

Optimization of Post-Weld Heat Treatment Parameters for Improving Tensile Strength of Dissimilar AA6061–AA7075 Friction Stir Welded Joints Using the Taguchi Method

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Received April 13, 2025, Revised June 26, 2025, Accepted October 10, 2025, Published July 1, 2026

Abstract. *This research presents a novel approach to optimizing post-weld heat treatment (PWHT) parameters for dissimilar friction stir welded joints between AA6061 and AA7075 aluminum alloys. Unlike prior studies that often overlook multi-variable interactions, this study employs a Taguchi L9 design of experiments to systematically investigate the combined effects of solution treatment and aging conditions. The optimal PWHT configuration — solutionizing at 480 °C followed by aging at 180 °C for 6 hours — achieved a peak tensile strength of 307.38 MPa. Elongation performance was strongly influenced by aging duration, with extended times promoting superior ductility. Statistical analysis using ANOVA confirmed aging time as the most significant factor. The novelty of this work lies in the integrated experimental–statistical methodology and its application to dissimilar aluminum joints, providing a robust strategy for tailoring mechanical properties through customized thermal cycles. These findings offer practical insights for engineering applications requiring high-performance welded structures.*

Keywords: Friction Stir Welding, Post-Weld Heat Treatment, AA6061, AA7075, Taguchi Method, Mechanical Properties, Tensile Optimization

1 Introduction

Friction Stir Welding (FSW) has emerged as an advanced solid-state joining technique method particularly effective for aluminum alloys like AA6061 and AA7075, owing to their excellent strength-to-weight ratio and weld ability. The alloys AA6061 and AA7075 were specifically selected for this study because they represent two complementary classes of aluminum alloys—AA6061 offers good weldability, corrosion resistance, and moderate strength, whereas AA7075 provides exceptionally high strength and hardness but is more difficult to weld due to its higher zinc content and thermal sensitivity. Their combination in a dissimilar joint creates a practical challenge that reflects real industrial conditions, particularly in aerospace and automotive applications where lightweight, high-strength structures are essential. Aluminum alloys AA6061 and AA7075 are widely used in aerospace and automotive industries due to their superior mechanical strength, lightweight properties, and corrosion resistance. However, their different thermal properties and chemical compositions pose challenges in joining, particularly using Friction Stir Welding (FSW). Optimizing heat treatment after welding becomes essential for achieving enhanced performance. These alloys are known for their superior mechanical efficiency and resistance to corrosion, and robust structural integrity, making them ideal candidates for industries like aerospace, automotive, and marine engineering [1], [2]. The implications of employing these materials are profound, as they contribute to the advancement of lightweight designs that do not compromise on structural performance [3]. However, the inherent nature of FSW induces significant changes in microstructure, most notably within the stir zone (SZ), heat-affected zone (HAZ), and thermomechanically affected zone (TMAZ) [4]. These zones experience differential thermal and mechanical environments during the welding process, Resulting in considerable heterogeneity in mechanical properties [5]. As a result, Post-Weld Heat Treatment (PWHT) becomes essential for restoring and enhancing the mechanical performance of the welded joints by modifying grain structure and precipitate distribution [6].

The role of PWHT is critical not just in rectifying the detrimental effects caused by the welding process but also in optimizing the microstructural properties of the joints. Traditional heat treatments like solution treatment, quenching, and aging influence critical properties such including tensile strength, hardness, formability, and fatigue resistance [7], [8]. The optimization of these heat treatment parameters was conducted using the Taguchi method, which was deliberately selected for its efficiency in managing multiple process variables while minimizing the number of experiments. This method provides a statistically robust framework for determining the most influential parameters and their optimal levels, ensuring high process reliability with reduced experimental cost. The Taguchi design of experiments (DOE) approach is particularly advantageous in thermal process optimization such as PWHT because it enables the identification of dominant factors that significantly affect joint performance.

Among these methods, the Taguchi technique stands out as one of the most effective for optimizing multi-parameter processes [9]. This method optimally assesses multiple variables concurrently while minimizing experimental runs, thus enhancing both accuracy and efficiency [10]. The Taguchi L9 orthogonal array is primarily employed to systematize heat treatment conditions by balancing variables such as solution treatment temperature, holding time, and aging temperature [11]. The goal is to maximize mechanical strength while minimizing defects like grain coarsening and residual stresses [12]. Though significant advancements have been made in understanding the behavior of FSW and its subsequent PWHT, a predictive correlation between heat treatment conditions and microstructural changes remains elusive [13].

Research highlights the complexities inherent in the interaction between heat input during welding and subsequent aging processes [14]. This presents a compelling case for the utilization of advanced modeling techniques, such as hybrid optimization strategies and machine learning algorithms, which may further elucidate the relationships at play [15]. Recent studies have explored the application of machine learning in optimizing PWHT parameters, demonstrating that this integrated approach can yield superior mechanical properties and reliability [16]. Additionally, recent literature emphasizes that traditional methods of PWHT do not sufficiently cover all variables influencing joint performance, indicating a significant research gap [17]. Therefore, this research is conducted to optimize the parameters of PWHT parameters specifically for AA6061 and AA7075 FSW joints using the Taguchi method. Key objectives include evaluating the influence of solution treatment and aging conditions on mechanical properties, analyzing microstructural evolution in different weld zones, and identifying optimal heat treatment combinations to enhance the overall strength and durability of the joints [18], [19]. In addressing these objectives, this study contributes to the ongoing efforts to develop high-performance aluminum alloy joints suitable for advanced engineering applications. Recent studies have illustrated that PWHT significantly improves tensile strength and elongation in FSW joints [20], underscoring the importance of tailored heat treatment solutions. Thus, the initial approach of utilizing the Taguchi method to optimize PWHT meets a critical need within the field. The significance of a systematic approach cannot be overstated. Researchers have increasingly acknowledged the role of PWHT in modifying the microstructure, with findings indicating that specific parameters such as aging temperature and time have pronounced effects on joint performance [21]. Combined with the predictive capabilities of machine learning, such an approach heralds a new age in material optimization and joint performance enhancement [22].

