International Journal of Innovative Solutions in Engineering
2025, Vol. 1 No. 1 (pages 33–39)
DOI: 10.47960/3029-3200.2025.1.1.33

Review Article

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Innovations, Prospects, and Future Directions in Wire and Arc Additive Manufacturing

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Abstract

Over the past three decades, extensive research has been conducted on Wire and Arc Additive Manufacturing (WAAM), a production technology with roots dating back almost a century to its initial patent. WAAM has garnered increasing attention due to its ability to fabricate large near-net-shape metal products. Leveraging existing welding equipment for both the heat source and material feedstock provides a significant advantage in terms of lower initial investment costs. Initially prominent in the aerospace sector with a focus on lightweight metal alloys, WAAM has recently expanded its application scope to include stainless steels, functionally graded materials, and combinations of diverse alloys. This study aims to explore the latest advancements and potential pathways in WAAM technology, offering valuable insights and recommendations for future research directions.

Article history
Received: 29. 08. 2024.
Revised: 28. 09. 2024.
Accepted: 01. 10. 2024.

Keywords
Wire Additive Manufacturing,
Welding,
Stainless Steels,
Alloys,
Functionally Graded Materials.

1 Introduction

The continuous advancement within the industry acts as a catalyst, pushing researchers to consistently investigate innovative production technologies. Additive manufacturing technologies have recently surged in popularity due to their ability to produce complex components more efficiently. Nevertheless, before the substantial progress of Wire and Arc Additive Manufacturing (WAAM), most additive manufacturing techniques were ineffective in producing metal parts. WAAM is best described as a combination of welding and additive manufacturing. It utilizes an electric arc as the primary heat source and employs welding wire as the feedstock material, all while being precisely guided by robotic arms or CNC machines [1, 2]. Despite the first patent for WAAM dating back to 1925 [3], researchers did not begin to take a keen interest in the technology until its potential for reducing material waste in the aerospace sector was recognized. [4]. Consequently, a significant portion of research and experimentation has been focused on producing aerospace components, thereby influencing the selection of materials, including titanium, aluminum, and nickel-based alloys [5]‑[8]. With increasing global interest and application, a broader range of metals and alloys are now being produced using this technology. For instance, one of the distinctive capabilities of WAAM compared to traditional technologies is the production of functionally graded materials (FGM) ‑ composite materials characterized by a gradual variation in their composition, microstructure, or properties throughout their volume. Unlike traditional homogeneous materials, these materials are engineered to exhibit smooth transitions from one constituent to another, resulting in unique and desirable properties along the gradient [9, 10]. Furthermore, valuable insights have been gained from research focusing on thermal management during the WAAM process, stress relief, and post-processing machining techniques. These combined efforts aim to produce parts that not only match but potentially surpass the quality and performance of conventionally manufactured counterparts. This includes achieving superior mechanical properties, such as greater strength and durability, and enhanced functional characteristics, making WAAM an increasingly viable option for high-performance

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aerospace, automotive, and medical device manufacturing applications.

2 Current Trends and Developments in WAAM

2.1 Stainless steels

Researchers are showing heightened interest in stainless steels due to their diverse applications. WAAM appears to be a promising solution to several issues encountered in conventional production processes.

In paper [11], researchers investigated the impact of interpass temperature on the fabrication of two "walls" using ER2594 super-duplex stainless steel wire (25 9 4 N L). While keeping other parameters constant, they set the interpass temperature at 150 °C for the first wall and adjusted it to 100 °C for the second wall. The second wall exhibited a lower ferrite content, approximately 10% less, resulting in higher maximum fatigue limit stresses. These findings underscore the significant influence that minor adjustments to process parameters, such as interpass temperature, can have on the final product.

