is to choose the best friction stir welding process parameters for the alloy AA6061-AA7075 based on a multi-criteria decision-making technique. The tool rotational speed, feed, and tilt angle were selected as the input parameters for the friction stir welding experiments, which were carried out using a L9 orthogonal array. The measured responses are tensile strength, hardness, and elongation percentage of a welded joint. The multi-criteria decision-making technique namely Desirability Function Analysis (DFA) is used to find the optimum process parameters combination. The optimum conditions are tool rotational speed of 710 rpm, feed of 30 mm/rev, and tilt angle at 2$^o$.*

***Key Words:*** *Friction stir welding, Tensile strength, Hardness, DFA, ANOVA*

## 1. INTRODUCTION

Using conventional welding to join the two aluminium alloys at different melting temperatures is quite difficult. A solid-state joining method is friction stir welding (FSW). Solid state welding techniques are more advantageous for joining dissimilar aluminium alloys. It has several benefits over traditional fusion-welding methods, including better mechanical qualities, safety, non-use of consumables, and the ability to operate in all positions [1]. The mechanical properties of welded joints are primarily influenced by welding techniques, the characteristics of the parent material, the kind of weld joint, the heat-affected zone, metallurgical transformations occurring during welding, and process parameters [1]. On the mechanical properties of FSW and the influence of process variables such tool rotational speed, tool tilt angle, and tool pin profiles, numerous research have been done. When compared to conventional welding, FSW produces less heat [2]. Since plastic deformation occurs during welding and grain recrystallization does not occur, FSW results in fine-grain structures [3].

Prabhu et al. [4] optimized the process parameters using TOPSIS during FSW of aluminium matrix composite (Al6061-4.5Cu-5SiC). The obtained optimum process variable combinations are square pin profile, revolving speed of 1000 rpm and tool traverse speed of 80 mm/min contributing better closeness coefficient value. Palani and Elanchezhian [5] optimized the process parameters in FSW of AA 8011 aluminium alloys using RSM Based GRA coupled with DEA. Rajakumar et al. [6] optimized the process and tool parameters in

FSW of AA7075–T6 aluminium alloy. The obtained optimal parameters are rotational speed of 1438 r/min, welding speed of 67.64 mm/min, the axial force of 8.29 kN, shoulder diameter of 15.54 mm, pin diameter of 5.13 mm, and tool material hardness of 600 HV. Ravikumar et al. [7] carried out the optimization of welding parameters during dissimilar FSW of AA6061-T651 and AA7075-T651 aluminum alloys. The results demonstrated that multiple performance characteristics are significantly influenced by tool pin profile followed by rotational speed and welding speed.

The optimum process variables for the dissimilar FSW between the aluminium alloys AA6061 and AA7075 were established by Shah et al. [8]. The results revealed that using 1000 rpm rotating speed, 110 mm/min travel speed, and 3 tilt angle, a high tensile value of 219.6 MPa was achieved. Koilraj et al. [9] performed optimization process parameters during FSW of dissimilar aluminium alloys AA2219-T87 and AA5083-H321 plates. The weld joints were tested for tensile strength and process parameters were optimized using S/N ratios to maximize the tensile strength. ANOVA showed that the significance of D/d was more predominant followed by pin geometry and traverse speed. Ravi Sankar & Umamaheswarrao [10] optimized process parameters during friction stir welding of AA 6061 using the response surface method coupled with GRA and PCA. Palanivel et al. [11] optimized the process parameters through RSM to maximize the ultimate tensile strength. (welding speed, rotational speed and axial force) in FSW of aluminium alloy AA5083-H111. The adequacy of the linear model developed by the RSM was checked by the ANOVA. Based on the MCDM technique, Sudhagar et al. [12] achieved the ideal process parameters for FSW of the aluminium 2024 alloy. Optimum conditions are tool rotational speed of 710 rpm, feed of 30 mm/rev and tilt angle at $2^o$. Using the response surface method, Ravi Sankar and Umamaheswarrao [13] modelled and optimised the friction stir welding of AA 6061.

Tensile strength was shown to be higher at lower speeds; as speed increases, the joint's hardness initially rises and subsequently falls. Chanakyan et al. [14] optimized process parameters by utilizing the GRA in friction stir welding of 5052 aluminium alloy. The results revealed that tool rotational speed and traverse speed are the most prominent parameters for multiple performance characteristics.

The impact of TRS and WS on the tensile behaviour of friction stir (FS) welded AA6061-T651 alloy was identified by Lim et al. [15].

