

# Process-Property Characterisation of Wire Arc Additive Manufacturing Assisted by Post-Deposition Friction Stir Welding for Aluminium Alloy 4043

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## Abstract

This study characterises the process-property relationship of Wire Arc Additive Manufacturing (WAAM) assisted by post-deposition Friction Stir Welding (FSW) for Aluminium Alloy 4043 (AA4043) deposited on an AA6061-T6 substrate. WAAM samples were fabricated using a robotic Gas Metal Arc Welding (GMAW) system, with deposition parameters (arc current, arc voltage, travel speed) optimised via a Taguchi L9 design of experiments, evaluating bead height and bead width as dual responses. The optimised WAAM parameter set (140 A, 20 V, 400 mm/min) was subsequently treated with post-deposition FSW (900 RPM, 30 mm/min) using a custom-fabricated jig. Microstructural evolution was evaluated using FE-SEM and EDX, while mechanical performance was assessed through Vickers microhardness testing. As-deposited WAAM samples exhibited coarse columnar  $\alpha$ -Al dendrites, Mg<sub>2</sub>Si-rich eutectic segregation, and interlayer porosity, yielding a mean hardness of 66.3 HV. Post-deposition FSW induced dynamic recrystallisation, refining the microstructure into fine equiaxed grains, homogenising the Mg<sub>2</sub>Si-rich phase, and eliminating visible porosity, raising the mean hardness to 95.3 HV (an increase of approximately 44%). These findings indicate that post-deposition FSW is an effective post-processing strategy for mitigating the inherent defects of WAAM-fabricated AA4043 components, offering a viable pathway toward producing aluminium parts with superior structural integrity for aerospace, automotive, and marine applications.

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## Keywords

Wire Arc Additive Manufacturing, Post-Deposition FSW, Aluminium Alloy 4043, Microstructure Refinement, Microhardness, Taguchi Method

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## 1. Introduction

Wire Arc Additive Manufacturing (WAAM) is a Directed Energy Deposition (DED) technique that uses an electric arc to melt and deposit metal wire feedstock layer by layer, offering high deposition rates and cost-effectiveness for fabricating large-scale metallic components [1] [2]. However, WAAM-fabricated parts commonly exhibit porosity, coarse columnar grains, and anisotropic mechanical properties that compromise structural integrity [2]. Aluminium Alloy 4043 (AA4043), an Al-Si-based filler material valued for its weldability and corrosion resistance, is frequently used in WAAM [3]-[6]; yet components built from AA4043 can still suffer from weak interlayer bonding and microstructural inhomogeneity [7] [8].

To mitigate these limitations, Friction Stir Welding (FSW) has been proposed as a solid-state post-processing technique applied to WAAM-fabricated components, either between successive deposited layers or as a single pass following complete deposition [9] [10]. The stirring action of a rotating tool induces severe plastic deformation and dynamic recrystallisation, refining the coarse columnar grains into finer, more homogeneous structures while closing porosity and improving interlayer bonding [11]-[14]. Prior studies have reported that interlayer friction stir processing effectively eliminates porosity and refines microstructure in WAAM-fabricated aluminium alloys [11] [12] [15]-[17]. Despite these promising results, comprehensive process-property characterisation of the WAAM + post-deposition FSW hybrid route specifically for AA4043 remains limited.

The combined effects of WAAM deposition parameters and post-deposition FSW treatment on the grain structure, phase distribution, and hardness of AA4043 are not yet well understood, which constrains optimisation of this hybrid process for reliable, high-performance applications in the aerospace, automotive, and marine sectors [18]-[21].

This study therefore aims to: (1) investigate the effect of WAAM and post-deposition FSW parameters on the microhardness of AA4043 deposits; (2) analyse the microstructural evolution of AA4043 before and after post-deposition FSW; and (3) propose optimised process parameters for the WAAM + post-deposition FSW route for AA4043.

## 2. Materials and Methods

### 2.1. Materials and Sample Preparation

AA4043 aluminium wire (1.2 mm diameter) was used as the feedstock material [3] [5] [22], deposited onto a T-shaped AA6061-T6 substrate (10 mm × 25 mm ×

150 mm). Prior to deposition, the substrate surface was cleaned with alkaline water, air-dried, and mechanically abraded to remove oxide layers and ensure adequate bonding of the initial WAAM layer.

