A REVIEW ON WIRE ARC ADDITIVE MANUFACTURING FOR INDUSTRIAL COMPONENT REPAIR AND RESTORATION

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DOI: http://doi.org/ 10.57001/huih5804.2025.245

ABSTRACT

This review paper summarizes recent advancements in wire arc additive manufacturing (WAAM) for repairing and restoring industrial components under harsh conditions. WAAM, a directed energy deposition process with a wire feed system, offers rapid production, high material efficiency, and a sustainable alternative to conventional repair methods. Key studies on process optimization, surface preparation, shielding gas selection, thermal management, and post-deposition heat treatments are discussed. Additionally, hybrid approaches combining WAAM with precision machining for complex components, such as forging dies and aerospace parts, are examined. The review also identifies current challenges and outlines future research directions in WAAM-based repair and restoration.

Keywords: *Wire arc additive manufacturing, repairing, restoration.*

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Received: 10/4/2025
Revised: 25/6/2025
Accepted: 25/7/2025

1. INTRODUCTION

In the current global market, repairing existing products is crucial for reducing costs, conserving resources, and promoting sustainability. Advances in Additive Manufacturing (AM) allow for precise layer-by-layer restoration of only the damaged areas based on digital designs, thereby minimizing waste and enhancing performance. Among these techniques, Wire Arc Additive Manufacturing (WAAM) is especially effective for reconstructing large, complex metallic components with high strength and durability, benefiting industries such as aerospace and shipbuilding while reducing downtime. The integration of digital simulation and 3D modeling further ensures optimized repair strategies, making AM and WAAM key to efficient and sustainable manufacturing practices.

1.1. WAAM definition and classification

Wire Arc Additive Manufacturing (WAAM) is an advanced process that fabricates metal components by depositing material layer by layer through welding. It transforms digital designs into intricate metal structures with high precision while significantly reducing raw material waste and production time compared to traditional methods. In WAAM, a welding arc melts a continuously fed metal wire, which is then deposited onto a substrate following a predetermined pattern. This build-up continues until the desired thickness and structural integrity are achieved, with a CNC system ensuring exceptional consistency and accuracy. WAAM can be categorized by the welding technique used, such as Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW) (see Fig. 1). GMAW-based WAAM (Fig. 1a), including techniques like MIG, MAG, and CMT, is particularly renowned for its high deposition rate up to 9.5 - 10kg/h [1] making it ideal for large-scale production and repair applications.

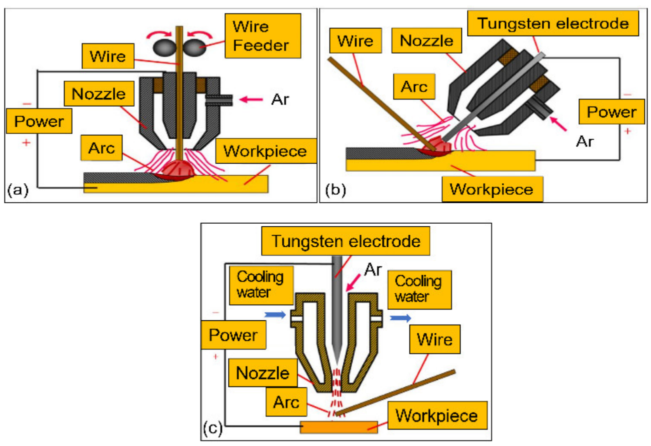

Fig. 1. Schematics of the WAAM process base on (a) GMAW, (b) GTAW and (c) PAW [2]

GTAW-based WAAM (Fig. 1b) utilizes a non-consumable tungsten electrode to produce smooth, high-quality weld beads, particularly suitable for precision materials like aluminum and titanium. PAW-based WAAM (Fig. 1c) employs plasma to generate very high temperatures and rapid material deposition, resulting in components with superior strength and load-bearing capacity. Overall, WAAM offers a versatile and efficient solution for fabricating and repairing complex metal components while significantly improving production efficiency.

1.2. Industrial applications of WAAM

Wire Arc Additive Manufacturing (WAAM) offers significant advantages across a wide range of industrial sectors. It has emerged as a transformative technology for producing steel components in industries such as construction, maritime, oil and gas, and wind energy, largely due to its ability to fabricate complex geometries while minimizing material waste. WAAM's flexibility and high deposition rates make it ideal for creating large-scale metal parts required in aerospace, automotive, and healthcare applications, where design freedom and enhanced product quality are critical [3, 4].

