

Optimizing underwater friction-stir welding parameters for AA356/SiC composites using CoCoSo and MEREC: enhancing joint performance and quality

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ABSTRACT

This study investigates the underwater friction stir welding (UFSW) of stir-cast A356 reinforced with 2,4 and 6wt% silicon carbide (SiC) to enhance weld joint performance. A hybrid optimization approach integrating CoCoSO (Combined Compromise Solution) and MEREC (Method based on the Removal Effect of Criteria) was employed to determine the optimal welding parameters. The study optimized welding speed (A), rotational speed (B), axial force (C), and SiC content (D) to maximize tensile strength (TS), elongation (E), and microhardness (HV). The L16 orthogonal array with four factors at four levels was implemented, followed by ANOVA. Optimization results significantly improved welding quality, with CoCoSO identifying ideal parameter combinations, MEREC determining influential parameter weights and RSM optimizing the relationship between process parameters and output responses. The optimal process parameters—welding speed (0.57 mm/s), rotational speed (1300 rpm), axial force (6000 N), and SiC content(8wt%)—enhanced joint efficiency from 63.81% to 97.90%. As a result, tensile strength increased from 191.7 MPa to 222.3 MPa, elongation improved from 2.4% to 7.9%, and yield strength from 117.7 MPa to 261.84 MPa. Microstructural analysis revealed that tensile strength decreased with increasing strain on the advancing side(AS) due to tool deviation ranging from −1.6 to 1.6 mm. These findings validate the effectiveness of optimization in UFSW, demonstrating their potential for achieving superior mechanical properties and defect-free welds in SiC-reinforced aluminum alloys.

Keywords: Underwater friction stir welding; Hardness; Elongation; Tensile strength; MEREC; CoCoSo.

1. INTRODUCTION

Friction stir welding (FSW) and its advanced technique, underwater friction stir welding (UFSW) have been widely employed to improve mechanical performance in lightweight alloys, particularly aluminum-based materials. These techniques are advantageous in minimizing heat-related defects, refining microstructures, and preserving joint integrity—especially in temperature-sensitive applications such as aerospace and automotive manufacturing. UFSW helps in retaining the desirable mechanical properties of A356 by minimizing heat-related defects, making it an optimal choice for joining complex components that demand both strength and durability. Several studies have focused on enhancing tensile strength and joint quality through FSW and UFSW of aluminum alloys. For example, AA7075–T6 and AA6061–T6 have shown improved tensile and yield strengths under optimized tool conditions [1, 2]. Medium-thick Al/Mg dissimilar metals were joined using submerged friction-stir welding (SFSW), which reduced intermetallic compound (IMC) coarsening and improved weld strength, achieving an ultimate strength of 171 MPa for a 6 mm thick Al/Mg joint [3]. AA6061–T6 aluminum alloy, reinforced with Al₂O₃ nanoparticles, was used in cooling-assisted stationary shoulder FSW, achieving 91% joint efficiency and enhanced mechanical properties, including 494 MPa tensile strength. AA6061–T6 and T2 pure copper were joined with UFSW, achieving thinner and more uniform IMC layers with reduced peak temperature. This method increased tensile strength to 255 MPa and joint efficiency to 91.1% [4]. AA6061–T6 was welded by FSW under submerged conditions with varying water heads and

rotational speeds. The study analyzed torque, power, and macrostructure to assess feasible process parameters, observing improvements in ultimate tensile strength (UTS) and microhardness for submerged FSW samples [5]. The study investigated the impact of intermetallic compounds and tool rotational velocity on the joints of Mg-AA6061 alloys that were produced through FSW. The tensile strength was improved by this mechanical interlocking. The joint achieved a maximal tensile strength of 242 MPa, which is 78% of the TS of the AA6061 aluminum parent metal of 310 MPa [6].

Aluminum-copper dissimilar joints were produced using SFSW, achieving a thinner IMC layer and refined grains in the aluminum nugget zone (NZ). The SFSW method improved the tensile strength to 221.5 MPa, which is 24% higher than conventional FSW, and changed the fracture location to the aluminum matrix, enhanced the performance of weld joints [7]. The parameters analyzed for UFSW of Al-Mg alloy included thermal profile, surface heat flux, strain rate in the stir zone (SZ), and compression pressure at the trailing edge, which influenced grain structure, joint hardness, and tensile properties [8]. Optimization by central composite design (CCD) and grey relational analysis (GRA) was helped to maximize mechanical outputs like hardness and elongation in AA6061-T6 [9, 10]. In the study of SiCp/AlSi10Mg composites created by laser metal deposition (LMD), the submicron-composite demonstrated the maximum hardness with a microhardness value of 118.37 HV, attributed to uniform particle distribution and minimized porosity [11]. The high-velocity oxygen fuel (HVOF) coating process on Ti-6Al-4V alloy optimized through GRA-PCA and PSO achieved improved hardness in the coated specimens, and it was verified by Vickers microhardness testing [12].

Friction-stir processing (FSP) on AA5086, reinforced with graphene and SiC, resulted in a high micro-hardness of 1.75 GPa, showing significant enhancement in hardness due to the even distribution and bonding of reinforcing particles within the matrix [13]. Researchers determined that transverse speed was the most significant factor influencing the silicon (Si) particle size, ultimate tensile strength (UTS), and force of the composites [14]. Various laser-welding methods for SiC/Al composites yielded welds with inhomogeneous hardness profiles, influenced by SiC particle distribution and porosity. Single laser beam welding produced the highest shear strength and showed varied hardness across different weld zones due to particle dissolution and reaction with the aluminum matrix [15]. The underwater FSP of AA6082/AA8011 dissimilar aluminum joints enhanced the TS compared to the FSW joints. Submerged friction stir processing (SFSP) resulted in grain refinement, leads to improved tensile strength, which was higher than the AA8011 parent metal but still lower than AA6082 [16]. The joint produced at 1200 rpm exhibited a TS of 224 MPa, which is equivalent to approximately 77.78% of the AZ80A TS and 72.26% of the AA6061 TS. The brittleness of the fractures was evident in the thermo-mechanically affected zone (TMAZ) and stir zone (SZ), where the structures had amalgamated, as evidenced by the rift-like patterns [17]. UFSW of AA5083 improved the tensile toughness from 340 MPa to 370 MPa. This increase was attributed to refined grain structures and high dislocation density, enhancing the toughness, particularly in the minimum hardness zone [18].

Recent research in FSW and related processes has increasingly focused on Multi-Criteria Decision-Making (MCDM) methods to optimize process parameters for enhanced mechanical and surface properties. Studies applying GRA-TOPSIS, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), CoCoSo, and MACROS have examined variables like tool shoulder diameter, rotation speed, and traverse speed to optimize tensile strength, hardness, and surface finish. Among these, GRA-TOPSIS and TOPSIS showed greater consistency in yielding top-ranked solutions, while CoCoSo and MACROS demonstrated variable performance across datasets [19]. Further work explored UFSW parameter optimization, particularly on AA6063 aluminum, using response surface methodology (RSM) and CoCoSo to assess the impact of transversal speed, rotating speed, and pin length on tensile strength and hardness. CoCoSo proved to be effective in fine-tuning process variables [20]. Similarly, hybrid MCDM approaches like MEREC and median/perimeter similarity improved ranking stability over traditional techniques [21]. Beyond welding, MCDM has been instrumental in robotic system selection and drilling/milling optimization. For instance, the Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) and Preference Selection Index (PSI) models reliably identified optimal welding robots across seven techniques [22]. Multi-Objective Optimization by Ratio Analysis (MOORA) and Combined Compromise Solution (CoCoSo) were employed to optimize drilling parameters in hybrid aluminum composites, while IF-MCDM methods like Multi-Attributive Ideal-Real Comparative Analysis (MAIRCA), COmbinative Distance-based ASsessment (CODAS), and CoCoSo demonstrated high correlation in identifying optimal WEDM settings [23, 24]. In advanced machining contexts, genetic algorithms (GA), Taguchi designs, and Box-Behnken designs (BBD) have been paired with MCDM to optimize parameters for processes like High speed wire electrical discharge machining on CFRP and milling of Ti-6Al-4V. These methods ensured improved hole quality, tool life, and surface characteristics [25, 26]. Taguchi and Whale Optimization Algorithms were also used to optimize milling of Carbon nano-onions (CNO) reinforced epoxy composites, identifying ideal material and cutting conditions through CoCoSo and SEM validation [27].

Studies on hybrid AA356 composites fabricated by stir casting—reinforced with Al_2O_3 , SiC, graphite, or zirconium silicate—also used Analytic Hierarchy Process (AHP) – GRA, Taguchi-GRA, and Grey-Fuzzy Reasoning Grade Analysis (GFRGA) to optimize compositions and test conditions, yielding composites with superior mechanical and tribological performance [28, 29]. Moreover, investigations into micromachining of AA356 highlighted tool wear mechanisms influenced by axial cutting depth, with optimization by RSM and other algorithms enhancing surface quality [30]. Finally, the robustness of CoCoSo across fuzzy environments was confirmed in drilling aluminum MMCs, reinforcing its value in subjective and multi-response decision-making contexts [31]. A tool deviation of up to 1 mm towards the softer AA2024 alloy improved material mixing and grain refinement in the stir zone, enhancing joint strength. However, deviation beyond 1.5 mm led to grain coarsening and a significant drop in mechanical properties, regardless of material positioning [32].

Despite its numerous advantages, the FSW and UFSW of AA356 alloys have been relatively understudied. The effect of tool deviation (TD) in UFSW welding has not been extensively examined, and only a limited number of papers have been published. Although prior research has thoroughly examined friction stir welding (FSW) and underwater FSW (UFSW), the most of the researchers concentrate on single-response optimization or a restricted range of alloy compositions. This study presents a novel hybrid multi-response optimization method, employing MEREC-CoCoSo to simultaneously improve several mechanical properties of A356 aluminum joints. The aim of this study is to find the optimal values for the following factors of the UFSW process: Axial force (N), tool rotational speed (rpm), Welding speed (mm/s), and SiC content (%). To achieve this, a multi-objective optimization method with a CoCoSo – MEREC technique was used. The objectives of this study are to validate the process resilience and production control limits, as well as to evaluate the impact of TD on the superiority of ideal weld joints. The experimental design of this study investigates the effects of various adjustments on the tensile strength (TS) of transversal joints in a 5 mm thick A356 plate reinforced with nano-SiC filler, aiming to identify the optimal output control parameters by analyzing the influence of welding tool deviation on weld joint quality.

2. EXPERIMENTAL METHODOLOGY

A356 is a frequently used metal in casting applications. It is predominantly selected for its superior casting characteristics, resistance to corrosion, and favorable mechanical properties. Silicon carbide (SiC) is a multifaceted material characterized by great hardness, superior thermal conductivity, corrosion resistance, mechanical strength, and stability in harsh environments. Silicon carbide (SiC) is utilized as a filler in A356 welding to improve the overall performance of the materials. Figure 1 illustrates the scanning electron microscope (SEM) image of A356 and SiC particles.

The stir-casting procedure was used to fabricate A356 matrix composites reinforced with SiC nanoparticles in an electric resistance muffle furnace. The typical diameter of the SiC particles was 400 mesh. The A356 alloy and SiC nanoparticles were procured from Matrics enterprises, Kanyakumari, Tamil Nadu and the chemical composition of A356 was illustrated in Table 1.

The fabrication of composite specimens was illustrated in Figure 2. The fabrication of A356 aluminum alloy strengthened with silicon carbide (SiC) nanoparticles by stir casting begins with the preparation of the A356 matrix material. The alloy is melted in a crucible using a resistance furnace, maintaining a temperature of 720°C.