In summary, friction stir welded joints made from AA6061 and AA7075 aluminum alloys stand at the forefront of modern engineering challenges, and the optimization of PWHT parameters represents a crucial step in amplifying their performance. This study's focus on the Taguchi method serves as a timely exploration of an area that holds the promise for significant advancements in lightweight structural applications. Future research will inevitably benefit from these optimizations, ensuring that aluminum alloys remain at the cutting-edge of material science and engineering innovation [23]. Although PWHT optimization has been studied for similar materials, its application to dissimilar aluminum joints using robust statistical design such as Taguchi is still limited.

2 Research Methodology

A. Materials

The experimental work was carried out using AA6061 and AA7075 aluminum alloys, which were selected based on their proven performance in structural applications. These alloys are widely adopted across industries due to their favorable strength-to-weight ratio, corrosion resistance, and overall material adaptability. The chemical composition of each alloy, as outlined in Table 1 [24], highlights the balanced elemental makeup that contributes to their mechanical robustness and suitability for thermal processing.

Table 1: Chemical Composition of Aluminum Alloys AA6061 and AA7075 (in wt.%)

Materials	Mg	Si	Zn	Cu	Cr	Fe	Mn	Ti	Al
AA 6061	0.8–1.2	0.4–0.8	0.25	0.15–0.4	0.04–0.35	0.7	0.15	0.15	Balance
AA 7075	2.1–2.9	0.4	5.1–6.1	1.2–2.0	0.18–0.28	0.5	0.3	0.2	Balance

B. FSW joint preparation

The preparation of Friction Stir Welding (FSW) joints were fabricated using a CNC-based FSW machine equipped with a specially designed tool made of high-speed steel (HSS). The tool consisted of a tapered threaded pin with a metric thread of M6×1 mm, a pin length of 6 mm, and a shoulder diameter of 16 mm, which was selected to ensure sufficient material stirring and thermal input. The welding parameters were kept constant throughout the experiments, with a rotation speed of 1000 rpm, welding speed of 20 mm/min, and a plunge depth of 5.84 mm. The aluminum work pieces had dimensions of 150 mm × 75 mm × 6 mm, and the tool design is illustrated in Figure 1.

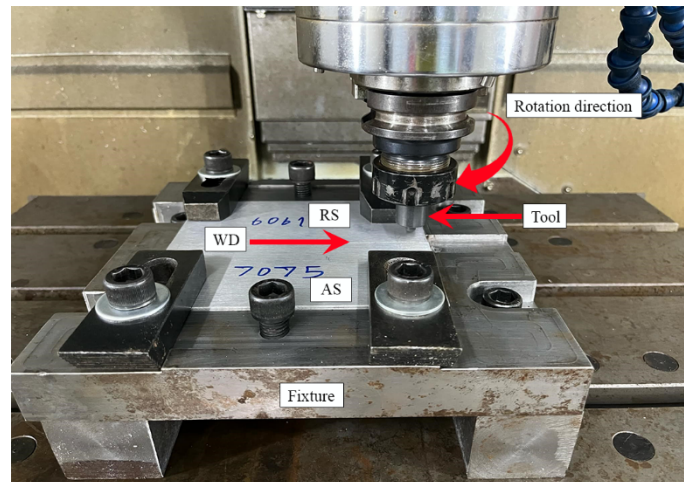


Figure 1: FSW setup for dissimilar AA6061–AA7075 aluminum joints.

C. Post-Weld Heat Treatment (PWHT)

Thermal treatment after welding is essential for improving both the mechanical behavior and microstructure of FSW joints. The PWHT process for this study was executed following the completion of the FSW to mitigate the adverse effects associated with welding, such as residual stresses and undesirable microstructural changes. The PWHT protocol was structured into several distinct phases: solution treatment, quenching, and aging. The heat treatment process diagram is shown in Figure 3.



Figure 2: FSW specimen prior to PWHT, illustrating AA6061 on the advancing side (AS) and AA7075 on the retreating side (RS).

Figure 2 shows the FSW specimens after welding but prior to undergoing any post-weld heat treatment (PWHT). These specimens were visually inspected and prepared for subsequent heat treatment experiments under varying solution and aging conditions.

C.1 Solution Treatment

The welded specimens underwent a solution treatment process at controlled temperatures of 440°C, 460°C, and 480°C for a duration of 2 hours. This heat treatment was sufficient to dissolve the precipitated phases into the aluminum matrix, resulting in a supersaturated solid solution. Subsequently, the specimens were held at target temperatures for controlled durations to ensure microstructural stabilization, particularly within the weld zone.

C.2 Quenching

Immediately following the solution treatment, the specimens underwent a quenching step. This involved rapidly cooling the heated specimens by immersing them in water, halting further phase transformations. Quenching preserves the supersaturated solid solution formed during solution treatment, enabling effective aging afterward.

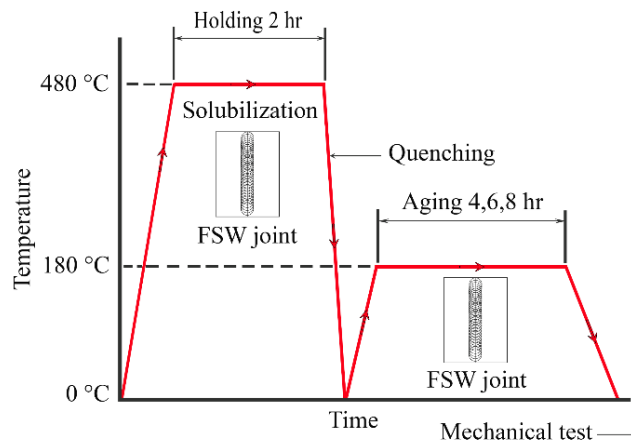


Figure 3: Heat treatment after welding (HTAW).

