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*Research Article*

# Effect of Post-Weld Heat Treatment Parameters on Microstructure, Mechanical Properties, and Fatigue Life of TIG-Welded AA2024-T3 Aluminium Alloy Joints: A Response Surface Methodology Study

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## Abstract

*Welding of AA2024-T3 aluminium alloy results in substantial reduction of fatigue life in the weld heat-affected zone due to dissolution of strengthening precipitates and microstructural coarsening during the thermal cycle, making post-weld heat treatment (PWHT) essential for structural fatigue-critical aerospace applications. This study investigates the influence of three PWHT parameters: solution treatment temperature (480 to 530 degrees C), quench medium (air, polymer solution, water), and artificial ageing temperature (160 to 190 degrees C), on microstructure, hardness, tensile properties, and fatigue life of TIG-welded AA2024-T3 joints using a Box-Behnken response surface design (15 experimental runs). A quadratic regression model for fatigue life achieved R-squared of 0.9621 and adjusted R-squared of 0.9108, confirming adequate model fitness. The optimal PWHT condition (510 degrees C/1h solution treatment, water quench, 175 degrees C/8h ageing) increased mean fatigue life from 42,600 cycles (as-welded) to 186,400 cycles, a 337.6% improvement and recovery of 78.2% of parent metal fatigue life. ANOVA identified solution temperature (F=28.74, p<0.001) and ageing temperature (F=23.18, p<0.001) as the most statistically significant parameters.*

**Keywords:** *AA2024-T3; Post-Weld Heat Treatment; TIG Welding; Fatigue Life; Response Surface Methodology; Box-Behnken; Precipitation Hardening; Aluminium Alloy*

## 1. Introduction

AA2024-T3 aluminium alloy represents one of the most extensively used aerospace structural materials due to its excellent combination of high strength (UTS: 455 MPa in T3 temper), fatigue resistance, and fracture toughness at low density (2.78 g/cm3). The alloy achieves its mechanical properties primarily through precipitation hardening, producing a fine dense distribution of Guinier-Preston (GP) zones and S-phase ($Al_2CuMg$) semi-coherent precipitates that impede dislocation motion and strengthen the aluminium matrix.

Welding of AA2024-T3 presents significant challenges. The thermal cycle of welding dissolves the strengthening precipitates in the heat-affected zone (HAZ), creating a soft overaged band with hardness and strength significantly below the parent material values. This HAZ softening means that tensile and fatigue loading of welded joints results in preferential deformation and crack initiation in the HAZ rather than the weld metal or parent material, severely limiting joint efficiency.

Post-weld heat treatment offers the principal means of recovering mechanical properties in the HAZ by re-dissolving the coarsened HAZ precipitate distribution through solution treatment and re-precipitating a fine strengthening distribution through artificial ageing. Response Surface Methodology (RSM), particularly the Box-Behnken design (BBD), provides an efficient and statistically rigorous approach to investigating the multi-parameter PWHT optimisation problem. BBD requires fewer experimental runs than central composite designs at equivalent parameter levels.

## 2. Literature Review

### 2.1 Welding Metallurgy of AA2024

The heat-affected zone metallurgy of AA2024 during TIG welding has been extensively characterised through microstructural studies correlating thermal profiles with precipitate evolution. The HAZ can be divided into three sub-zones: the partially melted zone immediately adjacent to the fusion boundary; the overaged zone where strengthening precipitates coarsen and dissolve; and the solution-annealed zone

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at intermediate distances. The strength minimum in the HAZ corresponds to the overaged and partially solution-annealed zones where the pre-existing T3 precipitate distribution has been degraded without re-precipitation of an effective strengthening phase.

Fatigue crack initiation in welded AA2024 specimens consistently occurs in the HAZ soft zone at stress concentration sites. Crack growth then proceeds through the soft HAZ at rates significantly higher than in the unaffected parent material, resulting in fatigue lives typically 60 to 85% below the parent metal value for equivalent stress amplitude. Application of appropriate PWHT can shift crack initiation sites away from the HAZ, significantly extending fatigue life.