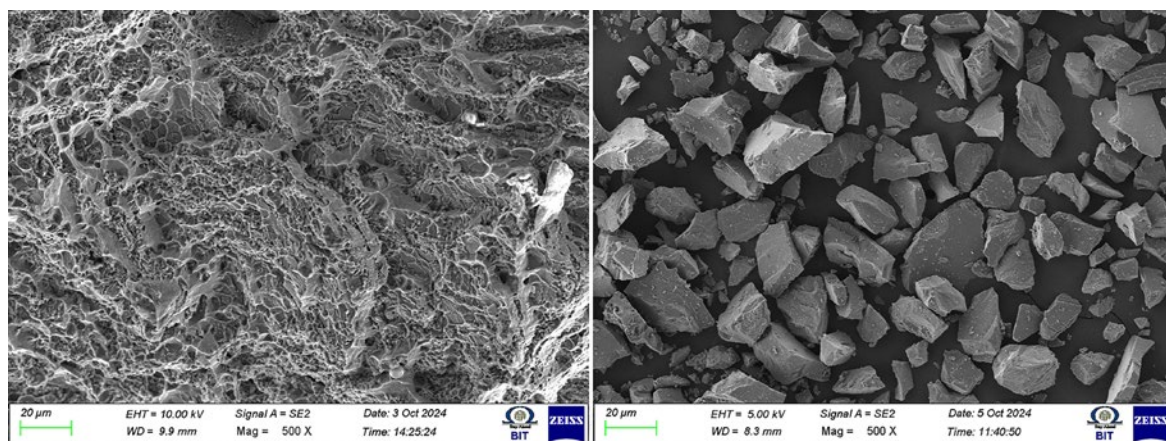
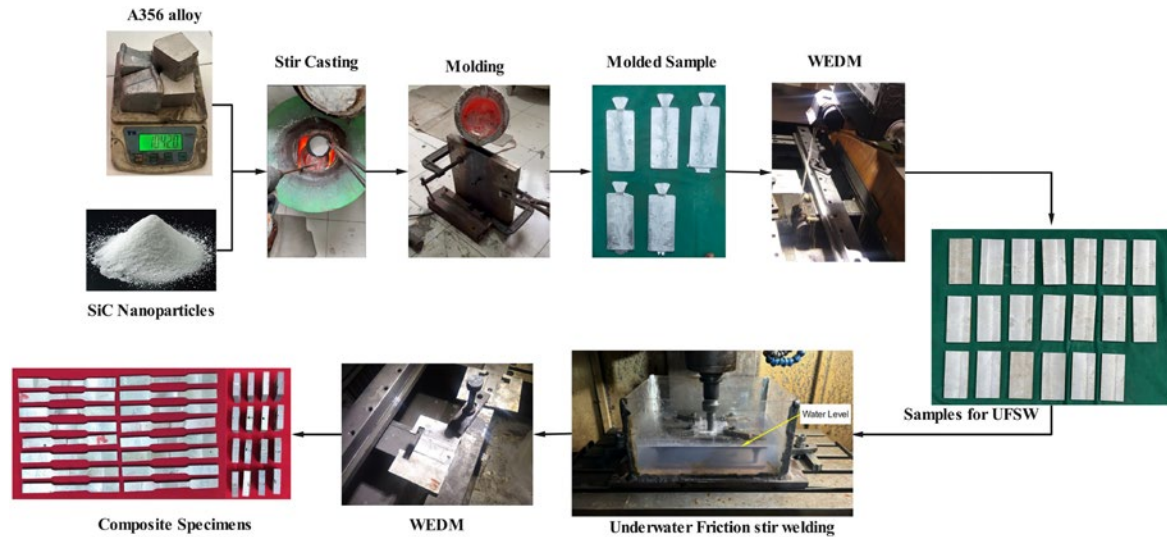


Figure 1: SEM image of A356 and SiC particles.

Table 1: Chemical composition of AA356.

ELEMENTS	Al	Si	Mg	Fe	Cu	Mn	Zn
wt%	92.05%	7%	0.35%	0.2%	0.2%	0.1%	0.1%

**Figure 2:** Fabrication of the composite specimens.

To ensure a high-quality melt, fluxes are added to remove impurities, and an inert gas such as argon is bubbled through the molten metal to eliminate dissolved hydrogen and reduce porosity. Simultaneously, SiC nanoparticles are preheated to 250°C to remove moisture and improve their wettability with the molten aluminum.

In this process, the SiC nanoparticle ratio is varied between 2 and 6 wt% at 2wt% difference to study the influence of reinforcement on the composite's properties. Once the matrix is fully melted and degassed, stirring is initiated using stainless steel stirrer, creating a vortex in the molten metal. The stirring process conducted at a speed of 300 rpm for 10 minutes to ensure uniform dispersion of the reinforcement. Preheated SiC nanoparticles are gradually introduced into the vortex at the designated weight percentages to prevent agglomeration and ensure uniform distribution within the matrix. The molten composite is then carefully poured into 300 mm × 200 mm × 5 mm mold.

The fabricated composite, initially molded into a rectangular plate was prepared for UFSW by cutting it into smaller specimens of dimensions 100 mm × 50 mm × 5 mm using Wire Electrical Discharge Machining (WEDM). The composite plate was firmly fixed on the WEDM machine, and the cutting parameters, including wire diameter (0.25 mm), feed rate, wire material (brass), and power settings, were optimized to suit the composite material.

The experimental setup of UFSW and welded samples were illustrated in Figure 3 (a & b). The prepared specimens (100 mm × 50 mm × 5 mm) were then subjected to UFSW, a process performed under a submerged environment to enhance thermal control and minimize the heat-affected zone (HAZ). The water level in the welding tank was raised to the level of the arm of the FSW tool to facilitate the UFSW process. Four key welding parameters were carefully selected to optimize the welding process. The welding tool utilized had a pin diameter and a shoulder diameter of 6 and 20 mm, respectively. The shoulder was made from 42CD4-treated medium-carbon steel, recognized for its excellent strength and toughness under heat and pressure. The tool pin, made of H13 steel was selected for its exceptional resistance to abrasion, ductility, hardness, and thermal stability, ensuring it remained intact under high heat and pressure during the welding process. To minimize defects in the welding zone and prevent material debris ejection, the FSW tool was angled at 1.5°. This angle facilitated proper material flow under the tool's arm, ensuring a seamless welding process. The design of the tool allowed for precise control over the axial force exerted during welding, further enhancing the quality of the weld. Additionally, a controlled lateral tool deviation ranging from -1.6 mm to +1.6 mm was introduced during welding to examine its effect on weld formation and joint quality (Figure 4). Deviation measurements were taken on both the advancing side (AS × mm) and the retreating side (RS × mm) relative to the central line, ensuring symmet-

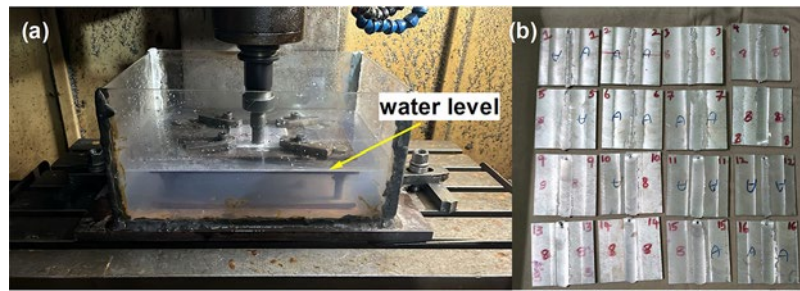


Figure 3: (a) Experimental setup of underwater friction-stir welding (b) welded samples.

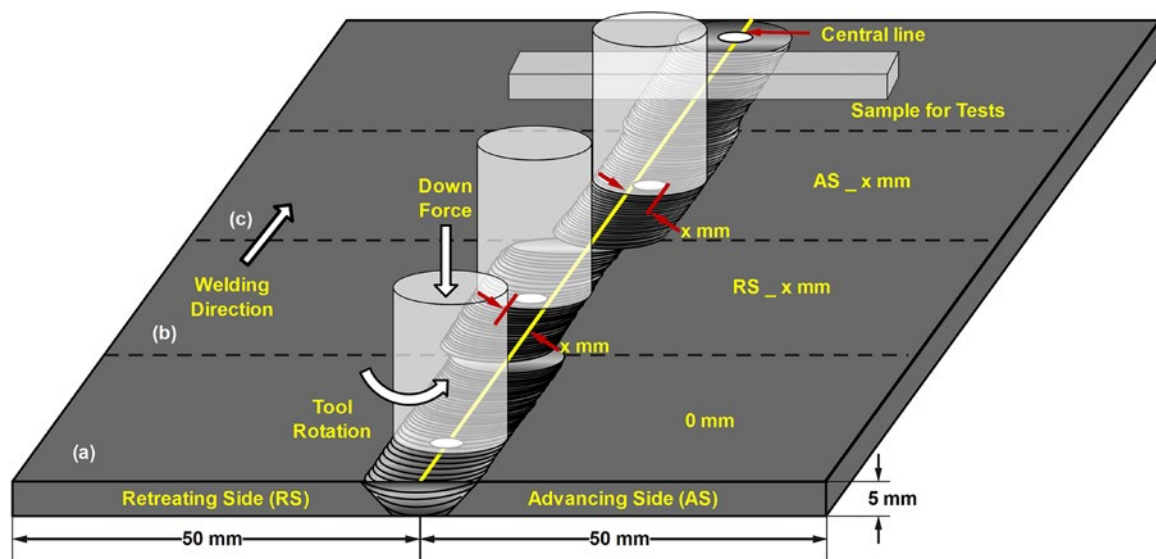


Figure 4: A schematic illustration of tool deviation with respect to 0 mm, +1.6 mm and -1.6 mm.

rical evaluation of tool offset effects. The tool's design facilitated precise control of axial force throughout the welding process, which contributed to improved weld integrity and consistency across the joint.

The welded samples were prepared for mechanical testing by cutting it into standardized specimens as per ASTM guidelines using WEDM. The plate was securely mounted on the WEDM machine table, and the cutting process was programmed to produce test specimens in compliance with ASTM standards.

The welded joint assemblies were analyzed using light optical microscopy, following the evaluation of mechanical properties like microhardness and TS. The tests were conducted on an INSTRON Universal testing machine (Figure 5a) with a maximal capacity of 50 kN, operating at a crosshead speed of 0.2 mm min^{-1} . The TS samples were extracted from the centerline of the welded plates to avoid burrs and reduce potential errors at the starting and ending of the welded bead. These specimens, fabricated with respect to ASTM B557M-06 and used for TS testing, are illustrated in Figure 5(b). For each set of welding parameters, three TS specimens were prepared and assessed to ensure consistency and compliance with ASTM standards.

The Vickers microhardness of the weld was measured at multiple points using a microhardness tester. The measurements were taken at increments of 0.3 mm, with a testing load of 300 g. To achieve a surface smoothness of $0.05 \mu\text{m}$, the weld sheets were cut vertical to the weld track and then polished for analysis. All materials that were examined were subjected to twenty-seven indentations at 1 mm intervals. The polished surfaces were etched at room temperature using Keller's reagent to analyze the microstructure. Scanning electron microscopy (SEM) was conducted on the fractured specimen surfaces at Bannari Amman Institute of Technology, Sathya Mangalam, Tamil Nadu to analyze the rupture mode.

3. EXPERIMENTAL DESIGN USING OPTIMIZATION TECHNIQUES

The operational parameters for UFSW, including welding speed (A), tool rotational speed (B), axial force (C), and SiC content (D) are outlined in Table 2. These parameters were optimized to improve the TS, elongation (E), and

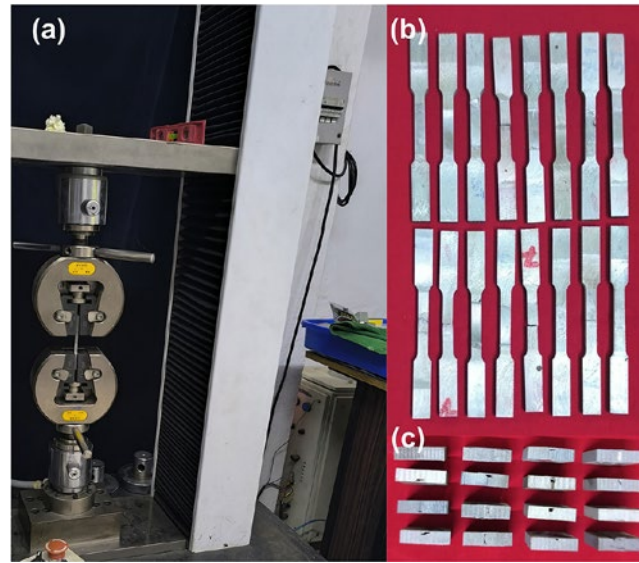


Figure 5: (a) Universal testing machine (b) tensile test samples (c) hardness test samples.

hardness (HV) of the UFSW joints while minimizing welding defects. To systematically collect results, reduce testing time, and save costs, a total of 16 experimental tests were conducted using the L16 orthogonal array of the Taguchi design. This array consists of 16 trials that evaluate the effects of four factors, each at four levels.

The weld joints were fabricated based on the parameter combinations specified in Table 3, with responses including TS, E, and HV measured across three distinct zones: (i) the advancing side (AS), (ii) the retreating side (RS), and (iii) the stir zone (SZ). Table 3 presents the real experimental design and the corresponding measured responses. Table 3 presents the average values obtained from the experimental tests. The detailed individual results, along with standard deviation and statistical error analysis were provided in the supplementary Tables S1 and S2.

Additionally, the MCDM problem was converted into a single-objective problem using the COCOSO method. The optimization process considered independent variables constrained within their specified ranges. The normalized sequence, summation of the weighted equivalence matrix (Si), power of the weightage equivalence matrix (Pi), and their respective aggregated evaluation scores were computed in accordance with the mathematical framework outlined in the study, as described in the following section. This approach ensures a systematic evaluation and efficient optimization of the welding parameters.

3.1. MEREC method

MEREC is a technique used to determine weights by analyzing the impact of eliminating criteria, making it distinct from traditional methods that typically evaluate the variance in alternative behavior associated with the criterion [33]. Unlike conventional techniques, MEREC focuses on the effects of removing each criterion to calculate weight distribution. The steps involved in evaluating weights using the MEREC method are outlined below.

