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Current progress on wire-arc and welding-based additive manufacturing with its potential application: a review

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Abstract

Wire-Arc Additive Manufacturing (WAAM) is one of the leading metal additive manufacturing procedures for producing medium to large-scale components due to its high deposition rate, low material cost, and compatibility with common structural alloys. This paper review provides a focused and critical assessment of welding-based Additive Manufacturing (AM) technologies, particularly WAAM processes utilizing Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW). The scope covers the fundamental process principles, thermal–metallurgical behaviour, mechanical performance, and deposition control methods. The specific contribution of this review is: (i) explaining key process–structure–property relationships documented in recent studies, (ii) identifying core technological barriers—such as thermal distortion, porosity, residual stresses, and anisotropic microstructures—that limit industrial deployment, and (iii) outlining strategic future research directions that important for improving process stability and weld results. Key findings indicate that heat input management governs bead morphology, cooling rate, phase formation, and residual stress accumulation across multi-layer builds. Advances such as adaptive arc modes, interpass temperature control, closed-loop sensing, and hybrid subtractive–additive workflows have shown significant reductions in geometric deviation and defect formation. Nevertheless, reproducibility, dimensional accuracy, and mechanical property predictability remain persistent challenges. Overall, the review shows that integrating real-time monitoring, predictive simulation, alloy design tailored for WAAM, and intelligent control systems represents the most impactful pathway toward achieving certified and industrial-grade components.

1. Introduction

Additive manufacturing (AM) has been developed as an alternative to traditional manufacturing methods (casting, forging, machining) for making complex metal part structures. In particular, wire-arc additive manufacturing (WAAM) – a class of AM that uses welding arcs and metal wire feedstock – offers a cost-effective route for fabricating medium-to-large metal components [1], [2].

In WAAM, a robotic welding arm uses an electric arc to melt a continuous metal wire feed, depositing molten metal layer-by-layer onto a substrate with the designated design [3]. The process is similar to traditional arc welding, but WAAM is equipped with computer control and multi-axis motion to create a more complex geometry. WAAM can achieve high deposition rates with a large building volume and minimum cost compared to other AM manufacturing methods [2], [3].

For example, Fig. 1 shows a typical WAAM setup in which a controlled arc continuously adds metal on an underlying substrate using a robotic arm. Because WAAM uses an arc heat source, it can build very large metal structures with relatively low capital equipment cost [4]. This process has been widely applied in industries that demand large, structural metal parts – such as aerospace, shipbuilding, and energy, where high material efficiency and design freedom are especially valuable [3], [5].

In practice, WAAM can produce almost finished components, which greatly reduces machining and assembly steps in the finishing process. For instance, large aerospace fuel tanks and frames have been successfully WAAM-printed, saving material and time with similar properties to the traditional fabrication process [3], [5]–[7]. In the next sections, the current arc-based AM technologies, their challenges, ongoing improvements, and applications will be reviewed with emphasis on the underlying theory and developments. Schematic diagram of the GMAW-based AM system with a double electrode in Fig. 2.

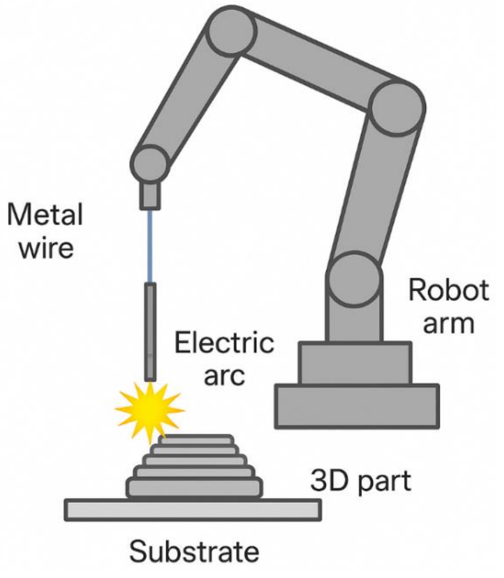

Fig. 1. Schematic illustration of a WAAM system with a robotic arm that guides the welding torch that melts metal wire, makes a layer on the substrate, and forms 3D deposition

