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A Review of Wire Arc Additive Manufacturing

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ABSTRACT

Wire Arc Additive Manufacturing (WAAM) is a metal additive manufacturing (AM) process based on the technique of Directed Energy Deposition (DED), which uses an electric arc to melt wire feedstock for the layer-by-layer fabrication of large, near-net-shape metallic components of complex geometries. In this review paper, the authors aim to provide a comprehensive overview of WAAM technology. It discusses the basic principles, major components, working principles and physics involved in WAAM process, major advantages including high deposition rates (10 kg/hr), low-cost, material flexibility, near-net-shape structures, industrial applications in aerospace, automotive, marine, construction, energy and infrastructure industries, major challenges such as thermal distortion and residual stresses, anisotropy, porosity, poor surface finish and low standardization, current research trends to address these challenges like process modeling and control, hybrid WAAM, advanced path planning strategies, inter-layer cooling and artificial intelligence (AI) integrated control systems and future trends in this field such as new materials and material systems, simulation-driven process optimization, certification and standards, sustainable WAAM. The current state-of-the-art and recent advancements in WAAM technology are discussed in terms of novel process techniques and applications. This paper will be of interest to a wide audience, including researchers and engineers working in the field of WAAM and high-performance scalable AM technologies.

Keywords: *Wire Arc Additive Manufacturing (WAAM), Directed Energy Deposition (DED), Metal 3D Printing, Process Optimization, Industrial Applications*

List of Abbreviations

Abbreviation	Full Form
AI	Artificial Intelligence
AM	Additive Manufacturing
ANOVA	Analysis of Variance
BHN	Brinell Hardness Number
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CMT	Cold Metal Transfer
CNC	Computer Numerical Control
CTWD	Contact Tube to Workpiece Distance
DED	Directed Energy Deposition

DIC	Digital Image Correlation
DoE	Design of Experiments
EBSD	Electron Backscatter Diffraction
FE	Finite Element
GMAW	Gas Metal Arc Welding
GMAW-DP	Gas Metal Arc Welding – Double Pulse mode
GMAW-P	Gas Metal Arc Welding – Pulse mode
GTAW	Gas Tungsten Arc Welding
HV	Vickers Hardness
MIG	Metal Inert Gas (welding)
NIAC	Near Immersion Active Cooling
OEM	Original Equipment Manufacturer
PA	Peak Arrest
PAW	Plasma Arc Welding
R&D	Research and Development
T	Thermal Scalar Field
TIG	Tungsten Inert Gas (welding)
TS	Travel Speed
UHFP	Ultrahigh-Frequency Pulsed
UTS	Ultimate Tensile Strength
WAAM	Wire Arc Additive Manufacturing
WFS	Wire Feed Speed
XRD	X-ray Diffraction

Material Designations & Chemical Notations

Material / Notation	Description
10CrNi3MoV steel	Low-alloy high-strength structural steel
300M steel	High-strength low-alloy steel (modified 4340)
308L	Austenitic stainless steel filler metal
316L	Austenitic stainless steel (low carbon)
AA5083	Aluminum Alloy 5083
AA5183	Aluminum Alloy 5183
AA5356	Aluminum Alloy 5356
Al	Aluminum
Al-Mg	Aluminum-Magnesium alloy
Al-Zn-Mg	Aluminum-Zinc-Magnesium alloy
Al–Cu	Aluminum-Copper alloy
Al–Si	Aluminum-Silicon alloy
Ar-CO_2	Welding gas mixture of Argon (Ar) and Carbon Dioxide (CO_2)
Cr	Chromium
CuAl8	Copper-Aluminum alloy with ~8% Aluminum
E120C-GH4	Metal-cored, ≥120 ksi tensile, Ni-Mo-Cr alloyed
EH36 steel	High-strength shipbuilding steel
ER120S-G	Solid wire, ≈120 ksi tensile, low hydrogen
G2205	Duplex Stainless Steel, 22% Cr, 5% Ni, high strength
G2209	Duplex Stainless Steel, 22% Cr, 9% Ni, more austenitic
He-Ar-CO_2	Welding gas mixture of helium (He), argon (Ar), and carbon dioxide (CO_2)
Inconel 625	Nickel-Chromium-based superalloy
Laves phases	Intermetallic phases in Ni-based alloys

MC carbides	Metal carbides (generic notation)
Mo	Molybdenum
Ni	Nickel
Ni-rich NiTi	Nickel-rich variant of NiTi alloy
NiTi	Nickel-Titanium shape memory alloy
S690QL steel	High-strength quenched and tempered structural steel
SS316	Stainless Steel 316
Ti-6Al-4V	Titanium alloy with 6% Aluminum, 4% Vanadium
TiAl	Titanium Aluminide
TZM alloy	Titanium-Zirconium-Molybdenum alloy
XC-45	Medium carbon steel
Zn	Zinc
α2 / γ phases	Alpha-2 and Gamma phases (TiAl intermetallics)
δ-phase	Delta phase (intermetallic phase in Ni-based alloys)

INTRODUCTION

WAAM is a recently developed metal 3D printing technology that can be used to build up large and complex components at a much faster and lower cost rate [1, 2]. It is a member of the Direct Energy Deposition (DED) family of AM processes [3, 4]. WAAM creates a 3D geometry by continuously layering the material on top of the previous one until a three-dimensional part is fabricated [3]. It is defined as an AM process that uses an electric arc as a heat source to melt a wire feedstock and deposit molten metal on the substrate layer-by-layer to form a component [5, 6, 7]. Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW) are among the most commonly used heat sources for WAAM [1, 8, 9]. However, GMAW is often preferred in WAAM due to its better process stability, control, and reduced heat transfer during deposition in combination with a co-axial wire and torch configuration that simplifies the tool path calculation [5, 10]. WAAM typically involves the combination of standard welding equipment such as a power source, welding torch, and wire and protective gas feeding systems with robotic systems or Computer Numerical Control (CNC) machines to provide the required motion during deposition [5, 10, 11].

The idea of using an electric arc as a deposition heat source in AM has been around for quite some time. In fact, the first patent for this was granted in 1925. However, the WAAM research and development (R&D) activities, in the context of AM, have gathered momentum in the last three decades [11]. It has since emerged as a promising technology that can be used to mass-produce metal components for a wide range of applications [8]. This is largely due to its primary advantage of high deposition rate, often above 10 kg/hr, in contrast to the relatively low deposition capabilities of powder-based AM approaches [5, 6, 10]. The high deposition rate, combined with low manufacturing costs and reduced production times, makes WAAM a technology of choice for large-sized components [1, 2, 12, 13, 14]. WAAM systems can be significantly less expensive than traditional AM technologies, as they are based on standard off-the-shelf welding equipment [5, 10, 11, 15]. The process also results in a high material utilization and thus reduces the so-called "buy-to-fly" ratio of the process (a measure of material wastage) to a fraction of traditional subtractive processes where a significant amount of raw material is machined away [5, 10]. WAAM can be used to produce fully functional, near-net-shape products with essentially unlimited build size, resulting in increased design freedom and the possibility of manufacturing geometries that may be unfeasible with conventional processes [5, 10, 11, 13, 16].