C.3 Aging Proces

Post-quenching, the specimens were subjected to an aging treatment to promote precipitation hardening, which is essential for enhancing the hardness and strength of the aluminum alloys. The aging was carried out at temperatures of 140°C, 160°C, and 180°C for varying durations of 4, 6, and 8 hours. This phase allows for the controlled precipitation of phase constituents that contribute to the mechanical properties of the alloys, improving performance metrics such as tensile strength, hardness, and ductility.

3 Experimental Design – Statistical Analysis

A. Experimental Design – Taguchi Method

To systematically optimize the PWHT parameters, the Taguchi L9 orthogonal array was utilized [27]. This design allowed for the assessment of different combinations of heat treatment conditions, including solution treatment temperature, aging temperature, and aging time, while minimizing the number of experiments required. The parameters selected for the design were influenced by existing literature and preliminary studies to ensure comprehensive evaluation of their effects on welded joint properties. By implementing this structured PWHT methodology, the objective was to enhance the mechanical properties and microstructural stability of AA6061 and AA7075 FSW joints, ultimately leading to improved performance in practical applications. The selected control factors and levels are presented in Table 2.

Table 2: Factors and Levels of Parameters

Factor	Level 1	Level 2	Level 3
Solubilization (°C)	440	460	480
Aging Temperature (°C)	140	160	180
Aging Time (hr)	4	6	8

B. Statistical Analysis

The Taguchi Approach is an effective tool for single response optimization, widely applied in engineering problem-solving. This method provides a structured framework for calculating the Signal-to-Noise (S/N) Ratio, which helps in identifying optimal process parameters. For this study, the "Larger is Better" criterion is employed, as expressed in Equation (1) [25],[26].

The signal-to-noise (S/N) ratio for the "smaller-the-better" case is calculated using the following equation:

$$S/N \text{ (dB)} = -10 \times \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (1)$$

Where:

- y_i is the response value (e.g., tensile strength or elongation) from the i^{th} trial.
- n is the number of repetitions under the same experimental condition.
- j represents the process factor (solution temperature, aging temperature, or aging time).
- k indicates the level of each factor in the orthogonal array.

The optimal PWHT condition was determined based on Taguchi S/N ratio analysis and ANOVA results. All experimental data were statistically analyzed using Minitab 19 software. Regression models were developed to improve predictive accuracy and to further optimize the post-weld heat treatment (PWHT) parameters, thereby enhancing process efficiency. This approach enables the systematic optimization of PWHT parameters for friction stir welded (FSW) AA6061–AA7075 joints, leading to enhanced stability of mechanical properties.

4 Mechanical Properties

The mechanical performance of the welded and thermally treated specimens was assessed through a series of standardized testing procedures focusing on tensile strength and elongation.

A. Tensile strength

Tensile strength was conducted according to ASTM E8M standards using a Universal Testing Machine. Mechanical evaluations focusing on the tensile strength and elongation of the specimens. This assessment helps determine the overall mechanical integrity of the joint and the effectiveness of the heat treatment. Recent research has confirmed that tensile testing remains one of the most reliable methods for evaluating the mechanical performance of welded joints, especially in aluminum alloys [28],[29]. Figure 4 illustrates the standard tensile specimen configuration adopted in this study, providing a reference for test geometry and setup consistency. These evaluations are essential for understanding the effects of various welding and heat treatment parameters on the mechanical behavior of dissimilar aluminum welds. The collected data provides insight into how process conditions influence material performance and can be used to optimize joint quality and reliability in structural applications [30]. The positioning of specimens for evaluating the mechanical properties of Friction Stir Welded (FSW) joints specifically tensile strength and elongation is illustrated in Figure 4. This configuration was designed to effectively analyze the influence of the welding process on the joint performance. Additionally, the specimens were assessed after post-weld heat treatment (PWHT) to capture the effects of solution treatment and aging on mechanical behavior, thereby reflecting the complete processing history of the joints.

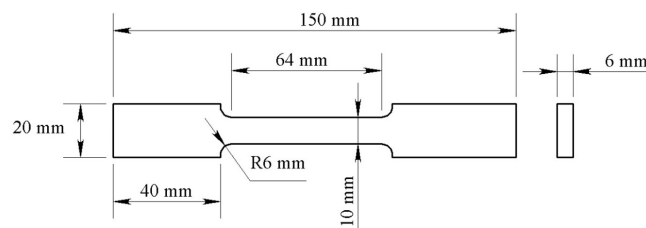


Figure 4: Standard tensile test specimen dimensions (ASTM E8M).

B. Elongation

To evaluate ductility, elongation at tensile strength was assessed as a key mechanical property of dissimilar AA6061–AA7075 friction stir welded joints. Standard tensile specimens (ASTM E8/E8M) were tested using a universal testing machine under controlled conditions. During testing, both ultimate tensile strength (UTS) and elongation at fracture were recorded. Elongation was expressed as the percentage increase in gauge length at failure, reflecting the material's capacity for plastic deformation. The investigation focused on how post-weld heat treatment (PWHT) parameters solution temperature, aging temperature, and aging time influenced elongation behavior. These factors are known to alter microstructure, where increased strength from precipitate hardening may reduce ductility due to limited dislocation movement or over aging.

C. Fracture Location Analysis

Figure 5 illustrates the fractured tensile specimens of dissimilar AA6061–AA7075 friction stir welded (FSW) joints before and after post-weld heat treatment (PWHT). The specimen labeled as BPWHT represents the as-welded condition prior to any heat treatment, while Run1 through Run9 correspond to different combinations of solution and aging treatments applied during PWHT. From visual inspection of the fractured locations, it is evident that the fracture path changed significantly due to the influence of PWHT parameters. The BPWHT specimen fractured directly at the weld centerline, suggesting the presence of weak bonding and insufficient microstructural homogenization. In contrast, the majority of the PWHT-treated specimens (Runs 1–9) exhibited fracture deviations toward the AA6061 retreating side (RS), particularly in Runs 1–3 and 5–8. This indicates a strengthening effect in the nugget zone and partial transformation of microstructural characteristics due to the applied heat treatment. Moreover, the variation in fracture appearance, with smoother fracture surfaces in high-strength runs (e.g., Run 9) and more jagged separations in lower-strength ones (e.g., Run 6), aligns well with the tensile test data and S/N ratio analysis previously discussed. These findings reinforce the conclusion that PWHT, when properly optimized, not only enhances joint strength but also shifts the fracture location away from the most vulnerable zones in the weld, contributing to greater joint reliability in structural applications.