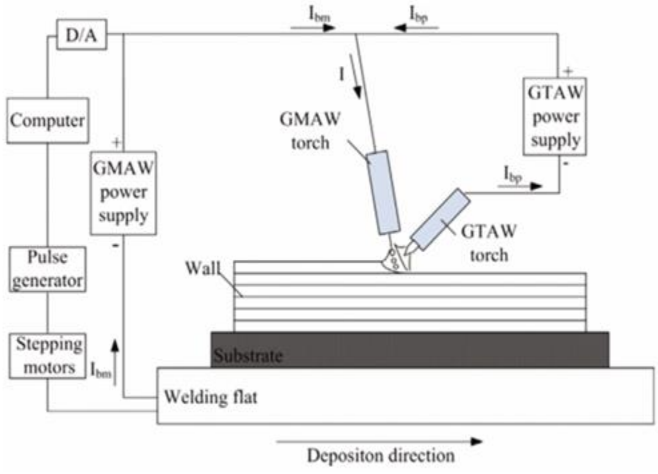

Fig. 2. Schematic diagram of the GMAW-based AM system with a double electrode [8]

2. Research Methods

This paper is presented as a critical narrative review, aiming to consolidate and evaluate the current body of knowledge related to Wire-Arc Additive Manufacturing (WAAM) and welding-based additive manufacturing technologies. Rather than reporting new experimental findings, the review systematically synthesizes prior studies to clarify process principles, establish process–structure–property relationships, identify technological limitations, and map emerging research directions. The focus is on integrating theoretical insights with experimental evidence to provide a comprehensive understanding of WAAM's capabilities and challenges.

The review primarily examines literature published between 2010 and 2025, a period that captures the evolution of WAAM from an emerging research topic to a globally recognized metal additive manufacturing technology. Early studies from 2010–2015 are included to establish foundational concepts in arc physics, deposition strategies, and metallurgical behavior. More recent works from 2016–2025 are emphasized due to their contributions to advanced arc modes, multi-material deposition, real-time monitoring, machine learning–based control systems, and industrial-scale applications. A smaller number of pre-2010 publications were selectively incorporated when necessary to support historical context or fundamental welding principles relevant to WAAM.

A structured literature search was conducted using major scientific databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, SpringerLink, and Wiley Online Library. Keywords and Boolean combinations employed in the search included: *"Wire-Arc Additive Manufacturing"*, *"WAAM"*, *"welding-based additive manufacturing"*, *"arc-based DED"*, *"GMAW additive"*, *"GTAW additive"*, *"PAW additive"*, *"WAAM microstructure"*, *"WAAM residual stress"*, and *"WAAM process control"*. To ensure comprehensive coverage, the search was supplemented with backward and forward citation tracking, enabling identification of foundational works and recently published studies not yet indexed by all databases.

Publications meeting the following criteria were included: (i) Relevance to WAAM or welding-based AM processes; (ii) clear methodological description, (iii) contribution to understanding process physics, microstructure, materials behaviour, or control systems; (iv) Publication in reputable journals, conferences, or standards documents

This structured and systematic approach ensures that the review is built upon a robust, diverse, and high-quality body of literature, thereby strengthening the validity of the synthesized conclusions and the recommended future research pathways.

3. Results and Discussion.

3.1 Current Welding-Based Additive Manufacturing Technologies

WAAM methods are typically categorized by the type of arc-welding process used to melt the wire. The most common and traditional processes are Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW) based systems [2]. In a GMAW-based WAAM (often called MIG/MAG-based WAAM), a consumable wire electrode is fed through a welding torch, creating an electric arc with the substrate that melts the wire. GMAW-WAAM can use various transfer modes (e.g., spray, pulsed spray) and is adaptable: for example, Cold Metal Transfer (CMT) – a variant of GMAW with controlled dip transfer which is widely used because it achieves a high deposition rate with relatively low heat input [9]. Multi-wire extensions have also been developed (Tandem GMAW), which uses two wires together to double the deposition rate and has even been explored for fabricating novel alloys [10]. Another innovation is Double-Electrode GMAW in Fig. 2., where a secondary arc (often a GTAW torch) provides additional current flow ("bypass current") to boost material utilization by over 10% [8]. Recent research that studies the effects of wire feed speeds and travel speeds from WAAM on weld shows that these parameters could categorize the result from very good to poor [11].