Moreover, WAAM is not limited to new production; it also plays a crucial role in repair and remanufacturing processes. By enabling the rapid production of replacement parts and the restoration of damaged components, WAAM provides a cost-effective and time-saving alternative to traditional methods like casting and machining. This approach supports sustainable manufacturing practices by extending the service life of high-value components and reducing overall resource consumption.

As advancements in process optimization and simulation techniques continue, WAAM is poised to further revolutionize the manufacturing landscape, driving greater efficiency, innovation, and sustainability in high-demand industries.

2. RELATED WORKS ON USING WAAM FOR REPAIRING AND RESTORATION

2.1. Materials employed in WAAM for the repair and restoration of components

In WAAM-based repair and restoration processes, a diverse array of metallic substrates and filler metals is utilized, with material selection tailored to specific application requirements. Typically, carbon steel, stainless steel, aluminum alloys, and titanium alloys are employed. In certain applications, specialized hard-facing alloys or composite materials are incorporated to enhance wear resistance and mechanical performance. The precise selection and integration of these materials are critical for achieving optimal metallurgical bonding and ensuring that the restored components exhibit the desired functional properties.

Oladoye et al. [5] fabricated 309 stainless steel via WAAM and, through optical microscopy, XRD, and corrosion tests in 1M H_2SO_4, found that microstructural variations diminished corrosion resistance despite minimal galvanic effects and no chromium-depleted zones. Li et al. [6] employed a robotic WAAM process to restore a large worn sprocket by generating a 3D digital model to guide automated deposition, with subsequent tests confirming the repair's quality.

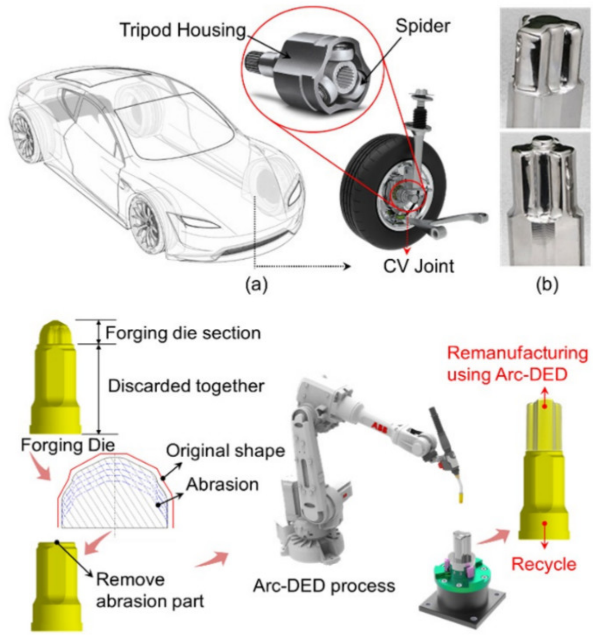

Fig. 2. Schematic of automotive components: a) CV joint, spider, and tripod housing; b) Remanufacturing method for worn tripod forging dies: application of arc-DED [8]

Wandtke et al. [7] demonstrated that slot milling on welded and AM high-strength steel components significantly reduced transverse residual stresses and angular distortion, enhancing repair welding and stress management. In a related study, Kim et al. [8] showed that on-site repair of high-hardness forging dies using arc-DED, aided by a novel slicer, produced remanufactured components with marked improvements in hardness and tensile strength, underscoring the process's potential to lower costs and environmental impact (Fig. 2). Fernandez et al. [9] employed advanced CMT-WAAM to restore industrial equipment, resulting in repaired areas with enhanced mechanical and metallurgical properties that exceed those of the original material.

Titanium alloys, renowned for their high strength-to-weight ratio and exceptional corrosion resistance, are increasingly employed in WAAM repair to restore critical components under extreme service conditions. Zhuo et al. [10] applied GTAW-WAAM to repair titanium alloys, achieving a deposition interface bonding strength of up to 88.2% of the base metal, while their numerical simulation for TC17 turbine blades [11] revealed that repeated thermal cycles cause significant microstructural differences between multi-layer and single-layer depositions in the heat-affected zones. Lee [12] demonstrated that PTAW-WAAM can precisely repair rotating gas-sealing components in gas turbines using high-performance titanium alloys, although further optimization is needed for consistent repair quality and durability. Jiang et al. [13] found that Multi-Wire Arc Additive Manufacturing (MWAAM) of TC11 titanium alloy offers higher deposition efficiency and produces thin-walled components with excellent mechanical and wear-resistant properties, underscoring its potential for aerospace applications.