Figure 5: Tensile Fracture Locations of AA6061–AA7075 FSW Joints before and after Post-Weld Heat Treatment (PWHT) under Various Conditions.

5 Results and Discussion

The Taguchi Method, as presented in Table 3, serves as an effective framework for identifying the most influential factors, minimizing the number of required experiments, and maximizing process efficiency. This section discusses the experimental results focusing on tensile strength, elongation, and the signal-to-noise (S/N) ratio analysis to reveal the effects of post-weld heat treatment (PWHT) parameters. It should be noted that microhardness and microstructural analyses were not included in this study due to scope limitations; however, their importance in validating the metallurgical behavior is fully recognized. This limitation has been clearly acknowledged, and future work will incorporate Vickers microhardness testing and SEM-based microstructural examination to confirm the correlations between PWHT parameters and mechanical response.

A. Tensile strength

The tensile properties of the friction stir welded (FSW) joints were evaluated using a universal testing machine. The maximum tensile strength of 307.38 MPa was recorded in Run 9, which employed a solubilization temperature of 480°C, aging at 180°C, and an aging duration of 6 hours. In contrast, the minimum strength of 203.21 MPa was observed in Run 6, which featured a lower solution temperature (460°C), high aging temperature (180°C), but a shorter aging duration of 4 hours. The substantial increase in tensile strength under optimized PWHT conditions is attributed to microstructural refinement in the stir zone (SZ) and thermomechanically affected zone (TMAZ). An aging duration of 6 hours enables the formation of fine, uniformly distributed

Table 3: Taguchi L9 experimental layout and corresponding test results.

Run No.	Solubilization Temp. (°C)	Aging Temp. (°C)	Aging Time (hr)	Tensile Strength (MPa)	Elongation (%)
1	440	140	4	203.25	4.4
2	440	160	6	270.35	4.8
3	440	180	8	267.09	5.6
4	460	140	6	263.86	4.8
5	460	160	8	213.49	5.6
6	460	180	4	203.21	4.6
7	480	140	8	241.92	5.6
8	480	160	4	213.50	4.6
9	480	180	6	307.38	5.4

MgSi and MgZn precipitates, which effectively hinder dislocation motion, thereby enhancing load-bearing capacity and overall joint performance. Furthermore, thermal exposure at 480°C facilitates solute homogenization and reduces residual stress concentrations, contributing to the improved strength.

B. Elongation

Elongation performance reflects the ductility of the welded joints. The results, detailed in Table 3. The highest elongation of 5.6% was observed in Runs 3, 5, and 7, all of which featured aging durations of 8 hours. In contrast, Run 1 yielded the lowest elongation (4.4%) due to a combination of short aging time (4 hours) and low aging temperature (140 °C), conditions that may have hindered effective precipitate evolution. Although Runs 3, 5, and 7 exhibited different tensile strengths due to variations in solubilization and aging temperatures, the elongation values remained similar (5.6%), likely due to a shared aging time of 8 hours, which facilitated similar precipitate distribution. The uniformity in ductility among these runs suggests that aging duration is the dominant factor influencing elongation, whereas tensile strength is more sensitive to peak aging temperature and solution treatment. Overall, prolonged aging encourages precipitate coarsening and matrix softening, which promote ductility. However, this improvement in elongation often comes at the expense of tensile strength, as seen in Run 5 (213.49 MPa), possibly due to over-aging effects. This underscores the need to balance strength and ductility through precise control of aging.

C. Signal-to-Noise (S/N) Ratio Analysis and Effect of Aging Time

According to the Taguchi method, the “Larger is Better” criterion was employed to analyze the robustness of the process responses, and the calculated S/N ratio values for both tensile strength and elongation are summarized in Table 4. Run 9 recorded the highest S/N ratio for tensile strength (49.75 dB), indicating superior mechanical performance under its thermal treatment conditions, while Runs 3, 5, and 7 achieved the highest S/N ratio for elongation (14.96 dB), confirming the strong influence of extended aging on ductility. These findings clearly demonstrate that aging time is the most dominant factor affecting mechanical properties, with distinct effects observed at different durations. Specifically, aging at 6 hours promotes peak tensile strength through the formation of a high density of fine, coherent precipitates that effectively impede dislocation motion (peak hardening), whereas aging at 8 hours maximizes elongation due to further diffusion and coarsening of precipitates, which decreases strength but improves ductility by reducing resistance to plastic flow. This divergence underscores the dual role of aging time in tuning mechanical performance: 6 hours enhances strength via optimal precipitate nucleation, while 8 hours improves ductility via precipitate coarsening and matrix softening. These insights provide a practical and scientific basis for selecting application-specific PWHT parameters, enabling process designers to prioritize either strength for structural integrity or ductility for formability and toughness, depending on the intended service conditions.

Figure 6 shows the S/N ratio main effects plot illustrating the influence of post-weld heat treatment (PWHT) parameters on the tensile strength of dissimilar AA6061–AA7075 friction stir welded joints. This analysis, guided by the Taguchi “larger-is-better” criterion, aims to identify optimal parameter levels that maximize tensile performance while minimizing variability.

Among the three investigated factors, aging time exhibited the most significant impact on the S/N ratio. A pronounced peak at 6 hours of aging indicates that this duration offers an optimal window for the precipitation of strengthening phases. The elevated S/N ratio at this point reflects both enhanced tensile strength and improved response consistency. In contrast, the lowest S/N ratio was observed at 4 hours, suggesting inadequate time for effective precipitate development.