## 2.2. WAAM Fabrication and Process Parameter Optimisation

The WAAM deposition was conducted using a Gas Metal Arc Welding (GMAW) system with a KUKA robot model KR 4C and EWM 352 Alpha Q welding as heat source, under an argon shielding gas flow ( $\geq 98\%$  purity, 20 L/min) (**Figure 1**).



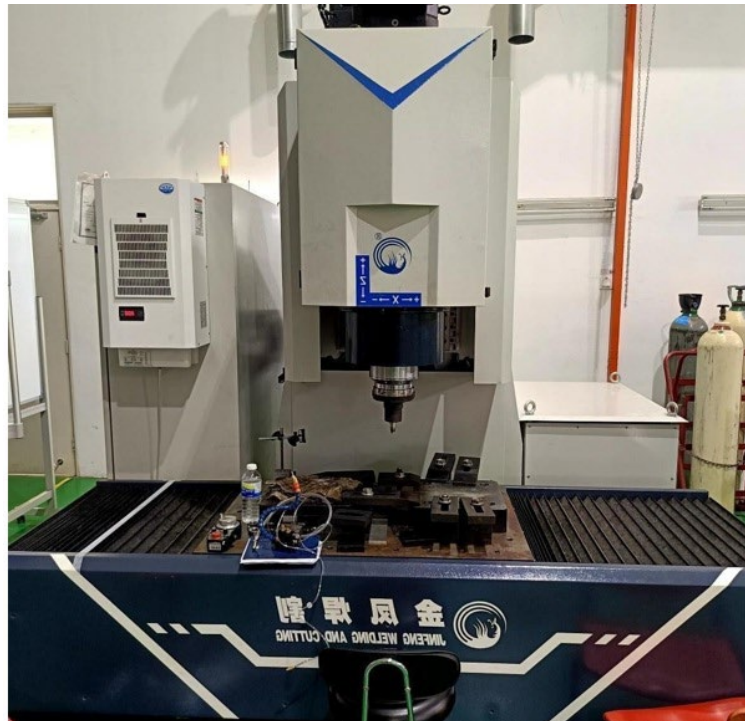
**Figure 1.** KUKA robot model KR 4C.

Three process parameters—arc current (80 - 140 A), arc voltage (17 - 20 V), and travel speed (300 - 500 mm/min)—were varied according to a Taguchi L9 orthogonal array generated in Minitab, producing nine parameter combinations (**Table 1**). Bead height (BH) and bead width (BW) were measured for each sample and jointly optimised using the mean-of-means approach to identify the combination yielding the most consistent and dimensionally favourable bead geometry.

## 2.3. Post-Deposition Friction Stir Welding Process

Upon completion of WAAM deposition, a single post-deposition FSW pass was applied across the top surface of the fully-built wall using a Jinfeng Welding and Cutting FSW machine [9]; FSW was not applied between individual deposited layers in this study. A custom aluminium jig (155 mm  $\times$  82 mm  $\times$  20 mm, secured with four M6 screws) was fabricated via CNC machining to hold the small WAAM samples securely during processing. Two parameter sets—900 RPM/30 mm/min and 1100 RPM/90 mm/min—were trialled; 900 RPM with 30 mm/min travel

speed was selected for further characterisation, as higher rotational and travel speeds produced overheating and inconsistent weld quality under the available equipment and operating expertise. Detailed FSW (**Figure 2**) tool specifications (tool material, shoulder and pin geometry, tilt angle, plunge depth, dwell time, and axial force) and additional WAAM parameters (wire-feed speed, contact-tip-to-work distance, torch angle, deposition path, interpass temperature, and inter-layer cooling time) were not systematically logged during this exploratory study; this is acknowledged as a limitation for full reproducibility and is addressed under Future Work.



**Figure 2.** Jinfeng welding and cutting (FSW).

## 2.4. Microstructural and Mechanical Characterisation

Samples were sectioned, mechanically ground (240 - 800 grit), polished with diamond lubricant, and etched using Keller's reagent for microstructural revelation. Field Emission Scanning Electron Microscopy (FE-SEM) was used to examine grain morphology, and Energy Dispersive X-ray Spectroscopy (EDX) was used to map elemental distribution (Al, Si) before and after post-deposition FSW. Vickers microhardness was measured using a 0.1 HV load with a 10 s dwell time at five locations per sample, for both as-deposited WAAM and WAAM + post-deposition FSW conditions.

