



## DESIGN OPTIMIZATION AND PERFORMANCE ANALYSIS OF TiO<sub>2</sub>-REINFORCED DISSIMILAR AA5083-AA6063 FRICTION STIR WELDED JOINTS USING TAGUCHI METHOD

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### ABSTRACT

This study investigates the design optimization of TiO<sub>2</sub>-reinforced dissimilar AA5083-AA6063 friction stir welded joints using the Taguchi method. Tool rotational speed, welding travel speed, and TiO<sub>2</sub> insertion depth were evaluated through an L9 orthogonal array, with tensile strength and hardness as response variables. The results show that tensile strength is mainly controlled by rotational speed, achieving a maximum value of 218.40 MPa at 900 rpm, 40 mm/min, and 3 mm TiO<sub>2</sub> depth, whereas hardness is primarily influenced by TiO<sub>2</sub> insertion depth, reaching 110.23 HV. Taguchi prediction and confirmation tests revealed errors below 2%, confirming result reliability. Microstructural and fracture analyses indicated effective material mixing and predominantly ductile fracture behavior. These findings demonstrate that distinct parameters govern tensile and hardness responses, providing useful guidance for parameter selection in EV and aerospace applications.



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### 1. INTRODUCTION

The growing demand for lightweight and energy-efficient structures has accelerated the use of aluminum alloys in modern transportation systems, particularly in electric vehicles (EVs) and aerospace applications. Components such as battery enclosures, structural frames, and aircraft panels require materials offering high specific strength, corrosion resistance, and reliable joining performance. Aluminum alloys remain a preferred choice due to their favorable mechanical properties and recyclability [1]. Among commercial aluminum alloys, AA5083 and AA6063 are widely used for different functional requirements. AA5083 provides high strength and corrosion resistance for load-bearing structures, whereas AA6063 is commonly employed in extruded components due to its good formability and surface quality. Combining these dissimilar alloys enables design flexibility and weight reduction in EV and aerospace structures; however, conventional fusion welding often leads to defects such as porosity, excessive heat input, and degradation of mechanical properties caused by metallurgical incompatibility [1],[2].

Friction stir welding (FSW) has emerged as an effective solid-state joining process that overcomes many limitations of fusion welding by avoiding melting and promoting severe plastic deformation and dynamic recrystallization [1]. Nevertheless, joint quality in FSW is highly sensitive to process parameters, including tool rotational speed, welding travel speed, and heat input conditions. Improper parameter selection in dissimilar aluminum alloy joints may result in insufficient material mixing, internal defects, and non-uniform mechanical properties, which are unacceptable for safety-critical EV and aerospace components [2]. To further enhance joint performance, the incorporation of ceramic nanoparticles during FSW has gained increasing attention. Titanium dioxide (TiO<sub>2</sub>) nanoparticles have been shown to improve microstructural refinement and mechanical performance when effectively distributed within the stir zone [3-5]. However, the effectiveness of nanoparticle reinforcement strongly depends on welding parameters and particle insertion strategy.

From an industrial viewpoint, achieving consistent and repeatable joint performance requires a clear understanding of parameter effects rather than reliance on trial-and-error optimization. The Taguchi method provides a systematic and efficient experimental design framework for evaluating multiple process parameters with a reduced number of experiments and has been successfully applied to FSW parameter analysis and performance evaluation [6],[7]. Therefore, the present study investigates the influence of tool rotational speed, welding travel speed, and TiO<sub>2</sub> nanoparticle insertion depth on the mechanical and microstructural characteristics of dissimilar AA5083–AA6063 friction stir welded joints, aiming to support design optimization and performance analysis for lightweight EV and aerospace applications [8],[9].

## II. MATERIALS AND METHODS

### II.1 MATERIALS

Dissimilar aluminum alloys AA5083 and AA6063 were selected as base materials due to their extensive use in lightweight structural components for electric vehicle and aerospace applications. AA5083 provides high strength and excellent corrosion resistance, making it suitable for load-bearing structures, whereas AA6063 is widely used in extruded components because of its good formability and surface quality. Prior to welding, both aluminum plates were machined to identical dimensions to ensure stable clamping and consistent heat generation during friction stir welding.