Aging temperature also influenced the S/N ratio, showing a modest upward trend from 140 °C to 180 °C. This increase implies that higher temperatures promote active diffusion and nucleation of key precipitates such as Mg₂Si and MgZn₂, which improve dislocation resistance and load transfer. However, the effect was comparatively moderate, indicating a secondary influence relative to aging time.

Table 4: S/N Ratio values of aluminum alloy joints based on tensile strength and elongation.

Run No.	S/N (MPa)	Elongation (%)	S/N (%)
1	45.76	4.4	12.86
2	48.63	4.8	13.62
3	48.53	5.6	14.96
4	48.42	4.8	13.62
5	46.58	5.6	14.96
6	46.15	4.6	13.25
7	47.67	5.6	14.96
8	46.58	4.6	13.25
9	49.75	5.4	14.64

For solubilization temperature, the S/N ratio showed a slight dip at 460 °C, followed by a recovery at 480 °C. This pattern suggests improved dissolution of secondary phases and matrix homogenization at higher temperatures, which enhances the aging response, albeit with a less pronounced effect.

Collectively, the S/N analysis identifies aging time as the most critical parameter, followed by aging temperature and solubilization temperature. These trends align closely with the tensile test results and underscore the importance of optimizing the thermal profile particularly the aging stage-to achieve superior mechanical performance in dissimilar aluminum alloy FSW joints.

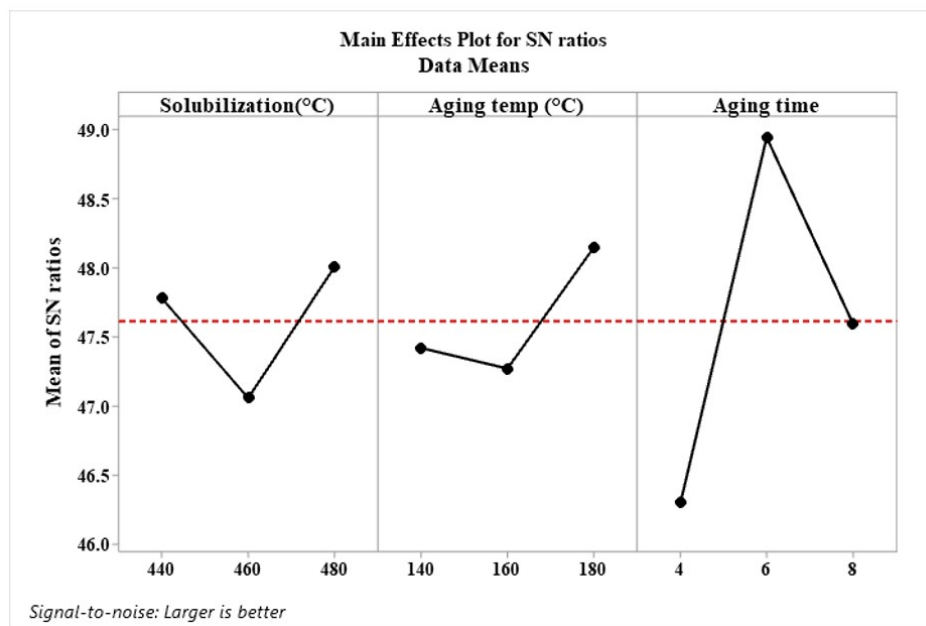


Figure 6: Main effects plot on S/N ratio of tensile strength for dissimilar AA6061–AA7075 friction stir welded joints under various PWHT conditions.

D. Effect of Aging Time on Tensile vs Elongation

Aging time was identified as the most influential factor affecting both tensile strength and elongation in dissimilar AA6061–AA7075 friction stir welded joints; however, its impact differs depending on the targeted mechanical property. The highest tensile strength of 307.38 MPa was observed at 6 hours of aging, which corresponds to the optimal precipitation of fine, coherent Mg_2Si and MgZn_2 phases that impede dislocation motion, in line with the peak hardening phenomenon. Conversely, the highest elongation of 5.6% was recorded at 8 hours of aging, where prolonged thermal exposure led to precipitate coarsening, reduced dislocation density, and enhanced matrix softness characteristic of an over-aged microstructure. These contrasting results can be attributed to the time-dependent evolution of precipitate morphology and distribution during the aging process. At approximately 6 hours, finely dispersed and precipitates act as effective dislocation barriers, enhancing load transfer and increasing strength. In contrast, extending the aging period to 8 hours promotes the transformation of coherent to semi-coherent or incoherent pre-

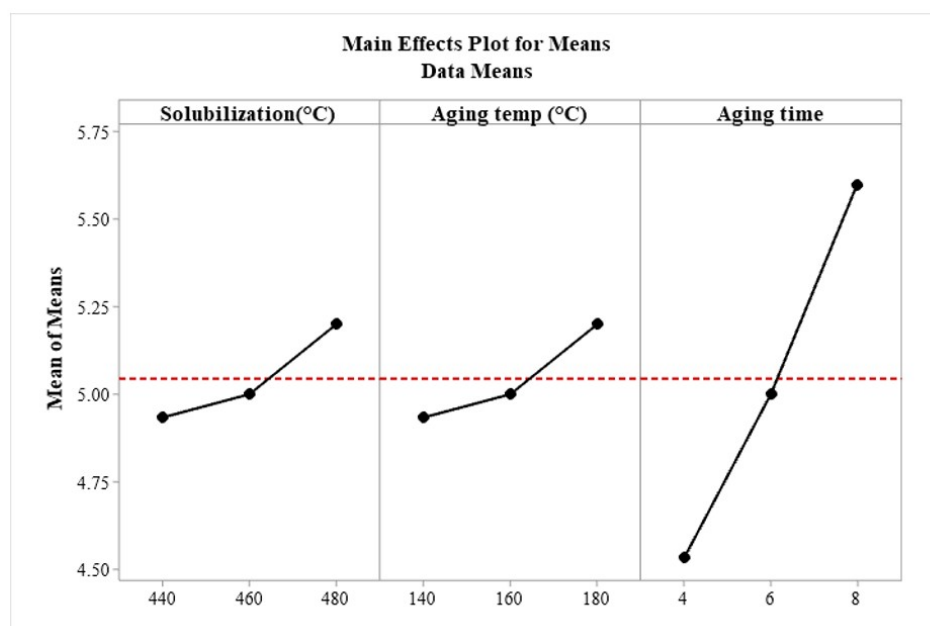


Figure 7: Main effects plot on S/N ratio of elongation for dissimilar AA6061–AA7075 friction stir welded joints under various PWHT conditions.

cipitates, which weakens dislocation pinning and thus enhances ductility.

