

Taguchi-Based Optimization and Artificial Neural Network Modeling of Post-Weld Heat Treatment Effects on the Microstructural and Mechanical Performance of Friction Stir Welded AA3103 Alloy

Ganesh Jagannath Pagar^{1,2}, Gajanan N. Shelke^{3*}

¹ Department of Mechanical Engineering, MET BKC's Institute of Engineering, Savitribai Phule Pune University, Adgaon, 422003 Nashik, Maharashtra, India

² Department of Mechanical Engineering, SNJB's Shri Hiralal Hastimal (Jain Brothers) Polytechnic, Chandwad, 423101 Nashik, Maharashtra, India

³ Department of Mechanical Engineering, Sandip Institute of Engineering & Management, Sandip Foundation, Trimbak Road, 422213 Nashik, Maharashtra, India

* Corresponding author, e-mail: gnshelke@gmail.com

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Abstract

This investigation evaluates the combined influence of Taguchi-optimized friction stir welding (FSW) parameters and post-weld heat treatment (PWHT) on the microstructural evolution and tensile strength of AA3103 aluminium alloy joints, complemented by Artificial Neural Network (ANN) modeling for mechanical property prediction. A Taguchi L9 orthogonal array was implemented independently for three tool pin geometries (square, circular, and triangular), incorporating shoulder-to-pin diameter ratios ($D/d = 3, 4, 5$), spindle speeds (355, 710, 1400 RPM), and welding speeds (20, 40, 80 mm/min), resulting in 27 experiments. A two-stage PWHT was applied, consisting of annealing at 350 °C for 2 h to promote dislocation recovery and residual stress relaxation, followed by artificial ageing at 200–225 °C and water quenching. Tensile properties, evaluated according to ASTM E8/E8M-22, were statistically analysed using S/N ratios, ANOVA, regression model, and ANN. The D/d ratio emerged as the dominant factor governing strength retention, showing the highest S/N delta for ultimate tensile strength and yield strength, and representing the only statistically significant parameter for yield strength. Spindle speed primarily influenced ductility stability. The optimized parameter set (circular pin, $D/d = 3$, 1400, 40 mm/min) demonstrated superior strength and microstructure. PWHT reduced regression residual errors to within $\pm 8\%$ and promoted fine equiaxed grain stabilization in the stir zone with a moderated hardness gradient across the TMAZ and HAZ.

Keywords

friction stir welding, AA3103 aluminium alloy, post-weld heat treatment, Taguchi L9 orthogonal array, tensile strength, microstructure

1 Introduction

Friction stir welding (FSW), conceived by Thomas et al. [1] at The Welding Institute, achieves material coalescence through thermomechanical energy dissipation rather than bulk melting, thereby eliminating solidification-related defects porosity, hot tearing, and dendritic segregation that routinely degrade fusion welds in age-hardenable and work-hardened aluminium alloys [2–4]. The rotating non-consumable tool simultaneously delivers frictional heat and intense sub-solidus plastic strain, driving continuous dynamic recrystallization (CDRX) in the advancing and retreating material streams. The resulting weld cross-section is heterogeneous

by design: a dynamically recrystallized, fine-grained stir zone (SZ) enveloped by a plastically deformed yet structurally retained thermo-mechanically affected zone (TMAZ), which in turn transitions to a thermally altered but strain-free heat-affected zone (HAZ) [5–7]. This zone hierarchy underpins both the mechanical assets and the scatter susceptibility of FSW joints and has motivated sustained investigation across aerospace, automotive, marine, and thermal management applications [2, 4]. Within the 3xxx aluminium family, AA3103 occupies a strategically significant position: its moderate strength, excellent formability, and

outstanding corrosion resistance render it indispensable for heat exchanger headers, evaporator cores, pressure vessels, and lightweight structural panels [8–10]. Fusion joining of AA3103 is, however, complicated by its elevated thermal conductivity and rapid solidification kinetics, which promote oxide entrapment and hydrogen porosity [11]. FSW naturally avoids these pitfalls, yet relative to the well-documented 2xxx, 6xxx, and 7xxx series alloys, FSW of 3xxx alloys and AA3103 in particular remains under-characterized in the open literature.

Tool pin geometry, D/d ratio, spindle speed, and traverse rate collectively regulate frictional heat flux, material plasticization, and SZ microstructure [8, 12, 13]. The shoulder-to-pin diameter ratio specifically modulates the thermal footprint of the tool shoulder on the workpiece surface: undersized shoulders restrict energy input and risk tunnel defects, whereas oversized shoulders over-heat the SZ–HAZ interface, inducing abnormal grain growth and strength loss [14]. Statistical experimental design particularly the Taguchi method and its derivatives (Grey Relational Analysis, ANOVA) has proven effective at mapping this multidimensional parameter space with economical experimental effort [14–16]. Complementary regression and machine learning models further exploit experimentally generated datasets for property prediction, provided the data exhibit adequate statistical stability [17–19].

As-welded FSW joints carry high dislocation densities and residual stress fields particularly at zone interfaces that introduce scatter into tensile measurements and compromise regression model fidelity [4, 7, 20]. Post weld heat treatment (PWHT) addresses both pathologies simultaneously: thermally activated recovery reduces dislocation density through climb and annihilation, partial recrystallization smooths grain boundary curvature at zone transitions, and residual stress relaxation homogenizes the elastic strain field [21–25]. The downstream consequence is improved ductility, diminished hardness gradients, and markedly tighter mechanical property distributions a benefit that also enhances the predictive accuracy of empirical models. Despite these well-established effects in 5xxx and 6xxx alloys, a study that simultaneously quantifies the Taguchi-optimized parameter hierarchy, ANOVA significance, regression residual improvement, and microstructural stabilization for PWHT-treated FSWed AA3103 has not yet been reported.

This investigation fills that gap through a four-pillar analytical framework: (i) Taguchi S/N ratio ranking of process variables in the post-PWHT state; (ii) ANOVA-based significance testing to isolate parameters that retain ANN-statistical influence after thermal homogenization; (iii) General Linear Model regression with quantitative residual analysis to gauge prediction reliability; and (iv) optical microstructural correlation of representative weld runs. The novelty resides in explicitly demonstrating how PWHT restructures the parameter sensitivity landscape of a non-heat-treatable aluminium alloy and in providing an industrially deployable optimization protocol validated at both the ANN-statistical and metallurgical levels.

The novelty of this study lies in the integrated evaluation of Taguchi optimization, post-weld heat treatment (PWHT), ANN modelling, regression analysis, and microstructural characterization for friction stir welded AA3103 alloy. Furthermore, the study demonstrates that PWHT reduces the sensitivity of most welding parameters while the shoulder-to-pin diameter ratio (D/d) remains the dominant factor governing joint strength, leading to an experimentally validated optimum process condition for industrial application.

2 Materials and experimental methodology

AA3103 aluminium alloy plates conforming to the compositional limits tabulated in Table 1 were adopted as the workpiece material. A plate thickness of 3 mm was selected to balance the competing requirements of adequate pin engagement, controlled axial force, and sub-size ASTM E8/E8M-22 [26] specimen extraction [9, 11]. This gauge is representative of AA3103 deployments in heat exchanger applications and falls within the parameter regime accessible on laboratory-scale FSW rigs [8–11].