Another group of researchers explored applying a novel TIG welding method employing a current waveform that combines AC and DC for fabricating stainless steel components [12]. They utilized an austenitic welding wire (G 18 8 Mn) as an additional material. The study varied the current modes from 100% DC to combinations like 70% DC and 30% AC, gradually increasing the AC ratio. As the AC ratio increased, the microstructure became more refined, transforming the austenite morphology from columnar dendrites to equiaxed dendrites. Consequently, the average grain size decreased, indicating improved refinement with higher AC content. This refinement contributed to enhanced tensile properties in both orientations, likely due to the grain size reduction effect.

Fatigue strength emerged as a significant focus for the paper's authors [13], who conducted a comparative study involving the use of ER410NiMo (G 13 4) welding wire in WAAM-produced components. Specifically, they evaluated these components against the traditionally forged 13Cr4Ni martensitic stainless steel commonly utilized in hydro turbine runners. The WAAM-produced part demonstrated superior fatigue performance with a fatigue strength of 468 MPa for 10^7 cycles at room temperature, compared to 370 MPa for the forged part. Moreover, the WAAM component exhibited higher yield strength and tensile strength relative to its forged counterpart. These findings highlight the potential of WAAM technology to enhance fatigue strength and mechanical properties, thereby offering competitive advantages over conventional manufacturing methods in critical applications such as hydro turbine components.

2.2 Light metal alloys

As previously mentioned, the aircraft industry has significantly contributed to the advancement of WAAM. Given the extensive use of light metal alloys in aircraft manufacturing, it is unsurprising that numerous research papers focus on them.

The optimization of parameters for producing high-quality aluminum alloy was explored in the paper [14] using the MIG method with a novel hybrid arc technology combining cold metal transfer and pulse transfer. The process utilized AA2024 filler wire. Three key parameters were varied: wire-feed speed (WFS), travel speed, and the CMT/P ratio, which denotes the ratio of cold metal transfer stages to pulse stages in a cycle. Among these parameters, WFS showed the most significant influence on porosity. Initially, porosity decreased with increasing WFS, but beyond a certain threshold, it began to rise again. Lower travel speeds contributed to reduced porosity, indicating higher heat input. Surface roughness was also markedly affected by WFS and travel speed. Higher WFS led to smoother surfaces, whereas the relationship between surface roughness and travel speed was more intricate, initially decreasing before increasing at higher travel speeds. The CMT/P ratio played a critical role in achieving optimal part formation quality, with the best results obtained within a moderate range. Increasing the ratio resulted in higher surface roughness. In summary, the study underscores the importance of parameter optimization–specifically WFS, travel speed, and CMT/P ratio–for producing aluminum alloy parts of superior quality. This approach ensures minimal porosity, reduced surface roughness, and improved formation quality, which are essential for applications requiring high-performance aluminum components.

Paper [15] presents a study focused on two aluminum alloys: Al-Mg and Al-Mg-Sc alloy. The inclusion of Sc (Scandium) was chosen for its ability to refine grains and transform non-heat-treatable strengthened alloys into heat-treatable strengthened alloys. Additionally, Sc enhances fatigue strength and resistance against microcrack growth in Al-Mg alloys. After the production process, an additional heat treatment was applied. The addition of Sc was found to be crucial in increasing the nucleation rate and significantly reducing grain size. The grain size was reduced by 86-93% depending on the heat treatment temperature. The uniform precipitation of Al3Sc particles during deposition through WAAM effectively hindered dislocation motion, further enhancing the strength of the deposited Al-Mg-Sc alloy. Mechanical properties such as yield strength, tensile strength, and elongation were also improved, attributed to the refined grain structure and precipitation strengthening. While there was only a slight improvement in hardness observed after heat treatment, likely due to the absence of supersaturated Sc available for precipitation, the heat treatment temperatures did not notably influence the mechanical properties, as shown in Figure 1.