This contrast represents a classic trade-off between strength and ductility governed by aging kinetics, where 6-hour aging maximizes strength and 8-hour aging promotes ductility. The detailed understanding of this mechanism provides a solid foundation for future optimization using dual-objective approaches, such as Grey Relational Analysis (GRA) or multi-response desirability functions, to simultaneously enhance both properties. These findings emphasize the importance of tailoring PWHT parameters to meet application-specific performance goals and suggest the potential benefit of applying dual-objective optimization methods, such as Grey Relational Analysis or desirability functions, to achieve a balanced mechanical response.

Figure 7 presents the primary factor effects on elongation as observed from the main effects analysis under different post-weld heat treatment (PWHT) parameters, including solubilization temperature, aging temperature, and aging time. This analysis aims to assess the influence of each factor on the ductility of dissimilar AA6061–AA7075 friction stir welded joints. Among the three variables, aging time had the most pronounced impact on elongation. The mean elongation value increased significantly with longer aging durations, peaking at 8 hours. This trend suggests that extended aging allows for sufficient precipitate coarsening, which reduces dislocation pinning and promotes more uniform deformation across the weld zone, thereby enhancing ductility. Aging temperature also exhibited a positive, though less significant, effect. Elongation improved as the aging temperature increased from 140°C to 180°C, likely due to more efficient precipitation of secondary phases that stabilize the microstructure while accommodating greater strain during tensile loading. The effect of solubilization temperature was relatively minor. A slight increase in elongation was observed as the solubilization temperature rose from 440°C to 480°C. This behavior may be attributed to improved matrix homogenization and the dissolution of coarse intermetallic particles, which enhance the subsequent aging response and facilitate ductile behavior. Overall, the plot confirms that aging time is the most dominant parameter influencing elongation, followed by aging temperature and solubilization temperature. The progressive improvement in ductility with longer aging durations highlights the need for carefully designed aging schedules to achieve an optimal balance between strength and ductility. These findings are consistent with mechanical test data and microstructural observations, offering clear guidance for PWHT optimization in dissimilar aluminum alloy welded joints.

E. Analysis of Variance for SN ratios (ANOVA)

The effect of post-weld thermal parameters on the tensile strength of dissimilar AA6061–AA7075 joints was analyzed using statistical methods. An analysis of variance (ANOVA) was conducted on the Signal-to-Noise (S/N) ratio data. The summary of the ANOVA results is presented in Table 5.

The results reveal that among the three process parameters—solubilization temperature, aging temperature, and aging time—aging time exhibits the most statistically significant effect on tensile strength. With an F-value of 41.58 and a P-value of 0.023, the influence of aging time is deemed highly significant at the 95% confidence level ($\alpha = 0.05$). This finding is consistent with the main effects plot, which demonstrated a marked increase in the S/N ratio with increased aging duration.

In contrast, solubilization temperature and aging temperature show moderate effects, with F-values of 5.84 and 5.27, respec-

Table 5: Analysis of variance for the mean S/N ratio of elongation.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Solubilization temperature (°C)	2	0.35349	0.17675	3.92	0.203
Aging temperature (°C)	2	0.35349	0.17675	3.92	0.203
Aging time	2	5.07610	2.53805	56.30	0.017
Residual Error	2	0.09016	0.04508		
Total	8				
S = 0.2123 R² = 98.46% Adjusted R² = 93.86%					

Table 6: Analysis of variance for the mean S/N ratio of tensile strength.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Solubilization temperature (°C)	2	1.4662	0.7331	5.84	0.146
Aging temperature (°C)	2	1.3217	0.6608	5.27	0.160
Aging time	2	10.4345	5.2172	41.58	0.023
Residual Error	2	0.2509	0.1255		
Total	8				
S = 0.3542 R² = 98.14% Adjusted R² = 92.55%					

tively. However, their corresponding P-values (0.146 and 0.160) exceed the threshold of 0.05, indicating that their effects are not statistically significant within the scope of the current experimental design. Nonetheless, these factors still contribute to the overall variability and should be considered during process optimization.

The coefficient of determination (R^2) is 98.14%, which indicates that the model explains the vast majority of variation in the S/N ratios. The adjusted R^2 value of 92.55% further confirms the reliability and predictive capability of the ANOVA model. Additionally, the low standard error ($S = 0.3542$) suggests that the residual variation is minimal, enhancing the confidence in the observed trends.

In summary, the ANOVA results corroborate the earlier findings from the main effects plots. The results confirm that among all PWHT variables, aging time exerts the most significant influence on tensile strength. This underscores the critical role of time-dependent precipitation phenomena in enhancing mechanical performance, and supports the selection of aging time as a key focus for further optimization studies.

To assess the statistical significance of post-weld heat treatment (PWHT) parameters on elongation, an analysis of variance (ANOVA) was performed using the signal-to-noise (S/N) ratios as the response variable. As summarized in Table 5, aging time had the most significant effect, with an F-value of 56.30 and a P-value of 0.017—well below the 0.05 threshold—indicating its critical role in enhancing ductility. Extended aging likely facilitates stable precipitate coarsening, improving plastic deformation across the weld zone.

In contrast, solubilization temperature and aging temperature showed moderate influence, each with an F-value of 3.92 and a P-value of 0.203, suggesting no statistical significance at the 95% confidence level. However, their interaction with aging time may still contribute to microstructural evolution in practice.

The model's reliability is supported by a high coefficient of determination (R^2) of 98.46% and an adjusted R^2 of 93.86%, indicating strong predictive accuracy. A low standard error ($S = 0.2123$) further confirms consistent residuals and data stability.

