Temperature-based optimization of friction stir welding of AA 6061 using GRA synchronous with Taguchi method

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Abstract
Friction stir welding (FSW) is a recent novel joining mechanism in the solid-state welding process. It is extensively used to join similar and dissimilar materials as well. This research studied and found the optimum process parameters of FSW based on the temperature simulation results on a 5-mm 6061 Al alloy sheet with a butt joint configuration. Steady-state heat transfer analysis was performed using a transient thermal workbench to predict and identify the optimum parameters based on the simulation welding temperature result. The parameters are optimized using the hybrid Taguchi L9 orthogonal array and grey relation analysis (GRA) method with a larger is better quality characteristic. The mechanical properties of the weld joints such as hardness and tensile strength were studied at an ambient temperature. The result revealed that a higher rotational and minimum welding speed with taper threaded tool pin imparts the optimum parameter settings. Analysis of variance (ANOVA) was carried out also to determine the effects of each process parameter. At a 95% confidence interval, rotational and welding speed are significant parameters. The joint efficiency reached 92.25% of the base metal at optimum parameter settings. Additionally, the microstructure of the stir weld zone of the specimen was studied as well. Metallographic characterization carried out using a scanning electron microscope (SEM) revealed the microstructure of the samples after the weld did not show much significant change with the base metal.

Keywords Friction stir welding · Taguchi · GRA · AA 6061 · Microstructure · Transient thermal

1 Introduction
The joining of materials without defects needs optimized engineering process parameters as one of the key measures in the engineering process. Fusion welding is one of in the record, usually used in the conventional joining practices. Unfortunately, this method is pigeonholed by high-temperature gradients, leading to high thermal stress and prompt solidification, which escalates the occurrence of the segregation phenomenon [1]. As natural resources grow increasingly scarce, novel joining procedures are being developed to mitigate the adverse effects of traditional fusion processes. Furthermore, the demand for lightweight and high-strength structures continuously expands to reduce fuel consumption and enhance cargo capacity in the transportation system [2–4]. The use of a smart joining process can diminish the weight of the adding elements on the components. Also, the latest and advanced joining process offers several benefits, particularly for the joining of lightweight materials, among which friction stir welding (FSW) is a prominent joining process [5, 6]. It is a solid-state joining process developed by Wayne Thomas and E.D. Nicholas at the Welding Institute (TWI) in Cambridge, UK, in 1991. The process is appropriate for welding ferrous and non-ferrous materials, especially aluminum, copper, nickel, titanium, and other soft materials are highly recommended [7–10]. The application area of this process is widely used in the nuclear industry for repairing the crack and construction of temporary structures where decommissioning is required [11], in the transportation industry such as aviation, maritime, and automotive industries for enhancing the weight of the joint [12], joining of high-density plastic materials like polyethylene, polyamide 6, and polyvinyl chloride materials [13]. Nowadays, FSW can be extended in metal matrix
composite material joining processes [14]. For instance, the aviation industry uses AA 6061 to make commercial and military aircraft parts such as wings, fuselages, and airframe mountings [15–17]. Furthermore, most transportation sectors such as aviation, automotive, and maritime used friction stir welding to reduce the manufacturing time of components, enhance the thermo-mechanical properties, boost the joint strength compared to fusion welding, and minimize the weight of weld joints [18]. AA 6061 and friction stir welding are essential materials and joining processes in the transportation industry. However, a recent subject of interest is joining AA 6061 utilizing FSW, requiring proper control process parameters. Furthermore, in the FSW process, inappropriate process parameters impact the joint’s mechanical qualities [19]. As a result, this article aims to discover the best process parameters for enhancing the highest hardness and tensile strength of the target materials. According to the study [20], the maximum temperature created by the FSW process ranges from 70–90% of the melting temperature of the welding material. This study established a novel approach for identifying the optimum parameters of FSW using a transient thermal simulation. The experiment has conducted the parameters, and their level temperature results in the simulation are in the range of 70–90% of the specimen melting point. The hybrid Taguchi method and grey relational analysis was utilized for optimizing and validating the experimental results. The result revealed that the experimental temperature results are very close to the predicted simulation temperature results.