WAAM has found applications in a range of industrial sectors, including aerospace, automotive, shipbuilding, oil and gas, chemical, and high technology industries [3, 8, 10, 17]. It is used widely for processing of materials such as Al, titanium, Ni, and different alloys of steel. In addition, there is a growing demand for these materials in manufacturing components with desirable properties such as high thermal resistance, hardness, toughness, and wear resistance [1, 3, 8, 10]. For example, in the aerospace industry, WAAM is emerging as a promising technology for fabricating components from titanium and Ni-based alloys. This is because this can significantly reduce material waste while producing large, complex-shaped components [10]. In automotive, WAAM has been used for the development of complex formed parts [10, 18]. WAAM has also been used in the nuclear industry to produce components that require high heat and corrosion resistance in nuclear power plants. In this application, it is suggested that it may reduce cost and weight by replacing Ni elements with stainless steel [10].

WAAM is still an area of research and investigation in the AM community despite its potential and the growing applications. This is due to a range of challenges and limitations in practical implementations [1, 14, 18]. For example, it is characterized by the existence of large residual stresses and distortion induced by high thermal input from the arc, which leads to mechanical property degradation and geometrical inaccuracy [1, 9, 10, 18, 19]. The method can also lead to other common defects, which are similar to those in traditional welding, such as porosity, cracks, lack of fusion, discontinuity, slag inclusions, and oxidation [3, 14, 19, 20]. In addition, WAAM can lead to under-matched mechanical properties and microstructural inhomogeneity, which arise from different heat cycles and non-equilibrium solidification, resulting in anisotropic properties and large columnar grain structures [1, 10, 18, 19]. The surface quality of WAAM components may be poor, and undercuts as well as humping can occur. Additional post-deposition operations are also often mandatory to form WAAM components [8, 18, 19, 20]. Finally, the WAAM process parameters, such as the current, voltage, travel speed (TS), and wire feed rate, must be precisely controlled, since they have a considerable effect on the characteristics of the deposit and frequency of defects [10, 20, 21].

Ongoing R&Ds are, however, targeted at addressing the existing challenges and opening up possibilities for new applications [1, 2, 10]. This includes, for example, optimizing the deposition strategies in terms of slicing and path planning algorithms and employing multi-sensor monitoring and intelligent control to improve geometric accuracy and reduce defects [2, 10, 12, 22]. It also includes the development of Hybrid-WAAM processes, which are characterized by various approaches to deposition, such as deposition methods, manufacturing processes, layering strategies, raw stock materials, and kinematics of the machine tool. The goal here is to address the inherent WAAM process challenges of poor surface quality, porosities, and residual stresses [19]. In addition, there is research on the development of WAAM process improvements, such as those for thermal control (e.g., the Cold Metal Transfer (CMT) technique and Near Immersion Active Cooling (NIAC)), to reduce heat accumulation and increase productivity, while having a positive effect on mechanical properties [10]. Other work is focused on extending the WAAM materials range for new alloys and multi-material components and on the applications of AI for WAAM process optimization [10, 12, 23, 24]. In this review article, we aim to provide a comprehensive review of WAAM, covering the fundamental aspects of the technology, including its principles, benefits, and applications, as well as past projects in manufacturing companies, recent research work, inherent challenges and open issues, and future directions that are likely to drive its continued development as an important AM technology.

FUNDAMENTAL PRINCIPLES OF WAAM

WAAM is an AM process that fabricates metallic parts layer-by-layer with the help of an electric arc as the source of heat input and wire as a feedstock (Figure 1) [3, 25, 26]. The process can be used for manufacturing large metal components, as it offers very high deposition rates. WAAM is a viable alternative to conventional manufacturing processes like casting and forging [25, 27, 28].

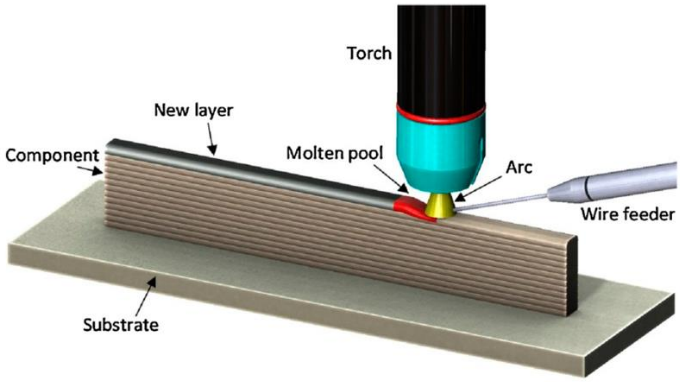

Figure 1: Visual representation of the WAAM process [29]

Working Mechanism of WAAM

WAAM is a metal AM process that is used to produce or repair metal parts through the deposition of layers of metal in order to form a desired three-dimensional shape [3]. WAAM is classified as a member of the DED family of AM processes [3]. The working mechanism involves melting electrode wire using the heat energy of an electric arc and then using the molten metal to form layers or composite structures [26]. The cross-section of the layers built with this process is usually about 1 to 2 mm in thickness [3]. WAAM is a completely automated process controlled by a Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) program running on robotic or CNC welding platforms [30]. Parts are built on the platform by depositing a bead of weld metal layer-by-layer [31]. The process can be used to build complex three-dimensional shapes that are difficult or impossible to produce with traditional processes [10]. The materials used with WAAM usually include titanium, steel, copper, bronze, and Al alloys, which are usually materials with high thermal resistance, hardness, toughness, and wear resistance [3].

Key Components of WAAM

A WAAM system mainly comprises the following components, which operate collectively to fabricate a metallic part [25]:

- Robotic Arm or Cartesian Work Frame: It acts as the manipulator, which imparts controlled movement for the deposition of the material [5]. CNC-controlled robotic manipulators are typically employed, which ensure precise location of each layer of the added material [32].
- Power Source: The power source provides the electric current required to form an arc and melt the wire feedstock [5].
- Wire Feed: This part of the system is responsible for feeding the consumable metal wire, which acts as the raw material to the welding torch [5].
- Welding Torch: This part of the system is used to form the electric arc as well as direct the molten wire from the wire feed onto the substrate [5]. GMAW, more commonly known as metal inert gas (MIG) welding, is widely considered to be the most suitable technology for WAAM, as coaxiality of the wire and torch simplifies the tool path calculations [5]. The CMT process is a relatively new GMAW process that is widely considered to be the best process for WAAM due to its improved process stability and process control as well as the reduced heat transfer, which mitigates many WAAM process problems such as

spattering and arc wander, leading to high-quality and high deposition rate deposition [5]. On the other hand, for deposition of titanium, Tungsten Inert Gas (TIG) welding is considered to be a more suitable process, as MIG welding leads to arc wandering and excessive surface roughness [5, 33].