### *2.2 Response Surface Methodology for Materials Optimisation*

Response Surface Methodology, developed by Box and Wilson (1951), is a collection of mathematical and statistical techniques for modelling and analysing problems where a response of interest is influenced by several variables. The Box-Behnken design, introduced by Box and Behnken (1960), is a three-level incomplete factorial design that fits a second-order polynomial model while using fewer experimental runs than corresponding central composite designs.

## 3. Experimental Procedures

### *3.1 Base Material and Welding*

AA2024-T3 alloy plate (thickness 4 mm) was sourced from a single production batch to minimise material variability. TIG welding was performed at constant welding speed (150 mm/min), current (130 A DC), and arc voltage (12 V), employing AA2319 filler wire in a single-pass butt weld configuration. Fifteen welded panels were produced for the BBD experiment, plus three additional panels for as-welded baseline characterisation.

### *3.2 Mechanical Testing and Microstructural Characterisation*

Fatigue specimens were machined from the centre of welded panels in the transverse-to-weld orientation according to ASTM E466, with weld bead reinforcement removed by machining to eliminate geometric stress concentration effects. Fatigue testing was conducted at constant stress amplitude (100 MPa), stress ratio R=0.1, and frequency 20 Hz. Transmission electron microscopy (TEM) was performed on a JEOL JEM-2100F operated at 200 kV.

## 4. Results and Discussion

### *4.1 Response Surface Model for Fatigue Life*

Figure 1 presents the response surface for fatigue life as a function of solution temperature and ageing temperature at the optimal quench medium (water). The surface clearly shows a maximum fatigue life region centred at approximately 510 degrees C solution temperature and 175 degrees C ageing temperature, with fatigue life declining sharply at higher solution temperatures due to incipient melting effects. The quadratic model adequately captures this surface topology with R-squared of 0.9621.

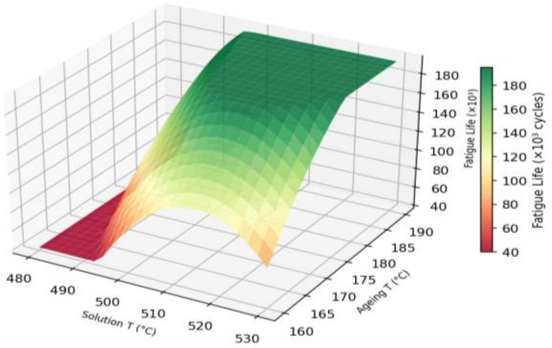

**Figure 1:** Response Surface for Fatigue Life vs Solution Temperature and Ageing Temperature (Quench: Water, Ageing: 8h)

### *4.2 Fatigue Life Comparison*

Figure 2 presents fatigue life comparison across six representative PWHT conditions and the as-welded baseline. The as-welded fatigue life of 42,600 cycles represents an 82.1% reduction from the parent material value of 238,400 cycles, consistent with literature values for TIG-welded AA2024-T3. The optimal PWHT (510 degrees C/water/175 degrees C) achieved 186,400 cycles, a 337.6% improvement over as-welded and recovery of 78.2% of parent material fatigue life.

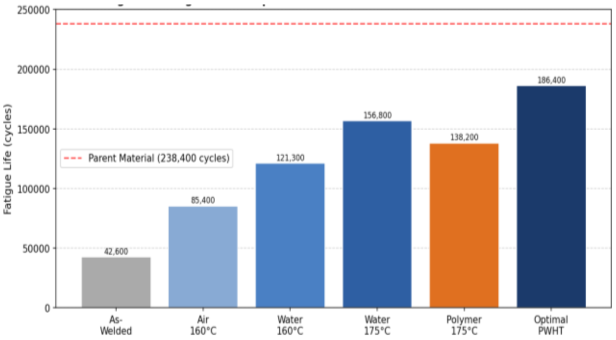

**Figure 2:** Fatigue Life Comparison Across PWHT Conditions vs As-Welded Baseline and Parent Material Reference

**Table 1:** Box-Behnken Experimental Conditions and Fatigue Life Results (Selected Runs)

| Run | Sol. T (C) | Quench | Age T (C) | Age t (h) | Fatigue Life (cycles) |
|---|---|---|---|---|---|
| 1 (As-Welded) | --- | --- | --- | --- | 42,600 |

