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RESEARCH ARTICLE

# Optimization of Friction Stir Welded Dissimilar Aluminum Alloys EN AW-5083-H111 and EN AW-6082-T651 using Hybrid Taguchi-Based Grey Relation Analysis

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**Abstract:** Friction Stir Welding (FSW) which is a kind of solid state welding process used essentially for joining nonferrous metals and their alloys. Involving pollution free and no filler material are the advantages of FSW when compared to other welding methods. The present work was focused on the multi objective optimization of friction stir welded EN AW-6082-T651 and EN AW-5083-H111 aluminum alloys using Taguchi based Grey relational analysis (GRA) method under different parameters of shoulder diameter (SD, mm), tool rotation (TR, rpm) and welding speed (WS, mm/min) on tensile strength (TS, MPa), percent elongation (E, %) and joint efficiency (JE). Taguchi related experiments were performed using $L_{27}$ Orthogonal Array. The grey relational analysis which relates between the FSW parameters and the responses applied to find the optimum condition. Additionally, the Analysis of Variance (ANOVA) approach was used to identify the most important factor and its impact on the multiple response. The results of the obtained tests were then verified using the confirmation test.

**Keywords:** Taguchi method, Grey relation analysis, Friction stir welding, Optimization, Tensile strength

## 1. Introduction

Friction stir welding (FSW) which was developed and patented in 1991 by TWI (The Welding Institute) in England is a new technology of solid state welding method for joining of similar and dissimilar metals [1,2]. The FSW technique is accomplished by rotating and advancing a tool made up of a pin and shoulder with a unique profile across the surface of the material to be connected. Surface friction and heat are produced as a result of the tool pin's pressure and rotating movement. This results a heat and softens the material locally and plastic deformation occurs on the area to be welded [2-4]. The welding procedure is carried out by the tool's advanced movement along the predetermined bond line [5-7]. The demonstration for the FSW process is given in Figure 1.

Where combining different metals and alloys that call for excellent performance, particularly when distortions and internal stresses are not sought, FSW is effectively used as a cold welding procedure [8-10]. The FSW process, which is used for creating high quality welds in a number of materials difficult to weld by conventional welding processes, finds application field such as ship and marine industry, aviation and space industry and land transport and railway industries [1,7,8]. There are numerous studies deals with modeling and optimization of friction stir welding using different kind of workpiece materials.

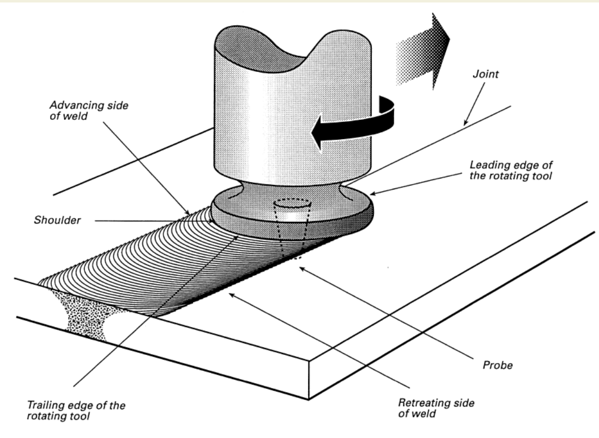


Figure 1. Schematic representation of FSW process [7]

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Kumar et al. [11] presented hybrid fuzzy assisted grey Taguchi method for optimization of friction stir welded Al/Cu joints. Sun et al. [12] studied the influence of friction stir welding on mechanical properties of AZ61 magnesium alloy. Shanik et al. [13] investigated multi response optimization in friction stir welding of aluminum alloy using grey relational analysis. Pratash et al. [14] presented a study for multiple response Taguchi based grey relation analysis for optimization of magnesium alloy. Palani et al. [15] examined friction stir welding aluminum alloy using grey relation optimization method. Vijayan et al. [16] optimized AA5083 aluminum alloy using Taguchi based grey optimization method. Gupta et al. [17] presented genetic algorithm based optimization study for friction stir welded AA5083 and AA6063-T6 aluminum alloys. Babu et al. [18] optimized friction stir welding process using artificial neural network with genetic algorithm. Yunus et al. [19] modelled friction stir welding process of two dissimilar aluminum alloys using experimental design technique and genetic algorithm. Yousif et al. [20] developed an artificial neural network model for prediction of mechanical properties of friction stir welded aluminum alloy.

Taguchi's method is developed by Dr. Genichi Taguchi in 1950s who is a Japanese quality management advisor. Design of the experiments through orthogonal array using Taguchi's philosophy is an effective way to optimize the design, cost and quality with a minimum number of trials [21]. In the Taguchi method, optimum parameter combination is selected by using a statistical measurement of efficiency which is named as signal to noise ratio (S/N). The S/N rate is related to the ratio of mean to the standard deviation. This ratio is affected by optimized quality characteristics of the process [21,22]. Taguchi uses three types of quality characteristics of nominal the better (NB), lower the Better (LB) and higher the better (HB). The optimal parameter setting requires the highest S/N ratio [21].

