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ORIGINAL RESEARCH ARTICLE

Cold Metal Transfer-Based Wire Arc Additive Manufacturing of AA4043: Microstructural, Mechanical, and Surface Characteristics

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Wire arc additive manufacturing (WAAM) has emerged as a promising near-net-shape manufacturing technology for producing large-scale metallic components with high material utilization and cost-efficiency. However, the widespread adoption of aluminum alloys in WAAM remains challenging due to the complex interactions between process parameters, thermal history, microstructural evolution, defect formation, and mechanical performance. In this study, the influence of wire current on the microstructure, porosity evolution, crystallographic characteristics, residual strain distribution, and mechanical properties of CMT-WAAM-fabricated AA4043 deposits was systematically investigated. Quantitative porosity analysis using ImageJ revealed porosity area fractions of 0.138, 0.033, 0.257, and 2.704% for samples fabricated at 75, 100, 125, and A, respectively, demonstrating the strong influence of heat input on pore formation. XRD confirmed the dominance of the α-Al phase across all processing conditions, while EBSD analysis revealed a transition from relatively refined cellular–dendritic structures at lower currents to coarse epitaxial columnar grains at higher heat inputs. Kernel average misorientation (KAM) analysis indicated progressive residual strain relaxation with increasing wire current due to enhanced thermal exposure. Excessive heat input at 150 A promoted abnormal grain growth ($> 100\ \mu$m), significant porosity formation, and deterioration of mechanical properties. In contrast, the 125 A condition provided the most favorable balance of microstructural refinement, texture development (MUD = 11.55), low defect content, and residual strain distribution, resulting in the highest average microhardness (108 HV) and ultimate tensile strength (162 MPa). The findings establish a comprehensive process–structure–property relationship for CMT-WAAM-fabricated AA4043 and provide practical guidance for optimizing deposition parameters to minimize defects and enhance structural performance.

Keywords AA4043, cold metal transfer, mechanical characteristics, microstructural evolution, wire arc additive manufacturing (WAAM)

1. Introduction

Wire arc additive manufacturing (WAAM) has attracted growing interest as a manufacturing method for large scale, moderately complex engineering parts owing to its high material efficiency and economic viability. However, the WAAM application for aluminum alloys is still limited due to insufficient information on WAAM process–structure–properties relationships (Ref 1-4).

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The arc-based WAAM techniques, including gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW) are commonly employed to fabricate the WAAM samples (Ref 5, 6). In this process, the welding torch is typically mounted on an automated motion-control platform, such as an industrial robot or CNC-based positioning system, to achieve precise and repeatable material deposition. During the deposition process, a continuous wire is melted using an electric arc and sequentially deposited in a layer-wise manner along a path programmed to produce a near-net shape of engineering structural components (Ref 5, 7). However, the WAAM process for aluminum alloys still has challenges. The high heat input of conventional arc processes will cause spatter, high residual stresses, and dimensional inaccuracies during deposition of highly heat-sensitive materials, such as aluminum and magnesium alloys (Ref 8-10).

While WAAM process offers significant advantages for large-scale metal additive manufacturing, the cyclic thermal history and multi-layer heat accumulation pose substantial challenges to microstructural control. Recent research works have extensively documented these phenomena across a wide range of complex alloy systems. For instance, recent studies on ferrous-based alloys (Ref 11-14) illustrate that variations in wire arc heat input result in different phase ratios, grain morphology, and mechanical anisotropy in 316L stainless steel (Ref 15), SS309L (Ref 16), SS308L (Ref 17), SS304L (Ref 18), and 1.0 Cr-1.25 Mo high-strength steels (Ref 19). Similar

dependencies between thermal gradients and microstructural evolution have been critically observed in advanced smart materials, such as NiTi shape memory alloys (Ref 20). Although these foundational studies establish the critical relationship between arc energy and mechanical performance in ferrous and titanium-based systems, applying these principles to highly thermally conductive and heat-sensitive non-ferrous alloys, such as the Al-Si series, presents unique challenges that require specialized low heat input processes like cold metal transfer (CMT).