It should be noted that the five reported hardness values for each condition were obtained from five locations on a single fabricated specimen rather than from independently fabricated replicate specimens; consequently, the reported standard deviation reflects within-specimen spatial variation rather than between-

specimen reproducibility, and no formal statistical hypothesis test was performed to compare the two conditions.

### 3. Results and Discussion

#### 3.1. Optimised WAAM and Post-Deposition FSW Parameters

The Taguchi L9 results (**Table 1**) show that bead height and bead width varied non-linearly with arc current, voltage, and travel speed, reflecting the coupled influence of heat input and deposition rate on melt pool behaviour [7] [23]. Applying the mean-of-means approach to the dual bead height/width response identified 140 A, 20 V, and 400 mm/min as the optimum WAAM parameter set, corresponding to Sample 9, which produced the most dimensionally consistent bead geometry among the nine trials. For post-deposition FSW, 900 RPM and 30 mm/min travel speed were adopted as the working parameters (**Table 2**), as this combination provided adequate plastic deformation and heat generation for grain refinement while avoiding overheating and excessive tool wear observed at higher RPM/travel-speed settings [9] [24].

**Table 1.** Taguchi L9 orthogonal array for WAAM parameters and resulting bead geometry.

| No. | Current (A) | Voltage (V) | Travel Speed (mm/min) | BH (mm) | BW (mm) |
|-----|-------------|-------------|-----------------------|---------|---------|
| 1   | 80          | 17          | 300                   | 14.04   | 4.15    |
| 2   | 80          | 18.5        | 400                   | 14.00   | 7.50    |
| 3   | 80          | 20          | 500                   | 14.10   | 6.05    |
| 4   | 110         | 17          | 400                   | 14.35   | 8.02    |
| 5   | 110         | 18.5        | 500                   | 13.70   | 8.75    |
| 6   | 110         | 20          | 300                   | 14.70   | 6.85    |
| 7   | 140         | 17          | 500                   | 14.20   | 8.35    |
| 8   | 140         | 18.5        | 300                   | 13.68   | 6.54    |
| 9   | 140         | 20          | 400                   | 13.34   | 17.20   |

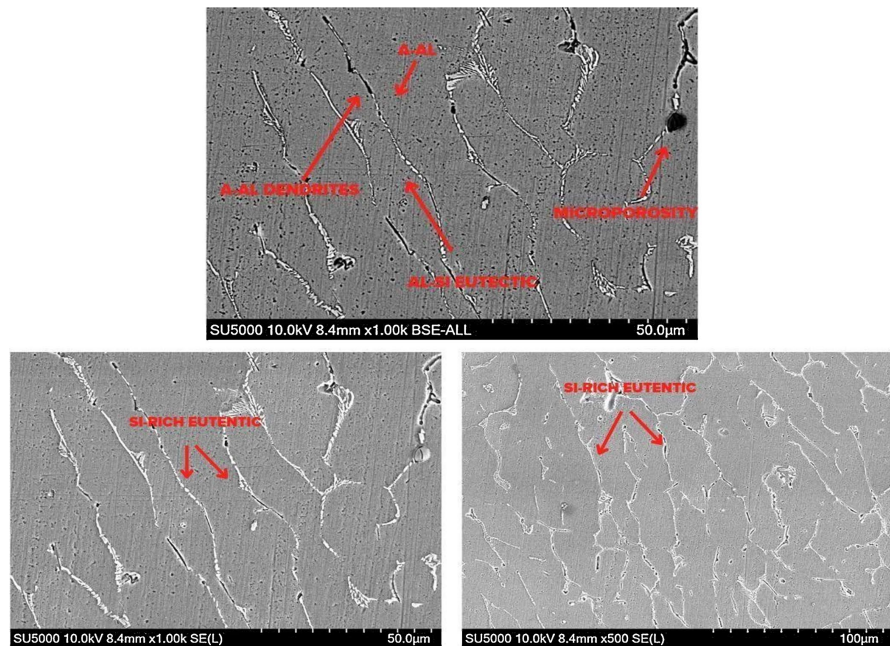
**Table 2.** Optimised WAAM and post-deposition FSW process parameters.

| Parameter                   | Optimised Value |
|-----------------------------|-----------------|
| Arc current (WAAM)          | 140 A           |
| Arc voltage (WAAM)          | 20 V            |
| Travel speed (WAAM)         | 400 mm/min      |
| Tool rotational speed (FSW) | 900 RPM         |
| Travel speed (FSW)          | 30 mm/min       |

#### 3.2. Microstructural Evolution

FE-SEM examination of the as-deposited WAAM samples revealed coarse colum-

nar  $\alpha$ -Al dendrites aligned along the build direction, consistent with the directional solidification and thermal gradients inherent to WAAM's rapid melting-cooling cycles [2] [6]. A Mg<sub>2</sub>Si-rich eutectic phase was observed segregated along dendrite boundaries, together with isolated microporosity [15] [25]—features expected to reduce ductility and produce anisotropic, spatially inconsistent mechanical properties (Figure 3).