In the present work, Taguchi based grey relational analysis (GRA) has been carried out for the multi response optimization of FSW process parameters such as shoulder diameter (SD, mm), tool rotation (TR, rpm) and welding speed (WS, mm/min) on the responses of tensile strength (TS, MPa), percent elongation (E, %) and joint efficiency (JE) during welding of dissimilar aluminum alloys of EN AW-5083-H111 and EN AW-6082-T651. So, an optimal FSW process parameters were determined through this method. Finally, the analysis of variance (ANOVA) was applied in order to examine the contribution of each FSW parameters on the responses.

## 2. Grey Relational Analysis

The Grey system theory, first put forward by Deng in 1989, is a system in which some of the information is known and some is unknown. In other words, grey system indicates the level of information between black and white. Although, black region does not have any information, the white region has the information completely. Grey modeling includes the subtitle "grey relation analysis" (GRA). To ascertain the degree of the link between the components, each component of the system was compared to a reference sequence [21].

### 2.1. Normalization of the Responses

The first step which is considering the conversion of the measured values come from different units is called as normalization. The criteria of "smaller is better," "larger is better," and "ideal is better" are used to make normalization of the experimental data between zero and one. In normalization calculation of this work, tensile strength (TS), joint efficiency (JE), and the normalized reference sequences were calculated using the "larger is better" (LB) criteria. Following formula expresses the larger the better criterion [21]:

$$x_i(k) = \frac{y_i(k) - min\, y_i(k)}{max\, y_i(k) - min\, y_i(k)} \tag{1}$$

Percent elongation (E) should follow the *smaller the better* (SB) criterion which is expressed as:

$$x_i(k) = \frac{max\, y_i(k) - y_i(k)}{max\, y_i(k) - min\, y_i(k)} \tag{2}$$

where $x_i(k)$ is calculated after the Grey relation generation, min$y_i(k)$ is the lowest value of $y_i(k)$ related to the $k^{th}$ response, and max$y_i(k)$ is the highest value of $y_i(k)$ $y_i(k)$ related to the $k^{th}$ response. A reference sequence is $x_0(k)$ ($k$=1, 2, 3......, 27) for the responses. The definition of the Grey relational degree in the process of GRG analysis is to show the degree of the connection between 27 sequences [$x_0(k)$ and $x_i(k)$, $i$=1, 2, 3.......,27].

### 2.2. Calculation of Grey Relational Coefficient

Normalization step should follow the calculation of grey relational coefficient (GRC) to determine the relation between the best and actual normalized responses. The Grey relational coefficient (GRC) $\xi_i(k)$ is calculated as [21]:

$$\xi_i(k) = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{0i}(k) + \psi\Delta_{\max}} \tag{3}$$

where $\Delta_{0i} = \|x_0(k) - x_i(k)\|$= difference of the absolute value $x_0(k)$ and $x_i(k)$; $\psi$ is the distinguishing coefficient $0 \le \psi \le 1$, $\psi$is considered as 0.333 for each responses; $\Delta min^{min\|x_0(k)-x_j(k)\|}{}_{min}$=the smallest value of $\Delta_{0i}$; and $\Delta max^{max\|x_0(k)-x_j(k)\|}{}_{max}$= highest value of $\Delta_{0i}$.

### 2.3. Grey Relational Grade Calculations

The Grey relational grade (GRG) $\gamma_i$ for each response of the FSW process is determined by averaging the Grey relational coefficients and is computed as follows [21]:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \tag{4}$$