### 2 Experimental methods

#### 2.1 Experimental devices and materials

The material used for this investigation was 6061 aluminum alloy produced in the form of a sheet. The materials’ chemical composition, mechanical properties, and thermos-physical properties are depicted in Tables 1, 2, 3, respectively. To minimize the residual stress induced in the material during the cutting process, a hand hacksaw was used, and the material was sliced at an equal dimension of 101.6 × 50 × 5 mm (L × W × T). The two mating materials are welded with a butt joint configuration at the faying surface using high-precision XHS7145 vertical CNC milling machines considered an FSW machine illustrated in Fig. 1. According to Taguchi L9 orthogonal array layout and GRA method, different parameters were carried out, depicted in Table 4. The welding temperature in advancing and retreating sides is measured using K-type thermocouples at the center point of the welding specimen. The tensile strength sample was prepared according to ASTM E8-04 requirements using a metalcraft VMBS 1610 band saw machine. Moreover, the tensile strength of the welded samples is examined using a computer-controlled universal testing machine (model HUT-600). Besides, the hardness of the joints is measured using a Rockwell hardness testing machine on scale A.

### 3 Numerical modeling

The creation and dispersion of heat in friction stir welding are an essential phenomenon, and enough heat generation is required for getting sound welding [23]. This simulation work was performed to select the parameters, and their level temperature results are in the range of 70–90% of the welding specimen to minimize the trial-and-error methods in the DOE. Dimensions of the model are similar to the experimental welded sample, and steady-state heat transfer analysis was performed using a transient thermal workbench. A self-developed Application Customization Tool (ATC) has been used for addressing all the necessary parameters in FSW, such as shoulder diameter, pin diameter, tool rotational, and welding speed. The model comprises a total number of hexahedral type elements, and nodes were 175,392 and 205,128, respectively. The

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| Table 1 Chemical composition of AA 6061 |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Material        | Mg              | Si              | Fe              | Cr              |
| AA 6061         | 0.92%           | 0.6%            | 0.33%           | 0.18%           |
| AL              | 97.6%           |

| Table 2 Mechanical properties of AA 6061 [21] |
|-----------------------------------------------|
| Material | Yield strength (MPa) | Ultimate tensile strength (MPa) | Hardness (HRA) |
| AA 6061  | 276                | 310                           | 40             |

| Table 3 Thermo-physical properties of AA 6061 [22] |
|---------------------------------------------------|
| Density (kg/mm³) | Melting point (°C) | Thermal conductivity (W/m k) | Specific heat (J/kg °C) |
| 68.9            | 652               | 167                          | 0.896             |
The region nearest to the faying surfaces is meshing with a fine cell size element, as illustrated in Fig. 2, to increase the solution accuracy and the areas beyond the faying surface meshing with a coarse cell size element. The amount of heat generated per unit surface area at the tool-workpiece interface during the FSW process can be calculated \([24–27]\) as

\[
\frac{Q}{A}(r) = \frac{3Q_{\text{total}}}{2\pi \left( R_{\text{shoulder}}^3 - R_{\text{probe}}^3 \right) (1 + \tan \alpha) + R_{\text{probe}}^3 + 3R_{\text{probe}}^2 H_{\text{probe}}}
\]

(1)

where: \(\alpha\) is the shoulder cone angle, and \(Q_{\text{total}}\) is total heat generation, and it is given by

\[
Q_{\text{total}} = \frac{1}{2} \pi \alpha \delta \tau_{\text{yield}} + (1 - \delta) \mu P
\]

(2)

where: \(P\) is contact pressure, \(\mu\) is friction coefficient, \(\omega\) is the angular velocity of the tool, \(r\) is the radial distance from the rotational axis, \(R_{\text{shoulder}}\) is shoulder radius, \(R_{\text{probe}}\) is probe radius, \(H_{\text{probe}}\) is probe height, \(\tau_{\text{yield}}\) are yield strength, and \(\delta = \frac{\tau_{\text{yield}}}{\sigma_{\text{yield}}}\) and its value varies between 0 and 1.