A broad range of dissimilar alloys, such as Al-Si-Mg, Al-Zn, Al-Mg, Al-Cu, and Al-Si, have been studied using additive manufacturing techniques. However, hot cracking, porosity, lower density, and surface oxidation are consistently reported in the previous studies, which impair the metallurgical integrity and mechanical performance of the produced components (Ref 21-26). Among these alloys, Al-Si-rich alloys (AA 4000 series) are of particular interest for material joining and welding applications due to their excellent fluidity and reduced hot-cracking tendency. However, the conventional WAAM processing of AA 4000 series alloys still faces issues of residual stress and spatter defects, causing surface irregularities and geometric deviations in WAAM-fabricated parts (Ref 27-31). In a study, Markus Köhler et al (Ref 32). investigated the WAAM deposition of AA and analyzed its process behavior, mechanical characteristics, and residual stress development. Their work reported that alloys with a broad solidification interval tend to promote smoother bead formation. In addition, a uniform material distribution across the deposited structure was achieved by carefully controlling the process temperature. Similarly, Horgar et al (Ref 33). examined the implementation of the WAAM technique for fabricating AA and observed the formation of imperfections, such as porosity and hot cracking, in the deposited AA material. However, the mechanical results were adequate for practical and commercial applications. Despite these results, the WAAM process for aluminum alloys remains challenged by defects such as porosity, hot cracking, and surface oxidation.

To overcome these WAAM process challenges, cold metal transfer (CMT) has become a suitable arc-based heat source for WAAM deposition of aluminum alloys. The CMT technique features controlled current waveforms and synchronized wire feeding, which considerably reduce the heat input and stabilize the material transfer. The resulting controlled material transfer mechanism provides a superior deposition geometry, lower spatter, reduced thermal distortion, and porosity, which makes CMT very well suited to the deposition of aluminum alloys. Accordingly, the performance of CMT-based WAAM critically depends on the control of numerous processing parameters such as welding current and voltage, arc length, dynamic pulse correction, travel speed, and the CMT cycle. Cong et al (Ref 34). investigated the effect of arc transfer mode during the deposition of components using a CMT-based WAAM process. The study showed that the CMT pulse advanced (CMT-PADV) mode was found to be the most favorable method among traditional CMT, CMT pulse, and CMT advanced methods for the deposition of Al-Cu alloy components due to lower heat input (HI) and enhancement of fine equiaxed grain structure. Chen et al (Ref 35). deposited a Ti alloy wall using a 1.2-mm diameter wire at five different welding currents (110, 120, 130, 140, and 150 A) and systematically characterized the resulting microstructure, dimensional fidelity, and the mechanical characteristics of the CMT-WAAM deposits. The results displayed that the bead width and penetration depth increased with increasing wire current. This phenomenon was associated with the higher heat input at the higher current, which facilitated the melting of the weld metal and, thus, deeper penetration. Previous studies suggested that optimum heat input (HI) is essential for improving both the microstructural features and mechanical behavior of the samples produced via CMT-based WAAM technique (Ref 36-39). Thus, precise control of thermal input is essential for systematically investigating the effects of CMT-WAAM process variables and material composition on microstructural refinement and mechanical performance of CMT-WAAM-fabricated parts.

In conclusion, the influence of CMT-WAAM process parameters on heat input, melt pool stability, grain morphology, and porosity formation in AA4043 has not yet been comprehensively understood. Establishing these process–structure–property relationships is essential for producing defect-free and mechanically reliable WAAM components. Although previous studies have reported the macroscopic and mechanical characteristics of CMT-WAAM-fabricated AA4043 alloys, the quantitative relationship between arc energy, crystallographic texture evolution, strain relaxation, and mechanical performance remains insufficiently explored.

To address this gap, the present study systematically investigates the microstructural evolution of CMT-WAAM AA4043 under different heat input conditions. EBSD and XRD analyses were employed to quantify the transition from a strong epitaxial fiber texture at lower heat input to abnormal grain coarsening at higher heat input, together with the suppression of coarse eutectic silicon phases. In addition, kernel average misorientation (KAM) mapping was utilized to correlate mechanical performance with geometrically necessary dislocations (GNDs), thereby providing a fundamental microstructural explanation for the observed property variations.

Accordingly, four AA4043 thin-walled structures were fabricated using different wire currents through the CMT-WAAM process. Their macrostructure, microstructure, phase constitution, porosity characteristics, surface roughness, and mechanical properties were comprehensively evaluated. Furthermore, the influence of heat input on pore formation mechanisms and tensile behavior in both longitudinal and transverse directions was analyzed. The findings of this work provide valuable insight into the fundamental process–structure–property relationships of CMT-WAAM AA4043 and offer practical guidance for optimizing process parameters to minimize defects and enhance the microstructural and mechanical performance of aluminum WAAM components.