Chen et al. [14] examined the microstructural evolution and mechanical properties of repaired ATI 718Plus samples. They observed that the deposited zone (DZ) featured columnar grains with significant Nb segregation, which promoted the formation of Laves, η, and γ′ precipitates, whereas the substrate zone (SZ) was characterized by equiaxed grains with a uniform distribution of γ′ precipitates. Elevated temperatures in the heat-affected zone (HAZ) promoted grain growth and precipitate dissolution, and after direct aging treatment, further precipitate coarsening yielded improved ultimate tensile strength but reduced elongation, with fractures consistently occurring in the DZ. Lee et al. [15] applied a GMAW-WAAM system to repair the slide of a machine tool fabricated from gray cast iron using nickel-based wire, with subsequent evaluations confirming the high quality of the deposition. Li et al. [16] developed a robotic hybrid platform that combines WAAM and milling for repairing aluminum alloy parts in low-gravity environments (Fig. 3). Reverse engineering was used to create 3D models, and Boolean operations isolated the damaged areas. Al5356 wire was selectively deposited via WAAM, followed by milling to improve surface quality. Tensile tests confirmed the repair's mechanical integrity, demonstrating a cost-effective, resource-efficient method for space applications.

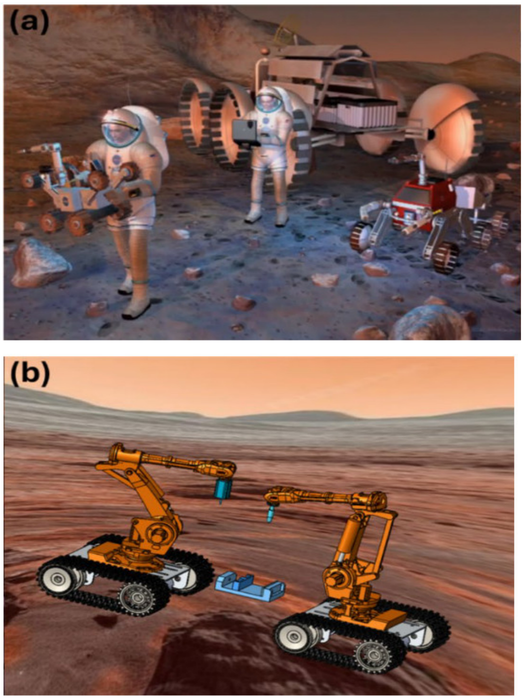

Fig. 3. a) Illustration of Human and Equipment Operations in Space, b) On-Mars Manufacturing: Robotic Arms Equipped with WAAM and Milling Machining Systems [16]

2.2. Surface preparation and toolpath strategy development in repairing and restoration of components by WAAM

In surface preparation for WAAM-based restoration, Li et al. [17] deposited a V-groove on a Q235 steel substrate using H08Mn2Si steel wire to restore the component's geometric profile, developing an experimental model to correlate groove geometry with weld bead formation and optimize WAAM parameters. Shen et al. [18] proposed a hybrid path generation strategy for the wire and arc additive remanufacturing (WAAR) of hot forging dies with arbitrary geometries and high heat input; their algorithm minimizes contour line lengths to reduce sharp angles, adaptively subdivides the internal region to avoid unfilled areas, and interconnects sub-paths to yield a flatter deposited surface, as validated by repair trials on four dies. In Fig. 4, the WAAR procedure for hot forging dies is illustrated, and the sequential steps involved in the process are detailed. Furthermore, Li et al. [16] employed high-precision 3D scanning and reverse engineering to create an accurate digital model of a simulated damaged aluminum component, which enabled the design of optimized printing paths tailored to the unique geometry of the damaged area.