**Figure 3.** FE-SEM micrograph of the as-deposited WAAM AA4043 sample, showing coarse columnar  $\alpha$ -Al dendrites, Mg<sub>2</sub>Si-rich eutectic segregation, and isolated microporosity.

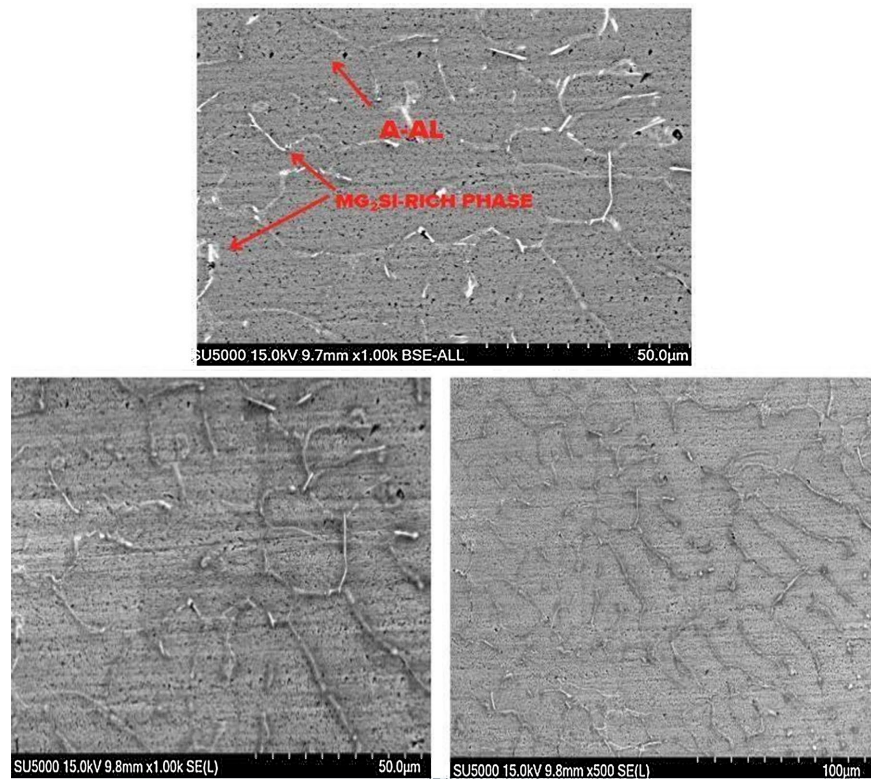
Following post-deposition FSW, the microstructure transformed into fine, equiaxed grains, indicating that the severe plastic deformation and localised frictional heating from the rotating tool promoted dynamic recrystallisation [11]-[13] [26]-[28]. The Mg<sub>2</sub>Si-rich phase was more evenly dispersed after FSW, and no porosity was visually apparent in the stirred zone, consistent with closure of gas pockets and improved interlayer bonding [11] [25] [29] [30] (Figure 4).

EDX mapping (Figure 5 and Figure 6) corroborated these observations: aluminium and silicon distributions were markedly more homogeneous after post-deposition FSW than in the as-deposited condition, supporting the interpretation that the stirring action redistributes alloying elements more uniformly across the matrix [12].