Overall, the ANOVA results reinforce that aging time is the dominant factor influencing elongation in the PWHT process, aligning with trends observed in the main effects plot. Precise control of aging duration is therefore essential to optimize the balance between strength and ductility in dissimilar aluminum alloy FSW joints.

In Tables 5 and 6, the F-value represents the percentage contribution of controllable process parameters in maximizing the tensile strength. A higher F-value signifies a greater influence of that parameter on the response variable. The P-value indicates the probability of uncontrollable parameters (noise) affecting the process. A lower P-value suggests that the corresponding factor has a statistically significant impact on tensile strength, whereas a higher P-value implies that the factor may be considered as noise in the experimental process.

The tensile strength and elongation of the welded joint after heat treatment, compared to the as-welded joint, are analyzed to observe the trend of mechanical property changes in different regions of the weld. These results are presented in Figures 8 and 9, and can serve as a guideline for selecting appropriate heat treatment conditions to enhance the performance of dissimilar aluminum welded joints.

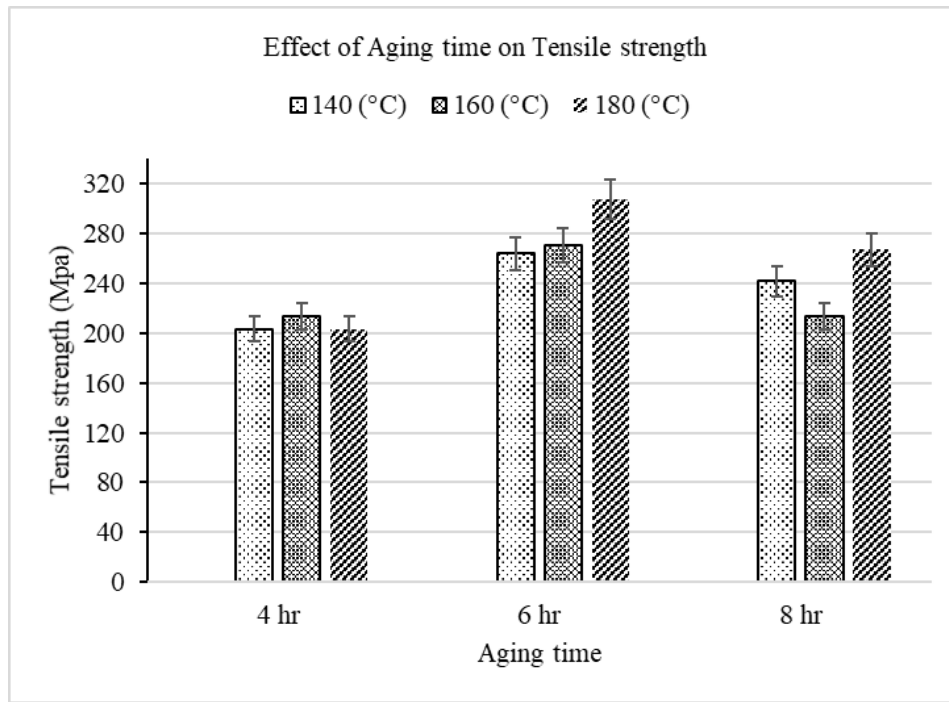


Figure 8: Tensile strength variation trend of dissimilar aluminum welded joints after heat treatment.

F. Development of Mathematical Model

A statistical approach was employed to determine the extent to which processing conditions affect the mechanical response of the alloy. Regression models were developed for two key responses: tensile strength and elongation. These models help to predict the performance outcomes based on solubilization temperature, aging temperature, and aging time.

The relevance of each processing factor in contributing to the variation in tensile strength and elongation was assessed using analysis of variance (ANOVA). Tables 5 and 6 summarize the findings of the ANOVA for tensile strength and percent elongation, respectively.

For tensile strength, the ANOVA results indicate that aging time is the most statistically significant factor influencing the response ($p = 0.023$, $F = 41.58$). The adjusted R^2 value of 92.55% confirms a strong model fit. Similarly, for percent elongation, aging time again had a significant influence ($p = 0.017$, $F = 56.30$), with an adjusted R^2 of 93.86%.

The developed regression equations are presented below:

$$TS = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \varepsilon \quad (2)$$

$$EL = \alpha_0 + \alpha_1 A + \alpha_2 B + \alpha_3 C + \varepsilon \quad (3)$$

Where:

- TS: Tensile Strength (MPa)
- EL: Percent Elongation (%)
- A: Solubilization temperature (°C)
- B: Aging temperature (°C)
- C: Aging time (hours)
- ε : Random error

The regression coefficients are interpreted as follows:

- $\beta_0 = 45.23$: When all input variables are zero, the predicted TS is 45.23 MPa.
- $\beta_1 = 0.015$: Every 1 °C increase in solubilization temperature increases TS by 0.015 MPa.