Numerous investigations have been done on the 6xxx and 7xxx series alloys [16], but especially few have been done on the dissimilar welds of AA6061 and AA7075. Moreover, a systematic study on the effect of tool rotational speed, feed, and tilt angle in dissimilar welds of AA6061 and AA7075 was not carried out. Hence the present work is aimed to determine the optimal welding parameters using DFA.

## 2. EXPERIMENTAL DETAILS

A power hacksaw is used to cut the 6 mm thick, rolled aluminium alloy AA6061 and AA7075 plates into the desired sizes (100 mm x 75 mm), and a square butt configuration is created. The plates were first clamped into place to create the initial joint configuration. To prepare the weld joint, a non-consumable tool manufactured of H13 steel was employed. The FSW procedure is carried out using a vertical milling machine. The work-holding fixture was designed and tested before the experiments. Acetone was used to completely clean the workpieces, removing any dirt, organic material, or small particles that may have remained after the machining process.

An experimental setup is shown in Fig. 1. Fig. 2 illustrates the usage of a commercial H13 steel tool with cylindrical geometry, 5.6 mm pin length, 6 mm pin diameter, and 20 mm shoulder diameter. The FSW tool holder is depicted in Fig. 3.

Friction stir welded specimens are shown in Fig. 4. The tool was heat treated to increase its hardness up to 62 HRC.

Tensile specimens were prepared as per the American Society for Testing and Materials (ASTM-E8). A universal testing machine was used to carry out tensile testing using a crosshead speed of 1 mm/min.

A Brinell hardness tester was used to determine the hardness of welded joints. Table 1 displays the chemical make-up of AA6061 and AA7075. Table 2 displays the process parameters and their levels.

The experimental findings are displayed in Table 3. Tensile test and hardness test specimens are shown in Fig. 5&6, respectively.

Table 1. Chemical composition of AA6061 and AA7075

| Alloy | Chemical composition (wt%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Si | Fe | Cu | Mn | Mg | Cr | Zn | Al |
| AA6061 | 0.62 | 0.33 | 0.28 | 0.06 | 0.9 | 0.17 | 0.02 | Bal. |
| AA7075 | - | 0.32 | 1.56 | - | 2.26 | 0.22 | 6.25 | Bal. |

Fig. 1 Experimental setup

Fig. 2 FSW tool

Fig. 3 FSW tool holder

Fig. 4 Friction stir welded specimens

Fig. 5 Tensile test specimens


Fig. 6 Hardness test specimens

Table 2. Process parameters and their levels

| Parameter | Symbol | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Tool rotational speed (rpm) | A | 710 | 900 | 1120 |
| Feed (mm/rev) | B | 30 | 40 | 50 |
| Tilt Angle ($^o$) | C | 0 | 1 | 2 |

Table 3. Experimental results

| Expt. No | Tool rotational speed (rpm) | Feed (mm/rev) | Tilt angle ($^o$) | Tensile strength (MPa) | Hardness (BHN) | % Elongation |
|---|---|---|---|---|---|---|
| 1 | 710 | 30 | 0 | 158.263 | 60.67 | 2.86 |
| 2 | 710 | 40 | 1 | 190.783 | 60.00 | 4.74 |
| 3 | 710 | 50 | 2 | 121.045 | 54.67 | 7.56 |
| 4 | 900 | 30 | 1 | 179.973 | 52.67 | 5.18 |
| 5 | 900 | 40 | 2 | 181.818 | 51.67 | 3.46 |
| 6 | 900 | 50 | 0 | 148.390 | 62.00 | 2.68 |
| 7 | 1120 | 30 | 2 | 187.702 | 58.00 | 7.12 |
| 8 | 1120 | 40 | 0 | 142.482 | 55.33 | 2.02 |
| 9 | 1120 | 50 | 1 | 156.040 | 53.33 | 3.18 |

## 3. METHODOLOGY

### Desirability Function Analysis (DFA)

**Step 1**: Use the formula proposed by Derringer and Suich to determine the individual desirability index (di) for the corresponding responses (1980). According on the features of the answer, there are three types of desirability functions.

**The-nominal-the best**: The desirability function of the nominal-the-best can be written as the term (1).

To reach a specific target T, the value of $\hat{y}$ must be met. When $\hat{y}$ equals T, the desirability value is 1. If $\hat{y}$ deviates outside of a certain range from the target, the desirability value is 0. This situation is the worst possible scenario.

$$d_i = \begin{cases} \left(\dfrac{\hat{y} - y_{min}}{T - y_{min}}\right)^s, & y_{min} \le \hat{y} \le T, \quad s \ge 0 \\ \left(\dfrac{\hat{y} - y_{max}}{T - y_{max}}\right)^t, & T \le \hat{y} \le y_{max}, \quad t \ge 0 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where s and t stand for the weights and $y_{max}$ and $y_{min}$ represent the upper/ lower tolerance limits of $\hat{y}$.