Step 1: Decision matrix. The ratings or values of each alternative in relation to the criteria are represented by a decision matrix at this stage. The elements of this matrix, denoted by x_{ij} , must be greater than zero. If any elements in the matrix have negative values, a method must be applied to transform them into positive values to ensure consistency and usability. For example, consider a decision matrix representing n alternatives and m criteria:

$$x_{ij} = \begin{bmatrix} x_{11} & x_{12} & x_{13} \dots & x_{1n} \\ x_{21} & x_{22} & x_{23} \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & x_{m3} \dots & x_{mn} \end{bmatrix}; i = 1, 2, 3 \dots, m; j = 1, 2, 3 \dots, n \quad (1)$$

Step 2: Normalization matrix (N). The components of the decision matrix are modified through the application of fundamental linear normalization in this step. The elements of the normalized matrix is denoted by the symbol n_{ij} .

Table 2: Input welding factors and its levels.

FACTORS	NOTATION	LEVELS			
		1	2	3	4
Weld speed (mm/s)	A	0.33	0.41	0.49	0.57
Tool rotational speed (rpm)	B	1000	1100	1200	1300
Axial force (N)	C	5100	5400	5700	6000
SiC Content (%)	D	2	4	6	8

Table 3: Design of experimented L16 orthogonal array inputs and its results.

S. NO	A (mm/s)	B (rpm)	C (N)	D (%)	TS (MPa)	E (mm)	HV		
							TMAZ- ADVANCING SIDE	TMAZ- RETREATING SIDE	STIR ZONE
1	0.33	1000	5100	2	191.7	2.4	72.3	65.2	62.1
2	0.33	1100	5400	4	187.9	5.7	78.4	70.8	66.5
3	0.33	1200	5700	6	196.6	7.9	75.1	68.3	63.2
4	0.33	1300	6000	8	200.8	8.3	81.2	73.9	68.4
5	0.41	1000	5400	6	208.1	2.8	74	67	63.8
6	0.41	1100	5100	8	216.8	4.4	80.3	72.7	67.4
7	0.41	1200	6000	2	199.1	7.3	76.2	69.1	64.5
8	0.41	1300	5700	4	195.9	6.2	83.1	75	69.9
9	0.49	1000	5700	8	210.1	5.5	72.7	65.5	62.5
10	0.49	1100	6000	6	219.7	6.7	78.8	71.3	66.9
11	0.49	1200	5100	4	202.8	3.6	75.6	68.7	63.5
12	0.49	1300	5400	2	209.4	4.8	81.7	74.2	68.9
13	0.57	1000	6000	4	213.7	7.3	74.3	67.3	64
14	0.57	1100	5700	2	215.8	7.2	80.7	72.9	67.7
15	0.57	1200	5400	8	218.4	7.5	76.5	69.4	64.8
16	0.57	1300	5100	6	222.3	7.9	83.4	75.3	70.2

$$n_{ij}^x = \begin{cases} \frac{\text{minimum } x_{kj}}{k} & \text{if } j \in \text{Beneficial factor} \\ x_{ij} & \\ \frac{x_{ij}}{\text{maximum } x_{kj}} & \text{if } j \in \text{Non - Beneficial factor} \end{cases} \quad (2)$$

Step 3: Evaluate the comprehensive performance of the substitutes, (A_i). To assess the overall performance of the alternatives, a log metric is employed with uniform criteria weightage. Based on the normalization values derived from the preceding phase, we can ascertain that those lower values of (n_{ij}^x) result in higher performance values (A_i). This computation employs the subsequent equation:

$$A_i = \ln \left(1 + \left(\frac{1}{m} \sum_j |\ln(n_{ij}^x)| \right) \right) \quad (3)$$

Step 4: Evaluate the factor characteristics by excluding criteria. At this stage, the process involves a logarithmic metric similar to the previous step. However, the key distinction from Step 3 is that, in this stage, the results of responses are evaluated by individually excluding each norm. As an outcome, m sets of performances are

generated, each corresponding to the exclusion of one of the m criteria. Let A'_{ij} represent the whole results of the i^{th} alternative when the j^{th} criteria is excluded. The subsequent formula is employed for calculating in this stage:

$$A'_{ij} = \ln \left(1 + \left(\frac{1}{m} \sum_{k, k \neq j} \left| \ln(n_{ik}^x) \right| \right) \right) \quad (4)$$

Step 5: Calculate the summation of deviations. In this phase, the impact of removing the j^{th} criteria is assessed using the data found from Steps 3 and 4. Let E_j represent the impact of eliminating the j^{th} criteria. The value of E_j can be determined through the subsequent equation:

$$E_j = \sum_i |A'_{ij} - A_i| \quad (5)$$

Step 6: Ascertain the conclusive weightage of the criterion. Here, the objective weightage of each factor is determined by utilizing the effects of removal, denoted as (E_j), from prior step. In the subsequent text, w_j denotes the weightage of the j^{th} criteria. The subsequent formula is employed for the computation of w_j [34]:

$$W_j = \frac{E_j}{\sum_k E_k} \quad (6)$$

3.2. CoCoSo optimization

The proposed strategy is based on a hybrid model that combines simple additive weighting (SAW) and exponential weighting for products [35]. This approach is designed to harmonize conflicting objectives and reconcile various preferences, offering a comprehensive solution to the problem. The CoCoSo method evaluates and resolves assortment conflicts by following these steps:

Step 1: Formation of the matrix

Step 2: Matrix normalization:

$$r_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}; \text{ for benefit criterion,} \quad (7)$$

$$r_{ij} = \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}; \text{ for non – benefit criteria} \quad (8)$$

Step 3: The total power weightage of the equivalence sequences for each factor and its results are represented as, Y_i and o_i , respectively:

$$S_i = \sum_{j=1}^n (w_j r_{ij}) \quad (9)$$

The value of S_i is attained by the gray relational generation method.

$$P_i = \sum_{j=1}^n (r_{ij})^{w_j} \quad (10)$$

Step 4: The comparative weightage of the substitutes is determined using the designated sum procedures. During this process, three assessment score approaches are utilized to provide comparative weightage for various solutions, based on formulas (11)–(13) [36]:

$$k_{ia} = \frac{P_i + S_i}{\sum_{i=1}^m (P_i + S_i)} \quad (11)$$

$$k_{ib} = \frac{S_i}{\min_i S_i} + \frac{P_i}{\min_i P_i} \quad (12)$$

$$k_{ic} = \frac{\lambda(S_i) + (1-\lambda)(P_i)}{(\lambda \text{maximum}_i S_i + (1-\lambda) \text{maximum}_i P_i)} \quad (13)$$

Equation (11) represents the numerical mean of the scores derived from the weightage sum model and the weightage power model, providing a balanced assessment of performance across criteria. Equation (12) computes the collective relative score, which combines the weightage sum and weightage power relative to optimal performance, facilitating a comprehensive evaluation. Equation (13) introduces a fair reconciliation of the two models' scores using a decision-maker-defined parameter λ , often set to $\lambda = 0.5$, to balance the influence of both models.

The flexibility and reliability of the CoCoSo method are influenced by key parameters, including the weights assigned to criteria, the normalization approach, and the choice of λ . These factors allow decision-makers to tailor the evaluation process based on specific needs, enabling robust and adaptable multi-criteria decision-making. By combining additive and multiplicative scoring models, the CoCoSo method ensures a comprehensive and harmonized assessment of alternatives, accounting for both linear and nonlinear relationships among criteria.

Step 5: The conclusive ranking of the response factors is established by the k_i values [37]:

$$k_i = (k_{ia} k_{ib} k_{ic})^{\frac{1}{3}} + \frac{1}{3} (k_{ia} + k_{ib} + k_{ic}) \quad (14)$$

Step 6: Rank the alternatives.

The optimal selection is determined by identifying the alternative with the maximum behavior score calculated in the final stage of the CoCoSo method. In this stage, all alternatives are ranked depends on their performance scores, which are derived from a combination of the weightage sum and weightage power models, as reconciled through the parameter (λ). The most favorable alternative is represented by the alternative with the highest score, while the remaining alternatives are arranged in descending order of their scores, thereby facilitating a systematic and transparent ranking of choices prior to decision-making.

3.3. Response surface methodology

Response Surface Methodology (RSM) was employed to analyze the effect of process parameters on weld quality. A central composite design (CCD) was chosen to systematically vary the input factors and generate response surface plots. The performance score $f(k_i)$ was evaluated based on experimental results. Statistical analysis was conducted using ANOVA (Analysis of Variance) to assess the significance of each parameter.

4. RESULTS AND DISCUSSION

The tensile stress, elongation, and hardness results for each sample, determined using the Taguchi L16 OA, are displayed in Table 3. In the UFSW of A356 aluminum alloy, the resultant responses are significantly influenced by changes in processing parameters (A, B, C, and D). Initially, optimum processing factors were identified to enhance the TS, elongation, and hardness of the weld joints, aiming to achieve exceptional weld quality.

The initial assessment matrix is shown in Table 3 and is transformed into a normalized decision matrix following Step 2 of the MEREC methodology. Using the normalized data, the overall behavior of response factor (S_i) and the outcome of response factor excluding specific criteria ($S(ij')$) are calculated using Equations (3) and (4), respectively. Finally, the absolute deviations and the effects of removing each criterion E_j are determined, as summarized in Table 4. Equation (5) is then applied in the final stage of the MEREC analysis to calculate the relative importance of each criterion. This structured approach ensures accurate evaluation and prioritization of criteria to optimize the welding process.

Using Phase Two of the CoCoSo methodology, the primary matrix was normalized depending on Equations (7) and (8), which are applied to benefit and cost criteria. The normalized values are presented in

Table 4: Evaluate attribute weight outcomes utilizing the MEREC methodology.

WEIGHT	TS (MPa)	E (mm)	TMAZ- ADVANCING SIDE (HV)	TMAZ- RETREATING SIDE (HV)	TMAZ-STIR SIDE (HV)
w_j	0.079	0.752	0.059	0.062	0.048

Table 5: Normalization and weighted comparability series (Si value) and Pi value.

S. NO	TS (MPa)	E (mm)	TMAZ- ADVANCING SIDE (HV)	TMAZ- RETREATING SIDE (HV)	TMAZ- STIR SIDE (HV)	Si	Pi
1	0.1105	0.0000	0.0000	0.0000	0.0000	0.0087	0.8403
2	0.0000	0.5593	0.5495	0.5545	0.5432	0.5135	3.5465
3	0.2529	0.9322	0.2523	0.3069	0.1358	0.7614	4.6056
4	0.3750	1.0000	0.8018	0.8614	0.7778	0.9197	4.8913
5	0.5872	0.0678	0.1532	0.1782	0.2099	0.1275	3.8126
6	0.8401	0.3390	0.7207	0.7426	0.6543	0.4413	4.3721
7	0.3256	0.8305	0.3514	0.3861	0.2963	0.7092	4.6110
8	0.2326	0.6441	0.9730	0.9703	0.9630	0.6665	4.6042
9	0.6453	0.5254	0.0360	0.0297	0.0494	0.4524	4.0739
10	0.9244	0.7288	0.5856	0.6040	0.5926	0.7215	4.6954
11	0.4331	0.2034	0.2973	0.3465	0.1728	0.2345	4.0245
12	0.6250	0.4068	0.8468	0.8911	0.8395	0.5008	4.4467
13	0.7500	0.8305	0.1802	0.2079	0.2346	0.7186	4.5910
14	0.8110	0.8136	0.7568	0.7624	0.6914	0.8010	4.7893
15	0.8866	0.8644	0.3784	0.4158	0.3333	0.7842	4.7267
16	1.0000	0.9322	1.0000	1.0000	1.0000	0.9490	4.9486

Table 4. Subsequently, Equations (12) and (13) were used to compute the summation of weighted equivalence sequences (Si) and the power-weighted equivalence sequences (Pi). The calculated results are also provided in Table 5 for reference.

This step ensures that all criteria are appropriately weighted and normalized, facilitating a fair and accurate comparison of alternatives. The consolidated appraisal scores (k_{ia} , k_{ib} , and k_{ic}) are calculated using Equations (11)–(13), with the results detailed in Table 6. The MEREC-CoCoSo method provides clear and precise outcomes, enabling the classification which is based on their respective rankings. Equation (14) is applied to evaluate the output scores of the response factor by determining the k_i values. This process ensures a systematic evaluation of alternatives, facilitating accurate ranking and decision-making for selecting the best-performing alternatives.

4.1. Identification of optimal parameters

To determine the optimal set of processing factors and establish the hierarchical importance of each factor combination, it is essential to evaluate the performance scores of alternatives (k_i) relative to the ideal benchmark, which is unity, in a multi-objective optimization context. The ideal combination of processing factors and response quality is identified by the highest k_i value, which approaches unity. Experimental run number 16 (Table 7) has the maximal k_i value of 7.6370, indicating that it represents the optimal combination of processing factors and performance scores within the experimental framework. This parameter combination ensures that the welded joint produced by the UFSW method possesses the highest quality attributes.

Table 8 presents the UFSW processing factor levels, calculated based on the mean performance scores (k_i) for each factor. The table highlights the significance hierarchy of the processing factors, evaluated by the variation (delta) among the maximal and minimal k_i values for each factor level. The entire performance is primarily affected by parameters in the following order: B, C, A, and D. The optimal arrangement of processing factors can be further analyzed by evaluating the k_i values and interpreting the main effects plot to achieve the

Table 6: Results of appraisal scores strategies.