2.1 Friction stir welding machine and experimental set-up

All welds were produced on a semi-automatic HMT FN2 vertical-spindle milling machine (technical specifications: Table 2) equipped with a purpose-built steel clamping fixture, as illustrated in Fig. 1. The fixture constrains both longitudinal and transverse workpiece displacement during plunge and traversal, preventing joint misalignment and bead waviness. Tool plunge depth and angular alignment were set *via* the knee-elevation and cross-traversal

Table 1 Chemical composition of AA3103 aluminium alloy (wt.%)

Element	Al	Mn	Si	Fe	Mg	Cu	Zn	Cr
wt.%	≤96.3	0.90–1.50	≤0.50	≤0.70	≤0.30	≤0.10	≤0.20	≤0.10

Table 2 Technical specifications of the milling machine used for FSW experiments

Parameter	Specification
Product Type / Brand	FN2 / HMT
Automation Grade	Semi-Automatic
Power Source / Voltage	Electric / 220 V
Machine Weight	222 kg
Overall Dimensions (L × W)	1520 × 310 mm
Clamping Area (L × W)	1350 × 310 mm
Maximum Safe Load on Table	350 kg

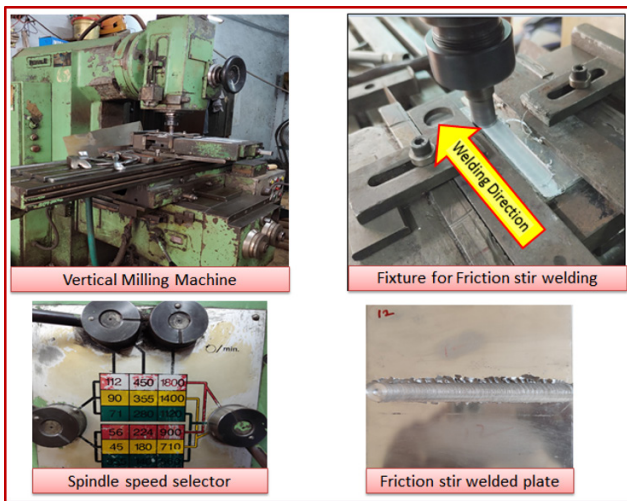


Fig. 1 Experimental setups for friction stir welding

mechanisms of the machine column, ensuring repeatable contact conditions across all 27 experimental trials. Manual traverse-speed control was adopted to accommodate the variable heat generation characteristics of the

three tool pin geometries while maintaining a consistent spindle-speed setting per trial.

2.2 Tool pin profiles

Three pin geometries were machined from H13 hot-work tool steel and assessed under identical shoulder conditions (Fig. 2). (i) Square pin: sharp edges generate a pulsating four-lobe shear field that intensifies stirring and elevates localized heat input; this promotes mechanical interlocking but also heightens sensitivity to heat-input fluctuations [8, 13]. (ii) Circular pin: the rotationally symmetric profile sustains laminar material flow with minimal turbulence, yielding reproducible heat distribution and diminished defect susceptibility attributes that are particularly advantageous in the post-PWHT state where geometric sensitivity is already attenuated [8]. (iii) Triangular pin: the three-lobe geometry occupies an intermediate stirring intensity, delivering a controlled degree of circumferential pulsation that enhances transverse material transport relative to the circular case, with an associated benefit in ductility at certain parameter combinations.

2.3 Process parameters and Taguchi L9 experimental design

Four control factors tool pin profile, D/d ratio, spindle speed, and traverse rate were investigated at three levels each (Table 3), following the parametric conventions established for aluminium alloy FSW optimization [8, 13, 14]. The D/d ratio was cast at 3 (15 mm/5 mm), 4 (20 mm/5 mm), and 5 (25 mm/5 mm) to span the practical



Fig. 2 Tools with different pin profiles – square, circular, and triangular

Table 3 Control factors and assigned levels for the Taguchi L9 orthogonal array design

Parameter	Level 1	Level 2	Level 3
Tool Pin Profile	Square	Circular	Triangular
D/d Ratio	3 (15 mm/5 mm)	4 (20 mm/5 mm)	5 (25 mm/5 mm)
Rotational Speed (RPM)	355	710	1400
Welding Speed (mm/min)	20	40	80

range of shoulder-area-to-pin-area ratios. Spindle speeds of 355, 710, and 1400 RPM represent low-, medium-, and high-thermal-input regimes, respectively. Traverse rates of 20, 40, and 80 mm/min modulate the heat input per unit weld length. A separate Taguchi L9 orthogonal array was assigned to each pin profile, producing 27 statistically balanced experimental runs whose full matrix is embedded in Table 4. The orthogonal structure guarantees unbiased estimation of main effects with a minimum number of trials [15, 16].

2.4 Post-weld heat treatment

Welded coupons were subjected to a three-stage PWHT cycle in a digitally controlled muffle furnace (temperature resolution ± 1 °C). Stage I: specimens were heated at a controlled ramp of 5–10 °C/min to 350 °C, a temperature confirmed by preliminary dilatometric trials to lie within the solid-state stability domain of the Al–Mn phase diagram,

where no undesirable intermetallic formation occurs. Stage II: isothermal hold at 350 °C for 2 h to promote subgrain coalescence, dislocation recovery, and residual stress relaxation; the 2-h duration was selected based on literature evidence that shorter holds leave significant dislocation debris in work-hardened Al–Mn welds, whereas longer holds risk static grain growth [23–25]. Stage III: controlled air cooling to room temperature, followed by a re-heat to 200–225 °C (artificial ageing plateau), and immediate water quenching to freeze a refined precipitate-free microstructure. Specimen placement on alumina trays with inter-specimen spacing ensured spatial thermal uniformity throughout the batch. The full PWHT sequence is depicted schematically in Fig. 3, and the furnace loading configuration is shown in Fig. 4. This protocol is consistent with PWHT strategies documented for analogous non-heat-treatable aluminium alloy systems [21–23].

Table 4 Experimental design matrix (Taguchi L9 $\times$ 3 pin profiles) with measured mechanical responses for PWHT-treated FSWed AA3103 joints

Run	Pin Profile	D/d	RPM	Speed (mm/min)	YS (N/mm ²)	UTS (N/mm ²)	%E
1	Square	3	355	20	195.21	199.80	22.4
2	Square	3	710	40	168.87	174.03	20.8
3	Square	3	1400	80	178.78	186.74	21.6
4	Square	4	355	40	146.90	171.29	21.2
5	Square	4	710	80	163.06	165.72	21.6
6	Square	4	1400	20	145.57	167.29	22.0
7	Square	5	355	80	81.67	89.72	21.6
8	Square	5	710	20	149.60	166.05	20.8
9	Square	5	1400	40	141.43	165.18	22.4
10	Circular	3	355	20	172.55	181.07	20.8
11	Circular	3	710	40	163.93	177.55	20.8
12	Circular	3	1400	80	169.46	183.59	22.8
13	Circular	4	355	40	139.65	169.54	23.2
14	Circular	4	710	80	136.03	162.40	20.8
15	Circular	4	1400	20	128.12	157.12	21.6
16	Circular	5	355	80	146.14	152.63	20.8
17	Circular	5	710	20	142.98	172.41	21.6
18	Circular	5	1400	40	148.61	165.01	20.4
19	Triangular	3	355	20	114.52	122.01	24.4
20	Triangular	3	710	40	158.43	175.44	20.4
21	Triangular	3	1400	80	161.93	182.37	20.8
22	Triangular	4	355	40	144.76	167.90	21.2
23	Triangular	4	710	80	150.76	170.30	20.0
24	Triangular	4	1400	20	148.63	166.47	22.0
25	Triangular	5	355	80	146.13	166.63	20.8
26	Triangular	5	710	20	145.77	173.04	20.4
27	Triangular	5	1400	40	143.38	174.07	21.6