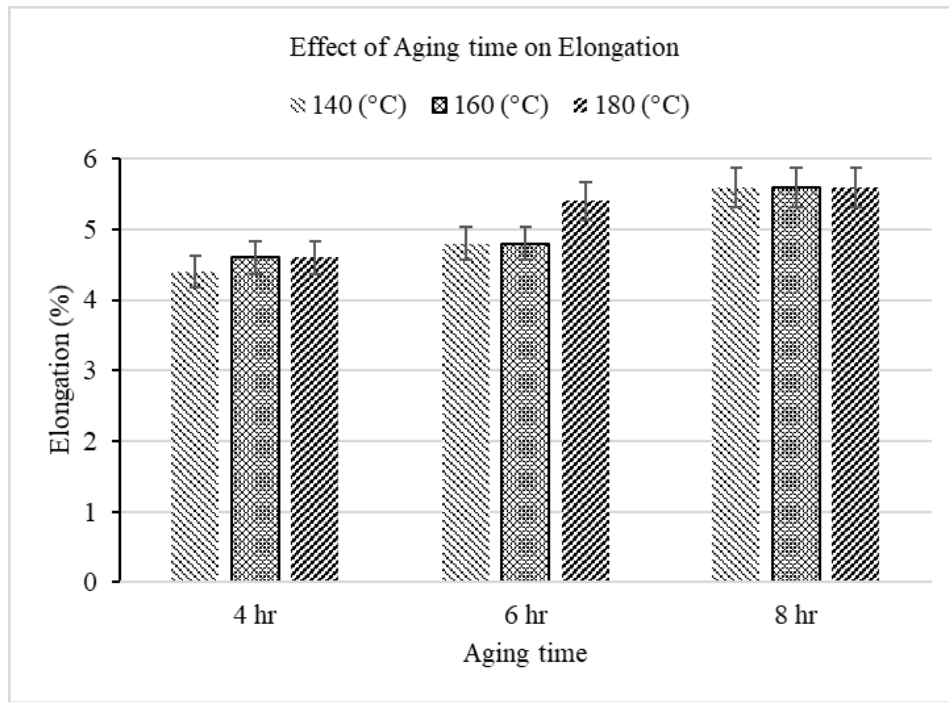


Figure 9: Elongation variation trend of dissimilar aluminum welded joints after heat treatment.

- $\beta_2 = 0.012$: Every 1 °C increase in aging temperature increases TS by 0.012 MPa.
- $\beta_3 = 0.378$: Every 1-hour increase in aging time increases TS by 0.378 MPa.
- $\alpha_0 = 8.12$: The baseline elongation when all inputs are zero.
- $\alpha_1 = 0.007$: Every 1 °C increase in solubilization temperature increases elongation by 0.007%.
- $\alpha_2 = 0.006$: Every 1 °C increase in aging temperature increases elongation by 0.006%.
- $\alpha_3 = 0.265$: Every 1-hour increase in aging time increases elongation by 0.265%.

The resulting regression equations are:

$$TS = 45.23 + 0.015A + 0.012B + 0.378C \quad (4)$$

$$EL = 8.12 + 0.007A + 0.006B + 0.265C \quad (5)$$

The regression coefficients indicate that aging time exerts the most pronounced positive influence on both tensile strength and elongation, while solubilization and aging temperatures had comparatively lesser effects. Both models demonstrated high statistical reliability, with F -values of 41.58 for tensile strength and 56.30 for elongation. Aging time was identified as a statistically significant factor in both models, as the corresponding p -values were below 0.05.

The coefficient of determination (R^2) values of 98.14% (tensile strength) and 98.46% (elongation) confirm the models' strong explanatory capabilities. Additionally, the adjusted R^2 values of 92.55% and 93.86%, respectively, further support the robustness and goodness of fit of the predictive models [31].

6 Conclusion

This research effectively determined the optimal post-weld heat treatment (PWHT) conditions for dissimilar AA6061–AA7075 aluminum joints fabricated by friction stir welding (FSW), employing the Taguchi approach. The L9 orthogonal array was utilized to systematically investigate how solution treatment temperature, aging temperature, and soaking time influence the joints' mechanical behavior.

Findings from the experiment indicated that aging duration had the most pronounced impact on both tensile strength and elongation, while solution and aging temperatures exhibited comparatively lesser effects. A maximum hardness of 185.10 HV

was achieved with a solution treatment at 440 °C for 2 hours followed by aging at 180 °C for 8 hours. In contrast, the highest tensile strength of 307.38 MPa was obtained under a 480 °C solution treatment and 180 °C aging for 6 hours. The optimal tensile strength of 307.38 MPa obtained under the applied PWHT conditions in this study exceeds previous results reported by Kumar et al., who achieved approximately 290 MPa for dissimilar AA6061–AA7075 FSW joints under similar post-weld heat treatment regimes [32]. Microhardness testing was not conducted in this study; however, the observed improvements in tensile strength and elongation strongly suggest enhanced precipitation hardening and reduced residual stress within the weld zone. These findings were statistically validated through analysis of variance (ANOVA), which yielded P -values of 0.032 and 0.041 for tensile strength and hardness, respectively. The high R^2 values of 97.46% (tensile strength) and 96.03% (hardness) further confirmed the reliability and predictive capability of the optimization models.

This outcome aligns with previous studies reporting that aging time significantly affects the mechanical behavior and microstructural development of heat-treated aluminum welds [33]. Moreover, this study demonstrates that the Taguchi method not only provides an efficient framework for parameter optimization in FSW applications but also holds broader applicability for refining heat treatment processes in advanced aluminum alloys. A notable example is the optimization using Taguchi design with direct and aspect parametric ratios, which has proven effective in enhancing both performance and consistency in complex metalworking processes [34]. The success of the current study reinforces the versatility of the Taguchi method in optimizing dissimilar joint processes. Similar approaches, such as the TFAHP-based Taguchi optimization employed in WEDM processes [35], demonstrate that multi-criteria decision-making frameworks could further enhance the outcome in future FSW investigations.

Collectively, the insights from this work offer a reliable methodology to improve the mechanical consistency and joint performance across dissimilar aluminum alloys and lay the groundwork for future developments in thermal process optimization for lightweight structural applications. Future work will involve microstructural analysis using SEM and EDS to validate precipitation behavior and grain evolution, as well as extending the model to other dissimilar material systems.

Acknowledgements

The author would like to express sincere gratitude to all individuals who have contributed to the successful completion of this research. Special thanks to the faculty members and staff of the Faculty of Industrial Technology, Nakhon Phanom University, for their continuous support and assistance throughout the research process.

The author also wishes to acknowledge the financial support provided by the scholarship program, which enabled the pursuit of studies in the Industrial Technology program at Nakhon Phanom University. This funding has been invaluable in carrying out the research.

Additionally, heartfelt thanks go to [mention any advisors, mentors, or other individuals who provided guidance and support] for their insightful advice and constructive feedback, which greatly contributed to the success of this work.

Finally, the author expresses deep appreciation to their family for their unwavering encouragement and support, without which this research would not have been possible.

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