S. NO	k_{ia}	k_{ib}	k_{ic}
1	0.0110	1.000	0.1440
2	0.0528	13.941	0.6884
3	0.0698	15.919	0.9100
4	0.0756	18.104	0.9853
5	0.0512	3.221	0.6681
6	0.0626	9.718	0.8161
7	0.0692	14.809	0.9021
8	0.0685	13.938	0.8937
9	0.0589	10.693	0.7675
10	0.0705	14.796	0.9185
11	0.0554	5.610	0.7222
12	0.0643	10.843	0.8389
13	0.0691	15.070	0.9003
14	0.0727	16.103	0.9479
15	0.0717	15.974	0.9344
16	0.0767	18.465	1.0000

Table 7: Computed performance scores of alternatives (k_i) and its order.

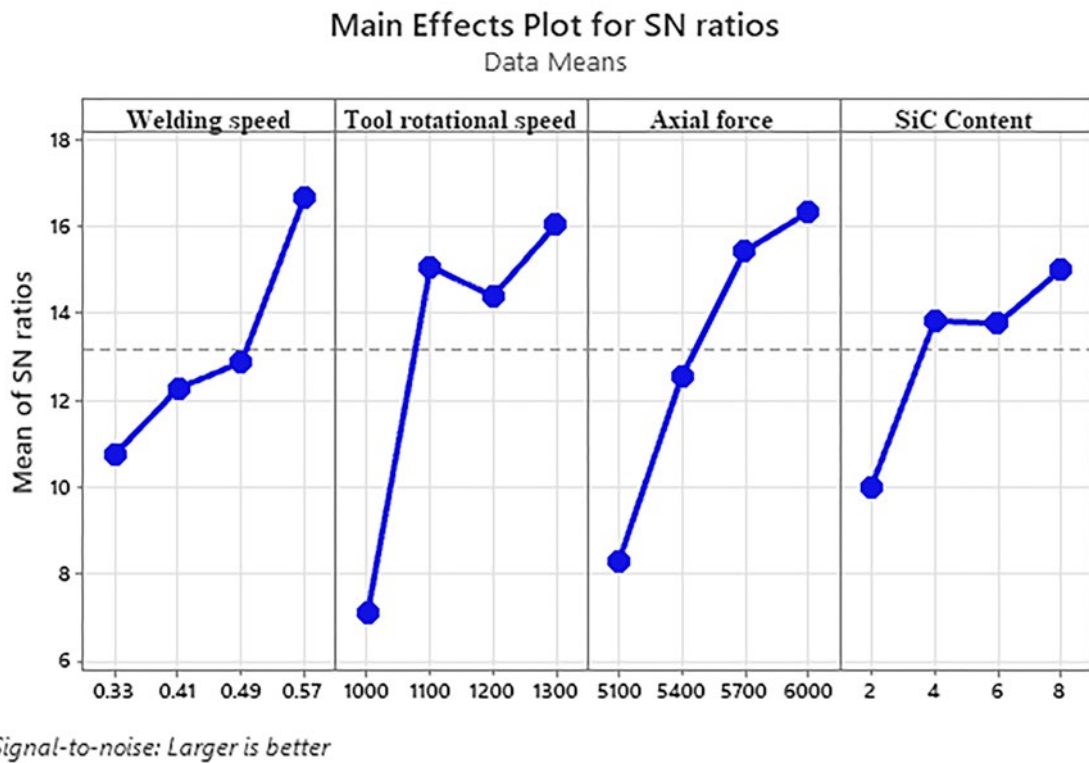
TRIAL. NO	k_i	RANKING ORDER
1	0.5017	16
2	5.6912	10
3	6.6365	5
4	7.4929	2
5	1.7929	15
6	4.3240	13
7	6.2340	8
8	5.9155	9
9	4.6245	12
10	6.2473	7
11	2.7369	14
12	4.7521	11
13	6.3251	6
14	6.7432	3
15	6.6829	4
16	7.6370	1

best possible quality characteristics. This approach ensures an accurate identification of the most influential parameters and their ideal combinations for optimizing the UFSW process.

Figure 6 illustrates the main effects plot for the processing factors, showing the mean k_i (performance scores of alternatives) values at various levels of the processing factors, as derived from the data in Table 7. Both Table 8 and Figure 6 identify the optimal combination of processing factors. The ideal parameter configuration is determined to be: 8 wt% for D4, 1300 rpm for B4, 6000 N for C4, and 0.57 mm/s for A4. An ANOVA analysis was conducted to evaluate the effect of the welding factors on the combined results of the UFSW process. The study found that optimal tensile strength and microhardness were achieved using a threaded cylindrical pin at 2100 rpm and a feed rate of 10 mm/min when welding A356 and AA2014 alloys. These results were further validated using fuzzy logic and Artificial Neural Networks (ANN) [38].

Table 8: Results on the mean of performance scores of alternatives (k_i).

LEVEL	A (mm/s)	B (rpm)	C (N)	D (%)
1	5.081	3.311	3.800	4.558
2	4.567	5.751	4.730	5.167
3	4.590	5.573	5.980	5.578
4	6.847	6.449	6.575	5.781
Delta	2.280	3.138	2.775	1.223
Rank	3	1	2	4

**Figure 6:** Main effects plot for performance scores of alternatives (k_i).

4.1.1. ANOVA

The objective function's sources of change are identified through the use of ANOVA. Additionally, it is implemented to assess the influence of each factor on the process. The F value, P-value, or percentage of contribution values can be employed to assess the influence of welding factors on the resulting performance of alternative k_i .

The processing factors' improvements and their associated significance were determined using the ANOVA of the dimensionless k_i values, as illustrated in Table 9. The rotational speed of the tool was identified as the most significant factor, contributing 35.25% to the overall evaluation. Welding speed accounted for 22.10%, axial force contributed 29.59%, and SiC content contributed 5.55%. All processing parameters were determined to be statistically significant at the 95% confidence level, supported by a coefficient of determination (R^2) of 92.49%. The adjusted R^2 value of 62.44% and R^2 of 92.49% indicate a strong correlation between the predicted and observed outcomes.

ANOVA is a powerful statistical tool for identifying which parameters most significantly influence test results. By using ANOVA, researchers can determine the welding factors that have a substantial impact on weld

Table 9: ANOVA for the performance scores of alternatives (k_i).

SOURCE	DF	SEQ SS	CONTRIBUTION	ADJ MS	F-VALUE	P-VALUE
Welding Speed (A)	3	13.919	22.10%	4.640	2.94	0.200
Tool Rotational Speed (B)	3	22.207	35.25%	7.402	4.69	0.118
Axial Force (C)	3	18.638	29.59%	6.213	3.94	0.145
SiC Content (D)	3	3.497	5.55%	1.166	0.74	0.595
Error	3	4.732	7.51%	1.577		
Total	15	62.993	100.00%			
	<i>S</i>	1.25586	<i>R</i> -Sq	92.49%	<i>R</i> -Sq (adj)	62.44%

quality. The results indicate that adjusting the welding parameters enhances the welding process and improves overall quality.

Based on the processing factors, a mathematical model can be developed following the ANOVA analysis to predict the k_i values for unique combinations of weld connections formed by the UFSW method. This relationship provides an efficient method to optimize the process and thereby achieve superior weld quality.

$$\text{Performance scores of alternatives } (k_i) = f(A, B, C, D) \quad (15)$$

For all four factors, the chosen polynomial is articulated as below:

$$\text{Performance scores of alternatives } (k_i = b_0 + b_1A + b_2B + b_3C + b_4D + b_{12}A * B + b_{13}A * C + b_{23}B * C) + b_{34}C * D \quad (16)$$

where,

- b_0 – constant
- b_1, b_2 , and b_3 – linear terms coefficients
- b_{12}, b_{13}, b_{23} , and b_{34} – coefficients of interaction terms.

The generated regression models demonstrated greater accuracy, and conformity tests were performed to validate these models [39]. The subsequent first-order polynomial equation is obtained by utilizing the average response values and the multiple regression analysis of the matrix:

$$\begin{aligned} \text{Performance scores of alternatives } (k_i) = & 5.271 - 0.191 A_{0.33} - 0.704 A_{0.41} - \\ & 0.681 A_{0.49} + 1.576 A_{0.57} - 1.960 B_{1000} + 0.480 B_{1100} + 0.301 B_{1200} + \\ & 1.178 B_{1300} - 1.444 C_{5100} - 0.541 C_{5400} + 0.709 C_{5700} + \\ & 1.304 C_{6000} - 0.713 D_2 - 0.104 D_4 + 0.307 D_6 + 0.510 D_8 \end{aligned} \quad (17)$$

To calculate the importance of the adjusted mean (k_i) of the performance ratings of alternatives, as defined in Equation (17), the ANOVA results detailed in Table 8 are consulted. The model's ability to accurately denote the correlation among the significant factors and the levels is demonstrated by a highly significant F-value.

The adjusted R^2 value of 62.44% indicates a strong relationship among the predicted and experimental values, although it is lower than the R^2 value of 92.49%. This discrepancy suggests that the adjusted R^2 accounts for the number of predictors and provides a more conservative measure of model fit. Despite this, the model effectively predicts responses with a reasonable degree of accuracy and low uncertainty, making it reliable for practical applications.

4.1.2. Response surface methodology

Using Response Surface Methodology (RSM), a correlation was identified between input parameters, such as tool factors, and output results, including joint mechanical properties, force and temperature. This correlation was then utilized to determine the optimal process parameters through a hybrid multi-objective optimization

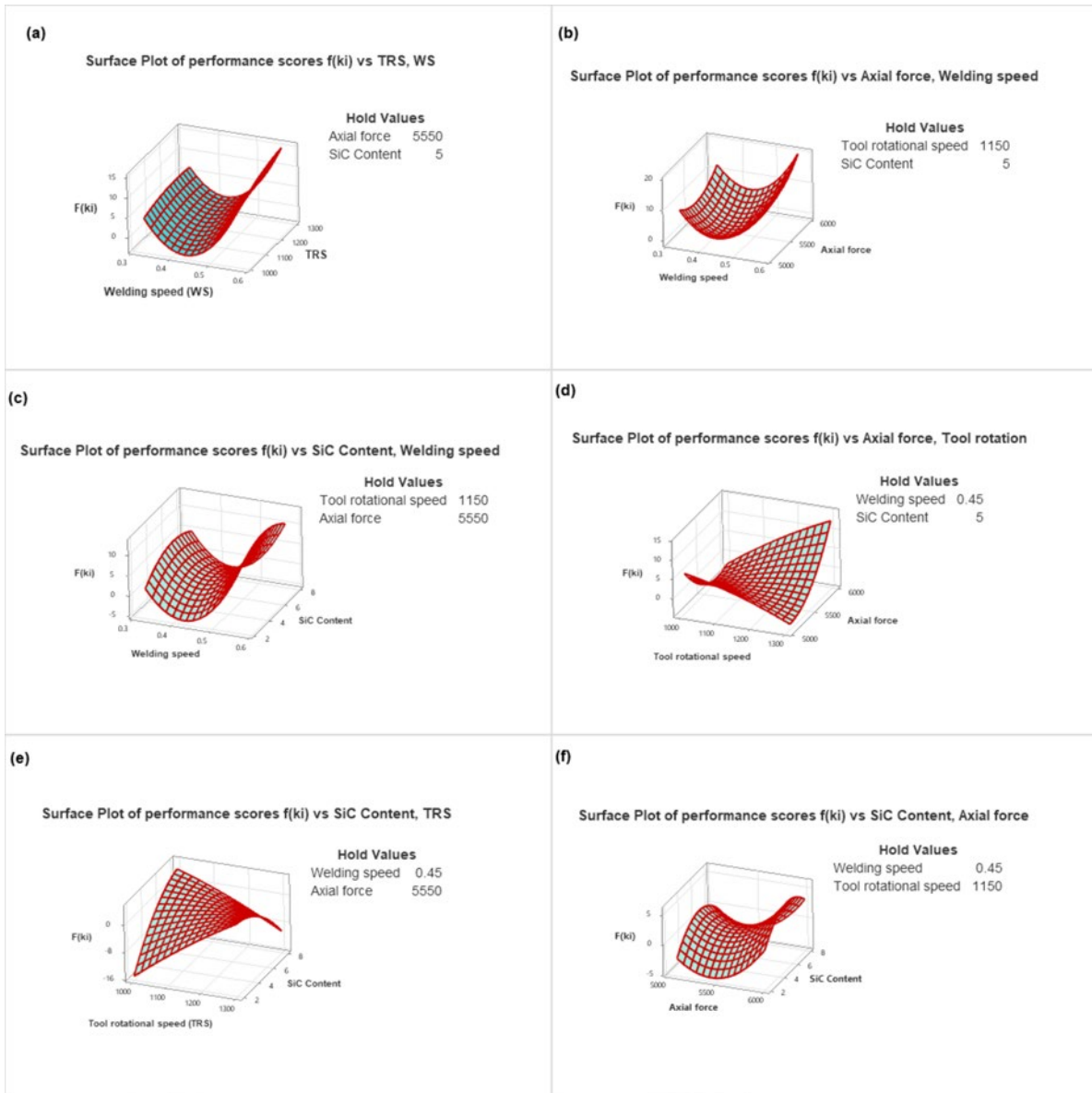


Figure 7: Response surface plots showing the interaction effects of tool rotational speed, welding speed, axial force, and SiC content on performance scores $f(k_i)$.

approach [40]. Response surface methodology (RSM) was utilized to examine the impact of critical process factors, such as tool rotational speed (TRS), welding speed (WS), axial force, and silicon carbide (SiC) content, on the performance scores $f(k_i)$. The response surface plots (Figure 7) demonstrate significant interactions among these parameters. Figure (7a) illustrates that augmenting TRS and WS improves performance scores until an optimal threshold is reached, beyond which flaws occur due to excessive heat. Figure (7b) demonstrates that increased axial force, when paired with appropriate WS, enhances material flow and bonding; however, excessive force may lead to material distortion. Figure (7c) illustrates that an increase in SiC reinforcement initially improves performance; nevertheless, elevated concentrations result in particle aggregation and reduced uniformity. Figure (7d) illustrates that an appropriate amalgamation of axial force and TRS enhances grain structure and mechanical characteristics. Likewise, Figure (7e) indicates that a moderate SiC concentration with appropriate TRS improves material mixing and reinforcement distribution. Figure (7f) illustrates that whereas augmented axial force enhances weld densification, excessive force in conjunction with elevated SiC concentration may result in porosity and reduced performance.