Titanium dioxide (TiO<sub>2</sub>) nanoparticles with a purity of 99%, as shown in Figure 1, were employed as the reinforcing material. Owing to their thermal stability and chemical inertness, TiO<sub>2</sub> nanoparticles are compatible with aluminum matrices. A longitudinal groove was precisely machined along the butt joint interface using a CNC milling machine, and the groove depth was varied according to the experimental design to examine its influence on joint performance. The TiO<sub>2</sub> powder was carefully packed into the groove before welding to minimize particle loss during tool plunging and material flow.

### II.2 EXPERIMENTAL AND METHODS

Friction stir welding (FSW) experiments were carried out using a vertical CNC milling machine under position-controlled conditions, as illustrated in Figure 2. A non-consumable tool fabricated from SKD11 tool steel was employed, consisting of a flat shoulder and a cylindrical pin to promote effective plastic deformation and material mixing. Prior to welding, AA5083 and AA6063 aluminum alloy plates were prepared by milling to identical dimensions of 75 × 150 × 6 mm. During the welding process, AA5083 was positioned on the advancing side (AS), while AA6063 was placed on the retreating side (RS), in order to enhance material flow stability in the dissimilar joint.

Titanium dioxide (TiO<sub>2</sub>) nanoparticles were introduced into the weld region through a longitudinal groove machined along the butt joint interface prior to welding. The groove had a cross-sectional dimension of 1 × 1 × 1 mm, and the insertion depths of the nanoparticles were set to 2, 3, and 4 mm, as shown in Figure 2(b). The groove depth was varied according to the experimental design, while the groove length was kept constant to ensure uniform distribution of the reinforcing material along the weld line. After filling the groove with TiO<sub>2</sub> powder, the welding tool was plunged and traversed along the joint line following the prescribed tool rotation and welding directions.

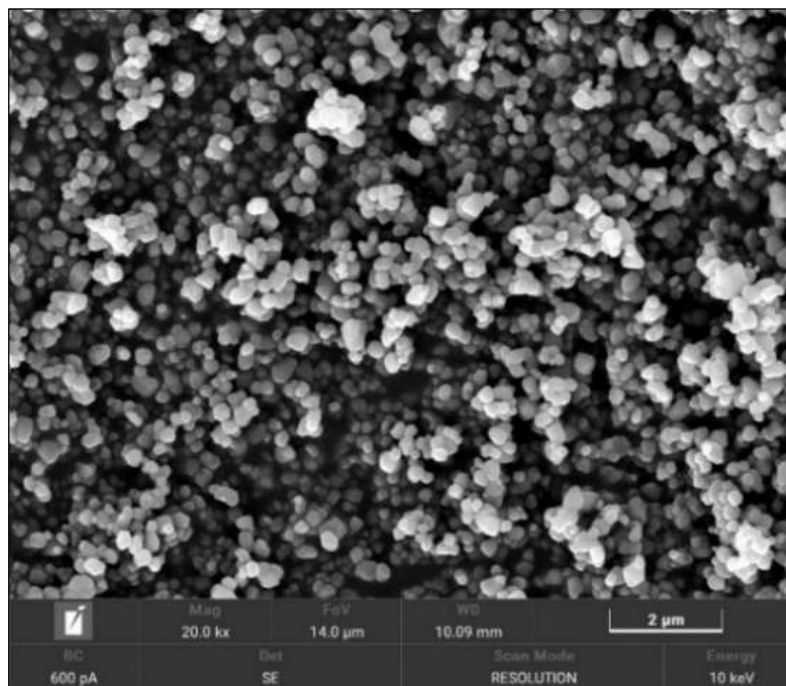


Figure 1: SEM image of TiO<sub>2</sub> nanoparticles showing particle size and agglomeration..

Source: Authors, (2026).

