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Review Article

From Process Parameters to Industrial Qualification: A Comprehensive Review of WAAM Technology

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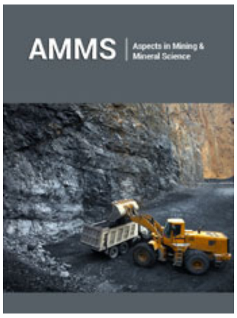

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Abstract

Wire Arc Additive Manufacturing (WAAM) has emerged as a promising metal additive manufacturing technology due to its high deposition rates, cost-effectiveness, and suitability for large-scale structural components. This review discusses the main research trends, process parameters, microstructural evolution, defect formation mechanisms, and mechanical performance associated with WAAM-fabricated components. Particular emphasis is placed on the influence of key processing parameters-current, voltage, travel speed, and wire feed rate-on heat input, bead geometry, melt pool stability, and resulting microstructure. The mechanics of bead formation and deposition geometry are analyzed in terms of thermal-fluid interactions and mass conservation principles, highlighting their impact on layer uniformity and structural integrity. Persistent technical challenges are examined, including porosity, lack of fusion, residual stresses, geometric distortion, and anisotropy in mechanical properties resulting from the layer-by-layer thermal cycling. The review further addresses the complexity of multi-material deposition, where thermal mismatch and intermetallic phase formation represent significant barriers to reliable structural integration. Emerging research directions are discussed, including advanced wire development, functionally graded materials, real-time process monitoring, predictive thermo-metallurgical modeling, robotic motion optimization, and process standardization. The need for harmonized qualification protocols and robust databases is emphasized as a critical step toward large-scale industrial adoption, particularly in aerospace, naval, energy, and advanced manufacturing sectors (Figure 1).

Figure 1: Graphical abstract illustrating key aspects, technical challenges, and future research directions.

Keywords: Wire arc; Material deposition; Fabrication; Superalloys; Stainless steels; Electrode; Geometry; Metallurgical simulation

Introduction

Researchers have continuously sought to improve traditional manufacturing methods in order to develop approaches that are more efficient in terms of capital investment, material utilization, and production time [1-10]. In this context, Additive Manufacturing (AM) has consolidated in recent years as a promising alternative for the production of three-dimensional components and rapid prototyping applications [11-15]. The term Additive Manufacturing was officially standardized by international standardization bodies to replace previously used designations such as rapid prototyping, rapid manufacturing, and freeform fabrication. According to ISO/ASTM 52900 [16], additive manufacturing is defined as the process of joining materials to fabricate objects from three-dimensional model data, usually through layer-by-layer deposition, in contrast to subtractive or formative methodologies.

Thus, this technology is based on a digital data workflow that guides the successive deposition of material in layers, enabling the construction of fully dense three-dimensional geometries [17-19]. Additive manufacturing offers significant advantages related to reduced production time and more efficient raw material usage, since material is added in a controlled and digitally driven manner [20]. This approach minimizes the need for conventional tooling, such as cutting tools, dies, fixtures, and complex machining operations. Furthermore, substantial reductions in production costs-particularly for low-volume batches-as well as shorter production cycle times have been reported [21-24]. In addition, there are publications addressing the fabrication of cutting tools for machining produced by additive manufacturing, as demonstrated by Wang, Li & Lu [25].

Another relevant aspect of AM is the possibility of functional consolidation of parts, reducing the number of individual components required in a final system. This feature contributes to the simplification of production steps and a reduction in assembly operations [26-31]. At the same time, material utilization efficiency tends to be higher than in conventional processes such as casting and forging [32]. When compared to subtractive methods, such as CNC machining, additive manufacturing presents advantages associated with improved structural integrity, enhanced mechanical performance, and the feasibility of designs with high geometric complexity. Owing to these benefits, AM is frequently associated with technological advances characteristic of the so-called Fourth Industrial Revolution [33,34] and is recognized as one of the leading emerging technologies for the production of high-performance components.

Wire Arc Additive Manufacturing (WAAM) is a metal additive manufacturing technology based on the deposition of wire feedstock melted by an electric arc, characterized by the fabrication of three-dimensional components from a digital model through the successive deposition of molten metal layers. From a technical classification perspective, WAAM belongs to the Directed Energy Deposition (DED) category, in which the energy source for melting is an electric arc and the feedstock material is a continuously supplied metallic wire [35-40]. Currently, components produced by additive manufacturing-particularly by WAAM-have been increasingly applied in demanding industrial sectors, including the automotive, aerospace, naval, oil and gas, energy, and biomedical industries. In these fields, the technology is used both for the fabrication of new structural components and for the repair and refurbishment of high-value parts [41-51].