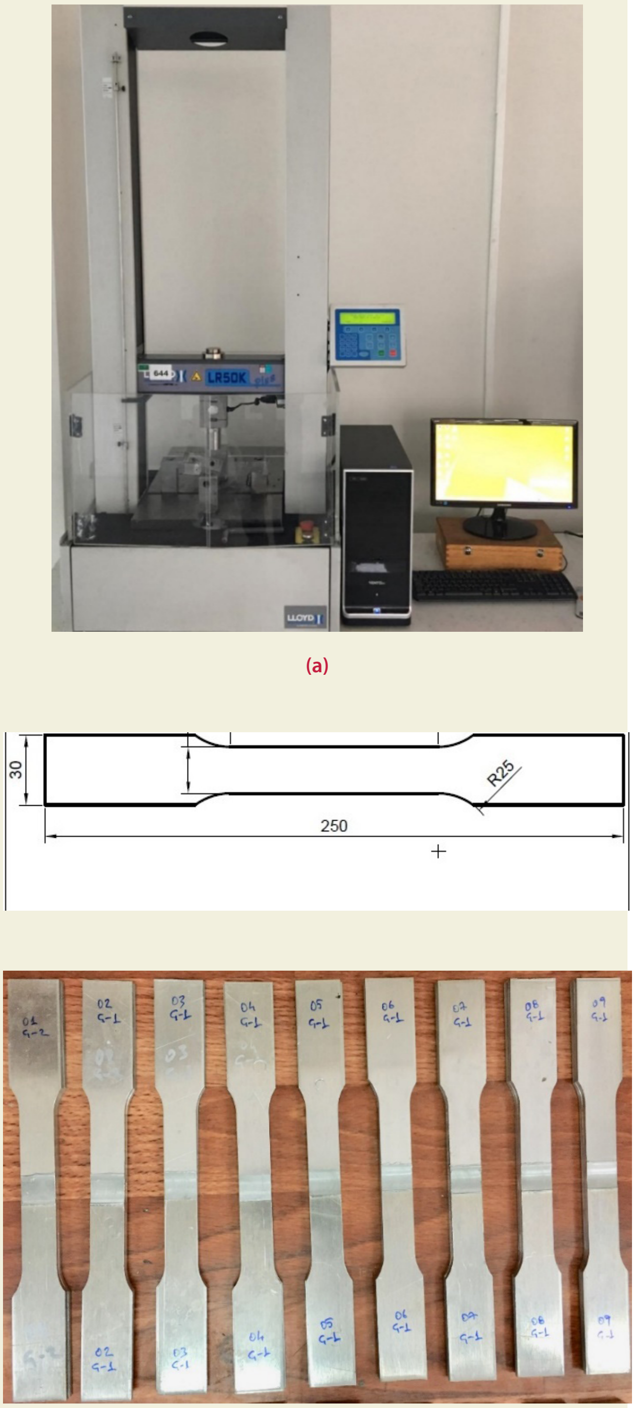

(a) (b) (c)

**Figure 2.** (a) Milling machine used in the FSW experiments, (b) Fixture and components, (c) Welding tool geometry

**Table 1.** Chemical (wt.%) and mechanical characteristics of the workpieces [23,24]

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | EN AW-5083-H111 | | | | | | |
| Chemical composition (wt.%) | Fe% | Cr | Mg% | Mn% | Cu% | Si% | Al% |
| | 0.40 | max 0.25 | 4.50 | 0.60 | max 0.10 | 0.40 | Balance |
| Mechanical properties | Tensile strength (MPa) | | Yield strength (MPa) | | % Elongation | | Hardness ($HV_{0.2}$) |
| | 310 | | 170 | | 17 | | 92.46 |
| | EN AW-6082-T651 | | | | | | |
| Chemical composition (wt.%) | Fe% | Cr | Mg% | Mn% | Cu% | Si% | Al% |
| | 0.50 | max 0.25 | 1.20 | 0.80 | max 0.10 | 0.80 | Balance |
| Mechanical properties | Tensile strength (MPa) | | Yield strength (MPa) | | % Elongation | | Hardness ($HV_{0.2}$) |
| | 330 | | 270 | | 16 | | 123.30 |

where $n$ is the number of the friction stir welding responses. The higher value of GRG means that there is a stronger relational degree between the reference sequence $x_0(k)$ and the given sequence $x_i(k)$. The reference sequence $x_0(k)$ represents the best process sequence; hence, higher Grey relational grade indicates that obtained parameter combination is very close to the optimal value. Both, the average response for the GRG and the main effect graph of GRG are very important for the evaluation of optimal welding process condition [21,22].




(a)

(b)

**Figure 3.** (a) Tensile testing equipment, (b) Prepared samples according to EN ISO 6892-1

## 3. Experimental Methodology and Test Results

### 3.1. Experimental Details

The aluminum alloys of EN AW-5083-H111 and EN AW-6082-T651 were used in this investigation with the dimensions of 125 mm x 400 mm x 4 mm and used for butt joint form using FSW process [1]. Table 1 provides the chemical composition (wt.%) and mechanical characteristics of the workpiece material.

The experiments were performed on the semi-automatic vertical milling machine. Hot work tool (H13) steel, due of its excellent wear resistance, hardness at elevated temperatures, and ease of availability, was employed as the friction welding tool [1]. Used tool pin profile was M5 screw type with a 3.8 mm pin length. Figure 2 also displays the experimental details, such as fixtures and experimental components, the pin profile and shape.

As shown in Figure 3, the tensile test specimens were cut perpendicular to the direction of welding, and then machined as per EN ISO 6892-1 standards and which were tested in the LLOYD Instruments tensile testing machine.

### 3.2. Experimental Details and Test Results

Taguchi experimental design offers an opportunity for designing and conducting the experiments using minimum resources. Throughout this work, the $L_{27}$ orthogonal array which consists of 27 sets of data was utilized to set the parameters for friction stir welding. Table 2 shows the input parameters and their levels.

The experiments were conducted in accordance with the Taguchi's $L_{27}$ orthogonal array assigning different levels values to the FSW parameters and the final results for tensile strength (TS), percent elongation (E) and joint efficiency (JE) is tabulated in Table 3. All of these $L_{27}$ array data have been used in a grey relation analysis to identify the best FSW parameter combinations for the desired weld quality in the experimental setting.