2. Materials

2.1 WAAM Setup and Materials

An overview and schematic representation of the CMT-WAAM machine system used in this study is shown in Fig. 1(a) and (b). The robot-assisted WAAM system comprised a 6-axis Fanuc Arc Mate 100iC/12 robotic welding unit integrated with a MIG torch, automated wire feeding mechanism, surface treatment module, and flexible mounting options (floor, inverted, and inclined orientations). Deposition was performed using a metal inert gas (MIG) heat source operating in CMT mode. During fabrication, the welding torch was maintained

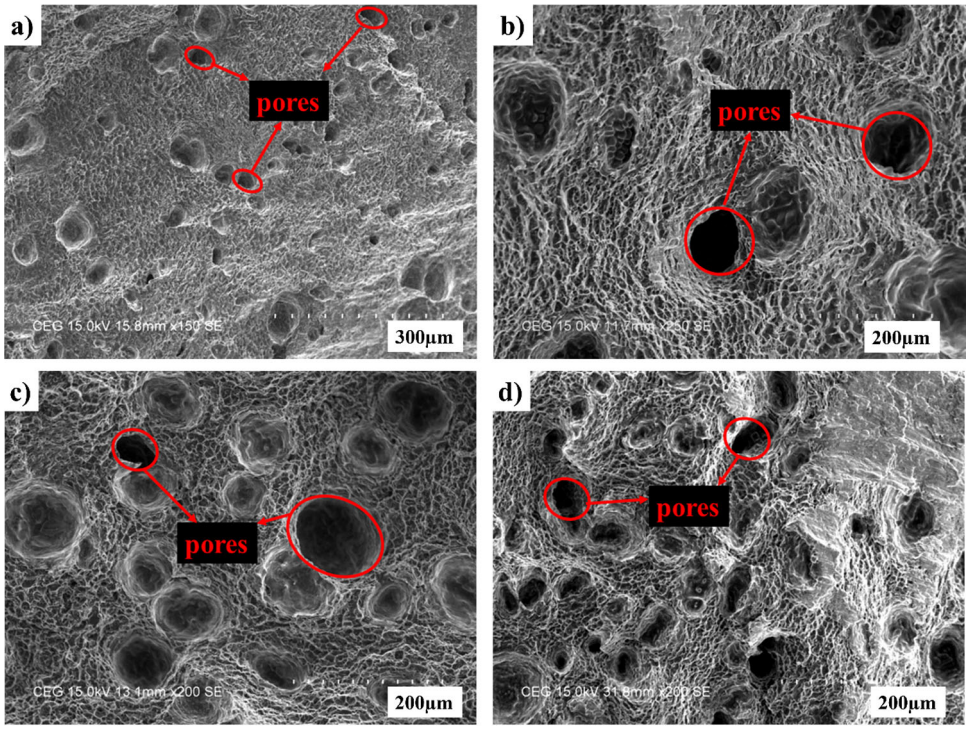


Fig. 11 SEM fractographic analysis of tensile-fractured AA4043 specimens in the transverse direction (a) S-75 (b) S-100, (c) S-125, (d) S-150

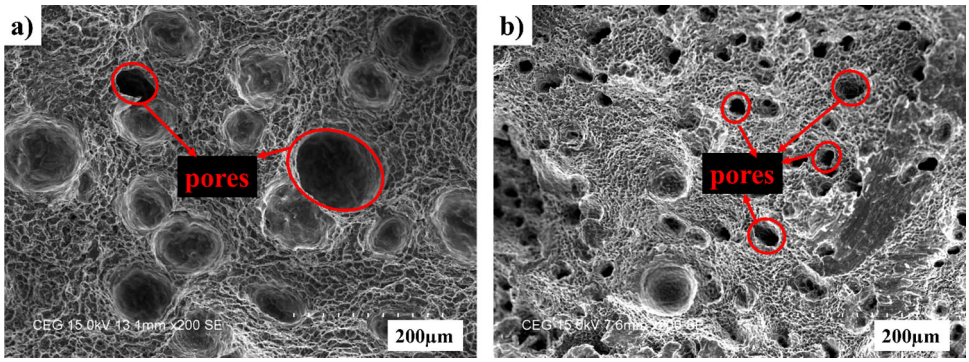


Fig. 12 SEM fractography images of tensile-fractured AA4043 specimens in the S-125 condition: (a) Transverse direction and (b) longitudinal direction

surface contains a higher density of larger pores and irregular voids. These features indicate localized brittle fracture along with ductile tearing, corresponding to a mixed ductile–brittle fracture mode.