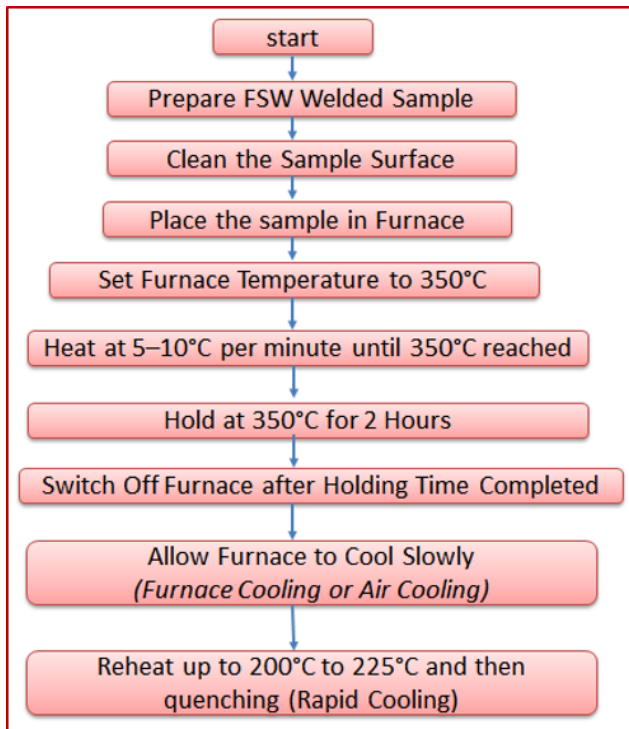


Fig. 3 PWHT procedure followed for the friction stir welded AA3103 specimens



Fig. 4 Furnace loading configuration

2.5 Tensile testing and mechanical characterization

Transverse sub-size flat tensile specimens were extracted from each PWHT-treated weld plate by water-jet cutting chosen over mechanical sawing to preclude any thermomechanical alteration of the weld zone adjacent to the specimen gauge section (Fig. 5). Specimen geometry conformed to ASTM E8/E8M-22 [26] sub-size proportions [9, 11]. Room-temperature uniaxial tensile tests were conducted at a constant crosshead displacement rate on a calibrated universal testing machine (Fig. 6). Three mechanical responses UTS (N/mm²), YS (N/mm²), and



Fig. 5 Water-jet cut tensile specimens prepared from friction stir welded AA3103 plates for mechanical testing



Fig. 6 Calibrated universal testing machine

%E were recorded for all 27 specimens (one per experimental run) and subsequently used as response variables in the Taguchi, ANOVA, and regression analyses.

2.6 Microstructural characterization

Cross-sectional metallographic specimens (30 mm × 5 mm, sectioned perpendicular to the weld direction) were

mounted in cold-setting epoxy, ground through successive SiC abrasive papers to 2000 grit, and diamond-polished to a 1 μm finish. Chemical etching with Keller's reagent revealed grain boundaries and zone boundaries for optical microscopic examination. Three runs Run 3 (Square pin, $D/d = 3$, 1400 RPM, 80 mm/min), Run 11 (Circular pin, $D/d = 3$, 710 RPM, 40 mm/min), and Run 21 (Triangular pin, $D/d = 3$, 1400 RPM, 80 mm/min) were selected for detailed microstructural investigation on the basis of their superior post-PWHT strength–ductility balance and the lowest S/N ratio prediction residuals. Three characteristic regions were examined in each specimen: base material (BM), stir zone (SZ), and the TMAZ–HAZ interfacial zone (IZ).

3 Tensile testing results

The consolidated mechanical response dataset for all 27 PWHT-treated experimental runs is presented in Table 4. Inspection of the strength data reveals a clear parameter hierarchy: the D/d ratio exerts the most pronounced discrimination among runs, with the $D/d = 3$ sub-group invariably occupying the upper UTS and YS quartiles regardless of pin geometry. The peak UTS of 199.80 N/mm² and YS of 195.21 N/mm² were recorded for Run 1 (Square pin, $D/d = 3$, 355 RPM, 20 mm/min), reflecting the combined effect of a compact shoulder footprint and moderate heat input on stir-zone consolidation. Conversely, Run 7 (Square pin, $D/d = 5$, 355 RPM, 80 mm/min) returned the minimum UTS of 89.72 N/mm², an outcome attributable to the synergistic deterioration caused by excessive shoulder contact area, low plasticization temperature, and high traverse rate a combination that generates incomplete bonding and a coarser SZ microstructure. The maximum ductility of 24.4% was attained in Run 19 (Triangular pin, $D/d = 3$, 355 RPM, 20 mm/min), consistent with the comparatively lower heat generation of the triangular profile and its associated moderate SZ grain growth.

Across pin profiles, the circular geometry exhibits the narrowest inter-run spread in both UTS and YS indicative of stable, turbulence-free material transport and

predictable heat partitioning. Triangular pin welds, while producing lower mean strengths, deliver comparatively higher elongation values, a trade-off attributable to the three-lobe pulsation that enhances transverse material displacement at the cost of reduced axial consolidation pressure. Intermediate welding speed (40 mm/min) consistently yields the most balanced UTS–ductility combination across all profiles, an observation that aligns with the thermal balance concept: at 40 mm/min, the weld thermal cycle achieves sufficient peak temperature for complete plasticization without the extended high-temperature exposure that accelerates HAZ grain coarsening.

4 Taguchi analysis and statistical optimization

4.1 Signal-to-noise ratio analysis

Because all three mechanical responses are desirable in their maximum, the larger-is-better S/N transformation was applied throughout:

$$\eta = -10 \log_{10} \left[\left(1/n \right) \sum (1/y_i^2) \right] \quad (1)$$

where y_i denotes the measured response for the i -th replicate and n is the replicate count per trial. S/N ratios were computed for each of the 27 runs and subsequently averaged at each factor level to construct the response tables.

4.1.1 S/N Analysis-Ultimate Tensile Strength

The D/d ratio commands the widest S/N delta ($\Delta = 0.99$, Rank 1), affirming that shoulder-driven heat flux is the primary determinant of post-PWHT UTS robustness. Level 1 ($D/d = 3$) delivers the highest S/N value (44.83 dB) (Table 5), reaffirming the superiority of a compact shoulder in controlling heat delivery without over-softening the HAZ. Spindle speed ranks second ($\Delta = 0.94$), with Level 3 (1400 RPM) yielding the peak S/N of 44.70 dB a reflection of enhanced thermomechanical mixing that generates a more homogeneous SZ grain structure. Traverse rate exerts moderate influence ($\Delta = 0.63$), peaking at Level 2 (40 mm/min, 44.66 dB). Notably, tool pin profile contributes least ($\Delta = 0.37$), demonstrating that PWHT effectively suppresses the geometric sensitivity of the pin

Table 5 Response table for S/N ratios (Larger-is-better criterion)- Ultimate Tensile Strength

Level	Tool Pin Profile	Shoulder/Pin Ratio (D/d)	Rotational Speed (RPM)	Welding Speed (mm/min)
1	44.54	44.83	43.76	44.40
2	44.18	44.42	44.64	44.66
3	44.38	43.84	44.70	44.03
Δ (delta)	0.37	0.99	0.94	0.63
Rank	4	1	2	3

surface an analytically novel finding with direct implications for process window widening in industrial contexts.