## 4. Fsw Parameter Optimization Using Grey Relation Method

### 4.1. Finding the Optimum FSW Parameter

Prior to creating the grey relation generation (GRG), ob-

**Table 2.** FSW parameters and their limits

| Welding parameters | Notation | Unit | Levels of parameters | | |
|---|---|---|---|---|---|
| | | | 1 | 2 | 3 |
| Shoulder diameter | SD | mm | 16 | 20 | 24 |
| Tool rotation | TR | rpm | 710 | 1000 | 1400 |
| Welding speed | WS | mm/min | 56 | 112 | 160 |


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**Table 3.** Experimental and calculated results

| Experimental run | Process parameters | | | Results | | | Fracture zones HAZ: heat affected zone WZ: weld zone |
|---|---|---|---|---|---|---|---|
| | SD | TR | WS | TS (MPa) | E (%) | JE | |
| 1 | 1 | 1 | 1 | 209.43 | 3.81 | 67.56 | EN AW-6082 HAZ |
| 2 | 1 | 1 | 2 | 219.73 | 4.97 | 70.88 | WZ |
| 3 | 1 | 1 | 3 | 223.49 | 4.61 | 72.09 | WZ |
| 4 | 1 | 2 | 1 | 159.55 | 2.28 | 51.47 | WZ |
| 5 | 1 | 2 | 2 | 213.18 | 3.76 | 68.77 | WZ |
| 6 | 1 | 2 | 3 | 230.43 | 5.44 | 74.33 | EN AW-6082 HAZ |
| 7 | 1 | 3 | 1 | 207.04 | 4.12 | 66.79 | EN AW-6082 HAZ |
| 8 | 1 | 3 | 2 | 212.53 | 4.33 | 68.56 | EN AW-6082 HAZ |
| 9 | 1 | 3 | 3 | 228.92 | 5.24 | 73.85 | EN AW-6082 HAZ |
| 10 | 2 | 1 | 1 | 201.11 | 4.06 | 64.87 | EN AW-6082 HAZ |
| 11 | 2 | 1 | 2 | 209.36 | 4.47 | 67.54 | EN AW-6082 HAZ |
| 12 | 2 | 1 | 3 | 217.13 | 4.82 | 70.04 | EN AW-6082 HAZ |
| 13 | 2 | 2 | 1 | 200.30 | 4.02 | 64.61 | EN AW-6082 HAZ |
| 14 | 2 | 2 | 2 | 206.92 | 4.24 | 66.75 | EN AW-6082 HAZ |
| 15 | 2 | 2 | 3 | 220.81 | 4.95 | 71.23 | EN AW-6082 HAZ |
| 16 | 2 | 3 | 1 | 193.62 | 4.38 | 62.46 | EN AW-6082 HAZ |
| 17 | 2 | 3 | 2 | 212.63 | 5.02 | 68.59 | EN AW-6082 HAZ |
| 18 | 2 | 3 | 3 | 221.05 | 4.92 | 71.31 | EN AW-6082 HAZ |
| 19 | 3 | 1 | 1 | 196.43 | 4.19 | 63.36 | EN AW-6082 HAZ |
| 20 | 3 | 1 | 2 | 200.96 | 4.29 | 64.83 | EN AW-6082 HAZ |
| 21 | 3 | 1 | 3 | 213.98 | 4.49 | 69.03 | EN AW-6082 HAZ |
| 22 | 3 | 2 | 1 | 206.65 | 4.58 | 66.66 | EN AW-6082 HAZ |
| 23 | 3 | 2 | 2 | 211.05 | 4.84 | 68.08 | EN AW-6082 HAZ |
| 24 | 3 | 2 | 3 | 225.81 | 5.23 | 72.84 | EN AW-6082 HAZ |
| 25 | 3 | 3 | 1 | 200.58 | 4.17 | 64.70 | EN AW-6082 HAZ |
| 26 | 3 | 3 | 2 | 207.80 | 4.28 | 67.03 | EN AW-6082 HAZ |
| 27 | 3 | 3 | 3 | 214.76 | 4.93 | 69.28 | EN AW-6082 HAZ |