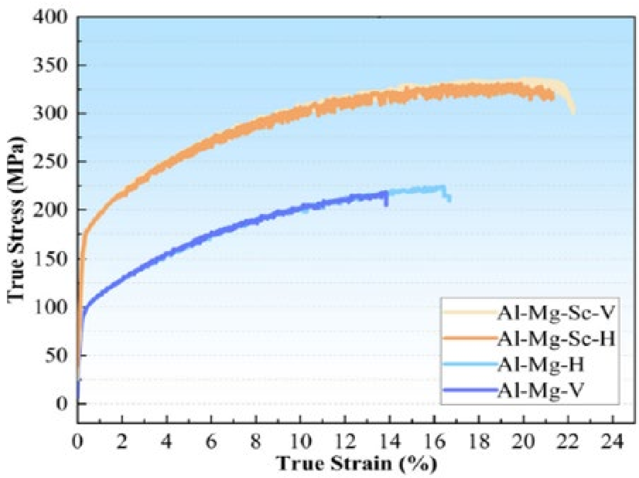

Figure 1 Mechanical properties of Al-Mg and Al-Mg-Sc alloys [15]

Minimal differences in mechanical properties were observed among Al-Mg alloys with varying heat treatment temperatures, and similar trends were noted for Al-Mg-Sc alloys. However, the presence of Sc significantly affected the mechanical properties, highlighting its critical role in alloy enhancement.

Paper [16] examines the influence of interpass milling on the microstructure and mechanical properties of TC4 titanium alloy thin-walled parts manufactured using WAAM. Using a multi-tooth milling cutter in intermittent cutting induced vibrations, leading to a plastic deformation layer on the milled surface and an increase in grain boundary density. This transformation refined the coarse columnar β grains into shorter and equiaxed grains while refining the α phase. Increasing the interpass milling depth progressively refined the α phase in different areas of the thin-walled parts. However, excessive depth sometimes led to non-uniform refinement, possibly due to end mill runout and complex thermal cycles. Interpass milling significantly enhanced the average microhardness across the parts' top, middle, and bottom areas.

Moreover, the tensile strength of the parts improved with interpass milling, demonstrating higher values in both horizontal and vertical directions. Ductile fracture behavior was observed in tensile specimens, characterized by numerous dimples on the fracture surface. The combined effects of β grain size and the proportion of α phase with size smaller than 15 μm had the greatest impact on microhardness and tensile strength. In conclusion, interpass milling proves effective in enhancing the microstructural refinement and mechanical performance of TC4 titanium alloy thin-walled parts produced via WAAM.

Research [17] showed a study similar to that in paper [15], investigating the influence of copper (Cu) as an alloying element on the properties of an aluminum alloy. Three different welding wires containing varying percentages of copper (5%, 5.65%, and 6.3% Cu) were employed. Copper acts as a strengthening agent by precipitating the θ' phase during solution aging, thereby enhancing the alloy's mechanical properties. The study found that increasing the copper content resulted in a higher number and larger size of θ phases precipitated in the as-deposited Al-Cu alloy. However, when the copper content exceeded 5.65%, larger remaining θ phases were observed after solid solution treatment.

Optimal mechanical properties were achieved after T6 heat treatment(solution treatment, quenching, and artificial aging) at a copper content of 5.65%, indicating an optimal balance for desirable mechanical characteristics. An important finding was the anisotropy of mechanical properties when the copper content exceeded 5.65%. Parts produced with the 6.3% Cu welding wire exhibited a change in fracture mode from ductile to brittle in specimens taken from the vertical direction of the part. Therefore, to maintain improved mechanical properties and mitigate anisotropy-related issues, limiting the copper content to 5.65% or below is recommended.