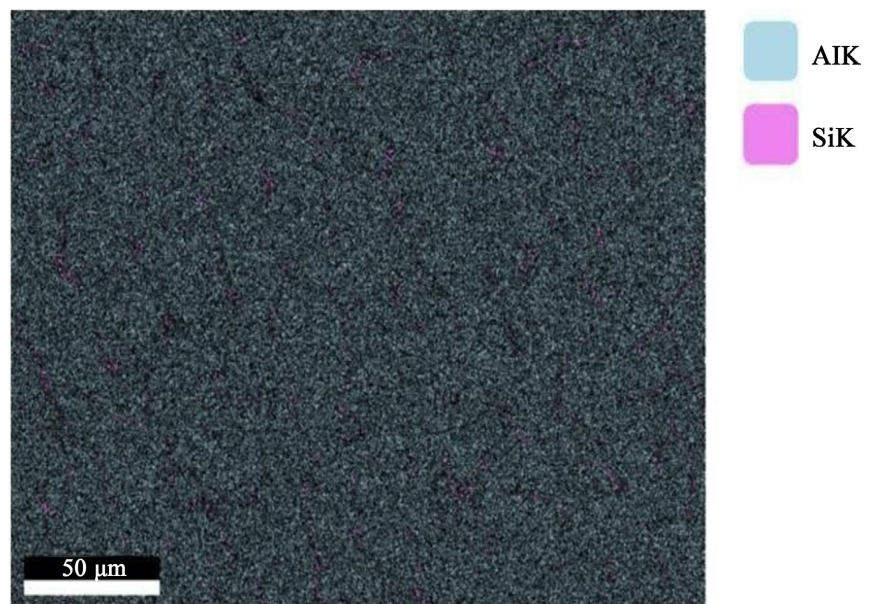
### 3.3. Microhardness Evaluation

Vickers microhardness measurements (Figure 7, Figure 8 and Table 3) showed a mean hardness of 66.3 HV (range 61.8 - 74.5 HV) for the as-deposited WAAM condition, consistent with the coarse-grained, porosity-containing microstructure. After post-deposition FSW, mean hardness increased to 95.3 HV (range 81.7 - 116.3 HV), an improvement of approximately 44%. This increase is attributed

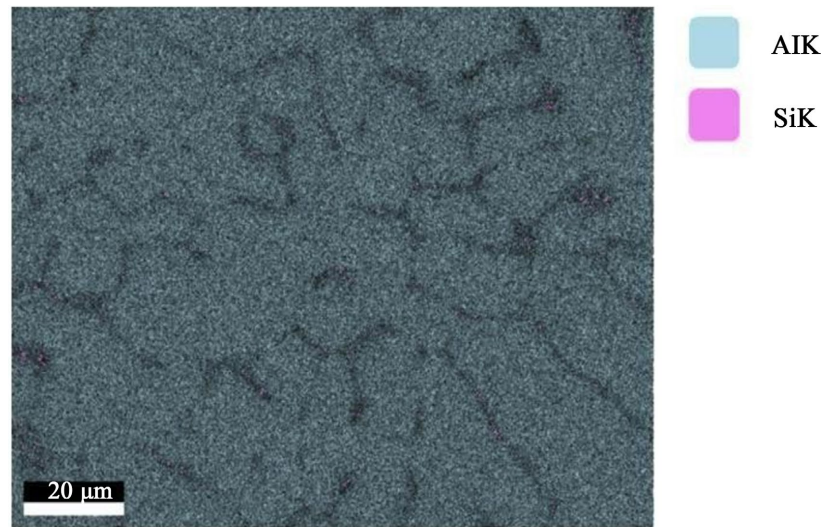
to grain refinement—via the Hall-Petch relationship, finer grains provide greater resistance to dislocation motion—together with reduced porosity and improved interlayer bonding [10] [11] [13] [29] [31].



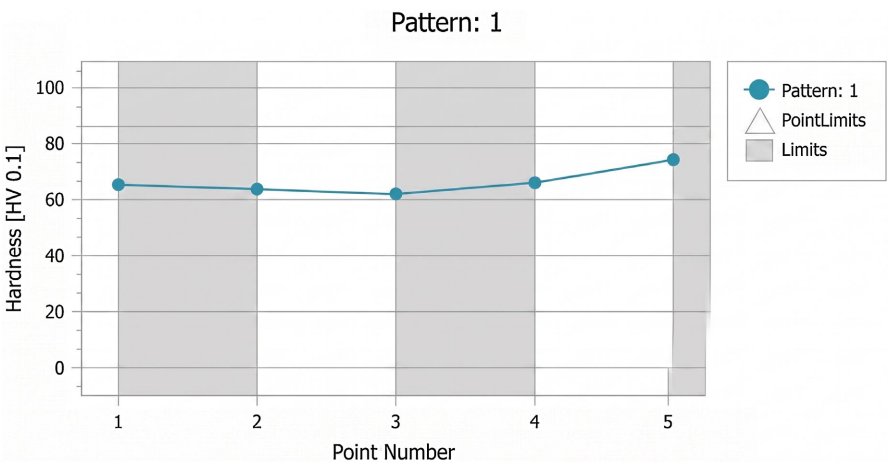
**Figure 4.** FE-SEM micrograph of the WAAM + post-deposition FSW AA4043 sample, showing fine, equiaxed grains and homogenised Mg<sub>2</sub>Si-rich phase distribution.