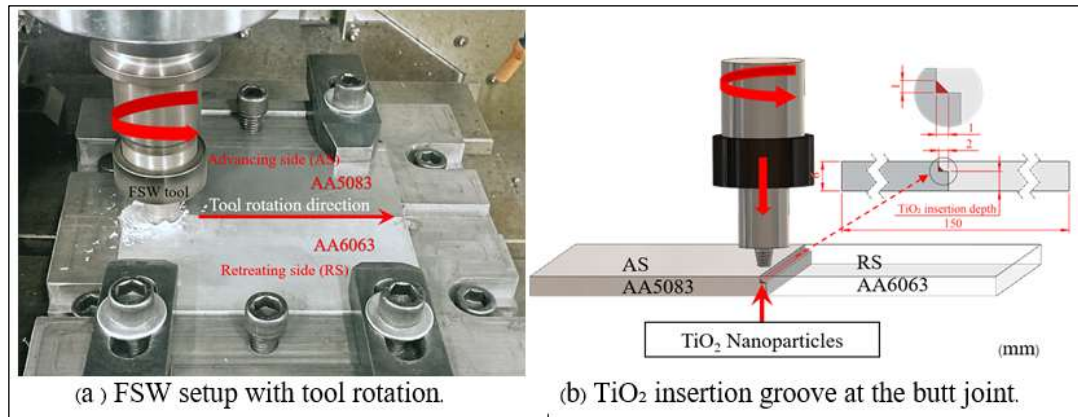


Figure 2: Friction stir welding setup and TiO<sub>2</sub> nanoparticle insertion scheme.  
Source: Authors, (2026).

### II.3 SPECIMEN PREPARATION AND MECHANICAL TESTING

After welding, the joints were sectioned for mechanical testing and microstructural examination, as illustrated in Figure 3. Tensile specimens were extracted transverse to the welding direction, and multiple samples were prepared from each welded plate to ensure repeatability, as commonly adopted in friction stir welding studies of dissimilar aluminum alloys [2]. Tensile tests were conducted at room temperature using a universal testing machine in accordance with ASTM E8/E8M, and the average tensile strength was reported for each welding condition [7],[10].

Microhardness measurements were performed across the weld cross-section using a Vickers hardness tester following ASTM E384. Indentations were placed at regular intervals covering the base material (BM), heat-affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and stir zone (SZ), as schematically shown in Figure 3. This procedure enabled evaluation of hardness variation across different weld regions and assessment of local mechanical behavior, which has been widely reported as an effective approach for characterizing FSW joints [4],[11].

Microstructural characterization was carried out using scanning electron microscopy (SEM) to examine material flow features, grain refinement, and the distribution of TiO<sub>2</sub> nanoparticles within the stir zone [5]. Selected regions near the weld center were analyzed to correlate microstructural characteristics with mechanical performance. Energy-dispersive X-ray spectroscopy (EDS) was employed to confirm the presence and dispersion of TiO<sub>2</sub> particles within the aluminum matrix, consistent with previous investigations on nanoparticle-reinforced FSW joints [12].

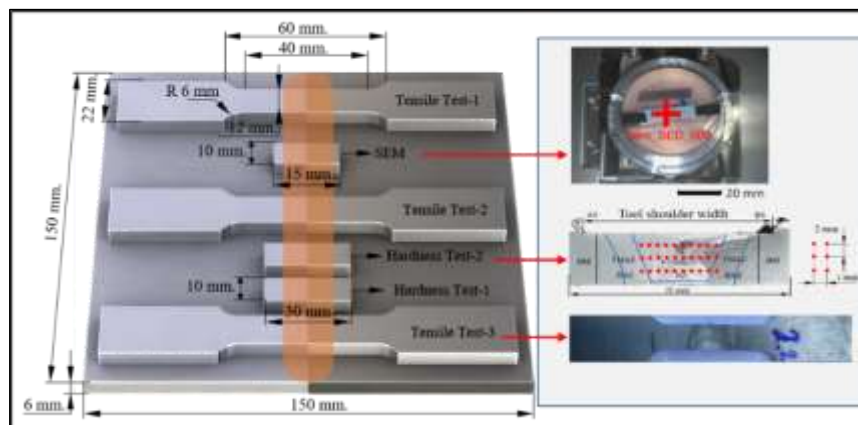


Figure 3: Specimen geometry and testing locations for mechanical and microstructural evaluation.  
Source: Authors, (2026).

### II.4 EXPERIMENTAL DESIGN USING TAGUCHI METHOD

The Taguchi method was employed to design the experiments and to evaluate the influence of selected friction stir welding parameters on the performance of TiO<sub>2</sub>-reinforced dissimilar AA5083–AA6063 joints. This method enables systematic assessment of multiple process variables while reducing the number of required experiments [8].