From a materials standpoint, WAAM exhibits high versatility and is widely used for the deposition of structural and high-strength steels [52-55], stainless steels [56-59], aluminum alloys, bimetallic materials [60-63], titanium alloys, and nickel-based superalloys [64-66], among others. This material diversity enables its application in components subjected to severe mechanical loading conditions, significant thermal variations, and corrosive environments, thereby expanding the potential of the technology for the production of complex and large-scale structures.

Contextualization of additive manufacturing

The development of Additive Manufacturing (AM) dates back to the 1980s, when the first rapid prototyping technologies emerged with the objective of accelerating product development cycles. Since then, this class of processes has evolved rapidly, transitioning from prototyping tools to fully integrated industrial manufacturing solutions applicable to a wide range of materials-including polymers, metals, ceramics, and composites-and industrial sectors such as aerospace, automotive, medical, and electronics.

Among the main benefits associated with AM are [14,67-71]:

a. The ability to fabricate components with highly complex geometries without a proportional increase in manufacturing costs;

b. Significant reduction in raw material waste, as only the material required for the component is deposited;

c. On-demand customization and personalization of parts, eliminating the need for dedicated tooling for each product; and

d. Increased flexibility in new product and prototype development, with shorter design cycles compared to conventional manufacturing methods.

In the current industrial landscape, AM is regarded as a key enabler of the transition toward Industry 4.0, integrating with intelligent systems, digitalization, and automation to transform production paradigms. Studies indicate that these technologies not only improve efficiency and reduce costs but also enable innovative manufacturing strategies, such as decentralized production and on-demand maintenance [72-76].

Despite significant technical advances and the growing adoption of additive manufacturing in industrial applications, several challenges still limit its large-scale implementation. Among the most frequently cited challenges in the literature are the high costs associated with equipment and feedstock materials-particularly in metal-based and large-scale processes-which can render cost comparisons unfavorable relative to traditional manufacturing methods at high production volumes. These factors contribute to the fact that, despite its considerable potential, additive manufacturing has not yet widely replaced conventional processes in industrial applications where certification, repeatability, and economies of scale are essential requirements [69,77].

Insertion of WAAM in this context

The physical principle of WAAM is closely related to conventional arc welding techniques, such as Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW), which are applied in an automated and controlled manner for layer-by-layer deposition rather than simply for joining components. An electric arc established between the wire electrode and the substrate generates sufficient heat to melt the feedstock material, which subsequently solidifies upon cooling and metallurgically bonds to the previously deposited layers, thereby forming a three-dimensional structure. This approach enables high deposition rates due to the substantial mass and energy transfer associated with the electric arc [78-87].

Although its adoption has been expanding, the integration of WAAM into mature industrial production lines still faces technical and standardization-related challenges. These include the need for material qualification and process certification, as well as integration with intelligent manufacturing systems (Industry 4.0) and advanced automation strategies to ensure repeatability and consistent quality [37,88-89].

Gaps in the literature and objectives of the review

In recent years, WAAM technology has gained considerable attention in both scientific research and industrial development due to its broad range of advantages and application versatility. Several review studies emphasize that, despite its significant potential, multiple technical challenges and knowledge gaps still limit its full adoption in critical industrial applications [37,82,90,91]. A recurring theme in the literature is the recognition that process parameters, resulting microstructure, defect formation (such as porosity, distortion, and residual stresses), and mechanical properties are not yet fully understood or standardized across different materials and deposition conditions. Numerous studies highlight that the complexity of thermal and metallurgical interactions inherent to the WAAM process hinders the reliable prediction of final component characteristics without systematic approaches to modeling, monitoring, and parameter optimization [12,92-94].

Furthermore, although a substantial body of experimental research and general state-of-the-art reviews exists-including analyses of processing parameters and material performance-the literature still lacks integrated syntheses that clearly identify specific gaps related to deposition quality, integration into industrial production lines, and guidelines for the certification of metallic components manufactured by WAAM. This absence of consolidated guidance complicates the transition of the technology from academic environments to demanding industrial settings, where repeatability, reliability, and compliance with standards are essential requirements [46,90,95-97].

In light of this context, the primary objective of the present review is to map and synthesize recent contributions from the scientific literature on WAAM, with emphasis on:

a. The main research and development trends, focusing on process parameters, microstructure evolution, and material performance;

b. Persistent technical challenges, including defect formation, thermal control, and mechanical properties;

c. Existing knowledge gaps that continue to limit the full industrial application of the technology, particularly regarding process standardization and component qualification methodologies; and

d. Emerging proposals and future research directions, including the integration of real-time monitoring techniques and data-driven optimization strategies.

e. Therefore, this review aims not only to present the current state of WAAM technology but also to provide a critical perspective on the research needs that must still be addressed to strengthen its scientific foundation and promote its broader adoption in the metallurgical and advanced manufacturing industries.