Underlying Physics of WAAM

WAAM involves a number of thermo-mechanical phenomena that underlie the working of the process and provide basic understanding to manufacture components [32]. The fundamental physics include the following:

- Heat Input and Management: The electric arc in the WAAM process causes very high heat input, which affects the shrinkage, deformation, and residual stresses resulting in the manufactured parts [13, 31, 34, 35]. The weld current directly affects heat and mass transfer as well as the morphology of the weld bead [36]. With an increase in weld current, the volume and temperature of the molten pool increase, and the convection within the molten pool is intensified due to the temperature gradient [36]. Changes in heat input account for more than 90% of changes in layer width and more than 76% of changes in layer height [37].
- Material Expansion and Contraction: The material being deposited by WAAM typically undergoes non-uniform expansion and contraction during the thermal cycle, which causes the resulting components to have residual stresses and distortion [19, 31, 38]. Accurate prediction of thermal cycles and the residual stresses is of prime importance for building components of large volume, and multiple strategies, such as interpass cooling using water bath cooling, high-pressure air cooling, or aerosol cooling, are deployed to offset heat accumulation and thereby improve mechanical properties of the parts [34, 39].
- Molten Pool Dynamics: The process also involves molten pool dynamics and the anatomy of molten material in the presence of wire motions (withdrawal and dipping cycles) [40]. High-speed photography-based studies of the molten material provide deeper insights into driving forces that are present in the melt pool and an increased frequency of ejection of a continuous stream or a large number of particles [40]. Surface tension as well as arc pressure, which are functions of arc voltage and weld current, are reported to be driving forces causing the molten pool temperature to rise with increasing current [36].
- Microstructure and Mechanical Properties: The microstructure and mechanical properties of parts built using WAAM are also found to be inhomogeneous and anisotropic within a component because of the thermal conditions of the process [38]. The process parameters and the resulting microstructure, as well as post-processing treatments, are reported to influence the mechanical properties of the resulting component [39]; for example, components made with WAAM and consisting of high-strength steel have been reported to exhibit typical microstructures of lath martensite, acicular ferrite, polygonal ferrite, martensite-austenite, and precipitated phases [41]. The yield stress of as-built WAAM high-strength steel has been reported to increase with strain rate, and grain refinement as well as dislocation density strengthening are key mechanisms behind the observed strengthening of the yield stress with strain rate [41].
- Defect Formation: Defects that can be seen in WAAM parts, like porosity, cracks, lack of fusion, burn-through, discontinuity, slag inclusions, and oxidation, can also be found in conventional welding processes [3]. Inter-layer rolling and careful optimization of process parameters have been reported to minimize defects and improve density and uniformity of the material [42, 43].
- Process Modeling and Simulation: Computational models based on finite element (FE) simulation are the most widely employed techniques to optimize process parameters and get insights into the thermo-mechanical performance of WAAM [31, 32, 44]. Physics-informed machine learning methods have also

been developed to predict and optimize process parameters and bead geometry in WAAM by considering physics-based variables of volumetric energy density, solidification time, surface tension force, and Marangoni number as constraints [45, 46].

BENEFITS AND APPLICATIONS OF WAAM

WAAM is a newly developed metal 3D printing process that exhibits many advantages and also finds its application in various fields [26, 47, 48]. Therefore, in the following sections, we will first discuss the merits of the WAAM process, followed by the potential applications of the WAAM in various industries [49, 50].

Benefits of WAAM

WAAM has many advantages as compared to conventional processing techniques and other AM methods.

- Cost-Effective and Efficient Manufacturing Process: WAAM is considered a cost-effective and efficient manufacturing method [15, 48, 49]. Since WAAM makes use of the existing welding power sources and robotic systems, it incurs a lower initial investment cost than that required by the other conventional AM technologies [11, 51]. Moreover, the use of the wire feedstock in WAAM is more affordable in comparison to the powder used in many other AM techniques [25].
- High Material Deposition Rate: The material deposition rate for WAAM is very high compared to other AM methods (generally ranges from 1 to 10 kg/hr) [29, 47, 48, 52, 53]. This high material deposition rate is possible because of the larger diameter of the wire that is used as the feedstock for AM. WAAM is, therefore, able to build metal parts at a much faster rate than other AM methods. This high deposition rate is generally more suitable for medium-to-large-sized metal parts, which are best built via WAAM among other metal AM technologies [9, 15, 16, 54, 55]. For instance, the deposition rate of the GMAW-based WAAM process is higher than the other processes, which made it fit to be used for AM [56].
- Design Complexity and Design Freedom: WAAM offers high design complexity and design freedom. This means it is able to build very complex geometries that cannot be made through conventional manufacturing technologies [16, 47, 55, 57, 58]. This will allow optimized structural components to be built, which can reduce weight and increase performance. These geometries are typically in the form of force-flow-optimized nodes or bionic-inspired spaceframes [57, 59].
- Material Efficiency and Less Material Waste: The layer-by-layer deposition makes WAAM have a high material utilization rate; thus, there is much less material wastage compared to the subtractive manufacturing process [25, 49, 59, 60, 61]. As a result of this high material efficiency, it has a low “buy-to-fly” ratio compared to other manufacturing technologies. This means it takes relatively little raw material for WAAM to produce the final part [9, 11, 52]. A reduction of the 20:1 buy-to-fly ratio to 2:1 was reported when the traditional machining was compared to WAAM processing.
- Processing a Variety of Materials: WAAM technology can be employed for processing a wide variety of weldable metallic materials in their wire form, which include Al, titanium, Ni alloys, stainless steel, copper, bronze, and many more [1, 3, 8, 29, 47]. The capability of WAAM to process a variety of metallic materials further increases its application in various industrial processes [53].
- Printing Large Parts with Good Structural Integrity: WAAM is suitable for printing the medium-to-large complex parts that have good structural integrity [49, 50, 55, 60, 62]. The printed part is fully functional with its near-net shape. Post-processing of the printed part can then be done to achieve the required final dimensions and properties of the component [11, 25, 63].

Applications of WAAM

WAAM is most often used in the following industries due to its advantages over other technologies.

- Aerospace Industry: The aerospace industry is the most significant and major application of WAAM. This is because of its lightweight, high-strength, and complex components [47, 49, 53, 60, 62]. These components can be made by WAAM, which provides significant design freedom, a very fast material deposition rate, and relatively good material properties [47]. WAAM is able to process Al alloys, which are very important and mostly used in the aerospace industry due to their lightweight, excellent strength, and corrosion resistance [47, 60]. Examples of these include aircraft structural parts and missile structure [62, 64].
- Automotive Industry: WAAM has already been proven to build medium-to-large-sized components, mostly those that are made of Al, for the automotive industry [3, 18, 48, 49, 60] and body-in-white (BIW) and other related industries [60].
- Shipbuilding and Marine Industry: The shipbuilding industry is an area where WAAM provides a more design-flexible and cost-effective approach for the manufacturing of large-scale metal parts, especially in complex double-curved components such as bulbous bows, propellers, and rudders [8, 65]. It can also be used for saltwater valves and pumps, among other shipbuilding and marine applications [52].
- Construction and Structural Engineering: In the construction and architecture industries, the potential of WAAM has been recognized for the free-form design of steel components, e.g., the force-flow optimized nodes or bionic-inspired spaceframes [57, 59]. In general, it is able to combine a high level of automation and geometric freedom with high process efficiency for steel components [57].
- Repair and Indirect Manufacturing: WAAM can be used for direct manufacturing, indirect manufacturing (tooling), and repair of metal parts [3, 25, 59].
- Other Industries: WAAM is also used in various other high-technology industries, including the nuclear industry, molds and dies, chemical industries, and oil and gas industries [3, 49]. This is the case because the WAAM process can produce functional, near-net-shape products with desirable mechanical properties in these industries [11].