The basic form of the heat flux equation, which ignores the heat created by the probe, is

\[
\frac{Q}{A}(r) = \frac{3Q_{\text{total}}}{2\pi R_{\text{shoulder}}^3 (1 + \tan \alpha)}
\]

(3)

A flat shoulder heat generation can be calculated by

\[
\begin{array}{c|c|c}
\text{Parameters} & \text{Levels} & \text{Levels} \\
\hline
\text{Tool pin profile} & \text{Cylindrical} & \text{Tri-flute} & \text{Taper threaded} \\
\text{Welding speed} & 37.5 & 42.5 & 47.5 \\
\text{Rotational speed} & 900 & 1200 & 1400 \\
\end{array}
\]

Table 4 Process parameters and their levels

**Fig. 1** Overall experimental setup of FSW and testing of the specimen
The heat generated by the pin surface is assumed to be volumetric heat flux and can be represented by

$$\frac{Q}{A} (r) = \frac{3Q_{\text{total}}}{2\pi R_{\text{shoulder}}^3}.$$  \hspace{1cm} (4)

The experiment and simulation analysis used a flat shoulder tool, and the temperatures generated from the specimen are modeled using heat flux. The maximum temperature has reached 559.9°C at the faying surface of the sample. The transient thermal simulation at different time travels is demonstrated in Fig. 3.

$$\frac{Q}{V_{\text{probe}}} (r) = \frac{3Q_{\text{total}}}{\pi (R_{\text{shoulder}}^3 + 3R_{\text{probe}}^2 H_{\text{probe}})}.$$  \hspace{1cm} (5)

4 Statistical analysis

4.1 Taguchi method

The Taguchi approach is highly effective and widely used to improve process parameters without eliminating noises. This method uses a specially designed orthogonal array to minimize the number of experiments without compromising the main and interaction effect of the parameters [28, 29]. It uses the signal to noise ratio (S/N) as a quality criterion, and it is divided into three categories: larger is better, nominal is best, and smaller is better. This study used an L₉ orthogonal array layout described in Table 5 with a larger is better quality criterion using Equation 6, and also, the hardness and tensile strength results are summarized in Table 6. In addition to this, the experimental and simulation temperature results are illustrated in Fig. 4.
where \( n \) is the number of replications and \( y_{ijk} \) is the response value of the \( i \)th performance characteristic in the \( j \)th experiment at the \( k \)th trial.

### 4.2 Grey relation analysis (GRA) for multi-objective optimization

One of the limitations of the Taguchi method is it is only used for a single response study. The multi-performance characteristic value can be converted into a single grey relational grade value using grey relational analysis, and it is suitable for the analysis of multi-objective responses [30]. This statistical analysis is highly effective for the multi-response optimization.
process, and it can be used to solve complex interrelationships between several responses [31]. The method has five basic steps illustrated in Fig. 5 to find the optimum values of the target responses [32, 33]. Therefore, this study used hybrid Taguchi and grey relational analysis (GRA) to study the multiresponse optimization process.

### 4.3 Data normalization

The first step in the GRA approach is to execute the grey relational generation, which involves normalizing the outcomes of the tests in the range of 0 to 1 [34, 35]. This step is required when the sequence scatter range is too large or the target direction sequences are different. If the response is maximized, then larger is better characteristics are intended for normalization to scale it into an acceptable range using Eq. 7 [36]. Results of data normalizations are summarized in Table 7.

\[
x_{i,k}^{\text{new}} = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)}
\]

where \(x_i(k)\) is the sequence after the data processing; \(x_i^0(k)\) is the original sequence of S/N ratio, where \(i = 1, 2, \ldots, m\) and \(k = 1, 2, \ldots, n\); \(\max x_i^0(k)\) is the largest value of \(x_i^0(k)\); \(\min x_i^0(k)\) is the smallest value of \(x_i^0(k)\).