Three control factors were considered in this study: tool rotational speed (S), welding travel speed (F), and TiO<sub>2</sub> groove depth (D). Each factor was examined at three levels, as summarized in Table 1, based on feasible welding conditions and preliminary observations. An L9 orthogonal array was used to arrange the experimental runs efficiently and to analyze the main effects of the selected parameters.

Joint performance was evaluated in terms of tensile strength and hardness. The signal-to-noise (S/N) ratio was calculated using the larger-is-better criterion, as defined in Eq. (1), in order to identify parameter levels that provide improved performance with reduced variability [9]. The Taguchi approach has been widely applied in friction stir welding studies for analyzing parameter effects on mechanical behavior [7].

Table 1: Selected FSW Parameters and corresponding levels.

| Parameter                              | Low | Medium | High |
|----------------------------------------|-----|--------|------|
| Tool rotation Speed ; S (rpm)          | 700 | 900    | 1100 |
| Welding travel speed ; F (mm/min)      | 40  | 60     | 80   |
| TiO <sub>2</sub> groove Depth ; D (mm) | 2   | 3      | 4    |

Source: Authors, (2026).

1. Signal-to-Noise (S/N) Ratio – Larger-is-Better Criterion [ 7].

$$S / N_{Ratio} = -10 \log \left( \frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (1)$$

where  $y_i$  represents the measured response value of the  $i^{th}$  experiment, and  $nnn$  is the total number of experimental runs.

## IV. RESULTS AND DISCUSSIONS

### IV.1 TAGUCHI EXPERIMENTAL RESULTS

Table 2 summarizes the experimental results obtained from the L9 orthogonal array, including tensile strength, hardness, and the corresponding signal-to-noise (S/N) ratios calculated using the larger-is-better criterion. The tensile strength of the TiO<sub>2</sub>-reinforced dissimilar AA5083–AA6063 joints ranges from 197.34 to 218.40 MPa, while hardness values vary between 98.56 and 110.23 HV. These results clearly indicate that variations in friction stir welding parameters significantly influence the mechanical performance of the joints. The maximum tensile strength was achieved at a rotational speed of 900 rpm, welding travel speed of 40 mm/min, and TiO<sub>2</sub> groove depth of 3 mm, whereas the highest hardness was observed at a higher rotational speed of 1100 rpm combined with a travel speed of 80 mm/min and the same groove depth.

To clarify the influence of individual parameters, the mean S/N ratios at different factor levels are presented in Table 3 and graphically illustrated in Figure 4. For tensile strength, the rotational speed exhibits the highest delta value, followed by the TiO<sub>2</sub> groove depth, while the welding travel speed shows the lowest contribution. This trend suggests that heat input associated with tool rotation plays a dominant role in enhancing joint strength by promoting effective material mixing and metallurgical bonding. Similar observations have been reported in previous Taguchi-based FSW studies, where rotational speed was identified as a key parameter governing tensile behavior in dissimilar aluminum alloy joints [8],[13].

In contrast, hardness is primarily influenced by the TiO<sub>2</sub> groove depth, which shows the highest delta value, followed closely by the rotational speed, as shown in Table 3 and Figure 4(b). The limited effect of welding travel speed indicates that hardness is more sensitive to reinforcement content and particle distribution within the stir zone than to variations in traverse motion. This behavior is consistent with earlier findings that emphasize the role of ceramic nanoparticles in enhancing local hardness through particle strengthening and grain refinement mechanisms [3],[5].

Overall, the combined analysis of Tables 2 and 3 together with the main effects plots in Figure 4 demonstrates that tensile strength and hardness are governed by different dominant parameters. While rotational speed is critical for maximizing joint strength, TiO<sub>2</sub> groove depth plays a more significant role in controlling hardness. These results highlight the necessity of balanced parameter selection when designing friction stir welding conditions for TiO<sub>2</sub>-reinforced dissimilar aluminum alloy joints, particularly for applications requiring simultaneous strength and surface hardness performance.