INDUSTRIAL APPLICATIONS OF WAAM: CASE STUDIES ACROSS SECTORS

WAAM is a new approach for industrial production that aims to combine the advantages of the rapid deposition of material with enabling technologies such as CNC machining and AI-driven process control [66]. WAAM can be used to manufacture large-scale and complex metal components with reduced lead times and material waste compared to traditional manufacturing methods [66, 67]. WAAM technology is an integration of arc welding with robotic automation and the layer-by-layer deposition of material to construct 3D metal parts [66]. The following are companies that are currently involved in some aspect of WAAM:

- Cranfield University and Thales Alenia Space: Cranfield University and Thales Alenia Space have partnered with WAAM3D and Glenalmond Technologies to manufacture large-scale space exploration components with WAAM [68]. The result is a full-scale manufactured prototype of a titanium pressure vessel for future manned space missions [69, 70, 71]. The titanium pressure vessel is approximately 1 meter tall and weighs 8.5 kg and is made from Ti-6Al-4V titanium alloy [70]. The technology was implemented with advanced simulation, interlayer machining, cold work, and smart toolpath planning and showcases the exciting future of large component manufacturing with WAAM [68]. WAAM has an advantage in design complexity and freedom, very fast material deposition rates, and decent material properties for aerospace-grade production [47].

- BMW Group: BMW Group has been testing and optimizing WAAM for automotive use cases, demonstrating that the technology can produce high-quality serial metal components meeting strict performance requirements. A WAAM system has been in use since 2021 for the production of test components. One such component, a suspension strut support, is now undergoing extensive testing against a die-cast Al series component [72]. WAAM enables the production of new shapes that would be difficult to produce otherwise, and the energy-intensive process can be counterbalanced by material savings in the component design, which can reduce material waste by 80% for certain components such as conventional head plates [35]. The process offers an innovative additive production process for metallic vehicle components and tools at BMW Group's Additive Manufacturing Campus in Oberschleißheim [73].
- Baker Industries: Baker Industries, a company of Lincoln Electric Company, has partnered with General Atomics Aeronautical Systems, Inc. (GA-ASI), on a R&D project to further investigate the WAAM technology and determine its feasibility for the production of steel layup tooling to make composites [74, 75, 76]. WAAM is a concept first proposed by Baker in 1925 to revolutionize the production of large-format metal parts with faster turnaround times, greater design freedom, and significant cost reductions [77, 78]. WAAM can be used to produce new 3D parts or repair damaged metal parts, and Baker Industries is also looking at using multi-layer deposition of materials such as CuAl8 and multi-material depositions that combine CuAl8 with mild steel [79].
- AML3D: AML3D has also partnered with Baker Industries in adopting WAAM in providing large-scale 3D metal printing solutions, particularly for critical parts in power generation equipment. WAAM can be utilized in the shipbuilding industry to significantly improve productivity by 3D printing marine-grade metal structures [80]. The WAAM process is known for its high deposition rates and is able to produce parts with complex geometries [38].
- WAAM3D: WAAM3D is a company at the forefront of WAAM technology, providing state-of-the-art WAAM systems and solutions to support industrial applications across a wide range of use cases [81]. WAAM3D was a part of Cranfield University and Thales Alenia Space's team developing a route for the manufacture of large-scale space exploration components with WAAM, and its success in this application is very promising for the future of WAAM in this field [68]. WAAM3D has recently introduced their new large-format RoboWAAM XP system at Formnext 2024 [81, 82]. The company is also working to enable robotic MIG to be capable of doing WAAM to become a feasible production technique for end-use functional products with adequate mechanical properties [83].
- Fronius USA LLC: Fronius USA LLC is a leader in the WAAM space, offering state-of-the-art systems and solutions that support a wide variety of industrial applications in the field. Fronius welding equipment is also commonly used in WAAM robotic workcells, with the Fronius TPS600i being one example [84, 85]. The company also advocates for the benefits of using its CMT welding process for prototyping and high-value small-batch component production, as it provides a lower heat input compared to conventional pulsed arc processes [85, 86]. Fronius also offers a complete robotic WAAM implementation, which takes the leap from a CAD file to a printed WAAM part, with part slicing, robot motion planning, part metrology, in-process sensing, and process tuning involved [87, 88].

- Lincoln Electric: Lincoln Electric has contributed to the advancement of WAAM with their innovative process control, digital twin integration, and in-process monitoring solutions. Lincoln Electric Additive Solutions is capable of using WAAM to produce large parts by depositing layers of metal wire using GMAW [89]. Lincoln Electric has designed a complete WAAM approach that uses five algorithms that enhance the quality of massive metal components in WAAM by improving accuracy, speed, and flexibility through adaptive layer thickness control, material versatility optimization, intelligent path planning, multi-material strategy, and real-time quality assurance [90]. Lincoln Electric has also collaborated with Baker Industries and GA-ASI on R&D projects in exploring the feasibility of WAAM for the production of steel layup tooling [74, 76].
- Thomasnet suppliers: Thomasnet suppliers are known to have contributed to the advancement of WAAM, which is a low-cost metal AM technique and is highly suitable for fabricating medium- to large-sized complex structures that are more flexible in design, more power efficient, and less costly compared to other existing processes [91]. The implementation of WAAM would allow for rapid design iterations and part/system optimization, which would then form the foundation for a reliable production. The expiration of some of the earlier patents for WAAM has also allowed for manufacturers, including suppliers, to introduce and implement WAAM techniques [92].
- Siemens Energy: Siemens Energy was the first company in the world to use the WAAM process in serial production [93]. In 2023, Siemens Energy printed its 1000th guide vane using the WAAM technique, which has been shown to be very effective in the manufacturing of high-quality steam turbine components [93, 94]. Siemens Energy was introduced to the WAAM technology, as their supply chain had been faced with some disruptions before, with supplier delays in 2018 that resulted in turbines not being delivered. This further increased interest in the field of AM, which ultimately resulted in the industry shifting from the need for outsourcing parts from external suppliers to manufacturing parts in-house for immediate availability [94]. Siemens Energy has also collaborated with the Raytheon Technologies Research Center to develop computational tools and methods for controlling WAAM process parameters, which is able to use online measurements with feedback and also track the material's evolution [95].
- Whittaker Engineering (through NMIS): Whittaker Engineering, a business based in Aberdeenshire, has been looking into the potential of the introduction of DED-arc (WAAM) as a service to offer to its customers in the marine and offshore industries. Seeing a surge in demand from oil and gas customers for faster parts and shorter lead times, Whittaker Engineering wanted to see if WAAM could be moved out of R&D to a commercial offering to meet this demand. With the help of the National Manufacturing Institute Scotland (NMIS) Additive Manufacturing Team, Whittaker Engineering went through their AM-BATS project, an approach that used knowledge and skills to assist and de-risk the adoption of this type of innovative technology. NMIS was also able to pair Whittaker up with an oil and gas original equipment manufacturer (OEM) to look into the long lead times that were currently being faced for pipeline forgings. As a result of the successful program, a test component was printed in a matter of days, which was a critical step in proving that large-scale parts can be printed and replacing traditional forgings for oil and gas components that could take months to produce with one that can be completed in days instead. The company now has confidence in its ability to offer WAAM to its customers and is also continuing to do R&D into the technology for new materials using it [96].

OVERVIEW OF PAST RESEARCH ON WAAM

The number of articles reviewed for research on WAAM in this study is presented in Figure 2, covering publications from 2019 through 2025.