3.9 Surface Roughness Measurement

Figure 13 shows the surface roughness (Ra) values of the WAAM-fabricated samples produced at different wire currents, while the corresponding 3D surface topography images illustrate the surface morphology (refer to Fig. 14). The measured Ra values are 9.719 μm for S-75, 8.622 μm for S-100, 6.178 μm for S-125, and 7.662 μm for S-150. Surface roughness decreases with increasing wire current up to 125 A and increases at 150 A.

Figure 14 further illustrates the influence of wire current on the surface morphology of the deposited walls. The S-75 specimen exhibits relatively irregular surface features, indicating insufficient material spreading under lower heat input (Ref 50). The S-100 specimen shows improved surface continuity with reduced height variations. Among all conditions, S-125 presents the most uniform surface morphology with the lowest peak-to-valley height, reflecting stable melt pool behavior and consistent layer deposition. In contrast, the S-150 specimen exhibits pronounced waviness, irregular surface features, and larger height variations due to excessive heat input, which promotes melt pool instability and reduces surface quality. These observations are consistent with the measured surface roughness (Ra) values presented in Fig. 13.

4. Conclusions

In the current study, thin-walled AA 4043 components were manufactured by the CMT-WAAM process on an AA2024 substrate. The resultant microstructural features and mechanical

properties were systematically studied. The key conclusions of the work are as follows:

1. Microstructural observation indicates a gradual transition from the relatively fine cellular–dendritic structure at low wire current to the coarse columnar–dendritic structure at higher current. While higher current enhances layer fusion, excessive heat input (150 A) causes a significant increase in hydrogen porosity (quantitatively measured at 2.70% area fraction), which acts as a stress raiser and causes the reduced tensile strength of S-150 noted above.
2. The XRD crystallographic analysis confirms that the rapid cooling in the CMT process delays the formation of coarse eutectic Si platelets, thus keeping more Si in solid solutions to improve the ductility. The grain texture showed a preferred (200) orientation under the steep thermal gradient in S-75, but transformed into a strongly aligned epitaxial structure in S-125, and then became less defined at the highest heat input due to grain coarsening.
3. Quantitative grain size and strain analyses reveal a significant transition from fine, unimodal ($\sim$ 2.4 μm) grain with high internal strain at low current to abnormal, multimodal ($>$ 100 μm) grain growth at high current, which suggests that the high heat input has an in-situ annealing effect, eliminating residual stress (thereby mitigating the risk of macroscopic part distortion) and increasing elongation, albeit with a loss in hardness due to the absence of grain boundary strengthening.
4. The microhardness values increased from 76 to 108 HV with increasing wire current from 75 to 125 A, with S-125 exhibiting the highest hardness due to grain refinement and uniform distribution of solute atoms; further increase in heat input resulted in grain coarsening and

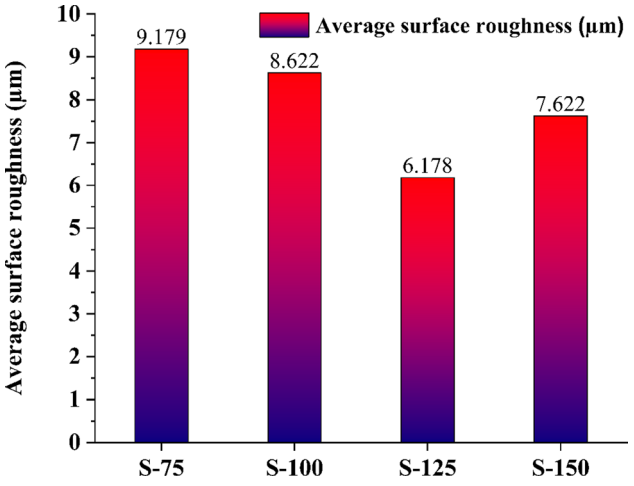


Fig. 13 Measured surface roughness (Ra) values of WAAM-deposited aluminum alloy samples produced under different wire current conditions