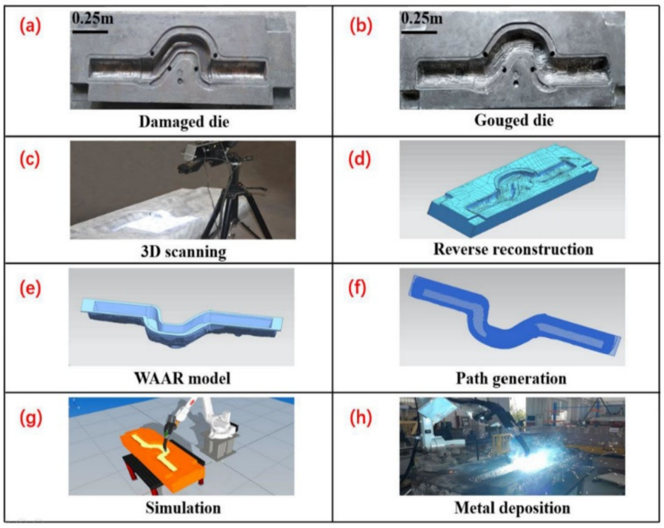

Fig. 4. The WAAR procedure for hot forging die: (a) Worn die, (b) Arc gouged die, (c) Digital 3D scanning, (d) Reverse engineering, (e) WAAR design, (f) Toolpath planning, (g) Process simulation, (h) Metal additive process [18]

Research on individual weld bead morphology is vital for developing effective toolpath strategies in WAAM. Sharifi et al. [19] examined the CMT welding process for fabricating steel components, showing that lower travel speeds yield higher weld bead heights while increased wire feed speeds produce wider beads; however, excessive wire feed speed (WFS) (> 4.5m/min) causes over-penetration and dilution, and adding CO_2 enhances penetration and bead width. Catalano et al. [20] characterized the CMT process for AWS ER 308L Si deposits, finding that process parameters primarily affect energy consumption and heat input rather than microstructural evolution, thereby supporting energy-efficient parameter selection without compromising material properties.

In addition to research on deposition process parameters, various methods and algorithms have been proposed to enhance deposition quality. For example, Shen et al. [18] investigated welding path strategies for repairing hot stamping dies and proposed an algorithm that combines the inner and outer boundary paths with a zigzag pattern to minimize both over-deposition and under-deposition. Hong et al. [21] implemented a WAAM deposition strategy in both vertical and conventional orientations during the remanufacturing of hot forging dies, which not only extended die lifespan but also reduced material usage and processing time by over 50% compared to manual repair methods. Baffa et al. [22] applied WAAM to restore a rectangular plate made of S235JR steel using ER70S-6 steel wire, and their investigation revealed that the layer overlap distance significantly influenced weld penetration and the thickness of the deposited layer, while the welding torch inclination angle was critical for repairing complex geometries.

2.3. Effects of shielding gas, heating, cooling, and heat treatment regimes in WAAM repairing and restoration of components

Teixeira et al. [23] proposed a method for selecting shielding gas in WAAM using austenitic stainless steel, validating three argon-based mixtures via the CMT process and showing that gas composition strongly influences metal transfer, deposition time, and thin-wall properties. Similarly, Badoniya et al. [24] demonstrated that forced CO_2 cooling of WAAM-fabricated SS 316L walls refines the microstructure, increasing microhardness by 21% and ultimate tensile strength by 16.3%, while also improving tribological performance.

Manokruang et al. [25] demonstrated that preheating the substrate to 400 °C in WAAM using CMT technology increases weld bead width while reducing bead height, with heat-affected bands forming due to repeated thermal cycles exhibiting a lamellar microstructure between bands and coarser α-phase at their centers. Ziesing et al. [26] examined the DED-Arc/M process for thin-walled X40CrMoV5-1 tool steel and discovered that rapid heat accumulation reaching approximately 1100°C within a few layers significantly influences solidification rates, segregation, and chemical homogenization. As a result, the microstructure becomes predominantly martensitic, exhibiting an average hardness of 611HV and a retained austenite content that varies from 5 to 13 vol% depending on the build height.

Wang et al. [27] introduced a novel liquid-nitrogen cooling strategy in WAAM of Al-Cu alloys to control hydrogen-induced porosity, achieving an 18.4% reduction in grain size, a 21.2% decrease in eutectic phase diameter, and a 53.3% increase in phase number density, which lowered pore density by 63.8% and overall porosity by 59.4% (final porosity of 0.39%) (Fig. 5). Consequently, the mechanical properties were enhanced, with the repaired components exhibiting a yield strength of 100.3MPa, ultimate tensile strength of 250.1MPa, and elongation to failure of 19.4%. These findings collectively underscore the importance of controlling thermal cycles and employing advanced cooling strategies to optimize microstructural evolution and mechanical performance in WAAM and DED-Arc/M processes.