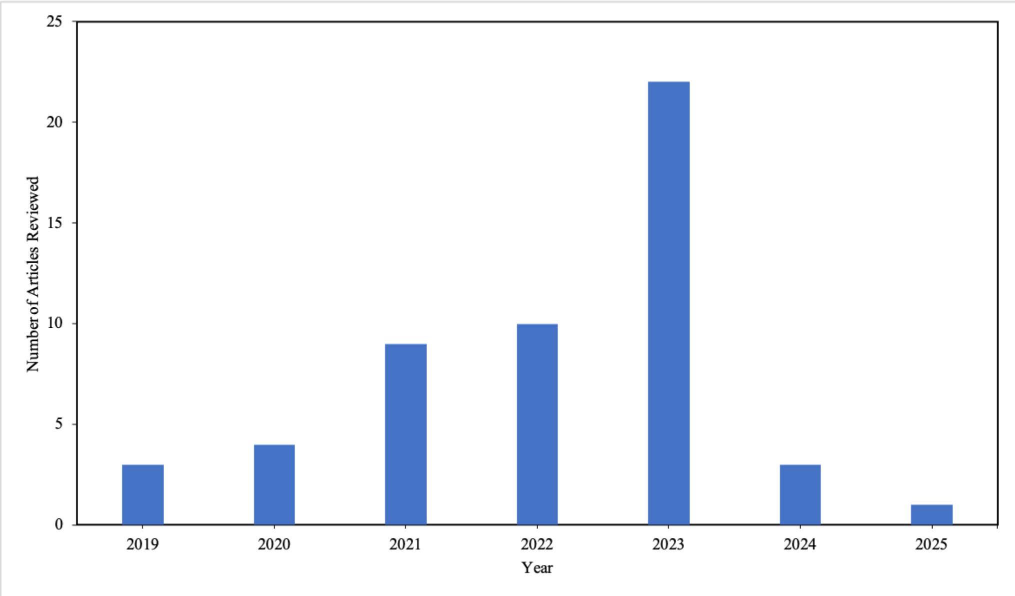

Figure 2: Articles reviewed (2019–2025) for research on WAAM

To provide insight into the publishing trends, Table 1 presents a quantitative distribution of these articles by publisher.

Table 1: Number of articles from different publishers reviewed for WAAM

Publisher	Number of Articles Reviewed
MDPI	19
Elsevier	9
Springer	7
Wiley	3
DergiPark AKADEMIK	2
IOP Publishing	2
Society for Manufacturing Engineers (SME)	2
American Society of Civil Engineers (ASCE)	1
Frontiers	1
Granthaalayah Publications and Printers	1
Military Institute of Science and Technology (MIST)	1
OPAST Publishers	1
Polish Academy of Sciences	1
Research Square	1
Taylor & Francis	1
Total	**52**

Eyercioglu et al. (2019) experimentally addressed the overhang angle in TIG-based WAAM, where a goal was to determine the maximum self-supporting overhang angle without the use of support structures. It was found that a maximum overhang angle of 28° was self-supporting when previous layers had a chance to cool down below 150°C between two layers, indicating the influence of thermal management on geometric supportability [97]. In comparison, Tanvir et al. (2019) investigated the microstructure and microstructural evolution of Inconel 625 components built by

WAAM using the CMT method under different heat treatment durations. The results showed that heat treatments at 980°C effectively eliminated undesired Laves phases, increased the δ-phase contents, and enlarged MC carbide size with time. The morphology of grains did not exhibit a clear trend with time [98]. On the other hand, Lin et al. (2019) studied the microstructure and mechanical properties of medium carbon steel deposited with a customized metal-cored wire via WAAM and reported a complex microstructure in the deposit due to continuous thermal cycles, and the final product featured a relatively consistent hardness, anisotropic tensile strength, and ductile fracture modes. The material from WAAM exhibited higher strength but lower elongation compared to the conventionally manufactured XC-45 [99].

Zeng et al. (2020) manufactured Ni-rich NiTi parts with WAAM and reported the microstructure evolution with layer number, which they stated transitioned from columnar to equiaxed due to thermal cycling. The final material possessed superelastic properties, suggesting that the as-built parts from WAAM may be successfully used as functional materials in their produced form [100]. In a separate work, Sun et al. (2020) studied low-carbon high-strength steel, which was intended for shipbuilding. The as-built material showed complex microstructure distribution with equiaxed, columnar, and interlayer zones. The tensile behavior was anisotropic with low strength in the longitudinal direction, which was a result of stress concentration in inter-layer zones and could be predicted with Electron Backscatter Diffraction (EBSD) and Digital Image Correlation (DIC) analysis [101]. Gierth et al. (2020) have reduced the porosity and lack of mechanical uniformity of Al alloy WAAM products by varying the energy input using GMAW CMT in different arc modes. Their experiments led to a porous fraction of below 1% and showed that mechanical properties such as hardness and tensile properties could be varied by the energy input per unit length [102].

Henckell et al. (2020) conducted an experimental study on energy reduction during WAAM (using GMAW) and reported that the detrimental effect of excessive heat input on layer geometry and microstructure can be eliminated by properly optimizing the energy input, where the predetermined optimization strategy of systematically adjusting the Contact Tube to Workpiece Distance (CTWD) enabled the reduction of energy up to 40% and simultaneously had a positive effect on geometrical consistency and microstructural characteristics of the WAAM parts made from low-alloyed steel [103]. In a later study, Song et al. (2021) worked on enhancing geometrical consistency and proposed a path-planning strategy for minimizing height error, particularly at the intersection region of multi-layer structure. The path-planning strategy enabled a minimum height error (intersection) of only 0.8%, validating the importance of the toolpath trajectory for the height uniformity of the WAAM-built part [104]. In another study, Ponomareva et al. (2021) worked on enhancing the material properties with WAAM and succeeded in depositing Al-Mg alloy with customized microstructure (scandium and zirconium alloyed wire) and mechanical properties, where the addition of scandium and zirconium, the parameter optimization of the WAAM process, and the subsequent post-heat treatment together resulted in a yield strength of 268 MPa, an ultimate tensile strength (UTS) of 403 MPa, and a stable plasticity (above 16%) [105].

In a study, Chintala et al. (2021) deposited Inconel 625 and focused on successfully fabricating a thick slab by WAAM that was free of defects, which was characterized with microstructural features. The reported microstructural characteristics include a transition from cellular to equiaxed dendritic microstructure, increased microhardness along the build height, and a large degree of variation in grain orientation with build height as confirmed through the EBSD analysis [106]. In contrast, Kyvelou et al. (2021) built stainless steel square hollow sections (SHS) with WAAM and experimentally showed that the geometric undulations and anisotropy in mechanical properties (material properties are changed as built as mentioned before in several other works of the literature as well) can significantly impact compressive behavior. The results from structural tests on specimens extracted from different layers of WAAM-built SHS show that it is essential to use the as-built material properties for safe strength prediction, and WAAM-induced imperfections and defects (geometrical non-uniformities and anisotropy) can lead to premature buckling and capacity variability; thus, a shift in design approach is necessary [107]. Tian et al. (2021) studied 10CrNi3MoV steel that was deposited by CMT WAAM and divided the whole structure into functional zones for microstructure, mechanical strength, and galvanic corrosion assessments. The microstructural results indicated high tensile strength (>760 MPa) and significant hardness in the heat-affected zone with a pronounced texture in the early layers, while the mechanical testing and galvanic corrosion results of different zones of the structure indicated the deposited layer as being more prone to corrosion compared to the matrix [108].

