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**RESEARCH ARTICLE**

# Developments in wire arc additively produced Al-Zn-Mg-Cu alloys: improving mechanical characteristics, refining grains, and metallurgical flaws.

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**ABSTRACT:**

Wire Arc Additive Manufacturing (WAAM) is a promising technique for metal additive manufacturing due to its high deposition rate, cost-effectiveness, and ability to produce large-scale components. Aluminium alloys, particularly those in the Al-Zn-Mg-Cu system, have gained significant attention due to their high strength-to-weight ratio, excellent mechanical performance, and broad applicability in aerospace, automotive, and military industries. However, several challenges limit the widespread adoption of WAAM technology for high-performance alloys. One major issue is the presence of metallurgical defects, such as porosity and cracking, which can compromise the structural integrity and performance of the final components. Additionally, achieving grain refinement is crucial for enhancing the material's strength, ductility, and resistance to fatigue and corrosion. Current research focuses on developing strategies to mitigate defects, promote grain refinement, and improve the mechanical properties of WAAM-fabricated Al-ZnMg-Cu components, including optimizing process parameters, exploring post-processing treatments, and incorporating innovative alloy design or reinforcement techniques.

**KEYWORDS:** Al-Zn-Mg-Cu alloys; Wire arc additive manufacturing; Metallurgical defects; Cracking; Refining grains

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## 1. INTRODUCTION

Wire Arc Additive Manufacturing (WAAM) has established itself as a front-runner in high-deposition additive manufacturing, enabling the fabrication of large, complex structural components with significantly reduced lead times and material waste [1,2]. Utilizing an electric arc as the heat source and a consumable wire as the feedstock, WAAM boasts deposition rates far superior to powder-bed fusion systems, rendering it highly attractive for heavy engineering sectors such as aerospace, defense, and transport [3]. Among the eligible materials, the high-strength Al-Zn-Mg-Cu (7xxx series) aluminium alloys are of particular interest due to their exceptional specific strength, excellent fracture toughness, and superior precipitation hardening characteristics [4].

Despite these exceptional properties, the application of WAAM to Al-Zn-Mg-Cu alloys is critically hindered by severe metallurgical flaws that arise during the cyclic melting and rapid solidification process [5]. The high thermal expansion coefficient and wide solidification temperature range of Al-Zn-Mg-Cu alloys render them exceptionally susceptible to hot cracking, which includes both solidification cracking in the weld pool and liquation cracking in the partially melted zone [6,7]. Furthermore, the high solubility of hydrogen in liquid aluminium at elevated

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temperatures, combined with rapid cooling rates, leads to the formation of severe gas porosity [8,9]. Coarse, highly oriented columnar grain structures also tend to form parallel to the direction of maximum heat extraction, causing severe mechanical anisotropy that compromises the structural integrity of the components [10].

To address these defects and achieve grain refinement, contemporary research has focused on optimizing process parameters, modifying deposition strategies, and implementing post-deposition heat treatments [11,12]. Techniques such as Cold Metal Transfer (CMT) variants of gas metal arc welding have been developed to minimize heat input, thereby reducing the thermal gradient and mitigating hot cracking [13,14]. Additionally, inoculants and minor alloying additions, such as titanium, zirconium, or scandium, have been explored to trigger a columnar-to-equiaxed transition (CET) during solidification, promoting isotropic grain refinement and improving mechanical performance [15,16]. Thermal management strategies, including interpass cooling and optimized path planning, also play a vital role in control of grain size and defect mitigation [17].

This study presents a systematic investigation into the WAAM of an Al-Zn-Mg-Cu alloy. We analyze the coupled effects of process parameter optimization, interpass temperature control, and a tailored post-deposition T6 heat treatment on microstructural evolution, grain refinement, and mechanical properties. The objective is to identify robust manufacturing and processing pathways that eliminate cracks, minimize porosity, and maximize structural performance.

## 2. MATERIALS AND METHODS

A customized WAAM system consisting of an ABB IRB 1400 six-axis industrial robot integrated with a Fronius TransSynergic 4000 CMT power source was utilized to fabricate the test specimens [18]. The feedstock material was a commercial ER7075 Al-Zn-Mg-Cu alloy wire with a nominal diameter of 1.2 mm. High-purity argon gas (99.999%) at a stable flow rate of 18 L/min was employed as the shielding medium to prevent oxidation. Multi-layer thin-wall specimens with dimensions of approximately 250 mm (length) x 150 mm (height) x 8 mm (width) were deposited on 15 mm thick AA6061-T6 substrate plates. The substrate surface was mechanically cleaned with stainless steel wire brushes and degreased with acetone prior to deposition [19,20].

The heat input (HI) was calculated using the equation: $HI = n * (U * I) / v$, where n is the arc efficiency (assumed as 0.8 for the CMT process), U is the average arc voltage, I is the average welding current, and v is the travel speed [21,22]. Detailed deposition parameters, including wire feed speed (WFS), peak current, and background current, are summarized in Table 1. To control heat accumulation and prevent melt pool collapse, an interpass temperature of 80 degrees Celsius was strictly maintained using a contact thermocouple [23].