GTAW WAAM uses a tungsten electrode for the arc, which is non-consumable, with a separately-fed filler wire. This process is often used for high-quality builds of titanium and stainless steels. Adjusting the feed orientation (back, side, or front feeding) can improve accuracy, and mathematical models have been developed to optimize the process [10]. GTAW-based WAAM tends to have a slightly lower deposition rate than GMAW but can produce finer control of the arc and is suitable for reactive alloys (tungsten shielded) [2]. Nur, et.al. [12] use this technique to deposit layer-by-layer which achieved a consistent deposition. But the heat accumulation during the process caused dimensional distortion and collapse zones in the upper layers which evidenced by a vertical grain evolution, from fine equiaxed grains at the bottom to coarse columnar grains at the top, accompanied by increased δ-ferrite content. Recent variants of GTAW WAAM include twin-wire configurations, enabling multi-material or functionally graded deposition [13].

Plasma arc welding (PAW) can be used for WAAM, offering a more concentrated arc with higher energy density. In PAW-WAAM, an electric arc passes through a plasma gas stream, producing a very high-energy arc (up to three times denser than GTAW) [14]. This yields deeper penetration and faster travel speeds with less heat spread, which reduces distortion per layer. Micro-plasma torches have been demonstrated for WAAM to achieve thin, precise bead geometry [4]. Veiga et.al. [15] successfully fabricated aeronautical materials Ti6Al4V using this technique which met AMS4928 standard. However, PAW equipment is generally more complex and costly than MIG/TIG torches.

Each of these welding processes can be combined with robotic gantries or multi-axis machines to automate deposition. The comparison of these 3 welding processes is summarized in Table 1. In practice, robotic WAAM systems consist of a power source, wire feeder, robot arm, and shielding gas setup, along with software for path planning [2], [4]. In general, welding-based WAAM is prized for its ability to fabricate large, load-bearing metal structures efficiently and forming near-net shapes that minimize waste [3], [5].

Table 1. Comparison of current WAAM technology

Processes	Advantages	Limitation
GMAW-based	- Easy to adjust parameters - Highest deposition rate with low heat input - Easy to automate - Wire feeding; widely available. - Good material utilization and relatively low operating cost. - Effective for steel, aluminum, and nickel alloys.	- Produce many spatters. - Poor surface finish. - Less stable arc can lead to porosity. - Heat input and bead geometry control is less precise. - Easy to defect when parameter is not optimized.
GTAW-based	- Use non-consumable electrode - Produce finer grain with control of arc - suitable for reactive alloy (Titanium, stainless steel) - Highest thermal stability and arc precision which enabling excellent control of bead geometry. - Produces low-spatter, smooth surface finish and high-quality weld deposits.	- Lower deposition rate and limiting productivity for large parts. - Accurate parameter is needed. - Sensitive to shielding gas disturbances. - Higher heat input cause larger (HAZ) if not optimized. - More difficult to automate compared to GMAW.
PAW-based	- Faster travel speed, narrow width, lower HAZ - Produce stable arc with high energy density deeper penetration - Moderate deposition rate - Better arc concentration than GTAW. - Minimal distortion. - Good repeatability - Suitable for automated systems.	- More complex and costly - Need precise setting of the plasma torch and orifice. - Sensitive to parameter variations. - Minimum standardized procedures and less industrial adoption.

3.2 Challenges of Welding-Based Additive Manufacturing

Despite its advantages, WAAM still has some challenges that researchers continue to address. The main problems are thermal management, defects, accuracy, and process control. The high heat input of welding causes high thermal gradients, leading to residual stresses, part warping, and distortion [16], [17]. These stresses can exceed material yield and lead to cracking or dimensional inaccuracy after cooling. Managing these stresses (through pre-heat, inter-layer cooling, or adaptive heat input) is important to minimize the internal defects.

WAAM parts typically have rough surfaces and limited dimensional precision (on the order of ±0.2 mm) [18]. Layer edges and rounded corners are common, requiring significant post-machining for tight tolerances. Efforts to improve accuracy focus on advanced tool-path control and real-time adjustment of arc parameters to correct deviations.

Entrapped gas porosity is the most common defect found, especially in materials like aluminium alloys that are prone to gas pick-up. As noted in an industrial study, aluminium wire rapidly absorbs moisture in air, leading to excessive porosity that degrades mechanical properties [3]. Even in steel WAAM, shielding gas quality and weld pool oscillations can trap bubbles. Unfilled gaps or lack-of-fusion between layers (inner voids) have also been reported [19]. Addressing porosity involves optimizing welding parameters, using clean wire storage, and in-situ non-destructive monitoring.