Fang et al. (2021) reported an experimental study on WAAM of a high-strength Al-Zn-Mg alloy and explored a series of arc modes to deal with the incompatibility of the 7xxx series Al with the WAAM technique. It was found that the mode of CMT + PA (peak arrest) arc mode had the least porosity (0.97%) and the highest tensile strength (316.3 MPa horizontal), the microstructure of which was more uniform and had a low heat input, while it was reported that anisotropy was still a major issue in their study due to interlayer pores [109]. On the other hand, Bercelli et al. (2021) simulated the fatigue reliability of WAAM with a probabilistic model to predict the high-cycle fatigue of porous parts induced by the AM process and quantified the effect of process-induced pores, which was seldom studied before. The numerical models based on real tomography data aligned well with experimental scatter and fracture analysis, and it was validated that even a rare occurrence of pores has an effect on the fatigue life of WAAM parts [110]. A complementary experimental study was conducted by Ying et al. (2021) to address WAAM for fabricating wear-resistant steel components and reported an excellent formability of the fabricated part in WAAM, which had a high tensile strength (945.3 MPa) and superior wear resistance. However, brittle fracture and insufficient toughness (Charpy value of 5 J) were reported, and a suggestion of toughness improvement was put forward in this study [111].

Manokruang et al. (2021) quantified and modeled the geometric attributes of weld beads during WAAM deposition of AA5083 wire by manipulating the surface temperature of multiple deposited layers while fixing the welding parameters. The bead width and height were quantitatively analyzed using 3D scanning, the results of which were then used to develop a geometric predictive model with the objective of improved dimensional control [112]. By contrast, Sydow et al. (2022) conducted an experimental and numerical investigation on fine-grained mild steel and proposed hybrid WAAM-forming techniques to eliminate the microstructural inhomogeneity caused by thermal gradients in the as-built material. The decoupled forming was shown to provide partial recrystallization in the lower layers in experiments, while a further optimized coupled process using two lateral rolls and one top roll applied to the same sample provided almost full recrystallization of the hot-stamped part, including the top layer, resulting in significantly reduced microstructural and hardness variation, and thereby achieving near-homogeneous material [113]. Xiong et al. (2022), on the other hand, established that WAAM-deposited 300M steel demonstrated higher resistance to deformation during hot working compared to the wrought material and reported the quantified value of activation energy for hot deformation and the corresponding optimized hot-working windows and finally developed a strain-compensated constitutive model that can accurately predict the flow behavior [114].

Rani et al. (2022) studied the microstructure, mechanical properties, and residual stress development of mild steel, austenitic stainless steel, and bimetallic components fabricated using an optimized GMAW-WAAM setup with a side-arm manipulator. The authors reported good tensile strengths (> standard weld wire), varied hardness across deposition zones attributed to phase transformation, and compressive residual stresses, especially at interfaces [56]. In a complementary study, Gürol et al. (2022) used robotic WAAM to fabricate a bimetallic cleaver for cutting operations, which was achieved by stacking stainless steel and hard-facing material with desirable mechanical properties in separate layers. The authors found the measured hardness to vary from ∼187 HV (Vickers Hardness) at the stainless-steel base to more than 600 HV at the cutting edge, a pattern that was then repeated across other commercial cleavers, suggesting purposeful functional performance customization; their microstructural analysis at the interface showed it to be well-bonded with a clear mixing zone and no defects and could be suitable for wear-intensive operations [115]. Meanwhile, Waldschmitt et al. (2022) demonstrated the application of WAAM in constructing geometrically complex architectural elements by fabricating free-form, multi-use steel column structures and their sub-components through a robotically integrated parametric programming workflow with a basic digital twin setup. The key takeaways from their study included the process repeatability and stability as well as layer accuracy (∼±0.3 mm deviation), in which the tensile strength was comparable to the filler wire standard, establishing the suitability of WAAM for large-scale free-form architectural production [116].

Silwal et al. (2022) looked at the shielding gas composition effect on build geometry, arc stability, and heat transfer during GMAW-WAAM of martensitic stainless steel. The authors' shielding gas blends of ternary He-Ar-CO_2 and binary Ar-CO_2 were compared, and helium-rich shielding was found to increase penetration depth, reduce weld width, increase heat flux, and improve dimensional accuracy, with most of these changes attributed to improved arc characteristics (as opposed to a surface tension contribution) [117]. On the other hand, Soni et al. (2022) considered the feasibility of processing commercially pure Zn via WAAM for biodegradable implant fabrication. The authors of the present study found WAAM-Zn to have a slightly coarser grain structure, lower hardness, and strong crystallographic texture as compared to wrought Zn, while corrosion behavior and cytocompatibility were found to be similar, thereby validating WAAM-Zn's application in biomedicine [118]. Ke et al. (2022) numerically studied the multilayer deposition mechanism in ultrahigh-frequency pulsed (UHFP) WAAM of NiTi shape memory alloys. The authors of this paper developed a 3D model that incorporated fluid flow, thermal transfer, and droplet transfer and showed that UHFP current created vibrations in the molten pool, which promoted microstructural refinement and can be further optimized for NiTi WAAM of complex components [119].

Vinoth et al. (2022) experimentally looked at the mechanical and structural properties of 316L stainless steel fabricated using WAAM. The authors observed improved tensile strength (559 MPa) and Brinell hardness (160–166 BHN (Brinell Hardness Number)) and confirmed good crystallinity through X-ray Diffraction (XRD) and a von Mises stress model developed in COMSOL [120]. In a different effort to improve WAAM, Giordano et al. (2022) proposed a continuous three-dimensional spiral toolpath strategy that was optimized and constructed based on a thermal scalar field (T), given by the transient temperature field, to tackle the inability of existing 2.5D-slicing strategies to directly account for the thermodynamics. The authors of this paper showed through the experimental fabrication of free-form 'Elephant's trunk' and 'Elephant's foot' parts that this continuous three-dimensional toolpath concept reduced start/stop phases (thus, manufacturing time) and staircase surface defects (thus, geometric complexity handling) and can be a useful addition [121]. Meanwhile, Halisch et al. (2023) studied the effect of oxygen content in the shielding gas chamber of Ti-6Al-4V during WAAM. The authors reported that yield and tensile strengths (maximum values of 863 and 917 MPa, respectively) were higher with increasing oxygen in the chamber, but ductility was lower (minimum value of 11.4%), and oxygen in the deposit was higher (higher than ASTM chemical limits). Despite this, the oxygen concentration was said to be within a level that aerospace mechanical standards (but not chemical standards) could tolerate [122].

Tischner et al. (2023) studied the bonding between the WAAM-produced reinforcements and concrete and found that despite the WAAM reinforcements having no transverse ribs like the common bars, the bond strength of WAAM bars was equivalent to steel bars due to surface roughness, with the maximum bond stress in the experiments following a linear relation with surface roughness. Therefore, the study concluded that the WAAM has comparable viability to standard steel bars in construction with similar bond work and smoother failure transition [123]. In contrast, Nguyen et al. (2023) sought to optimize process parameters for low-carbon steel. The authors' results showed that among all process parameters (TS, voltage, and current), microstructure and mechanical properties were affected by at least two of them, and their Taguchi-based analysis of high-level factors was able to single out optimal parameter sets, which were found to produce refined grain structures leading to substantial increases in tensile strength (maximum value of 694 MPa) and elongation (maximum value of 57%), both of which were much higher than those of base wire [124]. Complementing this, Uyen et al. (2023) studied different trajectory strategies and their effect on WAAM. The authors reported that among four investigated strategies, Strategy 3 (spiral trajectory) had the finest grain structure, highest UTS (616.5 MPa), and maximum elongation (47.2%). Strategies with more repeated heating, such as the lean zigzag, had coarser grains and lower mechanical properties [125].