4.1.2 S/N Analysis-Yield Stress

The D/d ratio retains its primacy for yield stress with $\Delta = 1.57$ approximately 59% larger than its UTS counterpart signalling that shoulder-controlled heat input governs the sub-structure strengthening mechanisms (Hall–Petch refinement and residual dislocation hardening) that dictate incipient plastic yielding more acutely than ultimate failure. Level 1 ($D/d = 3$) again attains the highest S/N (44.26 dB) (Table 6). Spindle speed occupies Rank 2 ($\Delta = 0.80$), while traverse rate and pin profile retain lower influence ($\Delta = 0.31$ and 0.21 , respectively), reinforcing the conclusion that PWHT equalizes pin-geometry effects.

4.1.3 S/N Analysis-Percentage Elongation

The ranking hierarchy inverts for ductility: spindle speed ascends to Rank 1 ($\Delta = 0.41$), with Level 1 (355 RPM) delivering the highest S/N of 26.77 dB (Table 7). This inversion is metallurgically coherent: lower spindle speeds limit the peak cycle temperature and attendant thermal softening of the HAZ, preserving a residual strain-hardening contribution

that sustains elongation. Traverse rate is Rank 2 ($\Delta = 0.23$), reflecting the role of heat input per unit length in controlling grain boundary cohesion during tensile loading. The D/d ratio (Rank 3, $\Delta = 0.19$) and pin profile (Rank 4, $\Delta = 0.14$) are minor influences on ductility after PWHT.

4.2 Analysis of variance (ANOVA)

A General Linear Model ANOVA was fitted independently for each response, treating all four control factors as fixed, orthogonal effects. Results for UTS, YS, and %E are reported in Tables 8, 9, and 10, respectively.

4.2.1 ANOVA for UTS

No single factor attains statistical significance at the 95% confidence threshold ($P > 0.05$) for UTS after PWHT (Table 8), and the model coefficient of determination is modest ($R^2 = 26.82\%$). The low R^2 and the correspondingly large error component (Adj SS = 7969.4) collectively indicate that welding-parameter-induced microstructural differences have been substantially erased by thermal treatment, shifting the dominant variance source from process control to inherent material variability a finding consistent with PWHT investigations on AA5xxx and AA6xxx FSW joints [21, 25].

Table 6 Response table for S/N ratios (larger-is-better criterion)-yield stress

Level	Tool Pin Profile	Shoulder/Pin Ratio (D/d)	Rotational Speed (RPM)	Welding Speed (mm/min)
1	43.46	44.26	42.89	43.38
2	43.45	43.20	43.69	43.54
3	43.25	42.70	43.58	43.24
Δ (delta)	0.21	1.57	0.80	0.31
Rank	4	1	2	3

Table 7 Response table for S/N ratios (larger-is-better criterion)-percentage elongation

Level	Tool pin Profile	Shoulder/pin ratio (D/d)	Rotational speed (RPM)	Welding speed (mm/min)
1	26.61	26.69	26.77	26.75
2	26.69	26.65	26.36	26.57
3	26.55	26.50	26.72	26.52
Δ (delta)	0.14	0.19	0.41	0.23
Rank	4	3	1	2

Table 8 ANOVA results for ultimate tensile strength of PWHT-treated FSWed AA3103 joints

Source	DF	Adj SS	Adj MS	F-value	P-value
Tool Pin Profile	2	72.1	36.06	0.08	0.922
Shoulder/Pin Ratio	2	1386.8	693.39	1.57	0.236
Rotational Speed	2	1105.5	552.75	1.25	0.311
Welding Speed	2	356.8	178.38	0.40	0.674
Error	18	7969.4	442.74	—	—
Total	26	10890.6	—	—	—

Table 9 ANOVA results for Yield Stress of PWHT-treated FSWed AA3103 joints

Source	DF	Adj SS	Adj MS	F-value	P-value
Tool Pin Profile	2	180.8	90.40	0.22	0.807
Shoulder/Pin Ratio	2	3423.7	1711.84	4.11	0.034 *
Rotational Speed	2	547.1	273.55	0.66	0.530
Welding Speed	2	27.2	13.59	0.03	0.968
Error	18	7488.3	416.01	—	—
Total	26	11667.0	—	—	—

* Statistically significant at 95% confidence level ($P < 0.05$).

Table 10 ANOVA results for Percentage Elongation of PWHT-treated FSWed AA3103 joints

Source	DF	Adj SS	Adj MS	F-value	P-value
Tool Pin Profile	2	0.4385	0.2193	0.24	0.787
Shoulder/Pin Ratio	2	1.1496	0.5748	0.64	0.541
Rotational Speed	2	5.5585	2.7793	3.08	0.071
Welding Speed	2	1.6474	0.8237	0.91	0.419
Error	18	16.2489	0.9027	—	—
Total	26	25.0430	—	—	—

4.2.2 ANOVA for Yield Stress

The D/d ratio emerges as the only statistically significant factor for YS ($F = 4.11$, $P = 0.034$) (Table 9), with an adjusted sum of squares of $3423.7 \text{ N}^4/\text{mm}^4$ constituting the dominant explained variance term. All remaining factors are insignificant ($P > 0.05$). The model R^2 of 35.82% reflects moderate explanatory power, with residual variance attributable to stochastic microstructural heterogeneity amplified by PWHT's homogenization of other parameter effects. The persistence of D/d ratio significance through the 2-h annealing cycle demonstrates that shoulder-contact-driven thermal gradients imprint on the sub-grain structure with sufficient depth to survive recovery annihilation of the surrounding dislocation network.

4.2.3 ANOVA for Percentage Elongation

No factor achieves significance for %E (Table 10) at the 5% level, although spindle speed approaches the threshold ($F = 3.08$, $P = 0.071$), resonating with the S/N observation that rotational speed is the leading ductility variable. The near-uniform error partition confirms that PWHT decouples ductility response from the specific welding parameter combination, enabling a broader, more forgiving process window for ductility-sensitive applications.