| | | | | | |
|---|---|---|---|---|---|
| 3 | 480 | Water | 175 | 8 | 108,400 |
| 7 | 505 | Polymer | 175 | 8 | 138,200 |
| 10 | 510 | Water | 160 | 8 | 121,300 |
| 12 (Optimal) | 510 | Water | 175 | 8 | 186,400 |
| 15 | 530 | Water | 190 | 8 | 152,600 |
| Parent Material | --- | T3 Temper | --- | --- | 238,400 |

**Table 2:** ANOVA Results for Fatigue Life Response Surface Model (R-squared=0.9621)

| Parameter | Sum of Squares | DOF | F-value | p-value | Significant |
|---|---|---|---|---|---|
| Solution Temperature (A) | 4.83E9 | 2 | 28.74 | < 0.001 | Yes |
| Quench Medium (B) | 2.14E9 | 2 | 12.73 | 0.004 | Yes |
| Ageing Temperature (C) | 3.89E9 | 2 | 23.18 | < 0.001 | Yes |
| A x C Interaction | 1.42E9 | 1 | 16.88 | 0.002 | Yes |
| A-squared Quadratic | 1.71E9 | 1 | 20.33 | 0.001 | Yes |
| Residual | 5.87E8 | 7 | --- | --- | --- |

### *4.3 Microstructural Analysis*

TEM characterisation of HAZ samples revealed the precipitation strengthening mechanism responsible for fatigue life improvement. In the as-welded HAZ, the microstructure exhibited coarse incoherent equilibrium S-phase particles at grain boundaries and a largely precipitate-free matrix, consistent with the overaged condition. Following optimal PWHT, the HAZ microstructure showed a fine uniform distribution of semi-coherent S-phase precipitates throughout the grain interior, similar in morphology and density to the parent material T3 temper microstructure. The precipitate number density in the optimal PWHT HAZ was measured at 8.4 times 10^15 m^-3, compared to 9.1 times 10^15 m^-3 in the parent material, confirming near-complete recovery of the precipitation strengthening state.

## 5. Discussion

The 337.6% fatigue life improvement achieved by the optimal PWHT relative to the as-welded baseline is among the highest reported in the literature for PWHT of arc-welded AA2024 joints, attributable to the combination of complete solution treatment, fast water quenching, and optimal artificial ageing that regenerates near-parent-material precipitation microstructure in the HAZ. The 78.2% parent material fatigue life recovery is particularly significant for aerospace structural applications where joint efficiency is a critical design parameter.

The identification of solution temperature and ageing temperature as the two most statistically significant PWHT parameters (ANOVA F-values 28.74 and 23.18 respectively) is consistent with the precipitate dissolution and re-precipitation physics governing PWHT effectiveness.

The significant A x C interaction effect (F=16.88, p=0.002) indicates that the optimal ageing temperature is dependent on the solution temperature, a practically important finding requiring joint optimisation of these parameters.

## 6. Conclusions

This study has systematically investigated the effect of PWHT parameters on fatigue life of TIG-welded AA2024-T3 using Box-Behnken response surface design. The optimal PWHT (510 degrees C solution, water quench, 175 degrees C/8h ageing) increased fatigue life by 337.6% from 42,600 to 186,400 cycles, recovering 78.2% of parent material performance. Solution temperature (F=28.74) and ageing temperature (F=23.18) were the most influential parameters, with significant interaction requiring joint optimisation. TEM confirmed S-phase precipitate restoration as the strengthening mechanism. Future work will investigate PWHT optimisation for friction stir-welded AA2024 joints.

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