The results demonstrate that an ideal amalgamation of factors markedly enhances mechanical capabilities, whereas deviations result in problems like porosity, inadequate bonding, and structural instability. The response

surface plots indicate that a TRS of 1000–1200 rpm, WS of 0.4–0.5 mm/s, axial force of 5200–5800 N, and SiC concentration of 3–5% produce optimal performance. Higher TRS and WS improve material mixing; nevertheless, excessive levels lead to overheating, compromising weld integrity. An axial force of approximately 5500 N is essential for optimal bonding, whereas SiC reinforcement of up to 5% enhances performance by augmenting hardness and strength. Elevated levels of these characteristics may result in problems like inadequate bonding, porosity, or material deterioration. This study offers a framework for determining optimal process parameters to improve mechanical characteristics and structural integrity. Future study may concentrate on experimental validation and supplementary parameters, like cooling rate and tool geometry, for enhanced optimization.

AZ80A exhibits the highest average tensile strength at 251.4 MPa. The stability and high precision of the quadratic models are validated by the analysis of variance (ANOVA), which implies that it is suitable for optimizing FSW [41]. ANOVA was employed to validate the model, which exhibited exceptional agreement with experimental data, particularly the impact of these parameters on the joint properties, as demonstrated by the use of 3D response surface plots. Tool RS of 1045 rpm, traversal speed of 1.5 mm/s, and axial force of 4.87 kN were identified as the optimal process parameters [42].

4.1.3. Confirmation test

The regression model specified in Equation (17) was validated by conducting two additional experimental runs with a revised set of UFSW process parameters. These runs were purposefully designed to deviate from the specifications of the L16 design matrix to ensure the robustness and reliability of the MEREC measuring method in delivering accurate results. The experiments utilized the optimal parameters obtained from solving the regression formula to construct weld joints.

Next, samples were produced to evaluate the mechanical properties and microstructural behavior of these weld joints. In order to evaluate advances, the results were contrasted with the baseline material and the initial experimental scenario. The primary objective of this research was to evaluate the quality of the optimal weld connection and examine the microstructural and mechanical characteristics of the weld joint, even in the presence of tool deviation. Despite variations in the welding apparatus, the study confirmed that the weld joints produced using the optimized parameters exhibited superior microstructural and mechanical properties, highlighting the robustness of the regression model and the reliability of the process.

4.1.4 Sensitivity analysis

The sensitivity of the optimization process has been examined through the use of various weight percentages, utilizing Entropy and CRITIC weighting methodologies. These methods offer a systematic framework for assigning weights by assessing the intrinsic significance of each criterion. Entropy quantifies the uncertainty and dispersion of data, whereas CRITIC evaluates the contrast strength and discord among criteria. This investigation verifies the robustness and reliability of the findings derived from the MCDM approaches (MEREC and COCOSO).

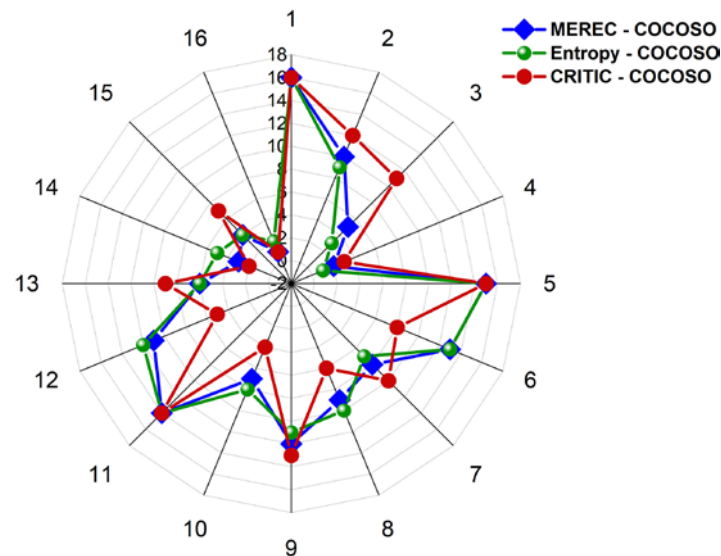
The sensitivity study utilized three distinct weighing methods—MEREC-COCOSO, Entropy-COCOSO, and CRITIC-COCOSO—to evaluate the stability and robustness of alternative rankings, as presented in Table 10 and Figure 8. The results reveal significant discrepancies among ranking places, highlighting the impact of various weight assignment methods on decision-making processes. The MEREC-COCOSO approach designated alternative 16 as the highest-ranked option, whereas alternative 1 was assigned the lowest rank, indicating a distinct preference for specific choices. Likewise, the Entropy-COCOSO technique recognized fourth run as the highest rank, although displayed variations in intermediate ranks, underscoring the influence of entropy-based weight allocation. The CRITIC-COCOSO method yielded a unique ranking pattern; yet, alternative 16 consistently emerged as the highest-ranked option, demonstrating its robustness across all the methodologies. Notwithstanding these discrepancies, the stability of the highest-ranked alternative indicates a dependable decision-making result, while variations in other rankings emphasize the necessity of choosing a suitable weighting approach tailored to the particular context of the problem.

4.2. Analysis of tensile strength in the weld joints

The stress–strain curves for baseline, ideal, and optimized weld joints are presented in Figure 9, while Table 11 summarizes the tensile parameters, including yield strength, elongation percentage, weld joint efficiency, and tensile strength (TS). According to the tensile tests, the parent metal exhibited an elongation at fracture of 29% and a tensile strength of 916.16 MPa. In comparison, the optimal weld joint showed a tensile strength of 896.96 MPa, which was 36.28% lower than that of the parent metal, with an elongation of 22%, 3% less than the parent metal. At an axial force of 5.3 kN, a welding speed of 47 mm/min, and a tool rotational speed

Table 10: Sensitivity analysis using different weight calculation method.

S. NO	MEREC–CoCoSo		ENTROPY–CoCoSo		CRITIC–CoCoSo	
	RESULTS	RANK	RESULTS	RANK	RESULTS	RANK
1	0.5017	16	0.5158	16	0.4549	16
2	5.6912	10	21.2467	9	1.1962	12
3	6.6365	5	25.4376	3	1.2364	11
4	7.4929	2	27.3545	1	1.6917	3
5	1.7929	15	3.6454	15	0.9705	15
6	4.3240	13	12.3367	13	1.5746	8
7	6.2340	8	23.3429	7	1.3033	10
8	5.9155	9	19.8328	10	1.5981	6
9	4.6245	12	16.3461	11	1.1227	13
10	6.2473	7	21.6233	8	1.6850	4
11	2.7369	14	7.7680	14	1.0235	14
12	4.7521	11	14.1587	12	1.6031	5
13	6.3251	6	23.4381	6	1.4135	9
14	6.7432	3	23.5796	5	1.7534	2
15	6.6829	4	24.3460	4	1.5900	7
16	7.6370	1	26.4480	2	2.0194	1

**Figure 8:** Comparison of COCOSO with various weighting methods.

of 1218 rpm, the optimal values for joint tensile strength and elongation were attained (AA7068-T6), which are 516 MPa and 21.57%, respectively [43].

The TS results indicated 740 MPa for the parent metal, 678 MPa for the optimum weld joint, and 603 MPa for the initial weld joint. Additionally, AA356 alloy was reinforced with varying fractions (0–8 wt%) of Zirconium Silicate (ZrSiO_4) using stir casting. The optimal tensile strength of 169.29 MPa was achieved at 5 wt% ZrSiO_4 . However, exceeding this reinforcement limit resulted in lessening of TS, compression strength, and hardness, suggesting that 5 wt% is the optimal reinforcement level for attaining the optimum mechanical characteristics [44].

Table 11 reveals that the TS and elasticity of the ideal weld joint were significantly enhanced compared to the original and previously optimized joints. Relative to the parent metal, the ideal welded joint demonstrated an

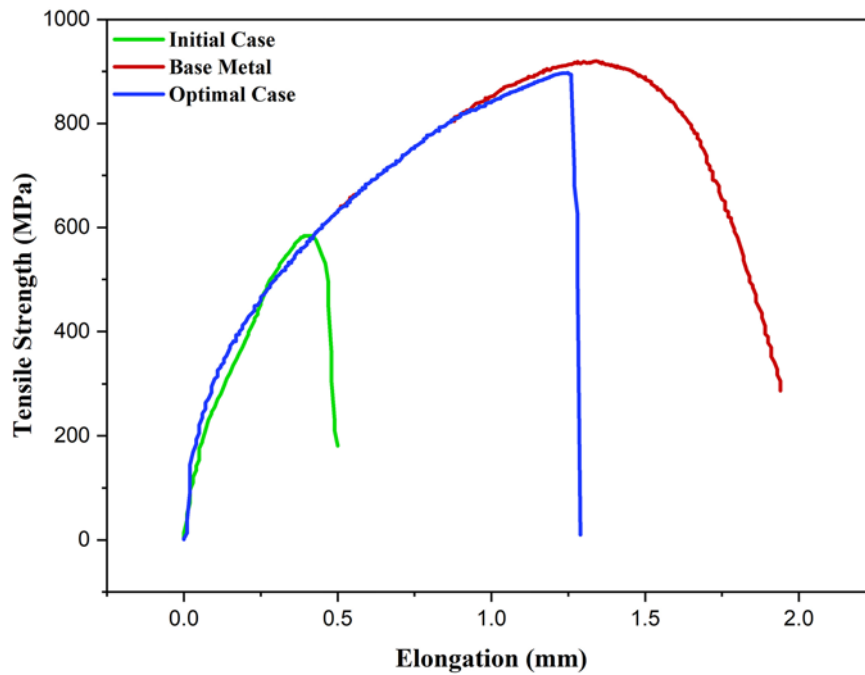


Figure 9: Evaluation of TS and elongation curve of weld joints.

Table 11: Transversal TS of weld joints.

	TENSILE STRENGTH (ULTIMATE) (MPa)	Yield strength (MPa)	ELONGATIONAL BREAK (%)	JOINT EFFICACY (%)
Parent metal	916.16	740.71	22	29.0
Initial case	583.73	603.6	3	63.81
Optimal case	896.96	678.35	6	97.90

efficiency of approximately 97.90%, with a tensile strength increase of 63.81% compared to the first joint. The efficacy of a weld joint is deemed to be of high-quality when it surpasses 66%. Additionally, the fracture location must correspond to the region of minimum hardness, and the weld joint should be free of defects.

The weld joint produced using the UFSW method with ideal parameters exhibited superior quality compared to the previous joints, as illustrated in Figure 10. This indicates that the optimized parameters contribute to achieving enhanced mechanical properties and weld integrity.

The tensile testing specimens revealed their fracture paths through cross-sectional macro images. The fracture paths are correlated with the microhardness distribution graph (Figure 11). With the RS and AS labeled, Figure 10 highlights the exact crack location in the ideal joint. Previous studies on tensile specimens from conventional (air-welded) joints identified the HAZ as the weakest area, with fractures typically occurring at the interface with the thermo-mechanically affected zone (TMAZ). In contrast, Figure 10 shows that in the submerged joint, the fracture occurred at the interface among the RS's TMAZ and the SZ, indicating a stronger HAZ. The fracture path in the optimally specified UFSW joint was oriented at 45° to the tensile loading direction and happened in the low HV dispersal zone (LHDR) of the micro-hardness graph, demonstrating a strong correlation between the fracture site and LHDR.

Figure 11 illustrates the HV dispersal among the centerline of the transversal zone of the ideal weld joint. A hardness value of approximately 80 Vickers (Hv0.2) was observed. Each test site was spaced out 0.3mm gap at 300 g force functional during two evaluations along the median line. The hardness distribution forms a “W” shape, with contours displaying consistent patterns. Notably, the weld joint showed a significant reduction in hardness compared to the base metal across all regions.