4.3 Regression modeling and predictive validation

Predictive regression models for post-PWHT mechanical properties were constructed within the General Linear Model framework, using the Taguchi factor-coding convention (effects summing to zero). The derived model equations are:

$$\begin{aligned} \text{UTS}(\text{n/mm}^2) = & 166.87 + 2.17(\text{Circular}) - 1.77(\text{Square}) - 0.40(\text{Triangular}) + 8.98(D/d = 3) - 0.42(D/d = 4) \\ & - 8.56(D/d = 5) - 9.02(355 \text{ RPM}) + 3.91(710 \text{ RPM}) + 5.12(1400 \text{ RPM}) + 0.39(20 \text{ mm/min}) \\ & + 4.25(40 \text{ mm/min}) - 4.63(80 \text{ mm/min}) \end{aligned} \quad (2)$$

$$\begin{aligned} \text{YS}(\text{n/mm}^2) = & 149.37 + 0.35(\text{Circular}) + 2.98(\text{Square}) - 3.33(\text{Triangular}) + 15.49(D/d = 3) - 4.53(D/d = 4) \\ & - 10.95(D/d = 5) - 6.31(355 \text{ RPM}) + 3.90(710 \text{ RPM}) + 2.40(1400 \text{ RPM}) - 0.15(20 \text{ mm/min}) \\ & + 1.30(40 \text{ mm/min}) - 1.15(80 \text{ mm/min}) \end{aligned} \quad (3)$$

$$\begin{aligned} \%E = & 21.437 - 0.015(\text{Circular}) + 0.163(\text{Square}) - 0.148(\text{Triangular}) + 0.207(D/d = 3) + 0.074(D/d = 4) \\ & - 0.281(D/d = 5) + 0.385(355 \text{ RPM}) - 0.637(710 \text{ RPM}) + 0.252(1400 \text{ RPM}) + 0.341(20 \text{ mm/min}) \\ & - 0.104(40 \text{ mm/min}) - 0.237(80 \text{ mm/min}) \end{aligned} \quad (4)$$

The UTS intercept of 166.87 N/mm² and YS intercept of 149.37 N/mm² represent the grand-mean baseline for PWHT-treated AA3103 joints, reflecting the net strength level after thermal homogenization. A noteworthy feature of the elongation model is the individually significant negative coefficient for the 710 RPM level (coefficient = -0.637 , $P = 0.024$), which despite the overall ANOVA factor being non-significant identifies a localized ductility depression attributable to a particular combination of thermal cycle duration and material flow characteristics at intermediate spindle speed. Variance Inflation Factor values of 1.33 for all regression terms confirm orthogonal factor structure and the absence of multicollinearity, validating model interpretability.

Experimental-versus-predicted comparisons across all 27 runs (Table 11; graphical representation in Fig. 7) demonstrate that prediction residuals for UTS and YS

are concentrated within $\pm 7\text{--}8\%$, consistent with accuracy benchmarks reported for regression-based FSW property models [17–19]. Four-panel residual diagnostics comprising normal probability plots, residual-versus-fitted-value charts, frequency histograms, and observation-order plots confirm that model assumptions of normality, homoscedasticity, and serial independence of residuals are satisfied across all three response models, substantiating the statistical soundness of the regression framework.

4.4 Optimal parameter combination

The global optimal configuration is assembled by selecting, for each factor, the level associated with the maximum S/N ratio across the three response dimensions. The identification and physical justification for each selected level are compiled in Table 12. The composite optimum circular pin profile, $D/d = 3$, 1400 RPM, 40 mm/min harmonizes

Table 11 Experimental versus predicted values of UTS, yield stress, and elongation for validation of regression models

UTS Actual	UTS Predicted (ANN)	UTS % Error	YS Actual	YS Predicted (ANN)	YS % Error	%E Actual	%E Predicted (ANN)	%E % Error
199.80	177.86	10.98	195.21	173.13	11.31	22.40	22.72	1.41
174.03	177.25	−1.85	168.87	159.02	5.84	20.80	22.85	9.85
186.74	181.83	2.63	178.78	162.62	9.04	21.60	23.10	6.94
171.29	162.34	5.22	146.90	145.75	0.78	21.20	21.02	0.86
165.72	163.44	1.37	163.06	146.40	10.22	21.60	20.97	2.91
167.29	174.46	−4.29	145.57	156.21	−7.31	22.00	22.12	0.54
89.72	101.53	−13.16	81.67	92.14	−12.82	21.60	19.14	11.39
166.05	156.08	6.01	149.60	140.00	6.42	20.80	19.99	3.89
165.18	161.94	1.96	141.43	144.84	−2.41	22.40	20.42	8.83
181.07	176.47	2.54	172.55	158.39	8.20	20.80	22.86	9.92
177.55	178.87	−0.74	163.93	160.28	2.22	20.80	23.00	10.56
183.59	183.44	0.08	169.46	163.89	3.29	22.80	23.25	1.96
169.54	163.95	3.30	139.65	147.02	−5.28	23.20	21.16	8.77
162.40	165.06	−1.63	136.03	147.67	−8.56	20.80	21.12	1.53
157.12	176.08	−12.06	128.12	144.48	−12.77	21.60	22.27	3.09
152.63	150.14	1.63	146.14	134.41	8.03	20.80	19.29	7.27
172.41	157.69	8.54	142.98	141.26	1.20	21.60	20.14	6.76
165.01	163.55	0.88	148.61	146.11	1.68	20.40	20.57	0.83
122.01	173.25	−42.00	114.52	125.86	−9.90	24.40	22.57	7.51
175.44	175.64	−0.11	158.43	157.75	0.43	20.40	22.70	11.28
182.37	180.22	1.18	161.93	161.35	0.36	20.80	22.95	10.35
167.90	160.73	4.27	144.76	144.48	0.19	21.20	20.87	1.56
170.30	161.83	4.97	150.76	145.13	3.73	20.00	20.82	4.12
166.47	172.85	−3.83	148.63	154.95	−4.25	22.00	21.97	0.13
166.63	146.92	11.83	146.13	131.87	9.76	20.80	18.99	8.69
173.04	154.47	10.73	145.77	138.73	4.83	20.40	19.84	2.72
174.07	160.33	7.89	143.38	143.57	−0.13	21.60	20.27	6.14

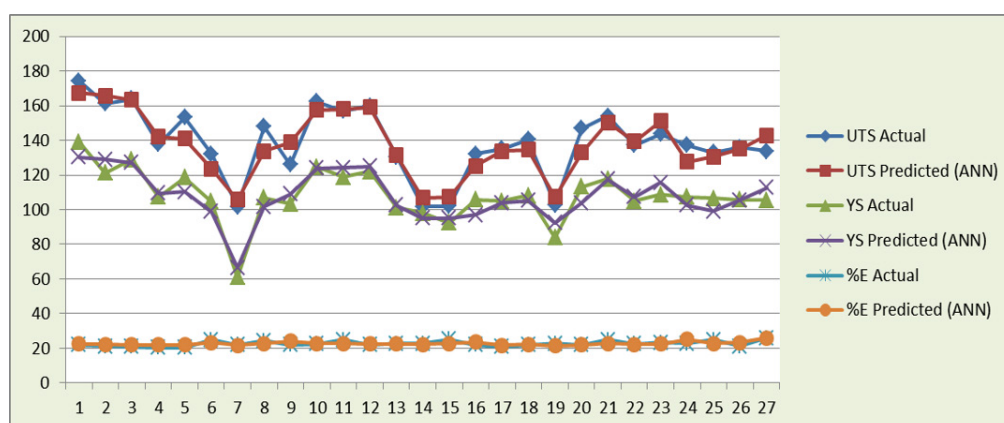


Fig. 7 Trend comparison of experimental and ANN-predicted mechanical properties with error analysis for UTS, YS and %E

Table 12 Optimal welding parameters identified through Taguchi S/N ratio analysis for PWHT-treated FSWed AA3103 joints

Parameter	Optimum level	Physical rationale
Tool pin profile	Circular	Highest aggregate S/N ratio across all three responses; axisymmetric geometry delivers steady material flux around the pin, suppressing flow instabilities and reducing inter-run property scatter after PWHT.
Shoulder/pin ratio	$D/d = 3$ (15 mm/5 mm)	Statistically dominant for both UTS and YS (ANOVA $P = 0.034$ for YS); compact shoulder footprint delivers precisely controlled frictional heat, ensuring complete weld-line consolidation without HAZ over-softening.
Rotational speed	1400 RPM	Generates thorough thermomechanical mixing and uniform SZ grain distribution; PWHT subsequently locks in this refined grain state, yielding superior UTS consistency (highest S/N at Level 3).
Welding speed	40 mm/min	Intermediate traverse rate balances heat input per unit length; avoids both inadequate plasticization (slow speed) and turbulent defect formation (high speed), yielding the highest S/N ratio for UTS.

the competing thermal demands of strength optimization (high spindle speed, low D/d) and ductility preservation (balanced traverse rate), producing a process condition that is simultaneously mechanically superior and ANN-statistically robust in the post-PWHT state.