Table 2: L9 orthogonal array design and results with mechanical responses and S/N ratios.

| Run | Parameter/Factor        |                          |                              | Responses |         | S/N Ratio |         |
|-----|-------------------------|--------------------------|------------------------------|-----------|---------|-----------|---------|
|     | Rotation Speed (rpm); S | Travel speed (mm/min); F | Depths for particles (mm); D | TS (Mpa)  | Hv (Hv) | Ts (Mpa)  | Hv (Hv) |
| 1   | 700                     | 40                       | 2                            | 203.18    | 98.56   | 46.15     | 39.87   |
| 2   | 700                     | 60                       | 3                            | 208.46    | 104.36  | 46.38     | 40.37   |
| 3   | 700                     | 80                       | 4                            | 201.46    | 102.87  | 46.08     | 40.24   |
| 4   | 900                     | 40                       | 3                            | 218.40    | 107.81  | 46.78     | 40.65   |
| 5   | 900                     | 60                       | 4                            | 208.68    | 103.51  | 46.38     | 40.29   |
| 6   | 900                     | 80                       | 2                            | 213.82    | 100.54  | 46.60     | 40.04   |
| 7   | 1100                    | 40                       | 4                            | 204.76    | 109.08  | 46.22     | 40.75   |
| 8   | 1100                    | 60                       | 2                            | 197.34    | 104.65  | 45.90     | 40.39   |
| 9   | 1100                    | 80                       | 3                            | 212.46    | 110.23  | 46.54     | 40.84   |

Source: Authors, (2026).

Table 3: Mean S/N ratios of tensile strength and hardness at factor levels.

| Level | Tensile strength |       |       | Hardness |       |       |
|-------|------------------|-------|-------|----------|-------|-------|
|       | S                | F     | D     | S        | F     | D     |
| 1     | 46.21            | 46.39 | 46.22 | 40.16    | 40.43 | 40.11 |
| 2     | 46.59            | 46.22 | 46.57 | 40.33    | 40.36 | 40.62 |
| 3     | 46.22            | 46.41 | 46.23 | 40.67    | 40.38 | 40.43 |
| Delta | 0.38             | 0.19  | 0.35  | 0.50     | 0.07  | 0.52  |
| Rank  | 1                | 3     | 2     | 2        | 3     | 1     |

Source: Authors, (2026).

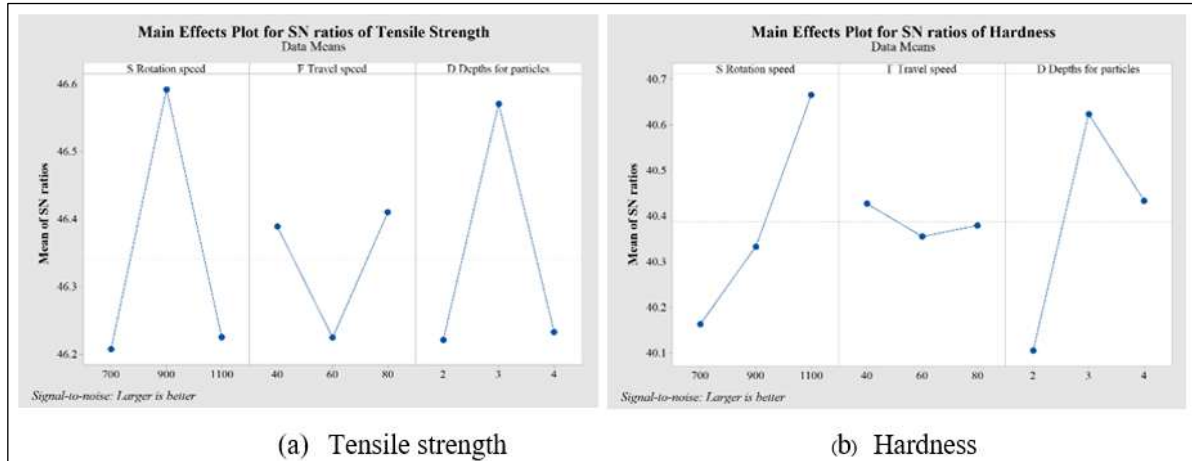


Figure 4: Main Effects Plot for SN ratios of (a) tensile strength and (b) hardness.

Source: Authors, (2026).