Paper [18] shows how the powder-pack aluminizing process enhanced the oxidation resistance of WAAM-produced IN625 alloy. Aluminizing at 700 °C for 3 hours significantly affected the alloy's microstructure, mechanical properties, and oxidation resistance. The process increased surface hardness and homogenized the interdendritic structures within the substrate. As a result, the microstructure exhibited greater stiffness and modulus of elasticity compared to the original as-built sample. Post-aluminizing, there was a notable improvement of 39% in matrix region hardness and a 30% reduction in modulus of elasticity values for the WAAM samples. The phases forming the aluminide coating layer (NiAl and Ni_2Al_3) demonstrated stability at temperatures exceeding 1000 °C, forming a protective Al_2O_3 layer on the surface. This coating enhanced corrosion resistance, exhibiting 6.63 times, 2.70 times, and 2.65 times better performance than the untreated as-built sample during oxidation tests at 1000 °C for 5 hours, 25 hours, and 50 hours, respectively. During the oxidation, forming Cr2O3 on the surface of the as-built WAAM samples after 5 and 25 hours was beneficial. However, prolonged oxidation for 50 hours led to the formation of undesirable $NiCr_2O_4$, $NiMoO_4$, and NiO spinel phases, significantly reducing oxidation resistance compared to shorter durations. Figure 2 shows the oxidation period's effect on the specimens' percent weight gains. After oxidation tests, local formations of Al_2O_3 and fragmentation of Kirkendall voids occurred in aluminized WAAM IN625 samples, in contrast to the continuous Al_2O_3 layer observed in wrought and cast Inconel alloys.

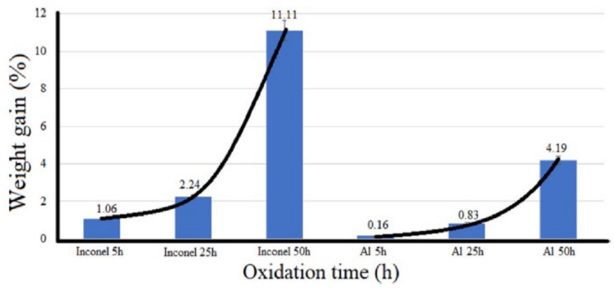

Figure 2 The effect of oxidation period on percent weight gains of WAAM IN625 specimens during oxidation test [18]

Increasing oxidation time exacerbated Kirkendall void formation and fragmentation, contributing to decreased oxidation resistance over time.

2.3 Functionally graded materials (FGM)

As it is said in the introduction, there is growing interest in the research of functionally graded materials, driven by the promising capabilities of WAAM to fabricate components from two or more distinct materials gradually and continuously.

An innovative approach was demonstrated in a paper [19], where the welding wire "3Dprint AM 718," composed of Inconel 718 alloy, was deposited onto a substrate made of steel grade S275. Three sets of specimens were examined at different stages: without any heat treatment (referred to as AB, as built), solution-treated (ST), and aged (STA). The AB sample revealed a significant presence of the Laves phase on the deposited side, which persisted even after the solution annealing process. However, the solution treatment led to undesired grain coarsening in both the substrate and the deposited "wall." Interestingly, the aging treatment did not induce noticeable grain growth. The substrate's hardness decreased by over half following treatment, a change that persisted after aging. Conversely, the "wall" exhibited increased hardness only after aging. The elastic and shear moduli showed an increase at greater distances from the interface (first layer) across all treatment conditions, likely due to relatively lower alloying element mixing in this region.

Research [20] utilized a complex alloy, Fe-Mn-Si-Cr-Ni-V-C, recognized as a shape memory alloy (SMA). The fabricated component underwent thorough characterization focusing on microstructure, mechanical properties, and functional behavior assessment. The fabrication process demonstrated advantageous characteristics such as low porosity, high deposition efficiency, minimal surface waviness, and reduced post-processing machining requirements. Mechanical testing revealed impressive results, including a yield strength of 472 MPa, fracture stress of 821 MPa, and elongation of 26%, highlighting excellent material performance. These properties make the alloy and its manufacturing process suitable for various construction applications. Cyclic testing further confirmed the material's robust mechanical response, showing high levels of absorbed energy and maximum stress with low irrecoverable strain. These findings underscore the alloy's potential in civil engineering applications, particularly in seismic systems, due to its capacity to endure repetitive loading while maintaining effective functional properties.