### 4.4 Deviation sequences and grey relational coefficients

The next step is to find a grey relational coefficient (GRC) using Eqs. 8 and 9, \(\xi_i(k)\), from the normalized values. The relation between the reference sequence and the comparability sequence is explained using the GRC. To integrate the data obtained from Eqs. 8 and 9, the GRC (\(\xi\)) is determined, and results are displayed in Table 11.

\[
\Delta_{0i}(k) = \|x_{r,i}(k) - x_{r,i}(k)\|
\]

\[
\xi_i(x_{r,i}(k), x_{p,i}(k)) = \frac{\Delta_{\text{min}}(k) + \xi \Delta_{\text{max}}(k)}{\Delta_{0i}(k) + \xi \Delta_{\text{max}}(k)}
\]

where \(\Delta_{0i}(k)\) is the deviation sequence of the reference sequence \(x_{r,i}(k)\) and comparability sequence \(x_{r,i}(k)\) and \(\xi\) is the distinguishing coefficient that takes a value between 0 and 1, and the value of 0.5 is used based on the principal component analysis result. The deviation sequences are calculated according to Eq. 8, and the results are depicted in Table 7. The deviation sequences must be calculated before the GRC.

### 4.5 Principal component analysis

The principal component analysis (PCA) has been created by Pearson and Hotelling to describe the variance–covariance structure using linear combinations of each quality feature. In terms of variance, it lines up in descending order, and the first principal component accounts for the largest variance in the data. The matrix comprises Eigenvalues, Eigenvectors, and quality characteristic contributions [36–38]. For subsequent analysis, the principal component with the greatest Eigenvalues was chosen to replace the original responses. In this study, the highest Eigenvalues were found in the UTS first principal component. Tables 8, 9, and 10 show the contribution of each quality feature to the first main components.

As a result, the grey relationship coefficients values of 0.5 are utilized.

### 4.6 Grey relational grade

The Grey Relational Grade (GRG) shows the correlation between the reference sequence and the comparability sequence. It is a weighted average of the grey relational coefficients of multi-objective [39]. The mathematical equations for determining GRG are depicted in Eq. 10, and its results are shown in Table 11.

\[
y_i(x_{p,i}, x_{r,i}) = \frac{1}{n} \sum_{i=1}^{n} w_i \xi_i(x_{p,i}, x_{r,i})
\]

where \(y_i(x_{p,i}, x_{r,i})\) is the GRG for the \(i^{th}\) experiment, \(w_i\) is the weighting value of the \(i^{th}\) performance characteristic, and \(n\) is the number of performance characteristics.

Figure 6b indicates the optimal combination of parameters and their levels obtained \(A_3B_1C_3\), i.e., a tapered threaded tool pin profile, welding speed of 37.5 mm/min, and tool rotational speed of 1400 mm/min at the optimum condition. The result obtained from the Taguchi-based GRA that are depicted in Table 12, is similar to the simulation study results.

### 4.7 Analysis of variance (ANOVA)

In this study, ANOVA was used to determine whether the parameter is significant or not, and its results are summarized in Table 13. The \(P\) value of rotational and welding speed is less than 0.05, and the \(F\) values are greater than the standard table reading of the \(F\) value. Therefore, rotational and welding speeds are significant parameters at 95% of the confidence interval. Their percentage of contribution of the parameters is the rotational speed of (64.21%), and welding speed of (27.49%) contributes to getting a sound weld joint. Due to uncertain or unpredictable circumstances, the total error pooled can be used to determine whether or not an experiment is feasible and sufficient. As indicated in Table 13, the error pooled contribution is 8.291%, indicating that the proposed optimization strategy and the study’s result are highly acceptable.
4.8 Confirmation experiment