#### IV.2 ANALYSIS OF VARIANCE (ANOVA) OF S/N RATIOS

The analysis of variance (ANOVA) was conducted to quantify the statistical significance and relative contribution of friction stir welding parameters on the tensile strength and hardness of TiO<sub>2</sub>-reinforced dissimilar AA5083–AA6063 joints. The ANOVA results for the S/N ratios of tensile strength and hardness are presented in Tables 4 and 5, respectively [14]. As shown in Table 4, tool rotational speed (S) is the most influential parameter affecting tensile strength, contributing 46.04% of the total variation. This is followed by the TiO<sub>2</sub> groove depth (D) with a contribution of 38.43%, while welding travel speed (F) exhibits a comparatively minor effect at 10.06%. The dominance of rotational speed highlights the critical role of heat input and plastic material flow in determining joint tensile performance [1]. Although the P-values of individual factors are slightly above the conventional 0.05 threshold, this behavior is commonly observed in Taguchi-based designs with limited degrees of freedom and does not diminish the practical significance of the contribution trends [7].

For hardness, the ANOVA results in Table 5 reveal a different governing mechanism. The TiO<sub>2</sub> groove depth (D) is identified as the most dominant factor, contributing 50.04% to the overall variation, closely followed by the rotational speed (S) with 47.44% contribution. In contrast, the welding travel speed (F) has a negligible influence, accounting for less than 1% of the total variation. The statistically significant P-values for both S and D ( $P < 0.05$ ) confirm their strong influence on hardness development. This behavior suggests that hardness enhancement is primarily controlled by the amount of TiO<sub>2</sub> reinforcement introduced into the stir zone and the associated thermo-mechanical conditions that govern particle dispersion and grain refinement [3]. The high coefficients of determination ( $R^2 = 97.53\%$  for tensile strength and  $98.47\%$  for hardness) indicate that the selected process parameters adequately explain the observed variations in joint performance. Overall, the ANOVA results demonstrate that tensile strength and hardness are governed by different dominant parameters, emphasizing the need for balanced parameter selection when optimizing friction stir welding conditions for multifunctional performance.

Table 4: ANOVA Results of S/N ratios tensile strength.

| Source         | DF | Seq SS  | Adj SS  | Adj MS  | F    | P     | %Contibution |
|----------------|----|---------|---------|---------|------|-------|--------------|
| S              | 2  | 0.28289 | 0.28289 | 0.14144 | 8.41 | 0.106 | 46.04        |
| F              | 2  | 0.06180 | 0.06180 | 0.03090 | 1.84 | 0.352 | 10.06        |
| D              | 2  | 0.23617 | 0.23617 | 0.11809 | 7.02 | 0.125 | 38.43        |
| Residual Error | 2  | 0.03364 | 0.03364 | 0.01682 | 0    | 0     | 5.47         |
| Total          | 8  | 0.61450 | 0       | 0       | 0    | 0     | 100          |

S = 0.1297, R-Sq = 97.53%, R-Sq(adj) = 78.11%.

Source: Authors, (2026).

Table 5: ANOVA Results of S/N ratios Hardness.

| Source         | DF | Seq SS  | Adj SS  | Adj MS   | F     | P     | %Contribution |
|----------------|----|---------|---------|----------|-------|-------|---------------|
| S              | 2  | 0.39078 | 0.39078 | 0.195392 | 31.08 | 0.031 | 47.44         |
| F              | 2  | 0.00812 | 0.00812 | 0.004060 | 0.65  | 0.608 | 0.99          |
| D              | 2  | 0.41221 | 0.41221 | 0.206105 | 32.78 | 0.030 | 50.04         |
| Residual Error | 2  | 0.01257 | 0.01257 | 0.006287 | 0     | 0     | 1.53          |
| Total          | 8  | 0.82368 | 0       | 0        | 0     | 0     | 100           |

S = 0.0793, R-Sq = 98.47%, R-Sq(adj) = 93.89%.

Source: Authors, (2026).