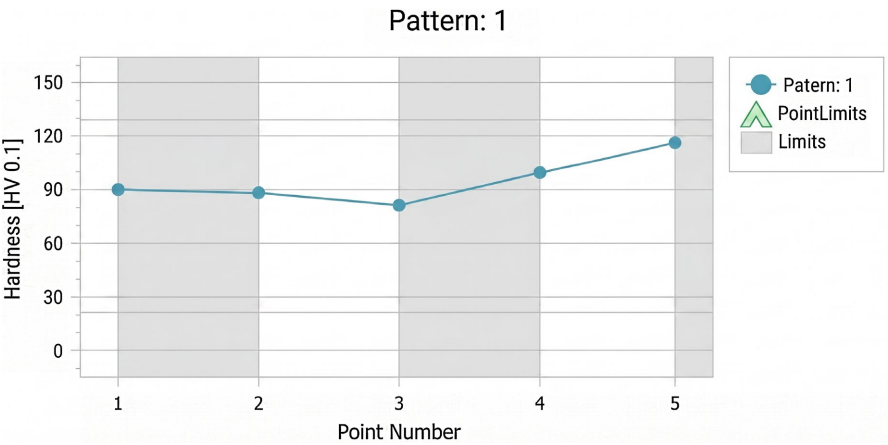
**Figure 5.** EDX elemental maps (Al, Si) of the as-deposited WAAM AA4043 sample.



**Figure 6.** EDX elemental maps (Al, Si) of the WAAM + post-deposition FSW AA4043 sample, showing more homogeneous elemental distribution.



**Figure 7.** Vickers microhardness profile of the as-deposited WAAM AA4043 sample across five measurement points.



**Figure 8.** Vickers microhardness profile of the WAAM + post-deposition FSW AA4043 sample across five measurement points.

**Table 3.** Statistical summary of Vickers microhardness before and after post-deposition FSW.

| Condition                  | Mean (HV) | Std. Dev. (HV) | Range (HV)   |
|----------------------------|-----------|----------------|--------------|
| As-deposited WAAM          | 66.3      | 4.8            | 61.8 - 74.5  |
| WAAM + Post-Deposition FSW | 95.3      | 13.4           | 81.7 - 116.3 |

The larger standard deviation observed after FSW (13.4 HV, versus 4.8 HV for as-deposited WAAM) reflects localised variation associated with non-uniform precipitate/phase redistribution during stirring [12] [17], suggesting that further refinement of FSW parameters (e.g., tool geometry, plunge depth) could improve hardness uniformity.

#### 4. Conclusion

This study characterised the process-property relationship of WAAM-fabricated AA4043 assisted by post-deposition FSW. Taguchi L9 optimisation identified 140 A, 20 V, and 400 mm/min as the optimum WAAM parameter set based on bead geometry, while 900 RPM and 30 mm/min travel speed were established as workable post-deposition FSW parameters. Post-deposition FSW transformed the coarse columnar, porosity-containing WAAM microstructure into a fine, equiaxed, more homogeneous structure, raising mean Vickers microhardness from 66.3 HV to 95.3 HV (~44% increase) [10] [11] [13]. These findings indicate that post-deposition FSW is an effective post-processing strategy for mitigating the inherent defects of WAAM-fabricated AA4043, supporting its potential for producing aluminium components with improved structural integrity for aerospace, automotive, and marine applications [19] [21]. Future work should incorporate complete documentation of WAAM and FSW process parameters (including wire-feed speed, torch geometry, interpass conditions, and FSW tool specifications), testing of independently fabricated replicate specimens with formal statistical analysis, quantitative image-based measurement of grain size and porosity, real-time thermal and residual stress monitoring, systematic evaluation of FSW tool geometry, and expanded mechanical testing (tensile, impact, fatigue) to further validate the hybrid process.

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#### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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