**The-larger-the better**: The expression "the-larger-the-better" can be used to express the desirability function (2). It is anticipated that the greater the value of $\hat{y}$, the better.

The desirability value is equal to 1 when the $\hat{y}$ exceeds a specific criteria value, which can be considered as the requirement; it is equal to 0 when the $\hat{y}$ is less than a specific criteria value, which is unacceptable.

$$d_i = \begin{cases} 0 & \hat{y} \le y_{min} \\ \left(\dfrac{\hat{y} - y_{min}}{y_{max} - y_{min}}\right)^r, & y_{min} \le \hat{y} \le T, \quad r \ge 0 \\ 1, & \hat{y} \ge y_{min} \end{cases} \tag{2}$$

If the weight is represented by r, the lower tolerance limit of $\hat{y}$ is represented by $y_{min}$, and the maximum tolerance limit of $\hat{y}$ is represented by $y_{max}$.

**The-smaller-the better**: The expression "the-smaller-the-better" can be used to represent the desire function (3). It is anticipated that the lower the value of $\hat{y}$ the better.

$$d_i = \begin{cases} 1 & \hat{y} \le y_{min} \\ \left(\dfrac{\hat{y} - y_{max}}{y_{min} - y_{max}}\right)^r, & y_{min} \le \hat{y} \le y_{max}, \quad r \ge 0 \\ 0, & \hat{y} \ge y_{max} \end{cases} \tag{3}$$

The terms (1) through (3) begin with the letters *s*, *t*, and *r*, which stand for weights. These weights are defined in accordance with the needs of the user.

**Step 2**: Compute the composite desirability ($d_G$): The following equation (4) allows the individual desirability index of each response to be merged to create a single value known as composite desirability (dG)

$$d_G = \sqrt[w]{\left(d_1^{w1} * d_2^{w2} \cdots\cdots d_i^{wi}\right)} \tag{4}$$

where $w$ is the total of the individual weights, $w_i$ is the weight of the property "$Y_i$" in the composite desirability, and $d_i$ is the individual desirability of the property $Y_i$

**Step 3**: Determine the optimal parameter and its level combination: A greater composite desirability value indicates a higher calibre of the product. The parameter influence and optimal level for each controllable parameter are therefore calculated using the composite desirability ($d_G$).

**Step 4**: Perform ANOVA: Run an ANOVA to find the important parameters. The relative importance of parameters in terms of their percentage contribution is established via ANOVA.

**Step 5**: Calculate the predicted optimum condition: Predicting and verifying the quality features using the optimal level of the design parameters is the last step after the optimal level of the design parameters has been chosen.

## 4. RESULTS AND DISCUSSIONS

Table 4. Calculated individual desirability and composite desirability

| Expt. No. | Individual desirability | | | Composite desirability |
|---|---|---|---|---|
| | TS | Hardness | % Elongation | |
| 1 | 0.812837 | 0.9555357 | 0.53660404 | 0.7469671 |
| 2 | 1 | 0.9314504 | 0.79076878 | 0.9031012 |
| 3 | 0 | 0.6649621 | 1 | 0 |
| 4 | 0.945935 | 0.4627505 | 0.83088040 | 0.7138093 |
| 5 | 0.955608 | 0 | 0.64106401 | 0 |
| 6 | 0.734218 | 1 | 0.49555433 | 0.7139021 |
| 7 | 0.985199 | 0.8507659 | 0.97306070 | 0.9343108 |
| 8 | 0.677547 | 0.7100609 | 0 | 0 |
| 9 | 0.796484 | 0.546994 | 0.59691557 | 0.6382990 |

Table 5. ANOVA for composite desirability

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | % Contribution |
|---|---|---|---|---|---|---|
| Tool rotational speed | 2 | 0.22461 | 0.004247 | 0.01 | 0.985 | 17.68 |
| Feed | 2 | 0.53467 | 0.195296 | 0.68 | 0.596 | 42.09 |
| Tilt angle | 2 | 0.29478 | 0.147390 | 0.51 | 0.662 | 34.55 |
| Error | 2 | 0.07204 | 0.288164 | | | 5.67 |
| Total | 8 | 1.27019 | | | | |

S = 0.536809, R-sq= 94.63, R-sq(adj)=0.00

Individual and composite desirability is revealed in Table 4. The results of the ANOVA analysis is tabulated in table 5.

From the ANOVA analysis, it can be said that feed is the most influencing parameter followed by tilt angle and tool rotational speed.