#### IV.3 TAGUCHI PREDICTION AND CONFIRMATION TEST

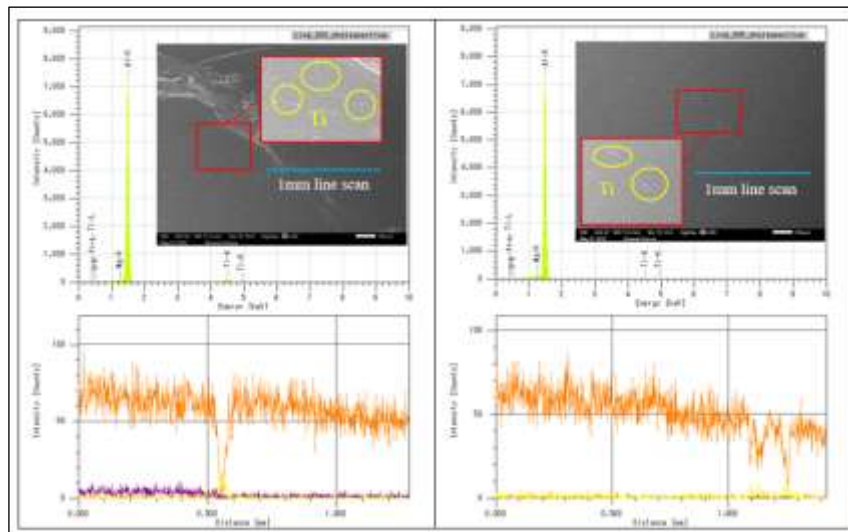
Based on the Taguchi analysis, the optimal combinations of friction stir welding (FSW) parameters were identified from the main effects of the signal-to-noise (S/N) ratios for tensile strength and hardness. To verify the reliability of these optimal parameter settings, Taguchi prediction was first conducted, followed by confirmation experiments. For the larger-is-better quality characteristic, the predicted S/N ratio at the optimal condition was calculated using the Taguchi additive model, expressed as Eq. (2):

2. The predicted S/N ratio was calculated using the Taguchi additive model. [ 2],[9].

$$\hat{\eta}_{pred} = \eta_m + \sum_{i=1}^k (\eta_{i,opt} - \eta_m) \quad (2)$$

where  $\hat{\eta}$  is the predicted S/N ratio,  $\eta_m$  is the overall mean S/N ratio obtained from all experimental runs,  $\eta_{i,opt}$  is the mean S/N ratio at the optimal level of the  $i^{th}$  control factor, and  $k$  is the number of control factors considered in this study ( $k=3$  : rotational speed, welding travel speed, and TiO<sub>2</sub>\_22 groove depth) [14]. Based on the Taguchi prediction, the optimal parameter combination for maximizing tensile strength was determined as S900–F80–D3, yielding a predicted S/N ratio of 46.8967 and a corresponding predicted tensile strength of 221.22 MPa. In contrast, the optimal condition for maximizing hardness was identified as S1100–F40–D3, with a predicted S/N ratio of 40.9556 and a predicted hardness of 111.63 HV. These results indicate that tensile strength and hardness are governed by different dominant process parameters, consistent with observations reported in previous Taguchi-based FSW studies [9],[15].

Confirmation experiments were subsequently conducted using the identified optimal parameter combinations [12],[7]. The experimental results were compared with the predicted values, as summarized in Table 6. The confirmation test produced an experimental tensile strength of 217.80 MPa and an experimental hardness of 109.95 HV, corresponding to prediction errors of 1.55% and 1.50%, respectively. The small deviations between predicted and experimental results demonstrate the reliability and robustness of the Taguchi prediction approach for optimizing the mechanical performance of TiO<sub>2</sub>-reinforced dissimilar AA5083–AA6063 FSW joints [16]. To further validate the prediction results, microstructural and compositional analyses were carried out at the optimal conditions. Figure 5 presents the experimental results corresponding to the predicted tensile strength and hardness conditions, including SEM–EDS line scan analyses, which confirm the presence and relatively uniform distribution of Ti-containing phases within the stir zone. This distribution contributes to enhanced load transfer and localized strengthening, supporting the observed mechanical performance [17],[18].



(a) Experimental Predicted Tensile Test (Ts). (b) Experimental Predicted Hardness Test (Hv).  
Figure 5: Experimental Predicted of (a) tensile strength and (b) hardness.  
Source: Authors, (2026).