WAAM processes often have narrow stable parameter ranges. In practice, too high or too low wire-feed speed or travel speed can cause weld pool instability (e.g. humping) or insufficient fusion. The recent AMRC project on aluminium WAAM noted a very limited process window, making parameter selection challenging [20]. Some parameters such as longitudinal and transversal orientations parallel to building and deposition directions respectively were found to influence the mechanical properties of weldments [21]. Complex geometries may require multi-axis deposition paths; five-axis robot motion is sometimes used, but this requires sophisticated programming.

The repetition of melting and solidification stages in WAAM produce inhomogeneous microstructures (often columnar grains) which can lead to anisotropy. For some alloys, cracking (hot cracking or cold cracking) can occur if thermal stresses and cooling rates are not controlled. For example, titanium and nickel alloys require tight control of shielding to prevent oxygen pickup and embrittlement. Material suppliers are also working on specialized wire chemistries for WAAM (e.g. modified stainless steels, aluminium alloys) to minimize cracking and distortion. The interplay of heat, fluid flow, and solidification in the weld pool is a complex system which require integrated modelling and sensing for improvement.

3.3 Future Improvements in Welding-Based Additive Manufacturing

To solve the problems descripted in the previous section, research on WAAM is continued in some topics. Future improvements should focus on process control, advanced wire arc processing, and raw materials selection.

The main aim is to integrate real-time monitoring and adaptive control into WAAM systems. Based on literatures, future WAAM machines will have automated path planning (CAD-to-part) and feedback control of arc parameters [20]. This would involve sensor fusion (vision, pyrometry, acoustic) to monitor the weld pool and adjust current, voltage, or travel speed on-the-fly. Algorithms may also detect defects in real time to rework troubled sections. In summary, enhanced process automation is expected to significantly improve reproducibility and accuracy [22].

The most up to date WAAM manufactures are utilizing two or more wires/arcs working simultaneously. Twin-wire WAAM has been shown to enable deposition of functionally graded materials or intermetallic composites [23]. By feeding different alloys in adjacent wires, graded composition can be built into a single part. This opens possibilities for built-in corrosion resistance or heat-resistant layers. Future suitable research is to refine deposition strategies and torch designs for reliable multi-material prints [23].

Predictive models are becoming important for WAAM planning. Finite element and computational fluid dynamics (CFD) models can simulate the moving heat source, temperature field, and resulting stresses. Such models help optimize parameters (arc power, speed, wire-feed) to minimize distortion and porosity. In parallel, data-driven and machine-learning models are emerging for example, neural networks trained on sensor data can predict structure outcomes or classify defects. These tools can reduce trial-and-error and enable “digital twin” simulation of each WAAM process [24]. Moreover, this simulation and formulation should be tested on different material and working conditions [25].

Techniques such as inter-layer cooling (forced air or cooling sprays) can refine microstructures and reduce residual stress on grain boundaries. As another study demonstrated, applying forced cooling between deposition increased ferrite formation and tensile strength in steel WAAM walls. Similarly, oscillating torches, auxiliary heat sinks, or in-situ rolling of deposited layers have been studied to improve grain structure and part density [5]. Future WAAM systems may incorporate such features (e.g. dual guns with cooling jacket). Stainless steel (SS400) turbine blade manufactured by WAAM in Fig. 3.

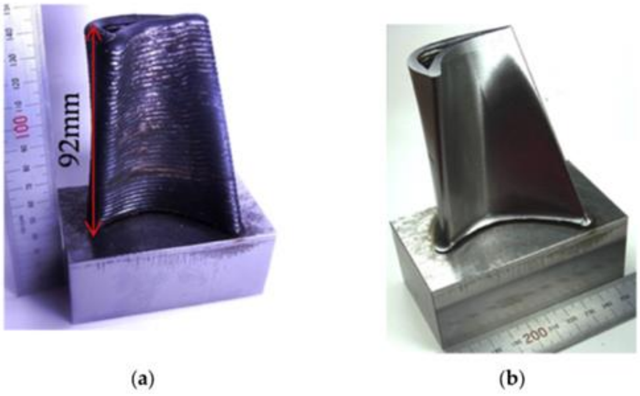

Fig. 3. Stainless steel (SS400) turbine blade manufactured by WAAM (a) before finishing, and (b) after finishing [26]

To overcome surface roughness, many applications combining WAAM with CNC milling subsequently – either in a single compact machine or through staged processing. Real-time or sequential machining during the manufacture can maintain dimensional tolerance. There is also interest in combining arc AM with other energy sources: for instance, “laser-wire” processes that supplement the arc with a laser beam for local reheating or deeper penetration. Such hybrid methods could further enhance build quality and material properties[26].