The confirmation test was performed on ten samples under the optimal parameter settings of $A_3B_1C_3$. A 95% confidence interval was used to predict the mean of grey relational grade. Equation 11 was used to produce the anticipated mean of grey relational grade ($\mu_{GRG}$) on a confirmation test [37].
\[ \mu A_1 B_2 = \bar{GRG} + \left( A_1 - \bar{GRG} \right) + \left( B_2 - \bar{GRG} \right) \]

\[ = A_1 + B_2 - \bar{GRG} \]

where \( \bar{GRG} \) is the overall mean of grey relational grade = 0.6194. \( A_1 \) and \( B_2 \) are the mean values of grey relational grade with parameters at optimum levels.

\[ \mu = 0.7535 + 0.7981 - 0.6194 = 0.9322 \]

To calculate the confidence interval for the expected mean on a confirmation run, Eq. 12 was used [40].

\[ CI = \mu \pm \sqrt{F \alpha (1, fe) \times Ve \left( \frac{1}{n_{eff}} + \frac{1}{r} \right)} \]

\[ \alpha \text{ Risk} = 0.05 \]

\[ fe \text{ Error DOF} = 4 \]

\[ Ve \text{ Error adjusted mean square} = 0.003044 \]

\[ n_{eff} \text{ Effective number of replications} \]

\[ R \text{ Number of replications for confirmation experiment} = 10 \]

\[ n_{eff} = \frac{Tn}{1 + Ts} = \frac{9}{1 + 4} = 1.8 \]

In addition, the effective number of replications \( (n_{eff}) \) was calculated by:

\[ \text{where} \]

\[ n_{eff} \text{ Is expressed in mathematical} \]

\[ Tn \text{ Total number of experiments} = 9 \]

\[ Ts \text{ The sum of the total degree of freedom of significant factors.} \]

Therefore, the calculated CI is

\[ CI = 0.9322 \pm \sqrt{7.71 \times 0.003044 \times \left( \frac{1}{1.8} + \frac{1}{10} \right)} = 0.1240 \]

The 95% confidence interval of the predicted optimal grey relational grade is

\[ (\mu - CI) < \mu < (\mu + CI) \]

\[ (0.9322 - 0.1240) < 0.9322 \]

\[ < 0.9322 \pm 0.1240 = 0.8082 < 0.9322 < 1.0562 \]

According to the DOE rule, the number of confirmation experiments must be greater than or equal to the number of experiments [41]. Therefore, in this study, the confirmation experiment has taken ten times at the optimal parameter.

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**Table 7** Data normalization and deviation sequence

| Step 1: Data normalized | Step 2: Deviation sequence |
|-------------------------|---------------------------|
| No | UTM | HRA | UTM | HRA |
|---|---|---|---|---|
| 1 | 0.7039 | 0.4693 | 0.2961 | 0.5307 |
| 2 | 0.7653 | 0.5337 | 0.2347 | 0.4663 |
| 3 | 0.8016 | 0.6849 | 0.1984 | 0.3151 |
| 4 | 0.8256 | 0.7495 | 0.1744 | 0.2505 |
| 5 | 0.8612 | 0.7610 | 0.1388 | 0.2390 |
| 6 | 0.0000 | 0.0000 | 1.0000 | 1.0000 |
| 7 | 1.0000 | 1.0000 | 0.0000 | 0.0000 |
| 8 | 0.4592 | 0.1380 | 0.5408 | 0.8620 |
| 9 | 0.7039 | 0.5007 | 0.2961 | 0.4993 |

**Table 8** Eigenvalues and explained variation

| Step 3: Principal component | Eigenvalues | Explained variation (%) |
|-----------------------------|-------------|-------------------------|
| UTS                         | 1.9571      | 97.9                    |
| HRA                         | 0.0429      | 2.1                     |