Kumar and Mandal (2023) determined SS316 structures to be affected by too low and too high heat input in terms of dimensional accuracy, surface roughness, and hardness by virtue of uneven deposition, unstable molten pools, and altered cooling rates. XRD analysis showed phase transformation from residual ferrite to austenite with increased heat input and an attendant reduction in microhardness [126]. In another study, Zhang et al. (2023) reported PC-WAAM of γ-TiAl intermetallics to have a layer-wise alternation of α_2 and γ phases, with decreasing tensile strength, UTS, ductility, and hardness from bottom to top, ascribable to thermal cycling effects [127]. Islam et al. (2023) determined that increasing heat input in the fabrication of TZM alloy structures had an influence on columnar grain growth and carbide dispersion but also caused a rise in defect density and that the 240A condition had the highest porosity of 2.04% of all the test conditions. These findings underline the observed brittle transgranular fracture behavior and a maximum yield strength of 195 MPa under the optimized condition [128].

In a quasi in situ study of WAAM-produced AA5356 Al components, Wang et al. (2023) found increasing grain size and porosity with deposition height. The increase caused a reduction in microhardness, with a slight decrease in tensile strength. However, the overall mechanical behavior still outperforms cast AA5356 [129]. Wieczorowski et al. (2023) also investigated AA5356 walls made using WAAM and found that while TS and cooling time had significant effects on pore size and volume, the porosity of the samples was lower than 0.12% and therefore does not strongly affect tensile strength, which varied from 230.57 to 274.88 MPa. The authors further found a 'back and forth' path to result in slightly improved strength and elongation and emphasize the relevance of path planning [130]. In contrast to the previous works that were focused on Al, Meng et al. (2023) investigated the application of WAAM-fabricated carbon steel square hollow section (SHS) stub columns, which are often used in construction as vertical support structures. The authors found that the WAAM element had a competitive load-carrying capacity compared to the reference in stocky conditions but was lacking in slender ranges due to an increase in geometric imperfections. The incorporation of optimized stiffeners was shown to significantly improve structural efficiency and to overcome the WAAM-related deficit [131].

Sharifi et al. (2023) set their focus on the determination of WAAM process parameters (wire feed speed (WFS), TS, and torch inclination angle) with the CMT process, which provides a weld geometry, microhardness, and structural quality that could be adequate for civil engineering component applications. Weld bead, heat-affected zones (HAZ), and microstructure were analyzed in a systematic way by means of cross-sectional examinations and HV measurements. The results showed that lower TS and medium WFS in the range of 2.5–4.5 m/min provided an appropriate width-to-height ratio and flank angle, while high values of WFS and TS allowed for a higher deposition volume and absence of lack of fusion. Two optimized multi-layer welding approaches were suggested to combine the two different parameter sets by applying the first one to the first layer and the second one to the remaining ones in order to trade-off between penetration and heat input. The obtained microstructure was ferritic-pearlitic with higher homogeneity [132]. Müller and Hensel (2023) investigated the fabrication of WAAM components with continuously varying wall thicknesses with regard to weld bead overlap tolerances, surface quality, and path planning for the realization of force-flow-optimized geometries. Macrosectional investigations and surface waviness measurements were performed in order to identify the limits of acceptable overlap, which ranged between 15 and 50%. Furthermore, a continuous lack of fusion was observed for parameter set 25-2, since low energy input or unfavorable toe angles can result in a lack of fusion that is not weldable. The achieved surface waviness decreased for lower wire feed, and a first example of the realization of a complex geometry for a steel node was presented, which was only possible by using an adaptive path strategy and parameter set 45-3, which was identified to provide a good quality and low energy input [133].

Feier et al. (2023) focused on an optimization of WAAM for the manufacturing of mechanical components on CNC machines with the aim of improved deposition strategy, thermal control, and post-processing steps to attain a maximum reduction in manufacturing cost (up to 72%) and time with a focus on high-value materials such as Ti-6Al-4V. The introduced process improvements, including dual-pass layers, controlled interlayer cooling, and active temperature monitoring, lead to good dimensional accuracy and structural quality, which are verified through microscopic evaluation of a single-layered specimen to confirm near-zero porosity and an even hardness distribution [134]. In a different study, Vishwanatha et al. (2023) investigated the impact of arc current and TS on bead geometry and microstructure of stainless steel 308L in WAAM, establishing that a larger arc current led to a wider bead and contact angle, whereas higher TSs led to lower bead height and higher ferrite phase fraction. A combination of optimal deposition parameters (120 A, 25 mm/min) led to uniform layers and was subsequently used in the fabrication of custom-designed orthopedic implants, demonstrating a possible biomedical application of WAAM [135]. In contrast, Wandtke et al. (2023) studied residual stress formation in high-strength structural steel (S690QL) in WAAM. Their results showed that higher heat input and an increase in interpass temperature led to a reduction in tensile residual stresses and a more even distribution over the height of a component. Furthermore, geometric factors (in particular component height) were seen to influence stress relief through reduced restraint by the substrate, while martensitic transformation and volume expansion are also involved in stress modulation [136].

Jin et al. (2023) addressed in-situ fabrication of Al–Cu/Al–Si gradient materials with alternating wire feed, which achieved defect-free transition layers with a well-mixed molten pool and effective suppression of columnar grain growth and, therefore, the possibility of customization of mechanical properties through compositional gradients [137]. In a different approach to process optimization in WAAM, Manikandan and Swaminathan (2023) compared pulse and double-pulse GMAW to be used for fabricating Al-Mg alloy wing stiffeners. The results demonstrate that Gas Metal Arc Welding – Double Pulse mode (GMAW-DP) resulted in more uniform beads and significantly reduced porosity with half the maximum pore size and better structural integrity than Gas Metal Arc Welding – Pulse mode (GMAW-P) [138]. In another work, Queguineur et al. (2023) presented a Design of Experiments (DoE) parametric study on duplex stainless steel walls made using CMT WAAM that revealed the influence of TS, wire feed rate, and wire chemistry on deposition rate, ferrite content, and hardness. The results showed a peak deposition rate of 3.54 kg/h with a combination of high WFS and low TS and that wire G2205 with low Ni content results in a higher ferrite percentage and hardness than G2209 [139].

Ali and Han (2023) used FE simulations from ABAQUS to study the effect of different scanning patterns and energy levels on the WAAM process with EH36 steel and noted that the zigzag scanning pattern resulted in the least amount of residual stress and that scanning pattern affected residual stress more than the energy input did [140]. Kumar et al. (2023) simulated the WAAM process for creating steel wall structures using SIMUFACT-Welding software in order to better visualize thermal cycles during fabrication and the effect of heat input on structural performance; although with less detail on quantitative results, they still provided more useful thermal information on the system and further justified the use of simulation tools to better understand heat accumulation and process-induced deformation in such scenarios [91]. On the other hand, Elitzer et al. (2023) studied the microstructure and mechanical properties of Ti-6Al-4V manufactured with the WAAM process, finding that WFS can be a useful and easily controlled process parameter for WAAM to aid in specific component geometry and desired strength. Experimentally, they were able to confirm that stress-relief heat treatment was beneficial to mechanical performance while solution annealing was detrimental to it and that components created by WAAM can be similar in properties to milled parts [141].