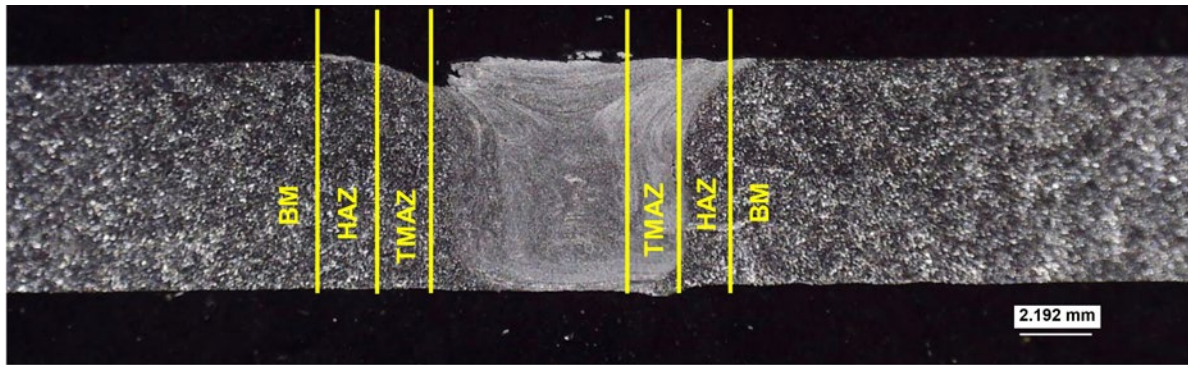


Figure 10: Optimal joint metallurgical cross sections of the weld specimen.

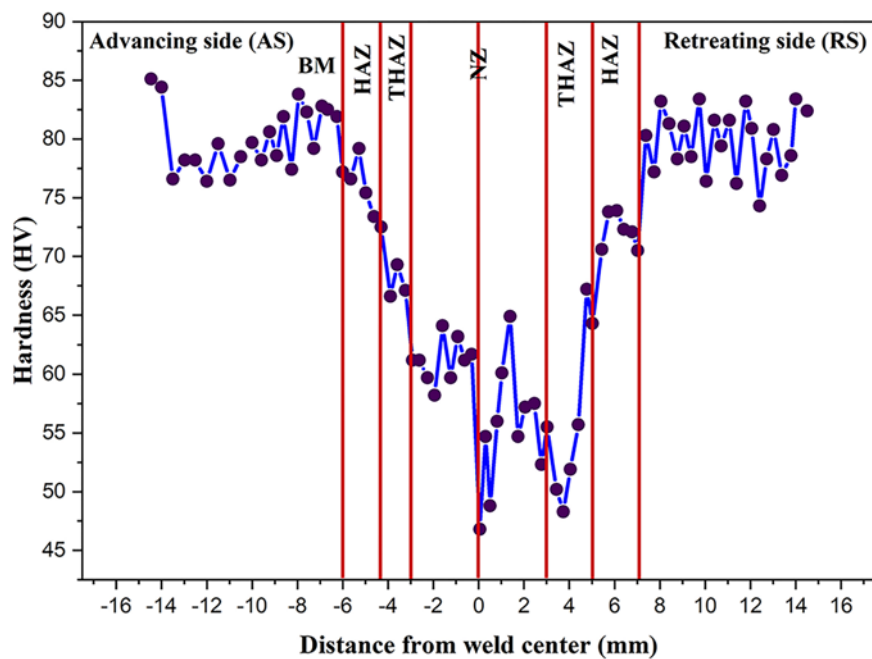


Figure 11: Cross-sectional macrographs and microhardness plots of the optimum joint.

A yield zone stretches to 9 mm from the welding center, with the minimal hardness range being roughly 4 mm from the weld's centerline. The macrostructure in the TMAZ leads to diminished hardness on both the AS and the RS. Nevertheless, in the SZ of the optimum joint, changes in hardness are minimal. The optimal joint formed by ultrasonic FSW has a marked rise in hardness from the HAZ to the parent metal, with the HAZ displaying considerably greater hardness than the TMAZ. Moreover, the core of the welded joint in UFSW has significantly greater strength than the LHDR sections commonly found in FSW (Figure 10).

4.3. Analysis of macrostructure and microstructure

Figure 12 denotes the macrostructure of the parent metal (BM), along with the distinct zones recognized over optical microscopy. Due to the elevated temperatures and deformations experienced during the UFSW process, precipitates dissolve differently in various regions, resulting in diverse textures.

The optical macrograph (Figure 12) identifies three various zones: SZ, TMAZ, and HAZ. The SZ is clearly separated from the TMAZ and HAZ by a well-defined boundary. The microstructural analysis exposes important variations in particle size across these regions.

The base metal (BM), as depicted in Figure 13, is characterized by elongated grains aligned with the rolling direction. In contrast, the SZ exhibits dynamically recrystallized structures with fine, equiaxed grains.

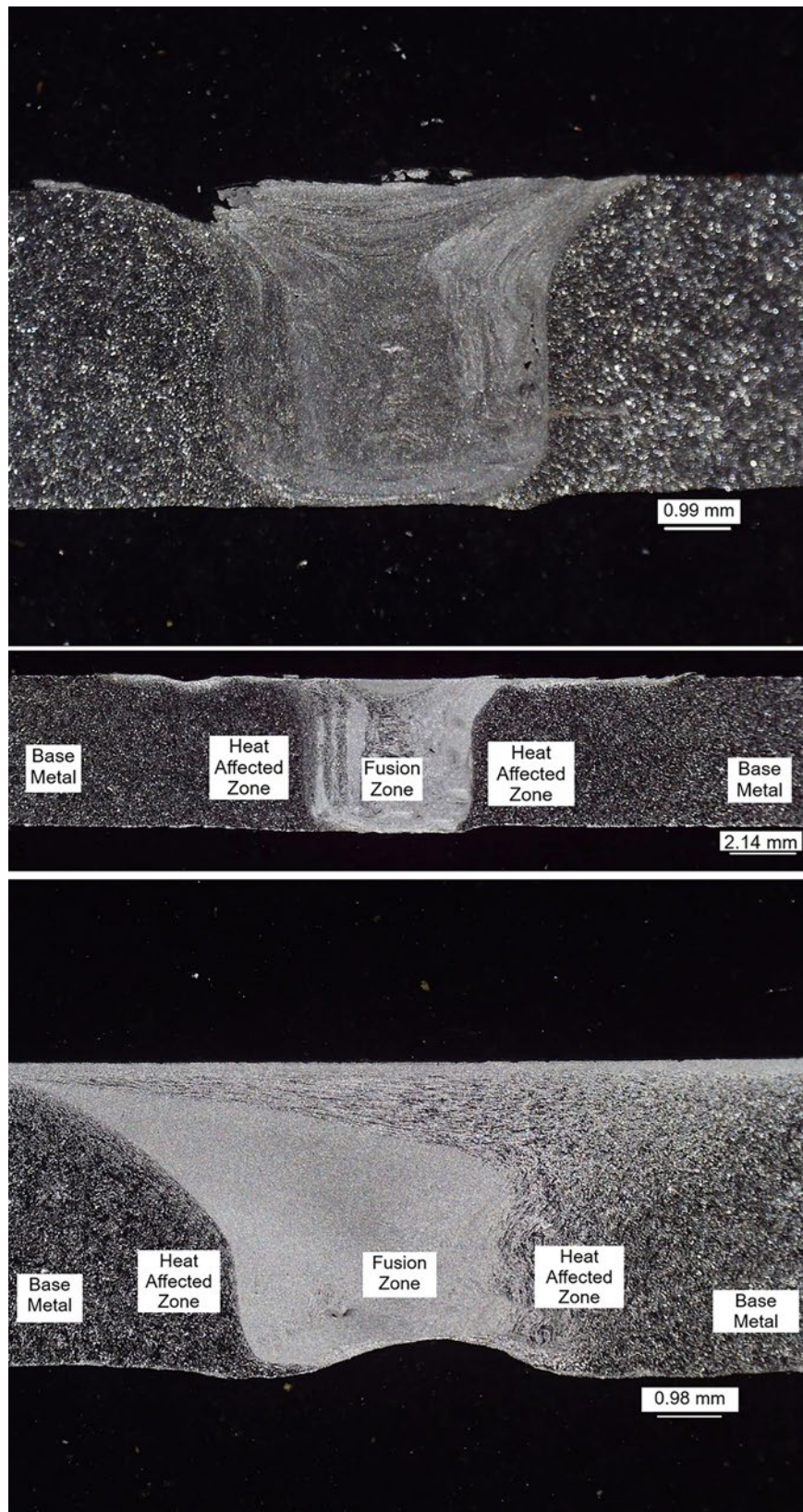


Figure 12: Macrostructure of the optimal joint.

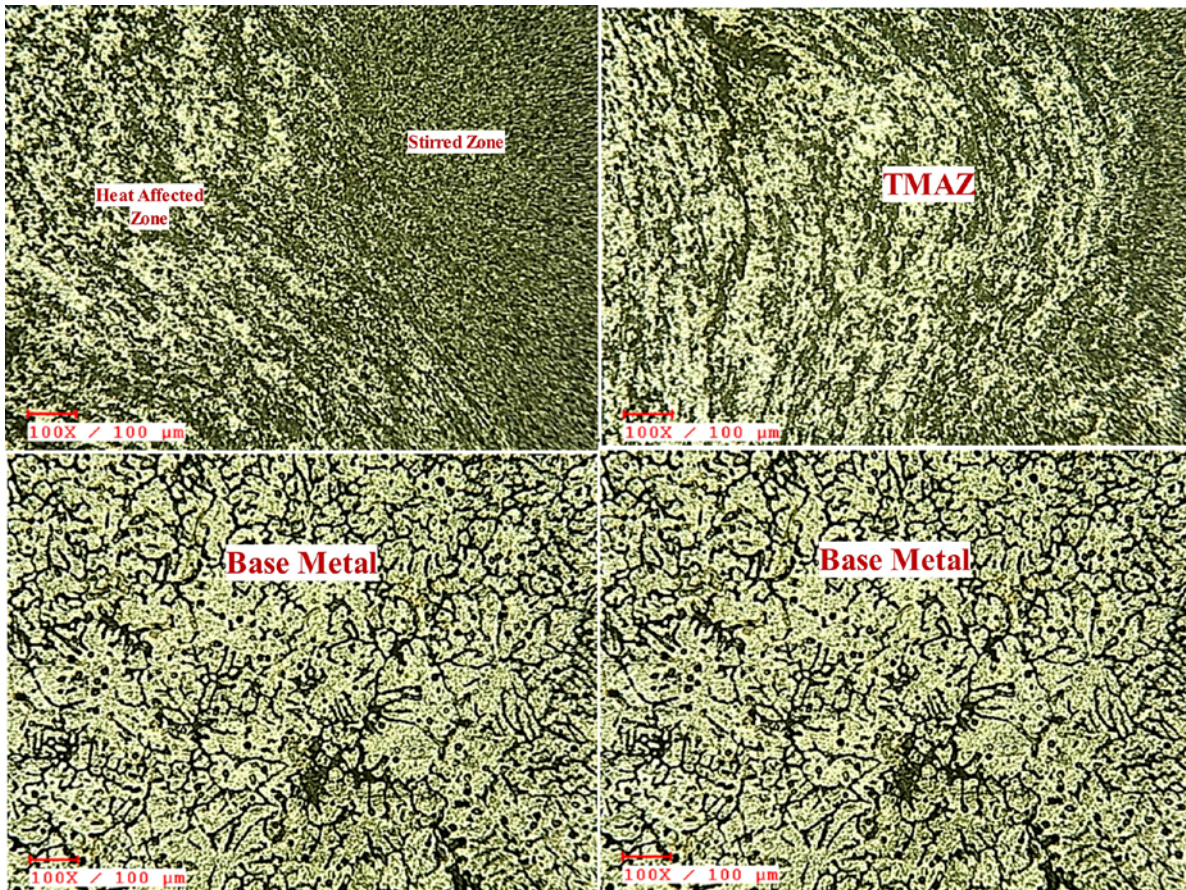


Figure 13: Microstructure of the optimal joint for various zones (base metal, stir zone, TMAZ, and HAZ).

The tool's agitation and friction-generated heat during the UFSW process accelerate the recrystallization, resulting in significant plastic deformation and the creation of fine grains in the SZ. The TMAZ shows notable deformation with granules oriented toward the SZ, exhibiting irregular sizes. Due to inadequate heat and plastic deformation, the TMAZ has coarser grains compared to the SZ.

The HAZ, situated near the boundary, is affected only by thermal exposure and experiences no plastic deformation. Its coarse grains are aligned with the rolling direction, resembling those of the BM. Additionally, the RS experiences higher temperatures than the AS, leading to larger grain sizes in the RS due to the increased thermal input. The microhardness is diminished as a result of the annealing effects of the FSW, while the particle size in the stir zone is remarkably refined in comparison to the base metal [45].

The research assessed the mechanical properties of recycled A356-AA7075 aluminum composites enhanced with Nb₂Al–ZrO₂–TiAl. SEM examination was utilized to examine the interface and microstructural attributes, offering comprehensive insights into the influence of processing on the performance of the material [46].