**Table 4.** Tabulation of normalization results and $\Delta_{0i}$ for TS, E, and JE

| Run | Grey relation generation | | | $\Delta_{0i}$ | | |
|---|---|---|---|---|---|---|
| | TS | E | JE | TS | E | JE |
| Reference sequence | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 1 | 0.704 | 0.516 | 0.704 | 0.296 | 0.484 | 0.296 |
| 2 | 0.849 | 0.149 | 0.849 | 0.151 | 0.851 | 0.151 |
| 3 | 0.902 | 0.263 | 0.902 | 0.098 | 0.737 | 0.098 |
| 4 | 0.000 | 1.000 | 0.000 | 1.000 | 0.000 | 1.000 |
| 5 | 0.757 | 0.532 | 0.757 | 0.243 | 0.468 | 0.243 |
| 6 | 1.000 | 0.000 | 1.000 | 0.000 | 1.000 | 0.000 |
| 7 | 0.670 | 0.418 | 0.670 | 0.330 | 0.582 | 0.330 |
| 8 | 0.747 | 0.351 | 0.748 | 0.253 | 0.649 | 0.252 |
| 9 | 0.979 | 0.063 | 0.979 | 0.021 | 0.937 | 0.021 |
| 10 | 0.586 | 0.437 | 0.586 | 0.414 | 0.563 | 0.414 |
| 11 | 0.703 | 0.307 | 0.703 | 0.297 | 0.693 | 0.297 |
| 12 | 0.812 | 0.196 | 0.812 | 0.188 | 0.804 | 0.188 |
| 13 | 0.575 | 0.449 | 0.575 | 0.425 | 0.551 | 0.425 |
| 14 | 0.668 | 0.380 | 0.668 | 0.332 | 0.620 | 0.332 |
| 15 | 0.864 | 0.155 | 0.864 | 0.136 | 0.845 | 0.136 |
| 16 | 0.481 | 0.335 | 0.481 | 0.519 | 0.665 | 0.519 |
| 17 | 0.749 | 0.133 | 0.749 | 0.251 | 0.867 | 0.251 |
| 18 | 0.868 | 0.165 | 0.868 | 0.132 | 0.835 | 0.132 |
| 19 | 0.520 | 0.396 | 0.520 | 0.480 | 0.604 | 0.480 |
| 20 | 0.584 | 0.364 | 0.584 | 0.416 | 0.636 | 0.416 |
| 21 | 0.768 | 0.301 | 0.768 | 0.232 | 0.699 | 0.232 |
| 22 | 0.665 | 0.272 | 0.664 | 0.335 | 0.728 | 0.336 |
| 23 | 0.727 | 0.190 | 0.727 | 0.273 | 0.810 | 0.273 |
| 24 | 0.935 | 0.066 | 0.935 | 0.065 | 0.934 | 0.065 |
| 25 | 0.579 | 0.402 | 0.579 | 0.421 | 0.598 | 0.421 |
| 26 | 0.681 | 0.367 | 0.681 | 0.319 | 0.633 | 0.319 |
| 27 | 0.779 | 0.161 | 0.779 | 0.221 | 0.839 | 0.221 |

**Table 5.** Calculated GRC and GRG in accordance with the order

| Experimental run | GRC ($\xi_i(k)$) TS | E | JE | GRG | Rank |
|---|---|---|---|---|---|
| 1 | 0.527 | 0.405 | 0.527 | 0.4859 | 14 |
| 2 | 0.686 | 0.279 | 0.686 | 0.5500 | 7 |
| 3 | 0.771 | 0.309 | 0.771 | 0.6165 | 4 |
| 4 | 0.248 | 1.000 | 0.248 | 0.4982 | 10 |
| 5 | 0.576 | 0.413 | 0.576 | 0.5210 | 9 |
| 6 | 1.000 | 0.248 | 1.000 | 0.7486 | 1 |
| 7 | 0.500 | 0.362 | 0.500 | 0.4535 | 18 |
| 8 | 0.566 | 0.337 | 0.567 | 0.4896 | 13 |
| 9 | 0.939 | 0.261 | 0.940 | 0.7126 | 2 |
| 10 | 0.444 | 0.369 | 0.444 | 0.4185 | 22 |
| 11 | 0.526 | 0.323 | 0.526 | 0.4579 | 17 |
| 12 | 0.638 | 0.291 | 0.637 | 0.5215 | 8 |
| 13 | 0.437 | 0.375 | 0.437 | 0.4158 | 23 |
| 14 | 0.499 | 0.347 | 0.499 | 0.4478 | 20 |
| 15 | 0.709 | 0.281 | 0.709 | 0.5655 | 6 |
| 16 | 0.389 | 0.332 | 0.389 | 0.3693 | 27 |
| 17 | 0.568 | 0.276 | 0.568 | 0.4700 | 15 |
| 18 | 0.714 | 0.283 | 0.714 | 0.5698 | 5 |
| 19 | 0.408 | 0.353 | 0.407 | 0.3890 | 26 |
| 20 | 0.442 | 0.342 | 0.443 | 0.4085 | 25 |
| 21 | 0.587 | 0.321 | 0.587 | 0.4978 | 11 |
| 22 | 0.496 | 0.312 | 0.496 | 0.4341 | 21 |
| 23 | 0.547 | 0.289 | 0.547 | 0.4606 | 16 |
| 24 | 0.835 | 0.261 | 0.835 | 0.6431 | 3 |
| 25 | 0.439 | 0.356 | 0.439 | 0.4110 | 24 |
| 26 | 0.508 | 0.343 | 0.508 | 0.4526 | 19 |
| 27 | 0.599 | 0.282 | 0.599 | 0.4929 | 12 |

**Table 6.** Calculated GRG and its S/N ratios

| Experimental run | GRG | S/N |
|---|---|---|
| 1 | 0.4859 | -6.27 |
| 2 | 0.5500 | -5.19 |
| 3 | 0.6165 | -4.20 |
| 4 | 0.4982 | -6.05 |
| 5 | 0.5210 | -5.66 |
| 6 | 0.7486 | -2.52 |
| 7 | 0.4535 | -6.87 |
| 8 | 0.4896 | -6.20 |
| 9 | 0.7126 | -2.94 |
| 10 | 0.4185 | -7.57 |
| 11 | 0.4579 | -6.78 |
| 12 | 0.5215 | -5.65 |
| 13 | 0.4158 | -7.62 |
| 14 | 0.4478 | -6.98 |
| 15 | 0.5655 | -4.95 |
| 16 | 0.3693 | -8.65 |
| 17 | 0.4700 | -6.56 |
| 18 | 0.5698 | -4.89 |
| 19 | 0.3890 | -8.20 |
| 20 | 0.4085 | -7.78 |
| 21 | 0.4978 | -6.06 |
| 22 | 0.4341 | -7.25 |
| 23 | 0.4606 | -6.73 |
| 24 | 0.6431 | -3.83 |
| 25 | 0.4110 | -7.72 |
| 26 | 0.4526 | -6.89 |
| 27 | 0.4929 | -6.14 |

served and computed data were first adjusted using Equations (1) and (2). For each of the replies, the normalized data and the difference in the absolute value ( $\Delta_{0i}$ ) have been computed and are shown in Table 4.