Zhao et al. (2023) also used both experimental and FE simulations to study the reinforcement of half-cylinder shell geometries with AA 5083 and AA 5183 Al alloys. Their research characterized distortion behaviors under different shell thicknesses and deposition patterns, and their data showed that there is a nonlinear relationship between the two and that an axial deposition pattern can cause much more distortion in shells with less thickness [142]. Harman et al. (2024) performed a comparison of Taguchi and regression methods for the optimization of process parameters in WAAM for two different wires, E120C-GH4 metal-cored and ER120S-G solid, and concluded that the metal-cored wire was able to make use of the optimized parameters to build at 43% faster rates and 74% greater deposition rates than the solid wire, thereby being able to reach a much higher efficiency in industrial settings [143]. Saravanakumar et al. (2024) focused on the study of microstructural and mechanical variations in WAAM-fabricated Inconel 625 and showed that rapid solidification of bottom layers leads to equiaxed grains and improved tensile strength, but a slower cooling rate in upper layers increases dendritic segregation and lessens strength [144]. Kim et al. (2024) introduced machine learning into WAAM, where a Support Vector Machine (SVM) classifier was trained to identify an optimal bead central angle to use in a multilayer build and thus prevent shape collapse; their results confirmed that the SVM was highly accurate and effective even in a small-data scenario and could be used to successfully identify a beneficial central angle to prevent deformations [145]. Lastly, Kumar et al. (2025) performed a study of AA5356 deposition with CMT-WAAM and applied statistical methods, such as Analysis of Variance (ANOVA) and response surface methodology, in their work to optimize process parameters. They reported that the core layers had high tensile strength (321 MPa) and toughness (23.57 J), and they were able to identify the effect of TS, standoff distance, and wire feed rate on bead geometry [146].

CHALLENGES AND FUTURE DIRECTIONS OF WAAM

The WAAM process presents several challenges, and its future research directions are as follows:

Challenges of WAAM

The accuracy, surface quality, and residual stresses are some of the issues WAAM often encounters. Due to the considerable heat input in the WAAM process, shrinkage, distortion, and deformation result in size inaccuracy and inferior product quality. The parts manufactured using this process possess residual stresses, and if not efficiently controlled, it can cause deformation and significantly deteriorate their mechanical properties. Porosity, inhomogeneities in microstructure, and the formation of cracks or delamination make it difficult to produce defect-free WAAM parts. Surface roughness of these components may cause a secondary operation to be executed, and the geometric accuracy of the produced parts is found to be lower when compared to other AM processes [13, 18, 28, 147, 148].

The variability in mechanical properties and anisotropy in microstructure remains a significant challenge that can be influenced by process parameters and heat treatment. Direct applications are hindered by a mismatch in mechanical properties and inconsistent tensile and fatigue performance, necessitating post-processing or additional treatments. Optimizing process parameters like heat input, WFS, and TS is complex due to the dynamic thermal cycle and microstructural evolution [17, 18, 28, 29].

The material-specific challenges, distinct in alloys such as Al, titanium, stainless steel, and copper, require process control to tailor properties and address post-processing requirements. For example, porosity and microstructural control issues in Al WAAM components [17, 29, 149, 150].

WAAM part qualification and certification lack standardization, which hinders their widespread acceptance, especially in safety-critical sectors. Establishing nondestructive evaluation and quality control methods to ensure part reliability and repeatability is crucial but underdeveloped for WAAM. This requires sophisticated monitoring and control mechanisms during the manufacturing process [15, 58, 151].

Process monitoring and control can be technologically challenging; the multi-physics nature of WAAM, such as thermal management and controlling the welding arc, can make it difficult to produce consistent quality components. Dimensional accuracy and tolerances in WAAM are restricted by the path planning and slicing algorithm, and the bead-on-plate start/stop points are challenging to control, needing additional post-processing steps for rectification [13, 152, 153].

Future Directions of WAAM

The future R&D of WAAM will primarily focus on increasing the quality of the components by exploring several new process strategies, and it is expected to be directed by the following topics:

- Advanced Process Monitoring and Control: The integration of multi-sensor systems, AI, and closed-loop feedback control will be anticipated to facilitate real-time defect detection and active process adjustments. In-situ monitoring and feedback control can minimize residual stresses, porosity, and distortion by dynamically managing heat input and deposition strategies [2, 15, 147, 151].
- Optimization of Path Planning and Slicing Algorithms: Sophisticated toolpath generation methods that consider geometric complexity, thermal effects, and deposition dynamics can improve dimensional accuracy and surface finish. Adaptive slicing and smoothing algorithms can help to avoid bead collapse and voids, contributing to better overall part quality [13, 152, 154].
- Hybridization and Multi-material Deposition: Hybrid WAAM processes that combine multiple deposition techniques, layering strategies, and raw materials offer opportunities to address surface quality, mechanical anisotropy, and material versatility. Multi-wire and tandem welding approaches are expected to become mainstream to improve deposition productivity and the possibilities of materials that can be used in WAAM [19, 155].

- Material and Process Innovation: Post-processing treatments such as interpass rolling, heat treatments, and ultrasonic assistance are to be researched to improve the microstructure uniformity, minimize residual stresses, and improve the mechanical properties. Functionally graded materials and combinations of alloys are to be explored to extend the possibilities of WAAM to be used in other sectors [53, 150, 156].
- Simulation and Modeling: Advanced numerical simulations of temperature fields, thermal cycles, and residual stress development can help in supporting the process parameters' optimization and to predict distortions and residual stresses, enabling proactive control strategies. Simulation can also be employed to reduce the time to trial different possibilities of the WAAM process by modeling with experimental data that can be coupled with FE analysis [50, 151, 157].
- Certification and Standardization Efforts: Robust quality assurance protocols, standardized testing, and certification frameworks are being developed to improve the industrial acceptability. Sectors such as aerospace require parts that need to have high reliability in their applications. Nondestructive testing techniques to assess the quality of complex WAAM parts are a must for wide industrial applicability and are under development [15, 58].
- Sustainability and Economic Assessment: Future studies will also include conducting life cycle assessments to benchmark WAAM against traditional manufacturing methods in material savings, energy usage, and environmental impact. Understanding the full extent of these factors in the application of WAAM will help to establish and encourage sustainable manufacturing [158].
- Industry-specific Applications and Scaling: The applications of WAAM in shipbuilding, construction, and aerospace industries are to be explored by coming up with customized solutions for industry-specific challenges and using large-scale parts to be used with structural materials and high-strength alloys. Modular and robotic implementations are to improve its automation and scaling [65, 159, 160].

CONCLUSION

The WAAM process requires the least cost to make an additive-manufactured metal part and achieves the fastest time-to-production through off-the-shelf welding hardware and large-volume deposition capability in comparison with other AM processes. Also, its ease of use and ability to build complex shapes in less time enables industries to go for rapid prototyping and to manufacture customized parts. However, there are certain limitations to WAAM, such as thermal-induced residual stresses, poor surface finish, inaccuracies and geometrical distortion, and anisotropic mechanical properties caused by layer-wise solidification during manufacturing. The review highlights that these limitations are currently being targeted by R&D activities in various areas, such as CMT, adaptive path planning, real-time monitoring with AI, and hybrid processes. There is also a continuous improvement in simulation tools for accurate predictability and control and a move toward standardization and quality assurance for certification in high-reliability industries like aerospace and energy. In the future, WAAM is expected to benefit from the incorporation of multi-material capabilities, sustainability aspects, and scalability through advanced robotic systems. With the expected process refinements in the future and with an increased focus on interdisciplinary collaboration, WAAM will be a primary choice for metal manufacturing in the future.

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