**Table 9** The Eigenvectors for principal component

| Quality characteristic | Eigenvector 1st principal | 2nd principal |
|------------------------|---------------------------|---------------|
| UTS                    | 0.707                     | 0.707         |
| HRA                    | 0.707                     | -0.707        |

**Table 10** Quality characteristic contribution

| Quality characteristic | UTS | HRA |
|------------------------|-----|-----|
|                        | 0.4999 | 0.4999 |

**Table 11** GRC and GRD

| Step 4: Grey relational coefficient | Step 5: Grey relational grade and it is rank |
|-------------------------------------|---------------------------------------------|
| No | UTM | HRA | GRG | Rank |
|---|---|---|---|---|
| 1 | 0.6280 | 0.4851 | 0.5566 | 7 |
| 2 | 0.6805 | 0.5174 | 0.5990 | 5 |
| 3 | 0.7159 | 0.6134 | 0.6647 | 4 |
| 4 | 0.7414 | 0.6663 | 0.7038 | 3 |
| 5 | 0.7828 | 0.6766 | 0.7297 | 2 |
| 6 | 0.3333 | 0.3333 | 0.3333 | 9 |
| 7 | 1.0000 | 1.0000 | 1.0000 | 1 |
| 8 | 0.4804 | 0.3671 | 0.4237 | 8 |
| 9 | 0.6280 | 0.5004 | 0.5642 | 6 |

Average GRG = 0.6194
settings. The predicted GRG at optimal condition is obtained between 0.8082 and 1.0562 at a 95% confidence interval. The grey relational grade for the experiment is 0.9323, with hardness and tensile strength of 286.8 MPa and 77.96 HR, respectively, as shown in Table 14. As a consequence, the confirmatory experiment tests indicate that the experiment was safest.

### 4.9 Simulation vs. experimental result

In this study, the experimental parameters and their levels are obtained from the simulation results. The maximum temperature recorded on the simulation and experiment was 559.9 °C and 554.0 °C, respectively, summarized in Table 15, at the optimum parameter settings. The percentage variation between the simulation and experimental results is very close, and its values are 1.1%. Predicting the effect of parameters using a finite element method can minimize the trial and error experiments.

#### 4.10 Metallographic characterization

A metallographic characterization was executed with the optimized process parameters to examine the microstructure changes between the weld and the base metal. The result revealed that no significant differences nor quantifiable volumetric flaws were observed in the macrographs. It showed similar macrostructural characteristics for all examined welds. All of the usual FSW microstructural weld zones, such as the stirred zone (SZ), illustrated in Fig. 7, thermomechanically affected zone (TMAZ), heat-affected zone (HAZ), and parent metal, showed good soundness.

### 5 Conclusion

This study used Taguchi-based GRA and temperature-based simulation analysis to find the optimal process parameters for friction stir welding 6061 aluminum alloy. The ultimate tensile strength and hardness of the joint

### Table 12 Main effects of GRG

| Level | Tool profile (A) | Welding speed (B) | Rotational speed (C) |
|-------|------------------|-------------------|----------------------|
| 1     | 0.6067           | 0.7535            | 0.4379               |
| 2     | 0.5889           | 0.5841            | 0.6223               |
| 3     | 0.6626           | 0.5207            | 0.7981               |
| Delta | 0.0737           | 0.2327            | 0.3602               |
| Rank  | 3                | 2                 | 1                    |

### Table 13 ANOVA result for a grey relational grade (GRG)

|                     | DF | Adj SS  | Adj MS  | F value | P value | Contribution | Remark   |
|---------------------|----|---------|---------|---------|---------|--------------|----------|
| Tool profile*       | 2  | 0.00875 | 0.004438| 1.45795 | 0.271   | Insignificant|          |
| Welding speed       | 2  | 0.08685 | 0.043425| 14.26577| 0.037   | Significant  |          |
| Rotational speed    | 2  | 0.194691| 0.097346| 31.97963| 0.017   | Significant  |          |
| Error               | 2  | 0.003301| 0.001651|         |         |              |          |
| Error pooled        | 4  | 0.012176| 0.003044|         |         | 8.291        |          |
| Total               | 8  | 0.293718|         |         |         | 100%         |          |