The feed has a percentage of contribution of 42.09%. Also, it can be observed from the response table 6. that feed is the most affecting parameter followed by tilt angle and tool rotational speed.

Since the experiment is performed according to the orthogonal array method, the effects of each FSW parameters on composite desirability at each level are calculated and the mean response of the composite desirability of all the FSW parameters with its levels is summarized in Table 6.

Table 6. Response table for means

| Level | Tool rotational speed | Feed | Tilt angle |
|---|---|---|---|
| 1 | **0.5500** | **0.7984** | 0.4870 |
| 2 | 0.4759 | 0.3010 | **0.7517** |
| 3 | 0.5242 | 0.4507 | 0.3114 |
| Delta | 0.0741 | 0.4973 | 0.4403 |
| Rank | 3 | 1 | 2 |

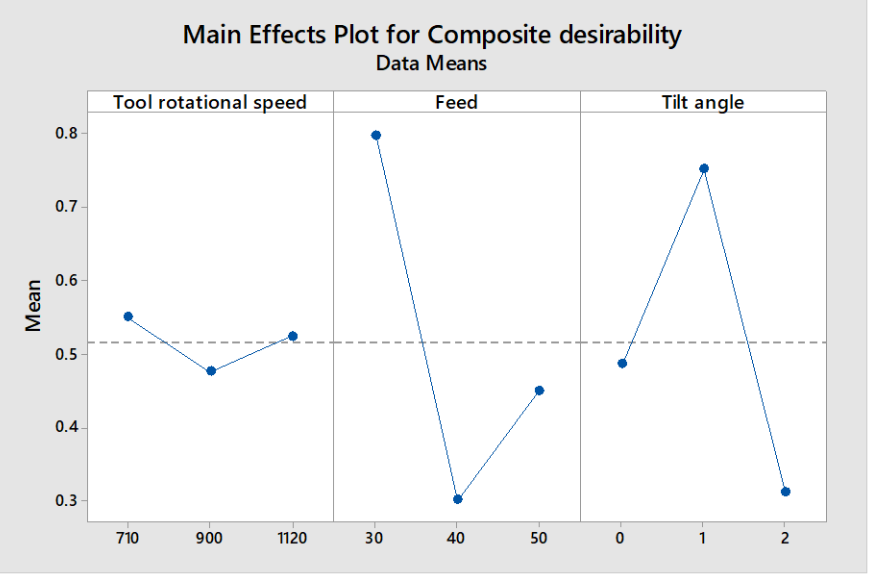


Fig. 7 Main effects plot for composite desirability

The larger the value of the composite desirability, the better will be the performance characteristics. The main effects plot for composite desirability is shown in Fig. 7. It is revealed from Fig. 7 that tool rotation speed at level 1, feed at level 1, and tilt angle at level 2 are the optimum condition. The optimal parametric setting is tool rotation speed at 710 rpm, feed at 30 mm/rev, and tilt angle at 1$^{o}$. Table 7 shows the regression coefficients.

The normal probability plot is presented in Fig. 8. The errors are distributed normally because the residuals fall on a straight line [17]. The non-parallel lines in the interaction plot shown in Fig.9 indicated that the two-way interactions were significant. The Regression equation for composite desirability is given in Eq. 5

$$\text{Composite desirability} = 1.35 - 0.000056 \times \text{Tool rotational speed} - 0.0174 \times \text{Feed} - 0.088 \times \text{Tilt angle} \quad (5)$$

Table 7. Regression coefficients

| Term | Coef | SE Coef | T-Value | P-Value | VIF |
|---|---|---|---|---|---|
| Constant | 1.35 | 1.14 | 1.19 | 0.289 | |
| Tool rotational speed | -0.000056 | 0.000908 | -0.06 | 0.954 | 1.00 |
| Feed | -0.0174 | 0.0186 | -0.93 | 0.394 | 1.00 |
| Tilt angle | -0.088 | 0.186 | -0.47 | 0.658 | 1.00 |