Paper [21] presented another complex alloy (Co-Cr-Fe-Mo-Ni-V), where FeNi36 formed the material's shell and other alloying elements were incorporated into the core. The study comprehensively covered chemical and microstructural analyses, mechanical properties testing, and assessment of the material's abrasive wear behavior using the G75 test. Chemical composition analysis revealed minimal deviations from the welding wire's nominal composition, with expected minor burn-off of Cr, Mb, and Co during manufacturing. The alloy demonstrated an average modulus of elasticity of 246 GPa, a yield strength of 530 MPa, and a tensile strength of 560 MPa, while hardness values ranged from 252 HV10 to 270 HV10. Of particular significance was the outcome of the G75 test, which showed that the alloy exhibited wear resistance comparable to cobalt-based alloys typically used for wear-resistant claddings. The wear loss measured approximately 110 mm^3, underscoring the promising potential of this complex Co-Cr-Fe-Mo-Ni-V alloy for applications requiring superior wear resistance.

Paper [22] explores the combination of an Inconel 825 with austenitic stainless steel 316L (1.4404), using a unique approach where the Inconel alloy served as the substrate. Twenty layers of Inconel were initially deposited, followed by an additional twenty layers of stainless steel on top, forming a Functionally Graded Material (FGM) structure, as depicted in Figure 3. Mechanical properties were evaluated by extracting specimens from all three sections for tensile testing, while fracture toughness testing focused on specimens from the middle part at the FGM interface. Tensile testing results showed no significant differences among the sections, all exhibiting plastic deformation indicative of ductile fracture behavior. The Crack Tip Opening Displacement (CTOD) values were similar, measuring 0.853 mm for the Inconel side and 0.873 mm for the stainless steel side. These comparable CTOD values suggest that this FGM configuration could be effectively utilized in challenging and demanding environments.

Figure 3 Building of the FGM with WAAM [22]

3 Conclusion

The dynamic evolution of the industry has spurred researchers to explore innovative production technologies, with additive manufacturing methods like Wire Arc Additive Manufacturing (WAAM) gaining significant traction. Initially recognized for its ability to minimize raw material waste in aerospace applications, WAAM has sparked intense research focusing on materials such as titanium, aluminum, and nickel-based alloys. Over time, WAAM's adaptability has broadened to encompass many metals and alloys, including stainless steels and functionally graded materials (FGM), which offer customized material gradients and distinct properties. Studies have yielded valuable insights into WAAM's capabilities, including optimizing process parameters to enhance part quality and the impact of alloying elements on mechanical performance. Moreover, WAAM has demonstrated versatility in producing complex alloys such as Co-Cr-Fe-Mo-Ni-V and Fe-Mn-Si-Cr-Ni-V-C, exhibiting impressive mechanical properties and wear resistance. These attributes position WAAM as a promising technology for wear-resistant claddings and civil engineering applications, highlighting its potential to revolutionize various industrial sectors.

Future work suggestions encompass a broad spectrum of possibilities, but key areas of focus include:

- **Further material exploration:** Continuously explore the compatibility of WAAM with a broader spectrum of materials, ranging from traditional metals to specialized alloys meticulously tailored for specific industrial applications. This ongoing research aims to push the boundaries of WAAM's versatility and effectiveness across diverse fields, ensuring it meets the exacting demands of modern manufacturing and engineering requirements.
- **Multi-material FGM development:** Research and develop complex FGM structures using WAAM, integrating multiple materials with tailored properties. This approach seeks to pioneer new designs that offer enhanced performance in targeted applications, pushing the boundaries of material engineering.
- **Industrial adoption and standardization:** Drive the adoption of WAAM technology across industrial sectors by collaborating on establishing standardized procedures and guidelines. This initiative aims to ensure consistent quality and reliability of WAAM-produced components, facilitating widespread acceptance and integration into manufacturing processes.
- **Quality Assurance:** Enhance in-situ Non-Destructive Testing (NDT) techniques to enable real-time monitoring during the process. These advancements are crucial for facilitating the immediate detection of defects or anomalies, ensuring proactive quality control throughout production. This continuous improvement approach underscores the commitment to achieving robust and reliable additive manufacturing outcomes across various industrial applications.

Conflicts of Interest: The authors report there are no competing interests to declare;

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