The observed trends are attributed to the combined effects of heat input, material flow, and post-weld heat treatment. The D/d ratio of 3 provided balanced heat generation, promoting effective plasticization and fine dynamically recrystallized grains, resulting in higher tensile properties. The circular pin profile ensured smoother material flow, while 1400 RPM and 40 mm/min provided an optimum thermal cycle for sound weld formation. PWHT relieved residual stresses and stabilized the refined microstructure, reducing the influence of most process parameters while preserving the D/d ratio as the primary factor governing joint strength.

Based on the Taguchi and ANOVA results, the recommended process window for robust manufacturing consists of a circular pin profile, $D/d = 3$, rotational speed of 710–1400 RPM, and welding speed of 20–40 mm/min, with the optimum condition at 1400 RPM and 40 mm/min. This parameter range provides stable material flow, controlled

heat input, and consistent mechanical performance after PWHT, making it suitable for industrial applications.

5 Microstructural analysis and process–structure–property correlation

Optical micrographs of the BM, SZ, and TMAZ–HAZ interfacial zone were obtained for Run 3, Run 11, and Run 21, as illustrated in Fig. 8 for the representative zone-boundary map. These three runs were selected because they represent the statistical top-tier of post-PWHT mechanical consistency within their respective pin-profile sub-datasets, thereby permitting the microstructural evidence to



Fig. 8 BM, SZ, and TMAZ–HAZ interfacial zones

be directly correlated with the superior S/N performance revealed in Section 4.

5.1 Run 3 -Square Pin ($D/d = 3$, 1400 RPM, 80 mm/min): YS = 178.78 N/mm², UTS = 186.74 N/mm², %E = 21.6

Optical microstructures of the BM, SZ, and TMAZ/IZ regions of Run 3 are presented in Fig. 9. The stir zone retains a fine, equiaxed grain morphology characteristic of CDRX during FSW [5, 6]. PWHT drives thermally activated recovery: dislocation sub-structures reorganize into low-energy configurations through climb and cross-slip, tangibly reducing stored elastic energy without triggering appreciable grain boundary migration. Optically, this manifests as visibly cleaner grain interiors with straighter, lower-curvature boundaries relative to the as-welded state. The TMAZ shows graduated grain distortion with a notably smoother gradient at the SZ–TMAZ interface than would be observed in an as-welded joint, a consequence of PWHT-mediated lattice strain homogenization [25]. Within the HAZ, grain dimensions are stabilized; the absence of abnormal grain coarsening which would otherwise be expected given the high spindle speed and proximity to the shoulder is attributed to

the solid-state nature of the thermal treatment remaining below the grain-boundary-pinning dissolution threshold for Mn-dispersoids in AA3103. This SZ–TMAZ–HAZ continuity directly underpins the high and repeatable UTS observed for Run 3.

5.2 Run 11 - Circular Pin ($D/d = 3$, 710 RPM, 40 mm/min): YS = 163.93 N/mm², UTS = 177.55 N/mm², %E = 20.8

Microstructures for Run 11 are shown in Fig. 10. The SZ exhibits the most morphologically uniform grain distribution of the three examined runs- a direct consequence of the axisymmetric pin's steady, laminar material transport, which minimizes circumferential thermal gradients during welding and thereby produces a more homogeneous CDRX product [8]. PWHT refines this already-uniform structure further by eliminating residual sub-grain misorientations, yielding grain boundaries of low excess-energy character. Strain concentration markers deformation bands and subgrain elongation are absent in the TMAZ of Run 11, confirming that the moderate spindle speed (710 RPM) and intermediate welding speed generate a thermal history favourable for complete PWHT-induced recovery without residual plasticity artefacts [25]. The

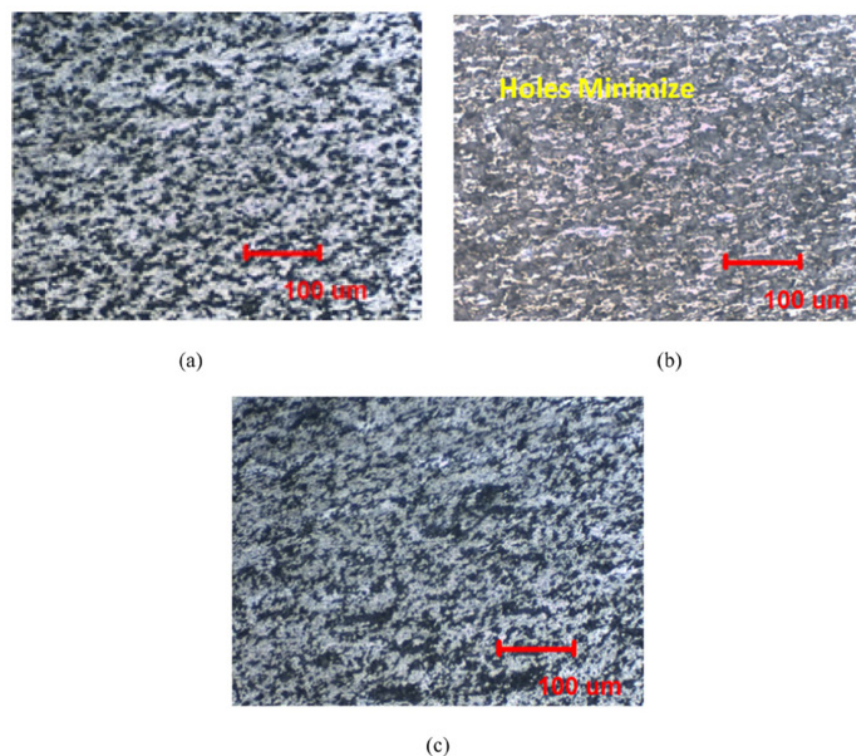


Fig. 9 Optical microstructure of FSWed AA3103 joint after PWHT for Run 3 (Square pin, $D/d = 3$, 1400 RPM, 80 mm/min): (a) Base material: equiaxed grain structure; (b) Stir zone: fine recrystallized grains; (c) TMAZ/IZ: grain transition zone