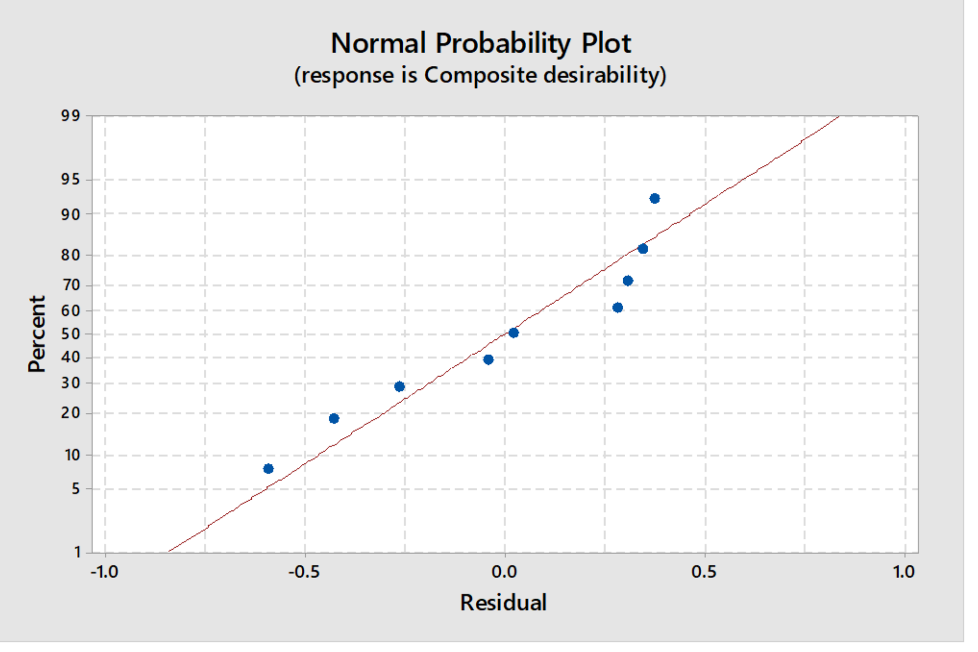


Fig. 8 Normal probability plot for composite desirability

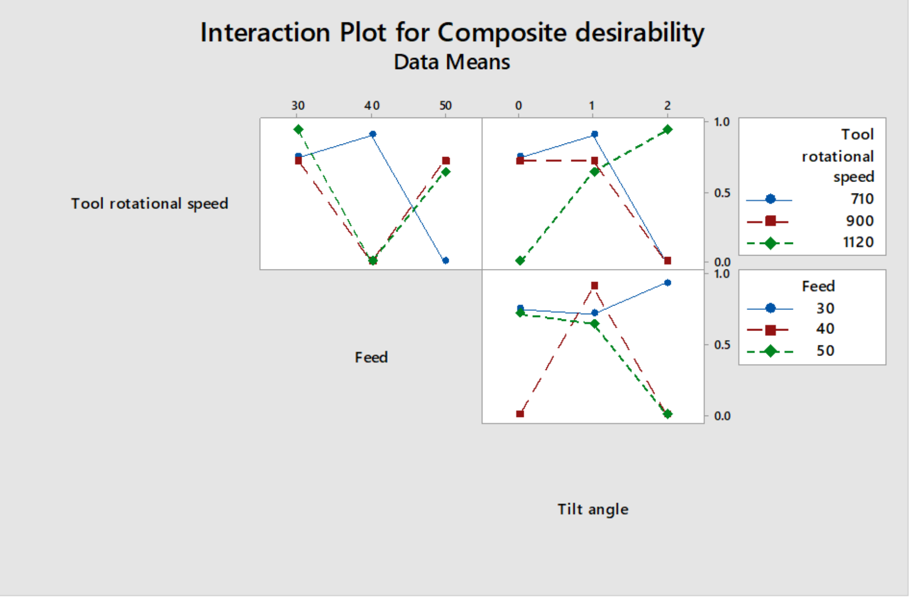


Fig. 9 Interaction plot for composite desirability

## 5. CONCLUSIONS

Tensile strength, hardness, and percent elongation were all optimized during the FSW of dissimilar alloys of AA6061 and AA7075. The process parameters were feed rate, tilt angle, and tool rotating speed. The DFA multi-objective optimization was utilized, and the trials were based on the L9 orthogonal array. The following conclusions were drawn from this study:

- It was discovered that feed had the greatest impact on the responses, followed by tilt angle and tool rotating speed.
- It is clear from the results of DFA that experiment no. 7 has the highest composite desirability value. The obtained optimum combinations of parameters are i.e. tool rotational speed-710 rpm, Feed rate-30 mm/rev, and tilt angle-1$^o$.
- From the ANOVA, the feed (42.09%) has a significant influence followed by tilt angle (34.55%); tool rotational speed (17.68%) has the least influence.
- The observed results and ANOVA were in good accordance.
- An improvement of 20.10% of the predicted weighted closeness coefficient confirms the optimality of the obtained results.
- It is clear from the results of DFA that experiment no. 7 has the highest composite desirability value. The obtained optimum combinations of parameters are i.e. Tool rotational speed-710 rpm, Feed rate-30 mm/rev, and tilt angle -1$^o$.

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