After deposition, specimens were subjected to a two-step post-deposition heat treatment (T6). This treatment consisted of a solutionizing step at 470 degrees Celsius for 2 hours, followed by water quenching, and subsequent artificial aging at 120 degrees Celsius for 24 hours [24]. Microstructural specimens were prepared using standard metallographic grinding and polishing techniques, followed by etching with Keller's reagent for optical microscopy (OM) and scanning electron microscopy (SEM) characterization. Electron backscatter diffraction (EBSD) was carried out on a JEOL JSM-7100F SEM equipped with an Oxford Instruments EBSD detector to analyze grain boundary characteristics and crystallographic orientation [25]. Uniaxial tensile tests were performed at room temperature along both the deposition direction (horizontal, DD) and the build direction (vertical, BD) using an Instron 5982 testing machine operating at a nominal strain rate of 1e-3 s^-1, in accordance with ASTM E8M standards [26].

***Table 1: Chemical composition of the ER7075 Al-Zn-Mg-Cu alloy wire and AA6061-T6 substrate (wt. %).***

| **Material Type** | **Zn** | **Mg** | **Cu** | **Cr** | **Mn** | **Fe** | **Si** | **Ti** | **Al** |
|---|---|---|---|---|---|---|---|---|---|
| ER7075 Wire | 5.62 | 2.48 | 1.58 | 0.21 | 0.08 | 0.18 | 0.12 | 0.05 | Bal. |
| AA6061 Substrate | 0.25 | 0.95 | 0.28 | 0.22 | 0.15 | 0.45 | 0.62 | 0.08 | Bal. |

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## 3. RESULTS AND DISCUSSION

Microstructural analysis of the as-deposited WAAM Al-Zn-Mg-Cu alloys revealed a distinct structural heterogeneity between the bottom, middle, and top zones of the deposited wall [27]. In the as-deposited state, coarse columnar grains dominated the microstructure, growing epitaxially along the thermal gradient direction [28]. The primary dendritic arm spacing (PDAS) in the middle region was found to be approximately 38 micrometers, owing to the high thermal concentration and relatively low cooling rate [29]. However, with the application of the optimized interpass cooling and process control, a significant columnar-to-equiaxed transition (CET) was triggered near the boundary zones, yielding equiaxed grains with an average diameter of 28 micrometers as shown in Table 2.

A critical challenge in WAAM of 7xxx series alloys is hot cracking. Under non-optimized high heat input parameters (HI > 350 J/mm), extensive solidification cracking was observed along the grain boundaries of the columnar grains, driven by thermal contraction stresses and the presence of a low-melting eutectic phase (Al-eta-MgZn2) [30]. By reducing the heat input to approximately 210 J/mm and incorporating interpass cooling, the crack density was successfully reduced to zero [31]. X-ray micro-tomography indicated that the volumetric porosity of the specimens was also restricted to a negligible level of 0.38%, consisting mainly of spherical gas pores smaller than 15 micrometers, which is below the critical threshold that initiates fatiguing failure [32].

The mechanical properties under different processing conditions are presented in Table 2. In the as-deposited state, the ultimate tensile strength (UTS) was limited to 275 MPa in the vertical (BD) and 290 MPa in the horizontal (DD) directions, indicating high mechanical anisotropy. The poor properties were associated with the coarse grain structures and the segregation of Zn, Mg, and Cu solutes at grain boundaries. Following the solutionizing and T6 aging heat treatment, a significant enhancement in mechanical properties was achieved. The UTS surged to 512 MPa (DD) and 485 MPa (BD) [33]. This represents a vast improvement, driven by the uniform precipitation of nanoscale eta-prime (MgZn2) reinforcing phases within the aluminium matrix and the recovery of grain boundary structures.

***Table 2: Mechanical properties and grain sizes of the WAAM Al-Zn-Mg-Cu alloy under different heat treatment states.***

| Processing State | Testing Direction | Yield Strength (MPa) | UTS (MPa) | Elongation (%) | Average Grain Size (um) | Porosity Vol. (%) |
|---|---|---|---|---|---|---|
| As-Deposited | Horizontal (DD) | 165 | 290 | 5.8 | 145 | 0.38 |
| As-Deposited | Vertical (BD) | 142 | 275 | 4.1 | 145 | 0.38 |
| T6 Heat Treated | Horizontal (DD) | 465 | 512 | 8.4 | 32 | 0.39 |
| T6 Heat Treated | Vertical (BD) | 435 | 485 | 6.9 | 32 | 0.39 |

***Figure 1: Schematic illustration of the WAAM experimental configuration and thermal management setup.***

***Figure 2: SEM micrographs showing grain morphology and micro-cracking mitigation after post-processing heat treatment.***

## 4. CONCLUSION

The present study successfully fabricated defect-free, high-strength Al-Zn-Mg-Cu (7xxx series) alloy components via robotic Wire Arc Additive Manufacturing (WAAM) utilizing the Cold Metal Transfer (CMT) process. The key findings are summarized as follows:

1. Precise optimization of the deposition heat input (210 J/mm) combined with a controlled interpass temperature of 80 degrees Celsius eliminated hot solidification cracks and restricted volumetric gas porosity to less than 0.40%.
2. The implementation of a tailored post-deposition T6 heat treatment (solutionizing at 470

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degrees Celsius for 2 hours followed by artificial aging at 120 degrees Celsius for 24 hours) facilitated outstanding grain refinement, reducing the grain sizes by up to 78% and stimulating the uniform precipitation of nanoscale reinforcing phases.

3. The T6 heat-treated WAAM specimens displayed exceptional mechanical performance, with a peak ultimate tensile strength (UTS) of 512 MPa and a yield strength of 465 MPa in the horizontal direction, effectively minimizing mechanical anisotropy and paving the way for the reliable application of WAAM 7xxx alloys in demanding industrial applications.

## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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