Generally, the distinguishing coefficient ($\psi$) takes the value between 0 and 1. A survey of the literature reveals that the grey relational grade is unaffected by the distinguishing factor [3]. Throughout this work, each response is given an identical weight of 0.333. Namely, $\psi_{TS} = \psi_E = \psi_{JE}$ =0.333. Table 5 shows the calculated Grey relational coefficients (GRC) for each response corresponding grey relational grade (GRG) calculated by using Eqs. (3) and (4).

The time has come to employ Eq. (7) to calculate the S/N ratio using the larger is better formula for total GRG [21].

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^{2}}\right] \tag{7}$$

where $n$ is the number of tests, and $y_i$ is the experimental value $i^{th}$performance in the$j^{th}$experiment at the $k^{th}$test. The computed GRG and its S/N ratio are shown in Table 6.

The highest GRG and S/N mean that within the experimental domain, the chosen parameter setting is extremely near the ideal value [21]. Throughout this work, maximum GRG and corresponding S/N ratios of 0.748 and

-2.52 respectively were obtained at the 6th experimental run for the FSW parameter combination of $SD_1TR_2WS_3$. S/N ratio and GRG graphs plotted vs parameter level are shown in Figure 4. Here, dashed line implies the average of the GRG and S/N ratio.

As indicated in Figure 4, the optimal FSW parameter level combination for EN AW-5083-H111 and EN AW-6082-T651 aluminum alloys obtained as $SD_1TR_2WS_3$ (shoulder diameter of level 1, tool rotation of level 2 and welding speed of level 3). Table 7 lists the corresponding averages of the GRG and S/N ratio for input parameters of the FSW.

Additionally, the method of Analysis of Variance (ANOVA) approach was used on GRG to determine the percent contribution and most important parameter which affects the selected responses. Therefore, in forthcoming section of this work ANOVA is tabulated and discussed.

**Table 7.** Mean GRG and S/N response table

| **Factors** | **Mean GRG** | | | | |
|---|---|---|---|---|---|
| | **Level 1** | **Level 2** | **Level 3** | **max-min** | **Rank** |
| SD | 0.56 | 0.46 | 0.47 | 0.10 | 1 |
| TR | 0.48 | 0.53 | 0.49 | 0.05 | 2 |
| WS | 0.43 | 0.47 | 0.60 | 0.17 | 3 |
| Total average GRG= 0.50 | | | | | |
| Factors | S/N | | | | |
| | Level 1 | Level 2 | Level 3 | max-min | Rank |
| SD | -5.10 | -6.63 | -6.73 | 1.63 | 1 |
| TR | -6.41 | -5.73 | -6.32 | 0.68 | 2 |
| WS | -7.36 | -6.53 | -4.58 | 2.78 | 3 |
| Total mean S/N= -6.20 | | | | | |