4.4. XRD analysis of the welded joints

The XRD pattern of the A356–SiC composite indicates a predominantly crystalline structure with clearly defined peaks. The most intense peak appears at $2\theta \approx 38.1^\circ$, corresponding to the (111) plane of face-centered cubic aluminum, confirming the presence of Aluminium as a primary phase. Additional peaks at 44.3° and 64.7° further support the presence of aluminum and associated alloying elements (Figure 14). The diffraction pattern also reveals contributions from reinforcing phases, with identifiable peaks for zinc (Zn), titanium (Ti), copper (Cu), magnesium (Mg), iron (Fe), and manganese (Mn). Quantitative phase analysis shows zinc and titanium as dominant constituents at 38% and 34% by weight, respectively, followed by copper (13%) and aluminum (11%), with minor contributions from other elements. This multi-phase composition is indicative of a structurally complex composite, capable of enhanced mechanical performance due to the combined effects of various strengthening mechanisms.

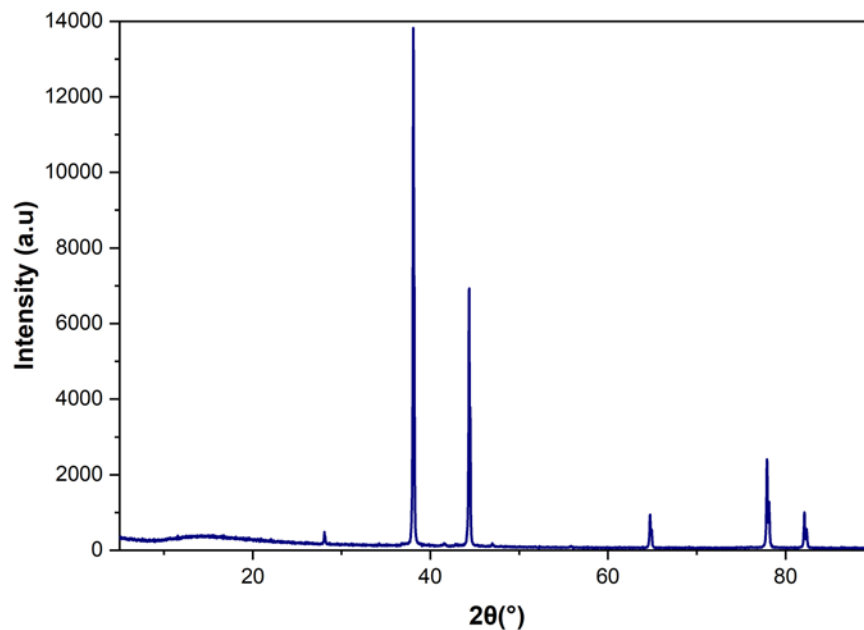


Figure 14: XRD analysis of the welded sample.

The diversity of phases in the composite plays a crucial role in improving mechanical properties through mechanisms such as solid-solution strengthening, dispersion hardening, and potential intermetallic formation. The high intensity and narrow width of the peak at $2\theta = 38.10^\circ$ (FWHM = 0.0936°) were used in the Scherrer equation to estimate an average crystallite size of approximately 89 nm. This nanometric scale of grain refinement supports the presence of dynamic recrystallization during processing and contributes significantly to strength enhancement. These results confirm the successful integration and uniform distribution of alloying and reinforcing phases in the A356 matrix, offering improved structural performance and minimal amorphous content within the material.

4.5. Impact of TD of optimum joint

The stability of the bond formed during the UFSW process depends significantly on the alignment of the components being welded. Common fit-up challenges include voids, misalignment of the weld path with the separation line, gaps, installation errors, and holes. These issues may arise from flaws along the joint line or variations in mechanical characteristics from the initial to the end of the welding. After determining and verifying the optimal UFSW process parameters, additional tests were conducted to evaluate the process's stability and reduce variations in weld joint quality from start to finish. To assess the robustness of the process and to identify the limitations of productivity control, weld connections were recreated using the optimal welding parameters under varying tool positions relative to the centerline. In four trials, the AS was offset by 1 mm to 1.6 mm, while the RS was shifted by -1 mm to -1.6 mm. The impact of these tool position shifts on the tensile properties of the weld joints, including microhardness, tensile strength, and macrostructure, was thoroughly analyzed. This evaluation provided insights into the effect of tool positioning on weld joints' quality and highlighted the critical importance of precise alignment for achieving optimal weld characteristics.

4.5.1. Analysis of tensile properties in tool deviation

Figure 15 illustrates the UTS, tool positioning relation to the welded line, and elongation for the weld joints. For the AS, weld joints exhibit UTS values ranging from 933 to 564 MPa when tool deviations are between 0 and 1 mm. These weld joints achieve an efficacy range of 94% to 76%, outstanding the minimal required efficacy of 67%, and are thus considered satisfactory in quality. However, the SZ, particularly in the zone of minimum hardness (HV), is a common site for joint failure.

When tool deviations exceed 1 mm, the weld joint efficiency drops below 66%, and UTS values decrease significantly, rendering these weld joints substandard. Without any adjustments, weld joints on the RS exhibit minimal ductility related to the ideal joint. Beyond the reference point (zero deviation), the TS of the weld joints decreases sharply, falling under the minimal adequate threshold for materials welded with the FSW technique.

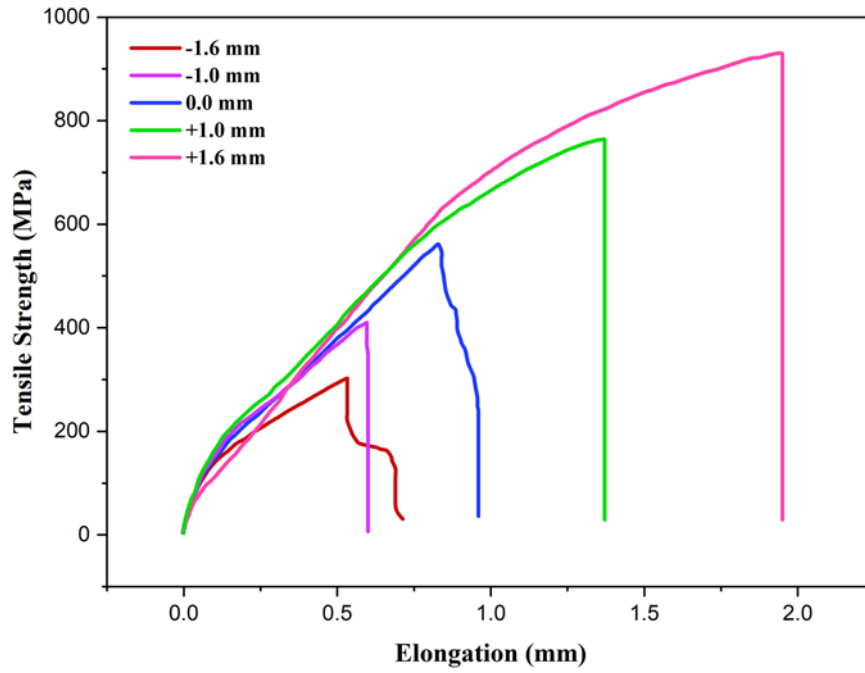


Figure 15: Tensile stress vs strain curvatures.

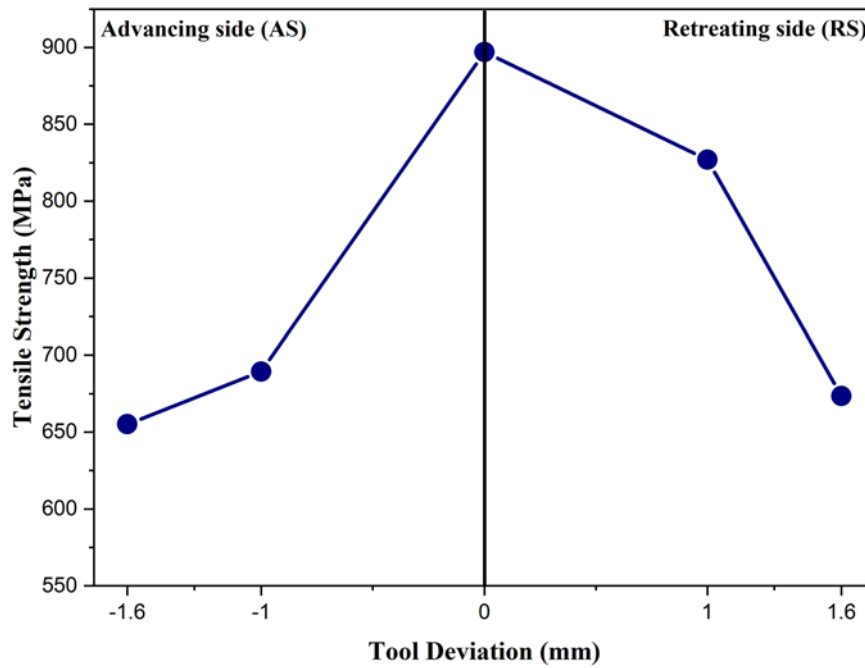


Figure 16: Impact of TD on the maximum range of tensile strength.

The decrease in TS and ductility, as well as the weld defects shown in Figure 9, are attributed to the significant deviation of the welding apparatus.

Figure 16 highlights the asymmetrical distribution of defects around the weld bead and the corresponding variation in tensile strength based on the tool's position. This phenomenon is caused by increased strain on the RS during UFSW. The welding tool shows no deviation toward the AS, maintaining a confidence level of 66%. At the same confidence level, the RS exhibits a tolerance for tool variation within 1 mm, which represents the

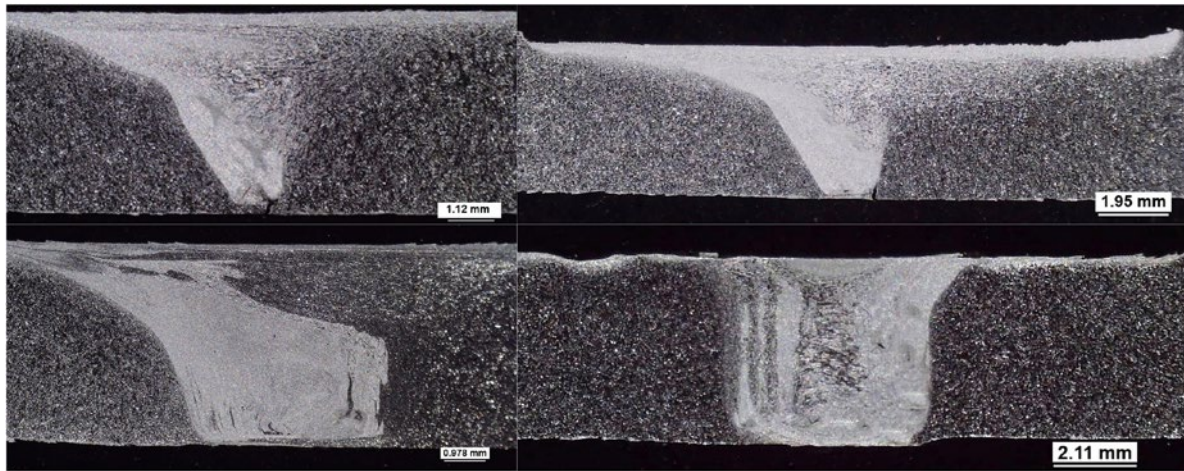


Figure 17: Impact of TD on macro-images.

minimum acceptable value for maintaining weld quality. This analysis underscores the critical importance of precise tool positioning in achieving defect-free, high-quality weld joints.

The integrity of the weld joint is demonstrated in the cross-sectional macrographs (Figure 17). Smooth and well-defined ripples are the distinguishing characteristics of all weld joint upper surfaces, which are devoid of any apparent surface defects. However, the cross-sectional macrostructure demonstrates significant variations that are dependent on the welding tool's deviation. In comparison to the zero deviation, a perfect weld joint with satisfactory mechanical properties is attained with a 1 mm deviation toward the RS, utilizing the previously established optimal parameters.

In contrast, a 1.6 mm tool deviation toward the AS results in tool deviation (TD) within the mixing zone, as shown in Figure 16. Additionally, weld joints with excessive deviation toward the AS exhibit defects, with the number and severity of imperfections increasing in proportion to the extent of the tool's deviation. This highlights the critical importance of maintaining precise tool alignment to ensure defect-free weld joints with high mechanical integrity.

4.5.2. Analysis of microhardness

The evolution of the microstructure serves as the theoretical foundation for the observed fluctuations in microhardness. Figure 18 illustrates the variation in microhardness at the center of the transverse zone of the weld joints, mapped across the cross-sectional image for different levels of tool deviation. A characteristic feature of friction-stir welding (FSW) in precipitation-hardened aluminum alloys is the formation of a softened zone within the UFSW joints. This softened zone consists of the NZ, TMAZ, and HAZ, regardless of the tool deviation values. These regions exhibit distinct microstructural transformations, which directly influence the microhardness distribution across the weld.