Fig. 3. depicts example of a component made by WAAM (a) and after machining stage (b) through staged processing. This example showed that the as WAAM fabricated component still lack smooth surface because of the deposition process done layer by layer. There is small gap between each layer that must be flattened so it has a smooth surface prior its application.

New wire alloys designed only for WAAM are under development. Alloys with refined solidification ranges, controlled amounts of ferrite or austenite, or microalloying additions can reduce cracking. Pre- and post-heat treatments (like inter-layer rolling or in-situ tempering) can also improve ductility. As a notable result, many WAAM model made from Ti-6Al-4V and other alloys which already achieve mechanical properties with the same level with conventional manufactured metals [27]. Ongoing work will expand the range of weldable alloys and optimize their properties.

To sum up, the future of welding-based AM lies in smarter, more flexible machines that combine advanced control, novel processes, and optimized materials to deliver high-quality parts.

3.4 Applications of Welding-Based Additive Manufacturing

Welding-based AM has found applications in many fields where large metal parts or complex structures are needed. Its primary advantage is the ability to produce very large, near-net-shape parts that would be difficult or costly to machine. For example, offshore industries have used WAAM to fabricate parts of onboard ships, and aerospace companies have built large fuel tanks and frames with WAAM [3], [5].

Aerospace: WAAM can produce structural parts like wing sections, fuselage frames, and engine mounts. Its large build envelope allows printing of near-net-shape fuselage panels or wing ribs that would otherwise require many weldments. Yu, et. al. [28] performed topology design optimization prior to manufacturing aircraft frame. The results indicate that WAAM can successfully manufacture topologically optimized components when the maximum overhang angle is considered, thus achieving a high level of forming accuracy. Veiga et. al. [15] also successfully fabricate aerospace materials Ti6Al4V using PAW-based WAAM. Moreover, WAAM is also used for repair and refurbishment of aircraft parts (e.g. re-cladding worn turbine casings) [5], [29]. For instance, researchers at the AMRC used WAAM to print a prototype aluminium liquid-hydrogen storage tank for aerospace use [3], [5]. By producing complex geometries (integral stiffeners, internal channels) in one piece, WAAM can reduce part count and lead time in aerospace manufacturing.

Automotive: The automotive industry uses WAAM for heavy-duty components where strength is critical. Examples include engine blocks, transmission housings, and chassis parts. BMW and other manufacturers have invested in WAAM-capable machines to produce or test high-strength steel parts [29]. WAAM can manufacture custom tooling (dies, jigs) and replacement parts for low-volume or legacy vehicles [30]. While the automotive sector often values cost reduction, WAAM's ability to deposit steel or aluminium in large quantities has made it attractive for trucks, specialty vehicles, and prototypes.

Energy and Power: WAAM is used in oil and gas to print replacement valves, pumps, and piping components, avoiding long supply delays. In renewable energy, WAAM can fabricate large components like wind turbine segments or towers. For example, wind-farm operators have begun using WAAM to produce thick-walled steel sections for turbine structures, where traditional forging would be impractical. A 3D printing supplier noted that WAAM enabled avoidance of supply-chain bottlenecks in refinery maintenance [29]. Zhou et. al. also utilizes WAAM to fabricate titanium aluminide low pressure turbine [31].

Shipbuilding and Marine: Large metallic structures such as hull segments, propellers, and offshore platform parts can be built with WAAM. The maritime industry values WAAM for on-site fabrication in shipyards and for repairing corrosion-damaged sections at sea. Petro *et al*. report that WAAM is usually used in high tech industries like shipbuilding and marine, where making large-sized and complex structure parts is important [5]. By printing whole subassemblies, shipbuilders can reduce the number of weld seams and achieve lighter, integrated structures.