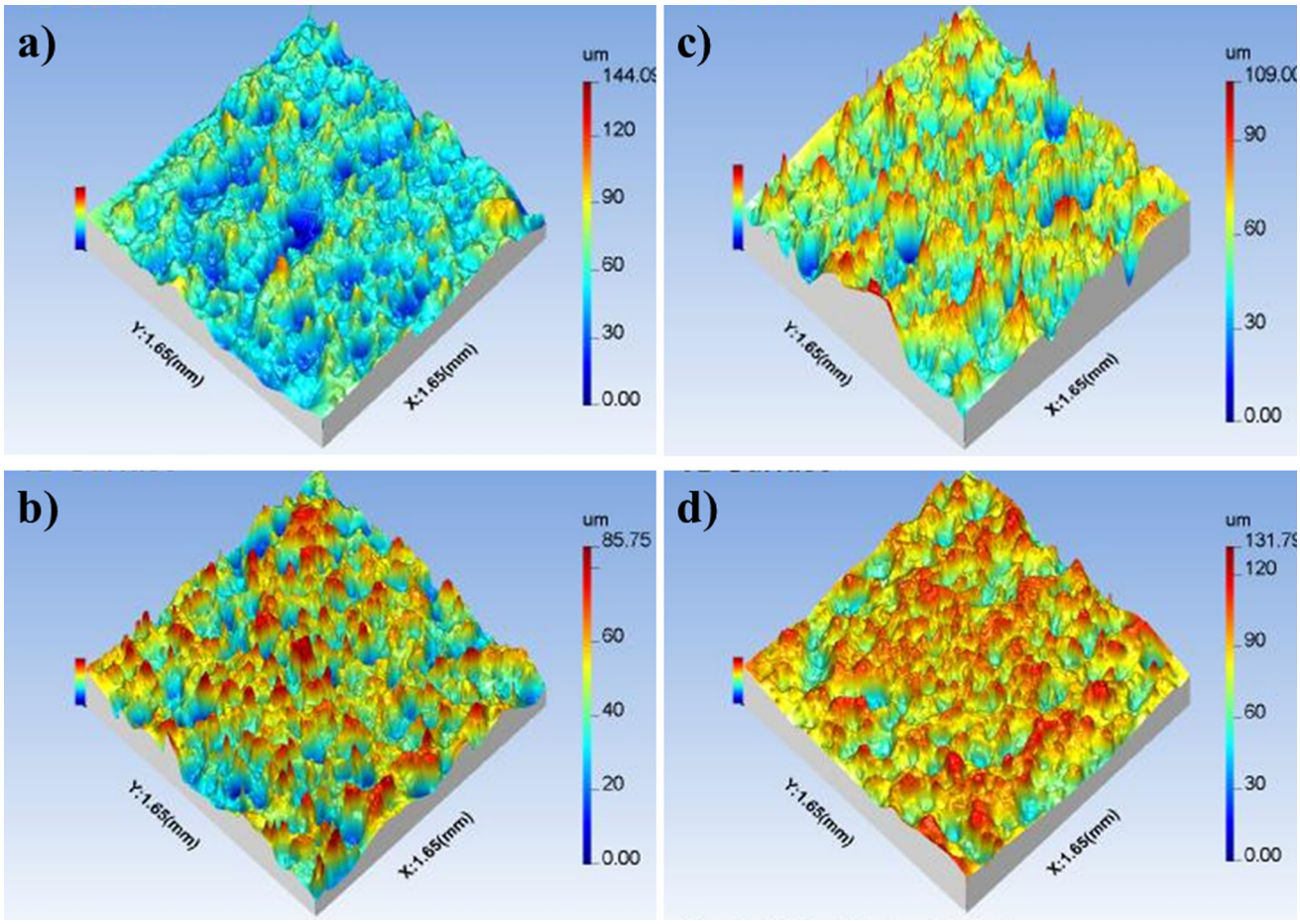


Fig. 14 3D surface topography of WAAM-deposited walls: (a) S-75, (b) S-100, (c) S-125, and (d) S-150

reduction in the hardness. Tensile properties were higher in the transverse direction (UTS 162 MPa, elongation 19%) compared to the longitudinal direction (UTS 152 MPa, elongation 17%), primarily attributed to lower porosity and predominantly ductile fracture mode.

5. Among all investigated conditions, the 125 A wire current produced the most balanced combination of microstructural refinement, low porosity, favorable crystallographic characteristics, high hardness, and superior tensile properties. In contrast, excessive heat input at 150 A promoted porosity formation and property degradation despite improved stress relaxation.
6. It should be noted that the optimum wire current identified in this study is specific to the investigated geometry, deposition strategy, interlayer cooling condition, and thermal boundary conditions. Future work should incorporate in-situ thermal monitoring, thermo-metallurgical simulations, advanced pore characterization techniques such as micro-CT, and validation on larger and more complex WAAM geometries to further optimize process performance.

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Author Contributions

Siddharthan Rajakumar helped in methodology, conceptualization, validation, software, formal analysis, investigation, data curation, funding acquisition, and writing—original draft. Narayanasamy Pandiarajan helped in supervision, writing—review & editing, resources, project administration, data curation, validation, and visualization. Abhilash was involved in formal analysis, data curation, software, validation, and visualization. Ramkumar Thulasiram carried out methodology and formal analysis.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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