Fonseca et al. [28] examined the effects of post-deposited heat treatments (PDHT) on HSLA steel produced via WAAM and its forged variant (HF-WAAM), finding that PDHT reduces specific cutting energy by 8 - 38% (pot-normalized) and 22 - 27% quenching & tempering (Q&T) compared to the as-built state, although increased surface waviness in HF-WAAM may impair machining. Kachomba et al. [29] applied WAAM for remanufacturing AISI 4130 steel, revealing that post-heat treatment induces microstructural homogenization, a 50.2% hardness increase, and a shift from brittle to ductile fracture, emphasizing the need for optimized heat treatment protocols.

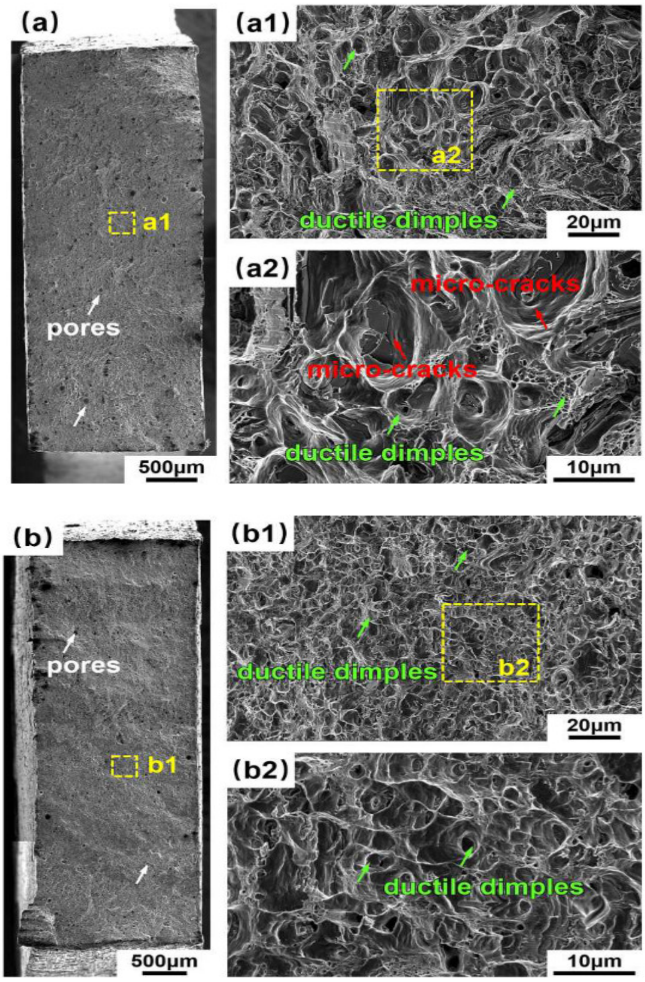

Fig. 5. Fractographic features of the CGC sample (a, a1, a2) and the LNC sample (b, b1, b2) [27]

2.4. Related works on evaluating economic and environmental benefits of WAAM in repairing and restoration of components

Research on the environmental impact of Wire Arc Additive Manufacturing (WAAM) highlights its advantages over conventional manufacturing methods. Sword et al. [30] compared WAAM with forging in the production of a Ti6Al4V component and found that WAAM reduces carbon emissions by 50%, energy consumption by 40%, and material waste by 55%. Kokare et al. [31] employed Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies to evaluate the economic and environmental performance of WAAM against Laser Powder Bed Fusion (LPBF) and CNC milling. Their findings indicate that CNC milling is the most cost-effective and environmentally sustainable option, followed by WAAM, with raw material production and labor costs being the primary influencing factors.