Construction and Infrastructure: WAAM is also applied in construction-scale projects. For example, a pedestrian bridge in Amsterdam was 3D-printed from stainless steel using WAAM techniques. The bridge in Fig. 4. demonstrates how WAAM can create large architectural structures with freeform design freedom. The bridge could be fabricated directly as a complete structure not part by part connected, which give less component to maintenance and more homogeneous structure. In general, WAAM is suitable for heavy construction components (steel frames, rebar cages) and has been explored for printing precast concrete reinforcement or even entire building structures in futuristic proposals. Illustration of a large structure fabricated by WAAM - stainless steel pedestrian bridge in Fig. 4.

Fig. 4. Illustration of a large structure fabricated by WAAM - stainless steel pedestrian bridge

Other Fields: WAAM also used in defence (armour plating, vehicle hulls) [32], biomedical (large titanium implant prototypes) [33], tool steel [34], and nuclear nozzle [35]. Its detailed is always in the production of large, load-bearing metal forms. As MakerVerse notes, WAAM has "gained traction" for precisely producing everything from crane hooks to entire bridges [29].

Each application strengthens WAAM's position in material efficiency and scale, while with some drawbacks on surface finish or fine detail. Because welding AM generally requires post-processing (machining, heat-treating) for final tolerance and properties, the most cost-sensitive uses are those where conventional machining would be even more expensive (large aerospace or marine parts, for example). In summary, WAAM has emerged from laboratory scale to a practical tool in industries that build big metal parts [3], [5].

4. Conclusion

4.1 Future Research Perspectives

Wire-Arc Additive Manufacturing (WAAM) and related welding-based additive manufacturing (AM) technologies have demonstrated potential to change the production of large-scale metallic structures. Their advantages in terms of material utilization, deposition rate, and cost efficiency make them strong candidates for industrial applications especially in aerospace, marine, energy, and construction sectors. Compared to powder-based AM processes, WAAM offers simpler feedstock handling, higher build rates, and scalability, enabling the manufacture and repair of complex, high-value components. However, the process still faces limitations related to surface roughness, dimensional accuracy, residual stress, and microstructural anisotropy. Solving these problems requires a deeper understanding of heat transfer, solidification, and metallurgical transformations occurring during multi-layer deposition.

From a research perspective, several topics remain open for development. They should focus on integration of real-time sensors, machine learning, and closed-loop feedback systems to ensure consistent layer geometry, temperature stability, and defect detection. Then, exploration of simultaneous deposition of different alloys or dissimilar metals to produce components with site-specific mechanical and thermal properties. Another topic, by combining WAAM with subtractive finishing or surface treatment processes to improve geometric precision and surface quality. Numerical modelling and simulation also should be studied where high-fidelity modelling of thermal and mechanical properties to optimize processing parameters and predict microstructure evolution of the final product. Moreover, evaluating energy efficiency, carbon footprint, and recyclability of WAAM-produced components to align with green manufacturing goals. Finally, there should be standardization and certification from international standards for process qualification, defect assessment, and mechanical property benchmarking to facilitate industrial adoption.

Overall, WAAM represents a significant step toward flexible, sustainable, and digitally integrated metal manufacturing. The continued integration with robotics, artificial intelligence, and advanced materials science will likely accelerate the maturity of this technology, enabling their transformation from laboratory prototyping to fully qualified industrial production systems.

4.2 Limitations of this review paper

The review focuses primarily on wire-arc additive manufacturing (WAAM) and closely related welding-based AM processes. As a result, other AM technologies (such as laser-based systems, powder-bed fusion, and hybrid subtractive approaches) are not discussed. Similarly, most used reference for this review paper involves only on commonly used alloys (steel, stainless steel, aluminium, titanium).

In addition, this review relies on academic sources, meaning that industrial data, especially proprietary process parameters, closed-loop control strategies, and robotic system configurations, are not described briefly. Consequently, the review may not fully capture the practical challenges and solutions used in real industrial WAAM applications.

Moreover, the WAAM literature shows significant variation in experimental setups, processing parameters, deposition strategies, test geometries, and characterization techniques. These inconsistencies make the comparability between studies challenging and restrict the possibility of conducting quantitative meta-analysis. The conclusions are therefore based mainly on qualitative synthesis.

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