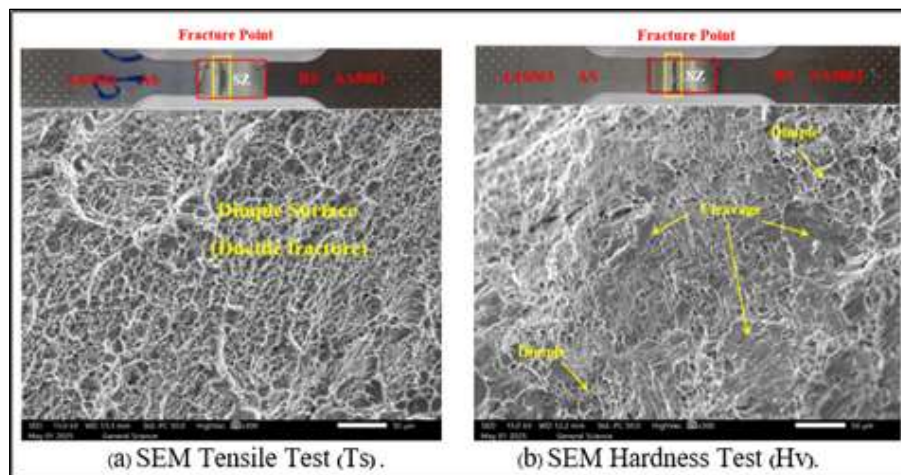
Table 6: Taguchi prediction confirmation test results.

| Response               | Predicted | Experimental | Error (%) |
|------------------------|-----------|--------------|-----------|
| Tensile strength (MPa) | 221.22    | 217.80       | 1.55      |
| Hardness (HV)          | 111.63    | 109.95       | 1.50      |

Source: Authors, (2026).

In addition, the fracture surface morphologies shown in Figure 6 reveal distinct failure characteristics. The tensile fracture surface (Figure 6a) exhibits fine and uniformly distributed dimples, indicating a predominantly ductile fracture associated with effective plastic deformation and sound material mixing in the stir zone [11],[6]. In contrast, the fracture surface corresponding to hardness optimization (Figure 6b) shows a mixed-mode fracture behavior, combining dimpled features with localized cleavage, which can be attributed to increased local hardness and enhanced particle–matrix interactions induced by TiO<sub>2</sub> reinforcement and higher rotational speed conditions [19],[20].

Overall, the close agreement between the predicted and experimental results, supported by consistent microstructural and fractographic observations, confirms the effectiveness of the Taguchi prediction and confirmation approach for optimizing FSW parameters. Similar validation outcomes have been reported in previous studies, demonstrating the suitability of the Taguchi method for process optimization in dissimilar aluminum alloy friction stir welding [21].

Figure 6: SEM images of fracture surfaces of TiO<sub>2</sub>-reinforced AA5083–AA6063 FSW joints after.

Source: Authors, (2026).

## V. CONCLUSIONS

This study successfully demonstrated the effectiveness of the Taguchi method for optimizing friction stir welding parameters in TiO<sub>2</sub>-reinforced dissimilar AA5083–AA6063 joints. The results revealed that tool rotational speed and TiO<sub>2</sub> groove depth are the dominant factors governing joint performance, while welding travel speed exhibits a comparatively minor influence. The optimal condition for maximizing tensile strength was identified at 900 rpm rotational speed, 40 mm/min travel speed, and a TiO<sub>2</sub> groove depth of 3 mm, achieving a tensile strength of 218.40 MPa. In contrast, maximum hardness was obtained under higher rotational speed conditions combined with appropriate nanoparticle insertion depth, highlighting the strong role of TiO<sub>2</sub> reinforcement in enhancing local hardness through particle strengthening and grain refinement. Microstructural and fractographic analyses confirmed effective material mixing in the stir zone and predominantly ductile fracture behavior, with localized mixed-mode features associated with increased hardness. The close agreement between experimental results and Taguchi predictions validates the robustness of the proposed optimization approach and provides practical guidelines for designing high-performance FSW joints for lightweight structural applications in electric vehicle and aerospace industries.

## VI. AUTHOR'S CONTRIBUTION

**Conceptualization:** Sittichai Charonerat, Chuthong Summatta.

**Methodology:** Sittichai Charonerat, Chuthong Summatta.

**Investigation:** Sittichai Charonerat, Thanatep Phatungthane.

**Discussion of results:** Sittichai Charonerat, Chuthong Summatta, Thanatep Phatungthane.

**Writing – Original Draft:** Sittichai Charonerat.

**Writing – Review and Editing:** Sittichai Charonerat, Chuthong Summatta.

**Resources:** Chuthong Summatta.

**Supervision:** Chuthong Summatta, Thanatep Phatungthane.

**Approval of the final text:** Sittichai Charonerat, Chuthong Summatta, Thanatep Phatungthane.

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