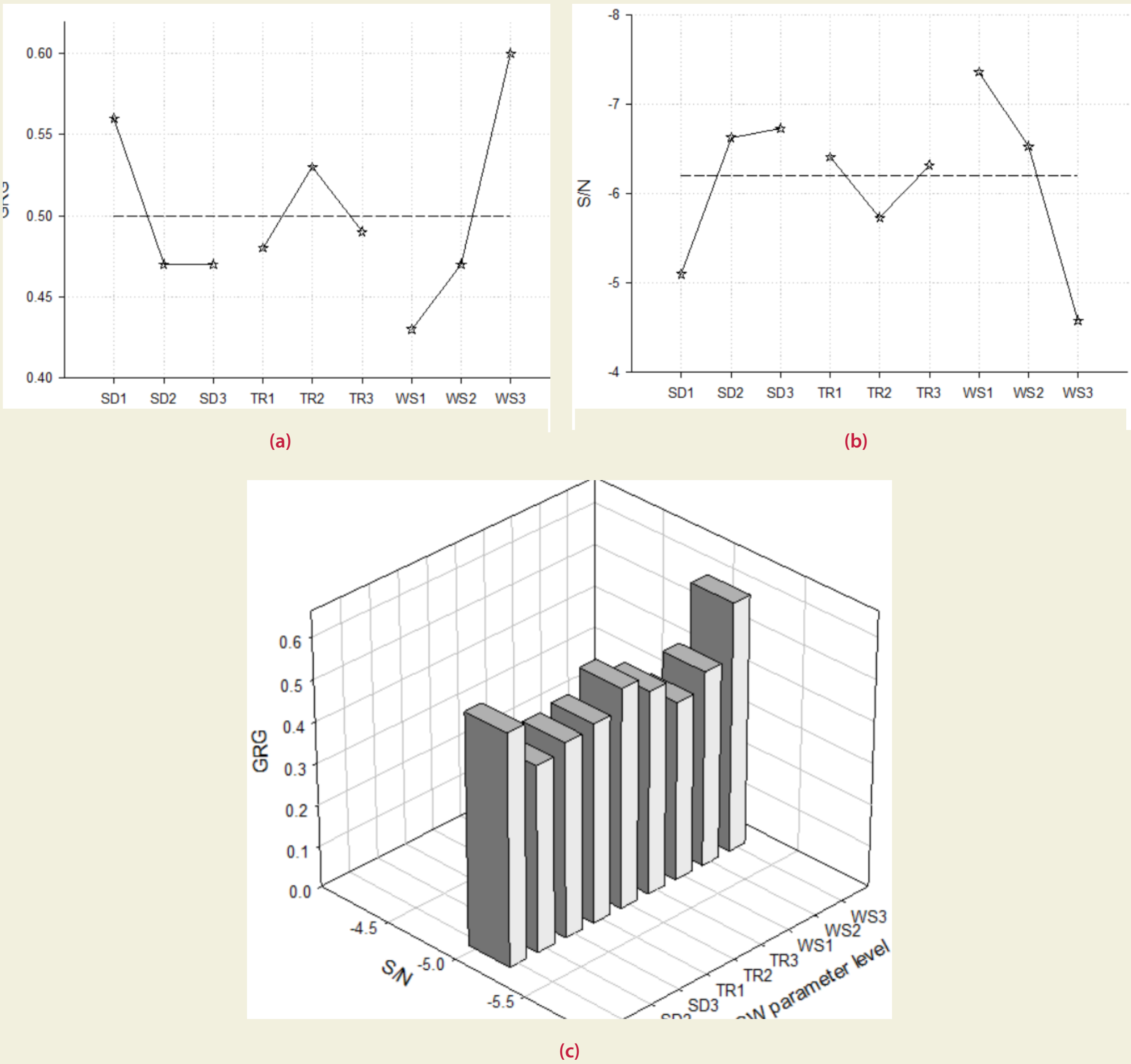



**Figure 4.** (a) GRG vs. Parameter level, (b) S/N vs. parameter level, c) 3D bar chart representation GRG and S/N vs. parameter level

**Table 8.** Calculated ANOVA for input parameters of FSW

| Parameter | Degree of freedom | Sum of square | Mean square | F ratio | Contribution (%) |
|---|---|---|---|---|---|
| SD | 2 | 0.055 | 0.028 | 25.01 | 24.66 |
| TR | 2 | 0.009 | 0.004 | 4.28 | 4.035 |
| WS | 2 | 0.130 | 0.067 | 60.44 | 58.29 |
| SDxTR | 4 | 0.004 | 0.001 | 0.950 | 1.798 |
| SDxWS | 4 | 0.007 | 0.001 | 1.720 | 3.139 |
| TRxWS | 4 | 0.010 | 0.002 | 2.280 | 4.484 |
| SDxTRxWS | 8 | 0.008 | 0.001 | 1.100 | 3.587 |
| **Total** | **26** | **0.223** | | | **100** |

**Table 9.** The results of Confirmation

| | Initial factor settings | Optimal process condition | |
|---|---|---|---|
| | | Prediction | Experiment |
| **Optimum parameter level** | $SD_1TR_1WS_1$ | $SD_1TR_2WS_3$ | $SD_1TR_2WS_3$ |
| **Shoulder diameter (mm)** | 16 | - | 16 |
| **Tool rotation (rpm)** | 710 | - | 1000 |
| **Welding speed (mm/min)** | 56 | - | 160 |
| **Grey relational grade** | 0.485 | 0.690 | 0.748 |
| | Improvement in GRG: 0.263 | | |

## 4.2. Analysis of Variance Method

A common statistical method for determining the importance of each component on the process's quality characteristics is the ANOVA methodology. Alternatively say, it provides a clear understanding of how much the process parameter impacts the answer and the relative importance of each parameter taken into account. [10,21,22]. Also, the F ratio test which is the ratio of the mean of squares deviations to the mean of the squared error was used in order to imply the significance of the parameters on the selected response. The ANOVA table for GRG is calculated and tabulated in Table 8.

According to the ANOVA analysis, welding speed of 58.29% and shoulder diameter of 24.66% are the most effective parameter while tool rotation of 4.03% is the primary factor that has the least impact on joint efficiency, elongation, and tensile strength. Binary interaction contributions of parameters becomes: shoulder diameter and tool rotation of 1.79%, shoulder diameter and welding speed of 3.13%, tool rotation and welding speed of 4.48%. Lastly, triple interaction contributions of shoulder diameter and tool rotation and welding speed of 3.587% were obtained. Figure 5 displays the graphical representation of the FSW parameters' percentage contributions and the effects of their interactions.