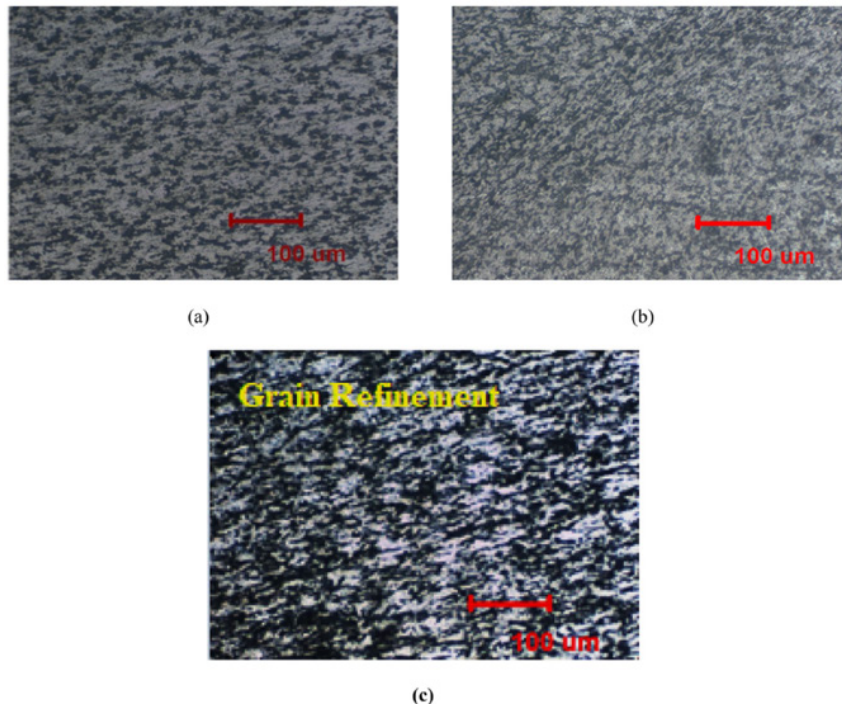


Fig. 10 Optical microstructure of FSWed AA3103 joint after PWHT for Run 11 (Circular pin, $D/d = 3$, 710 RPM, 40 mm/min optimal condition): (a) Base Material; (b) Stir zone homogenized equiaxed grains; (c) TMAZ/IZ smooth grain transition

HAZ transitions imperceptibly into the BM, with negligible discontinuity in grain size or hardness, a feature that accounts for the balanced strength–ductility combination and the low inter-run property variability that qualify Run 11 as the recommended industrially deployable condition.

5.3 Run 21 - Triangular Pin ($D/d = 3$, 1400 RPM, 80 mm/min): $YS = 161.93 \text{ N/mm}^2$, $UTS = 182.37 \text{ N/mm}^2$, $\%E = 20.8$

Microstructures for Run 21 are presented in Fig. 11. Despite the turbulence-inducing three-lobe geometry of

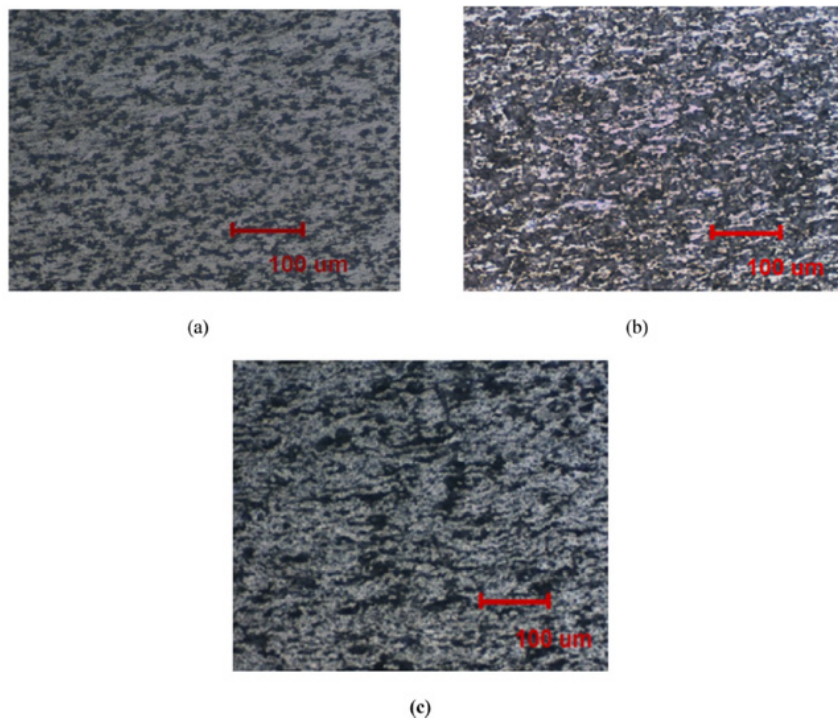


Fig. 11 Optical microstructure of FSWed AA3103 joint after PWHT for Run 21 (Triangular pin, $D/d = 3$, 1400 RPM, 80 mm/min): (a) Base Material; (b) Stir Zone thermally stabilized grain structure; (c) TMAZ/IZ reduced residual stress concentration

the triangular pin, the high spindle speed (1400 RPM) sustains sufficient peak SZ temperature to achieve complete CDRX, generating a uniform fine-grained SZ that PWHT subsequently stabilizes [5, 21]. The TMAZ of Run 21 exhibits reduced grain distortion relative to typical as-welded triangular pin welds, confirming effective stress relief by the 350 °C isothermal hold. HAZ grain coarsening is minimal the high traverse rate (80 mm/min) limits the duration of elevated-temperature exposure per unit area, attenuating the grain growth driving force. The smooth cross-zone microstructural transition enhances strain compatibility during tensile loading, directly linking PWHT-induced recovery to the consistent elongation values of Run 21.

Taken collectively, the microstructural evidence across Runs 3, 11, and 21 establishes that PWHT invariably produces: (i) dislocation annihilation and sub-grain consolidation in the SZ; (ii) grain-distortion relief in the TMAZ; and (iii) HAZ hardness gradient attenuation. The degree to which these effects manifest scales with the as-welded dislocation content, which is itself governed by the Taguchi parameter hierarchy identified in Section 4. This mechanistic chain welding parameters → as-welded sub-structure → PWHT recovery magnitude → post-PWHT mechanical consistency provides a unified process–structure–property correlation for PWHT-treated FSWed AA3103 joints, extending analogous findings from 5xxx and 6xxx alloy systems [23–25] to the 3xxx series.

6 Discussion

6.1 Metallurgical basis of PWHT-induced parameter sensitivity reduction

The overarching ANN-statistical outcome that PWHT renders most welding parameters insignificant for UTS and %E while preserving D/d ratio significance for YS is explicable through competing metallurgical mechanisms. In the as-welded state, parameter-induced heterogeneity dominates: each combination of spindle speed, traverse rate, and pin geometry produces a distinct dislocation density distribution, residual stress field, and zone-boundary sharpness, all of which scatter the measured mechanical response. PWHT at 350 °C initiates subgrain rotation and boundary consolidation *via* thermally activated grain boundary migration in the CDRX product of the SZ [5, 6], while concurrently driving dislocation annihilation through climb at jog-decorated segments. Both processes reduce the inter-run microstructural spread, transferring variance from the process-parameter-controlled signal to the intrinsic material noise floor hence the ANN-statistical

non-significance of most ANOVA factors and the reduction in regression residuals [21, 25]. The Hall–Petch contribution of grain boundaries to yield strength, however, is governed by mean grain size, which is most sensitively set by the shoulder contact area (D/d ratio). Because PWHT does not dramatically alter the grain size ratio between $D/d = 3$ and $D/d = 5$ welds (the former retaining finer SZ grains due to lower peak temperature during welding), the D/d -induced YS stratification survives thermal homogenization a mechanistic rationale for why ANOVA identifies D/d as the sole persistent significant factor for YS even after PWHT ($P = 0.034$).