Shah et al. [32] conducted a life cycle comparison between WAAM-produced steel beams and conventionally hot-rolled I-beams, revealing that WAAM carbon steel and stainless steel beams exhibit 7% and 24% lower climate change impact, respectively. Additionally, integrating WAAM with topology optimization can achieve mass reductions of up to 50%, significantly lowering CO_2 emissions. However, shielding gas is identified as a major contributor to WAAM's environmental impact, which can be reduced by over 30% through higher deposition rates or the use of renewable energy sources. Priarone et al. [33] demonstrate notable environmental benefits of using WAAM for mold insert repair. Their study shows that repairing mold inserts reduces the average energy demand by 16.1%, dropping from 330MJ for manufacturing and replacing a new insert to 277MJ for a repair scenario. Additionally, the repair process achieves a 20.2% reduction in CO_2 emissions, decreasing from 16.8kg to 13.4kg on average. Material usage is also dramatically curtailed, with the repair process requiring only 156g of H13 wire compared to 1568g of material needed for a new insert a reduction of 90.1% in material consumption. Although the study primarily focuses on environmental impacts, it also highlights that integrating a hybrid additive-subtractive system can streamline the repair process, potentially yielding significant efficiency gains in time and resource utilization for industrial applications. Overall, WAAM presents substantial potential for reducing the environmental footprint of industrial manufacturing, though further optimization of raw material usage and energy efficiency is necessary to enhance its sustainability.

3. GENERAL CONCLUSIONS AND REMARKS

In today's manufacturing landscape, repair and restoration via advanced additive manufacturing are essential for optimizing resources and enhancing sustainability. Wire Arc Additive Manufacturing (WAAM) builds metal components layer by layer using welding processes, enabling the precise restoration of damaged parts while reducing material waste, production costs, and energy consumption. This technology has been successfully applied to various materials including stainless steel, high-strength steel, titanium, and aluminum alloys demonstrating its versatility in both new fabrication and repair applications. Process parameters such as shielding gas composition, substrate temperature, and forced cooling significantly influence weld bead geometry and microstructural evolution, which in turn affect the mechanical properties of the repaired components. Post-deposited heat treatments further homogenize microstructures and enhance hardness and tensile strength, though they may increase surface waviness and impact subsequent machining. Advanced cooling methods, such as liquid nitrogen cooling, refine the microstructure and reduce porosity, ultimately improving overall quality and durability. The integration of digital simulation, 3D scanning, and reverse engineering ensures high-precision damage assessment and optimized repair strategies.

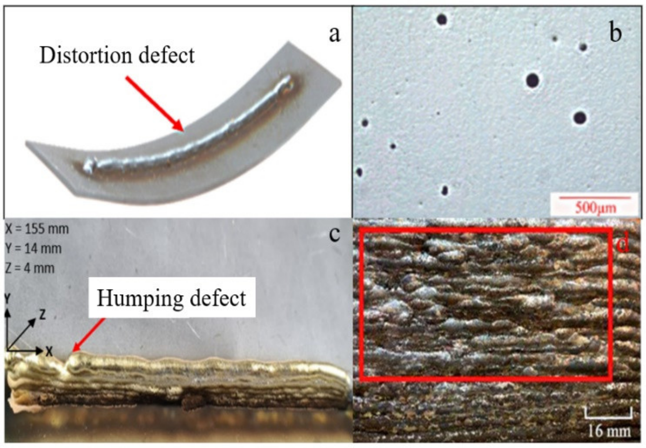

Fig. 6. Types of defects in the WAAM process: a) Distortion; b) Gas porosity; c) Surface irregularities; d) Material overflow [34]

Despite numerous studies on WAAM, challenges remain due to its inherent complexity as a thermal forming process, with key issues including the reduction of defects such as warping, residual stress, gas porosity, surface irregularities, material overflow, and cracking (Fig. 6) and addressing microstructural heterogeneity. Moreover, achieving consistent control over the mechanical properties to meet desired performance standards continues to be a critical focus for future research.

4. FUTURE WORKS

Future research will concentrate on enhancing the quality of component restoration through WAAM technology. Several avenues of investigation have been proposed, including the optimization of key process parameters such as voltage, current intensity, wire feeding speed, welding speed, and the spacing between single weld beads to ensure precise material deposition. Equally important is the development of advanced welding path strategies that promote uniformity and minimize defects. Additionally, selecting an appropriate shielding gas tailored to specific material properties and process requirements, as well as integrating WAAM with complementary technologies to improve both mechanical performance and microstructural integrity, are critical priorities. Moreover, the adoption of real-time monitoring and predictive methods using sensors (acoustic, optical, thermal, etc.) for early defect detection and error minimization, combined with the application of artificial intelligence and simulation techniques for optimized process control, is expected to significantly advance the WAAM process and enhance the overall reliability and performance of component restoration applications.

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