$F_{0.05} (2,4) = 6.94$
The influence of input parameters on the weld quality of friction stir welded joint was demonstrated and analyzed. At a rotational speed of 1400 rpm with a welding speed of 37.5 mm/min and a tapered tool pin profile, the maximum tensile strength and hardness of the weld joint, 286.8 MPa and 77.96 HRA, are bestowed, respectively. In addition to this, the maximum weld joint efficiency of 92.25% was also recorded in these parameter settings. Besides, the minimum tensile strength and hardness were obtained at a rotating speed of 900 rpm, a welding speed of 47.5 mm/min, and a tri-flute threaded tool.

According to the ANOVA results, rotational and welding speed each contribute 64.2 and 27.4% to the joint quality of the weld, respectively.

With a higher tool rotating speed, a lower welding speed, and a taper tool pin profile, the quality of the weld joint is improved.

### Table 14 Results of confirmation tests

| Optimal combination | Response of quality characteristics |
|---------------------|-------------------------------------|
| A_3 B_1 C_3         | UTS       | UTS_{SN} | HRA | HR_{SN} |
| Test 1              | 49.1273   | 286      | 78.0 | 37.841  |
| Test 2              | 49.1576   | 287      | 78.0 | 37.841  |
| Test 3              | 49.1576   | 287      | 77.6 | 37.797  |
| Test 4              | 49.1576   | 287      | 78.0 | 37.841  |
| Test 5              | 49.1576   | 287      | 78.0 | 37.841  |
| Test 6              | 49.1576   | 287      | 78.0 | 37.841  |
| Test 7              | 49.1576   | 287      | 78.0 | 37.841  |
| Test 8              | 49.1576   | 287      | 78.0 | 37.841  |
| Test 9              | 49.1576   | 287      | 78.0 | 37.841  |
| Test 10             | 49.15764  | 286      | 78.0 | 37.841  |

Mean of GRG for confirmation test = 0.9323

### Table 15 Simulation vs. experimental results

| Parameters          | Simulation results | Experimental results | Percent of temperature variation |
|---------------------|--------------------|----------------------|----------------------------------|
| Tool pin profile    | Taper threaded tool| Taper threaded tool  | -                                |
| Welding speed       | 0.625 mm/s         | 37.5 mm/min          | -                                |
| Rotational speed    | 1400 rpm           | 1400 rpm             | -                                |
| Shoulder radius     | 7 mm               | 7 mm                 | -                                |
| Pin radius          | 2.5 mm             | 2.5 mm               | -                                |
| Weld length         | 50 mm              | 50 mm                | -                                |
| No of steps         | 200                | -                    | -                                |
| Temperature result  | 559.9 °C           | 554.0 °C             | 1.1%                             |

Fig. 7 Scanning electron microscope result at different resolutions
v. An essential parameter for creating the requisite heat is the combination of rotational speed and welding speed. In the optimum parameter setting, the maximum temperature of 559.9 °C, which is (14.12%) less than the liquid temperature of the base material of AA 6061 (652°C), was obtained in the simulation. Both experimental and simulation results are quite similar, indicating that welding temperature is highly influenced by rotational and welding speed. In addition to this, the welding temperature has a significant effect on the thermo-mechanical properties of the weld joints. The temperature-based simulation results of each parameter and level is similar to the optimized Taguchi-based GRA optimal parameter setting results.

vi. No significant differences nor quantifiable volumetric flaws were observed in the macrographs, showing similar macrostructural characteristics for all the examined welds. All welds exhibited good soundness with all the typical FSW microstructural weld zones such as the stirred zone, thermo-mechanically affected zone, heat-affected zone, and parent metal.

vii. Furthermore, this study scheme can be extended to thick non-ferrous, ferrous, and metal-based composite materials, too.

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