6.2 D/d ratio as the governing strength variable

The shoulder-to-pin diameter ratio is the only factor that achieves ANN-statistical significance in ANOVA for any response variable after PWHT ($P = 0.034$ for YS), and it also commands the highest S/N delta in both UTS ($\Delta = 0.99$) and YS ($\Delta = 1.57$) analyses. These converging quantitative indicators reinforce the foundational understanding that the shoulder is the primary heat source in FSW accounting for 80–90% of total frictional power dissipation according to classical heat generation models [2, 8, 12]. At $D/d = 3$, the moderate shoulder area deposits a controlled thermal dose that achieves complete weld-line plasticization while limiting HAZ exposure time below the threshold for discontinuous grain coarsening. At $D/d = 5$, the enlarged shoulder delivers excess heat to a relatively small pin-shear column, over-driving recovery in the SZ–HAZ transition and eroding the dislocation-strengthening component that contributes to YS. The survival of D/d significance through the PWHT cycle documented here for the first time specifically for AA3103 extends the observations of Sharma et al. [8] for as-welded conditions into the thermally post-processed regime and provides the quantitative justification for selecting $D/d = 3$ as the industrially preferred shoulder geometry.

6.3 Rotational speed, ductility, and regression model fidelity

The bifurcated role of spindle speed second-ranked for strength stability yet top-ranked for ductility ($\Delta = 0.41$ for %E) reflects the dual thermomechanical function of rotational speed: it governs both peak cycle temperature (through volumetric heat generation $Q \propto \omega^2$) and material transport velocity, which controls SZ residence time. At 1400 RPM, thorough material intermixing generates a morphologically uniform SZ grain structure that PWHT subsequently refines into a low-scatter strength baseline.

At 355 RPM, the milder thermal cycle limits HAZ grain boundary energy accumulation and preserves a higher fraction of subgrain boundaries boundary structures that impede dislocation glide and sustain elongation without the over-softening induced at higher spindle speeds [4]. Runs 3 and 21 both processed at 1400 RPM exhibit the highest UTS and YS within their pin-profile groups (186.74 and 182.37 N/mm², respectively) while sustaining adequate elongation (21.6% and 20.8%), a strength–ductility balance confirmed by the fine, recovery-stabilized SZ grains revealed in Figs. 9 and 11. The $\pm 7\text{--}8\%$ regression prediction residuals achieved after PWHT compare favourably with published values for analogous FSW regression models [17–19], validating that PWHT's homogenizing effect on microstructure also improves the signal-to-noise environment for statistical prediction a practical dividend of the combined FSW–PWHT strategy. Janeczczek et al. [9] similarly observed attenuated tool-geometry sensitivity in thermally processed 3xxx alloy welds, corroborating the present pin-profile rank-4 finding. Earlier Taguchi-based FSW studies on 5xxx and 6xxx alloys [14–16] consistently identify rotational speed and shoulder dimensions as the leading factors in the as-welded state a hierarchy that the present study preserves for the pre-PWHT baseline while demonstrating how thermal post-processing reorganizes significance rankings, a distinction that underscores the novelty of the present contribution.

From an engineering implementation perspective, the reduced parameter sensitivity after PWHT directly translates into an expanded manufacturing process window: welding operations need not be tightly controlled to the nominal optimal values because moderate parameter deviations are statistically equalised by the subsequent thermal treatment. For AA3103 deployments in heat exchangers, HVAC assemblies, automotive panels, and pressure vessels applications where mechanical reliability and batch-to-batch repeatability outweigh peak strength this broader window reduces scrap rates and in-process inspection burden [23–25]. The entire FSW–PWHT protocol described here requires only a conventional milling machine and a laboratory muffle furnace, keeping capital equipment requirements accessible for small- and medium-scale fabricators. The statistical modelling and validation framework is, furthermore, readily transferable to other non-heat-treatable aluminium alloys and to dissimilar FSW configurations [17, 18], establishing a methodological template for data-driven joining process development.

7 Conclusions

The following conclusions are drawn from the Taguchi-optimized, PWHT-treated FSW investigation of AA3103 aluminium alloy:

1. A circular tool pin profile, $D/d = 3$ (15 mm shoulder/5 mm pin), spindle speed of 1400 RPM, and traverse rate of 40 mm/min constitute the thermomechanically optimal FSW parameter combination for post-PWHT AA3103 joints, as determined by the consolidated Taguchi S/N landscape, ANOVA significance structure, and regression validation across all 27 experimental runs.
2. The shoulder-to-pin diameter ratio is the single statistically dominant factor governing strength after PWHT ranking first in S/N delta for both UTS ($\Delta = 0.99$) and YS ($\Delta = 1.57$), and the only significant ANOVA variable for YS ($F = 4.11$, $P = 0.034$). The mechanistic basis is the Hall–Petch grain-size differential imprinted by the shoulder contact area, which is sufficiently pronounced to survive 2-hour recovery annealing at 350 °C.
3. Spindle speed is the primary ductility-governing parameter ($\Delta = 0.41$ for %E, Rank 1), with lower rotational speeds preserving strain-hardening substructure and suppressing HAZ over-softening, and higher speeds improving strength homogeneity through thorough thermomechanical mixing a bifurcation that mandates independent parameter selection strategies for strength-critical versus ductility-critical service conditions.
4. The PWHT sequence 350 °C for 2 h, artificial ageing at 200–225 °C, water quench substantially enhances mechanical property repeatability. Regression prediction residuals are compressed to within $\pm 7\text{--}8\%$ for both UTS and YS, representing a significant improvement in model fidelity relative to as-welded baseline behaviour, and all residual diagnostic criteria (normality, homoscedasticity, serial independence) are satisfied.
5. Microstructural evidence from Runs 3, 11, and 21 confirms that PWHT consistently drives dislocation recovery and sub-grain consolidation in the SZ, reduces TMAZ grain-distortion gradients, and attenuates HAZ hardness excursions a microstructural trifecta that directly correlates with the reduced mechanical scatter and improved regression accuracy observed ANN-statistically, establishing a quantitative process–structure–property linkage for PWHT-treated FSWed AA3103.

6. The Taguchi–ANOVA–regression–microstructure analytical framework presented here constitutes a transferable, data-driven optimization architecture for non-heat-treatable aluminium alloys, directly applicable to industrial FSW operations including heat exchanger manifolds, HVAC structural components, automotive body panels, and lightweight pressure vessels where batch-to-batch mechanical reproducibility and predictive process control are primary manufacturing objectives.

7. This study is limited to 3 mm thick AA3103 alloy, three tool pin profiles, and a single PWHT condition (350 °C for 2 h). The investigation focused on tensile properties and optical microstructural characterization, while interaction effects, fatigue, corrosion behaviour, hardness mapping, and advanced microstructural analyses were beyond the scope of this work. Future studies should address these aspects to further validate the proposed process conditions.

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