The microhardness curves display a W-pattern dispersion, with the lowest hardness values (40–90 HV) observed in the SZ on both the AS and RS, as indicated by the data. The hardness profiles of the optimal weld condition (no tool offset, Figure 12) and the weld joints with offsets (Figures 17) show significant differences. The interference between the TMAZ and the softened zone on both sides of the weld consistently exhibits the lowest hardness (40 HV), indicating a narrow-softened zone. The SZ shifts toward the AS and RS sides as the welded tool deviates along the joint line.

On average, the BM exhibits higher microhardness than any of the weld joints. This reduction in microhardness within the welded area is attributed to microstructural changes caused by the welding process. Specifically, grain toughening and the redistribution of precipitates across the weld zones play a significant role. The primary reason for the drop in microhardness is the melting or dissolution of hardening zone through the thermal series of welding. In the HAZ, plastic deformation and a minimal temperature gradient prime to the suspension of the coarse Al_2CuMg phases, resulting in coarser precipitates as the zone approaches the TMAZ boundary.

In the TMAZ, where the heat and distortion rates are greater than in the HAZ, the hardness of the coarse and heterogeneous precipitates decreases further. Conversely, the HV of the weld joint is positively influenced

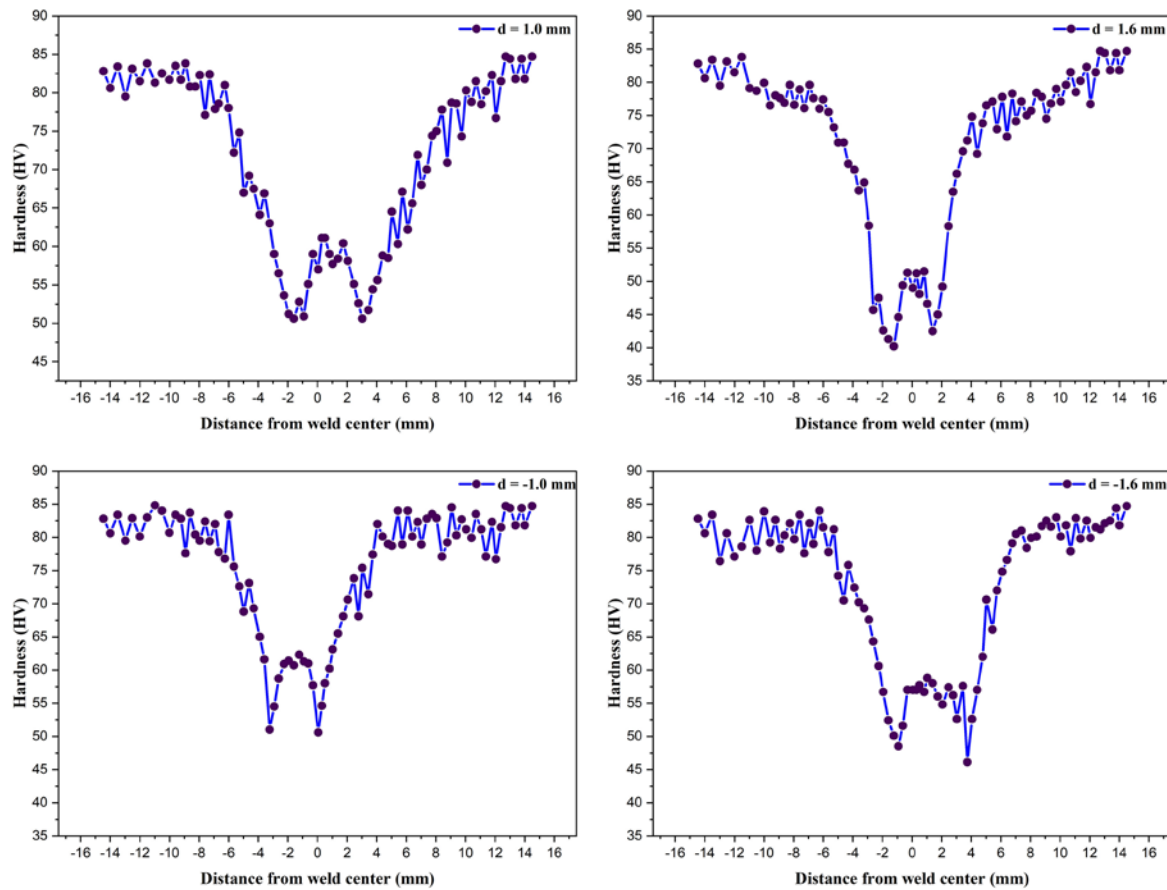


Figure 18: Impact of TD on HV of the weld joints.

in the NZ, where the dissolving of precipitates and the formation of Guinier–Preston–Bagaryatsky (GPB) zones promote complete, the granules undergo dynamic recrystallization, enhancing the mechanical properties in that region. This microstructural evolution explains the observed variations in microhardness across the weld.

This study extensively analyzes the impact of tool deviation (TD) on UFSW joints, providing insights into production control limits and process resilience. By optimizing axial force, tool rotational speed, welding speed, and SiC content, the research establishes a robust framework for improving the mechanical strength and quality of nano-SiC-reinforced A356 aluminum joints in underwater welding applications.

4.6. SEM analysis

An investigation was conducted to study how different rotational speeds affect the precipitation behavior in underwater friction-stir welded (UFSWed) A356-SiC alloy. The stirring action of the tool during UFSW fragmented the coarse and low-density precipitates present in the base metal's microstructure into finer particles (Figure 19a).

At a rotational speed of 1000 rpm, the microstructure showed a lower density of precipitates (Figure 19b). As the rotational speed increased to 1300 rpm, the density and size of the precipitates increased, indicating faster precipitation kinetics (Figure 19 c & d). At the highest speed of 1300 rpm, the precipitates were the largest and densest. SEM analysis revealed that lower speeds (1000 rpm) produced smaller and more evenly distributed precipitates, whereas higher speeds (1100 and 1300 rpm) caused the precipitates to grow larger and cluster, showing increased coarsening.

The changes in precipitation behavior can be attributed to the combined effects of higher rotational speeds, which generate more heat and plastic deformation, enhancing diffusion and nucleation kinetics. Additionally, the improved material flow and mixing during welding promote better nucleation and growth of the strengthening phases. Furthermore, prolonged exposure to elevated temperatures at higher speeds facilitates greater coarsening and growth of precipitates, leading to noticeable changes in their size and distribution.

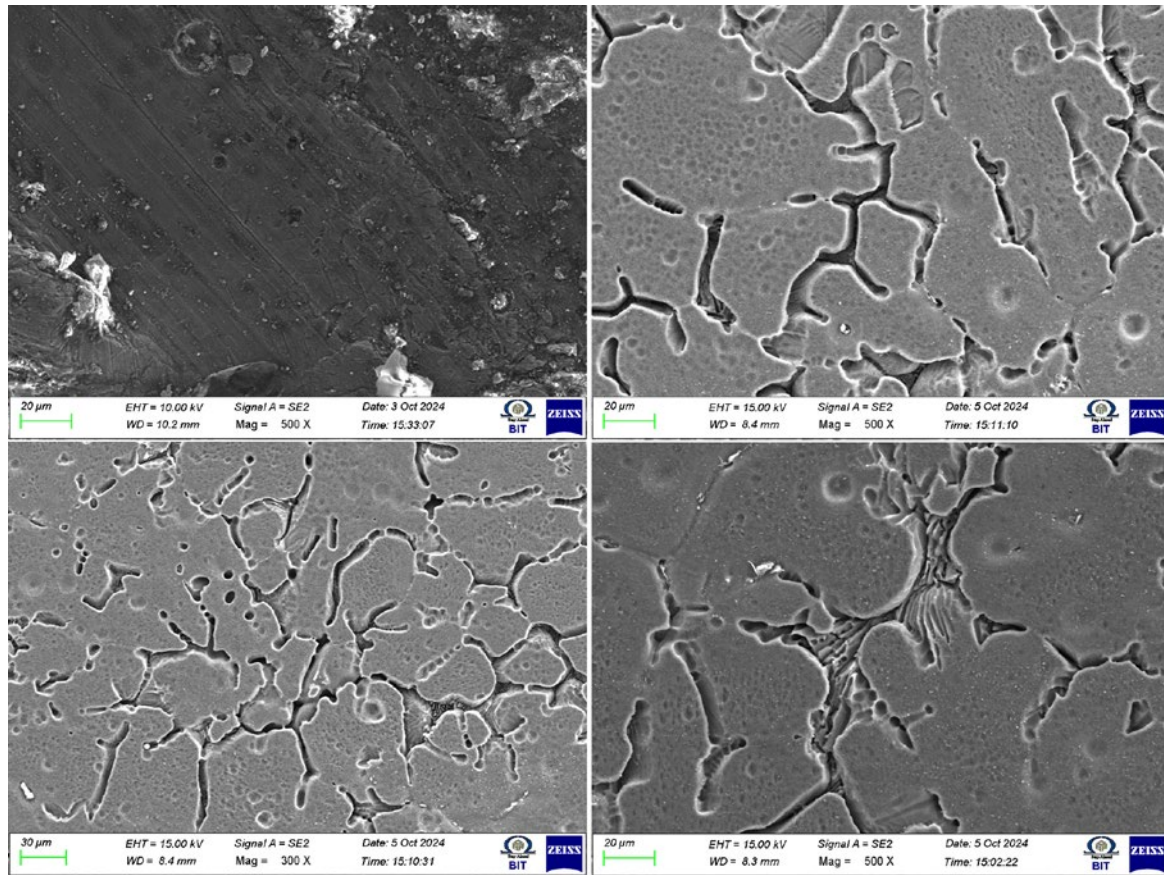


Figure 19: SEM images of the welded specimens.

At higher speeds, the material flow and deformation also cause precipitates to aggregate and cluster. The results show that rotational speed significantly impacts precipitation behavior in UFSWed A356-SiC alloy. Higher speeds (1100 and 1300 rpm) promote faster precipitation kinetics, resulting in larger and denser precipitates. These precipitate characteristics directly influence the mechanical properties of the materials, such as strength and hardness.

5. CONCLUSION

The objective of this study was to evaluate how UFSW is affected by conventional disparities in welded joints, such as misalignments of the welding apparatus from the centerline.

- Butt welds of AA356 were produced using UFSW by varying process parameters, such as weld speed, tool rotational speed, axial force, and SiC content. The study aimed to identify the optimum process factors to enhance the superiority of the UFSW joints.
- The methodology successfully optimized key process parameters (welding speed, tool rotation speed, and axial force) and quantified the impact of tool deviation on weld quality.
- Statistical validation using ANOVA, regression modeling, and confirmation tests demonstrated the accuracy and robustness of the results, with a significant improvement in weld joint efficiency, tensile strength, and elongation.
- These findings provide a solid foundation for industrial applications of UFSW, offering critical insights for quality control and process optimization.
- The approach of this study represents a meaningful advancement over traditional single-response optimization techniques, offering a more comprehensive and reliable method for enhancing the performance of aluminum alloy welds.

- The response surface plots indicate that an optimal parameter combination—TRS of 1000–1200 rpm, WS of 0.4–0.5 mm/s, axial force of 5200–5800 N, and SiC content of 3–5%—yields the best weld quality.
- Confirmation tests showed that these modified parameters significantly enhanced tensile strength, improving the overall weld quality. The optimized parameters (welding speed: 0.57 mm/s, rotational speed: 1300 rpm, axial force: 6000 N, SiC content: 8 wt%) resulted in a tensile strength increase from 191.7 MPa to 222.3 MPa (44.1% improvement), yield strength rise from 117.7 MPa to 261.84 MPa (122.3% improvement), and weld efficiency enhancement from 63.81% to 97.90%.
- It was observed that the distribution of microhardness played a crucial role in influencing tensile properties and producing flawless joints through UFSW. Microstructural analysis revealed improved grain refinement and SiC dispersion, leading to a microhardness increase from 62.1 HV to 70.2 HV.
- However, a tool offset variation of –1.6 to 1.6 mm revealed that the TS decreased as the strain increased, when the counterweight was positioned on the AS. Additionally, destabilizing effects were noted due to the tool deviation of the weld line, influenced by the UFSW process progression.
- These findings establish a robust, validated framework for optimizing UFSW in aerospace, marine, and automotive industries, paving the way for further research into fatigue performance, residual stress analysis, and hybrid welding techniques for enhanced joint quality.

6. ETHICAL APPROVAL

Hereby, I S. Mayakannan consciously assure that for the manuscript “Optimizing Underwater Friction-Stir Welding Parameters for AA356/SiC Composites Using CoCoSo and MEREC: Enhancing Joint Performance and Quality” the following is fulfilled:

- 1) This material is the authors’ own original work, which has not been previously published elsewhere.
- 2) The paper is not currently being considered for publication elsewhere.
- 3) The paper reflects the authors’ own research and analysis in a truthful and complete manner.
- 4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
- 5) The results are appropriately placed in the context of prior and existing research.
- 6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
- 7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

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SUPPLEMENTARY MATERIAL

The following online material is available for this article:

Supplement – Optimizing Underwater Friction-Stir Welding Parameters for AA356/SiC Composites Using CoCoSo and MEREC: Enhancing Joint Performance and Quality.

DATA AVAILABILITY

All data that support the findings of this study are included within the article.