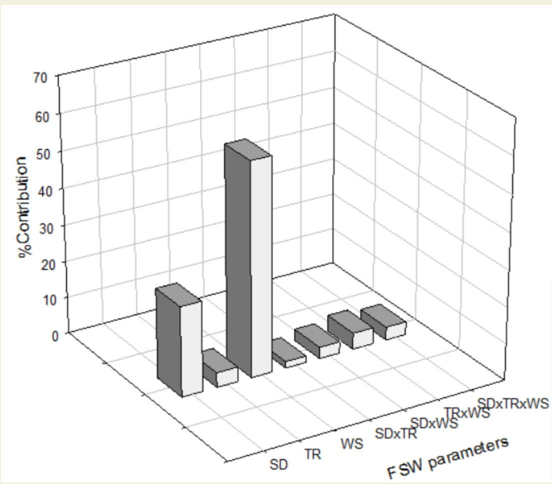



**Figure 5.** Multiple percentage contributions of parameters

## 4.3. The Test of Confirmation

The confirmatory test was conducted in the current study utilizing the perfect parameter combination to evaluate the effectiveness in the response parameters and the accuracy of the optimal welding condition ($SD_1TR_2WS_3$). The following formula was used for the prediction GRG ($\hat{\gamma}$) values [21,22]:

$$\hat{\gamma} = \gamma_a + \sum_{i=1}^{p}(\bar{\gamma}_o - \gamma_a) \tag{10}$$

where $p$ is the design parameter number, $\bar{\gamma}_o$ is the average GRG at the optimum level, and $\gamma_a$ is the overall average GRG [6,14]. The confirmation test results are given in Table 11.

The results of the confirmatory tests make it evident that the GRG has improved overall, coming in at 0.263. The suggested Taguchi-based grey relation optimization approach for the dissimilar friction stir welding process uses this as its primary indication. Also, the method showed that higher tensile strength of 230.43 MPa, elongation of 5.44% and joint efficiency of 74.33 were obtained under determined optimum welding condition. Figure 6 shows the friction stir welded sample at the optimal parameter setting.

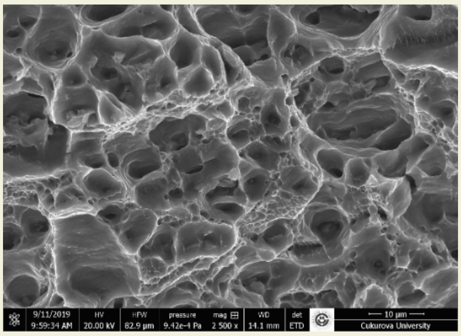
For the optimal weld parameter setting, the scanning electron microscope (SEM) analysis of dissimilar friction stir welded aluminum alloys shown in Figure 7 proved that due to the sufficient friction together with proper mixing and material flow promoted the plastic deformation in the weld interface and this caused regular microstructure at the welding zone [1,15].

(a)

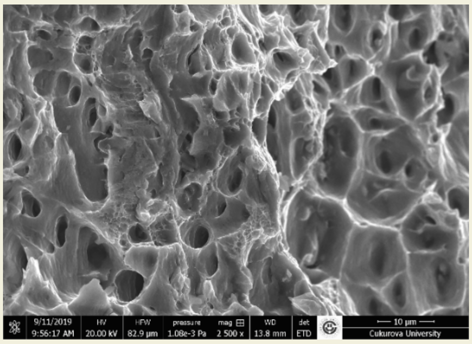
(b)

(c)

**Figure 6.** Friction stir welded samples at optimal parameter settings of; SD: 16mm, TR: 1000 rpm and WS: 160 mm/min. (a) top surface, (b) bottom surface, (c) fractured surface



(a) EN AW-5083-H111 weld zone



(b) EN AW-6082-T651 weld zone

**Figure 7.** SEM micrograph (2500X) and EDS image at the optimal process condition at the weld Interface

## 5. Conclusion

The Taguchi based grey relation analysis method was adopted in this investigation to optimize the friction stir welding process parameters of dissimilar welding for EN AW-5083-H111 and EN AW-6082-T651 aluminum alloys. The following conclusions can be drawn from this work as follows:

1. The Taguchi based grey relation method for FSW of dissimilar aluminum alloys were successfully applied.
2. Taguchi's $L_{27}$ orthogonal array was used to perform the experiments by varying the process parameters such as shoulder diameter, tool rotation and welding speed.
3. The FSW parameters of shoulder diameter of 16 mm, tool rotation of 1000 rpm, and welding speed of 160 mm/min resulted in the best performance for the responses of tensile strength of 230.43 MPa, elongation of 5.44%, and joint efficiency of 74.33.
4. The ANOVA analysis emphasize that the dominant welding parameters on the responses are welding speed (58.29 %), shoulder diameter (24.66 %) and tool rotation (4.03 %) respectively.
5. Significant improvement in grey relation grade of 0.263 was obtained at the optimal parameter setting.
6. The microstructure examination of the FSW joint at the weld interface demonstrated that sufficient friction between tool and samples was properly achieved for the optimal parameter setting condition.

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