Electric arc deposition process

WAAM is based on arc welding processes adapted for additive deposition. Among the main processes employed are:

A. GMAW (Gas Metal Arc Welding): Also known as MIG/MAG, this process provides high deposition rates and good productivity, making it suitable for large-scale components and applications requiring elevated material feed rates.

B. GTAW (Gas Tungsten Arc Welding): Offers superior thermal control and arc stability; however, it typically presents lower deposition rates compared to GMAW-based processes. It is often preferred when precision and microstructural control are critical.

C. PAW (Plasma Arc Welding): Characterized by a more constricted arc and higher energy density, resulting in deeper penetration and improved arc stability, which can be advantageous for specific geometries and materials.

D. CMT (Cold Metal Transfer): A modified GMAW process featuring advanced control of metal transfer through controlled wire retraction, leading to reduced heat input and improved control over droplet transfer. This makes it particularly attractive for thin walls and heat-sensitive materials. Figure 2 presents a summary of the main characteristics of each process.

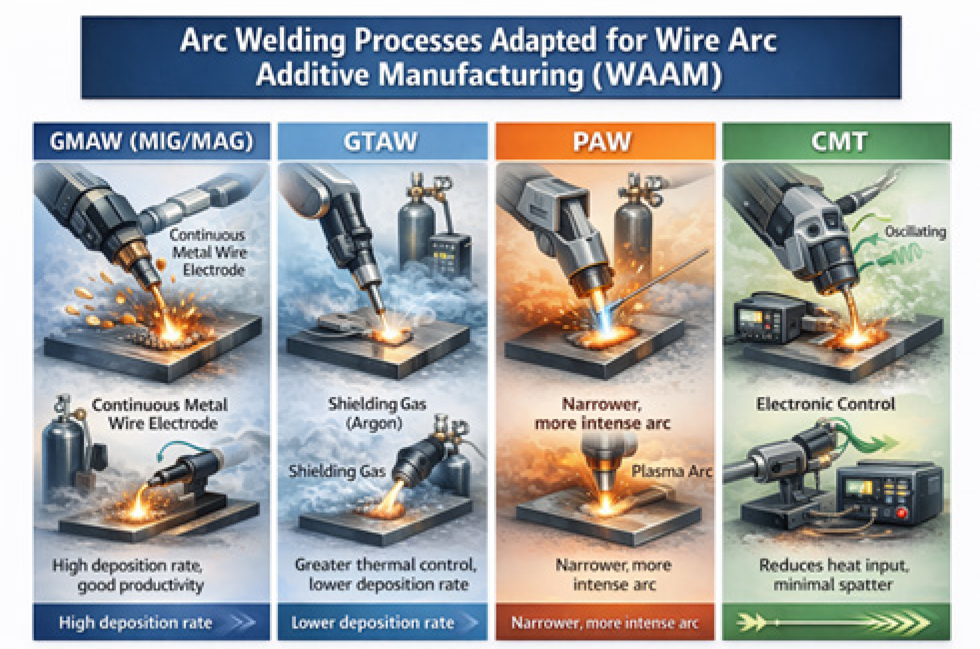

Figure 2: Main electric arc deposition processes.

These processes differ primarily in terms of arc stability, metal transfer mode (short-circuit, globular, or spray), heat input, and penetration characteristics. Recent studies indicate that low heat input processes, such as CMT, are particularly advantageous for dimensional control and distortion reduction, especially in thin-walled structures and geometrically complex components [37,98,99]. The underlying physical principle involves the formation of an electric arc between the electrode (wire) and the substrate, generating a molten pool (melt pool). The controlled solidification of this melt pool enables the incremental construction of the component through successive layer deposition.

Main research and development trends: process parameters, microstructure, and material performance:

Equipment configurations and process parameters: The optimization of process parameters in WAAM is a critical factor in achieving adequate geometric, microstructural, and mechanical quality in deposited components. Experimental studies and recent reviews demonstrate that parameters such as current, voltage, travel speed, and wire feed rate directly influence bead geometry, deposition rate, heat input, and the final properties of the component [41,100-103].

The heat input equation (Q), derived from classical arc welding theory, can be expressed as [37,104]:

where:

$$Q = \frac{n \cdot V \cdot I}{v} \quad (1)$$

i. V = voltage

ii. I = current

iii. v = travel speed

iv. η = thermal efficiency

Voltage and current: The electric current (I) in arc-based processes governs the amount of energy supplied to the arc, directly affecting penetration depth, bead width, and arc stability. In combination with voltage (V), these parameters determine the overall heat input and, consequently, influence melt pool formation, cooling rate, and resulting microstructural features.

Reviews indicate that variations in current and voltage lead to significant differences in bead geometry and mechanical properties of the final component, acting as primary control variables for surface roughness and penetration characteristics of the deposited bead [12,41,100,105,106]. The effect of current (a) and voltage (b) on the geometry of the deposited material is illustrated in Figure 3.

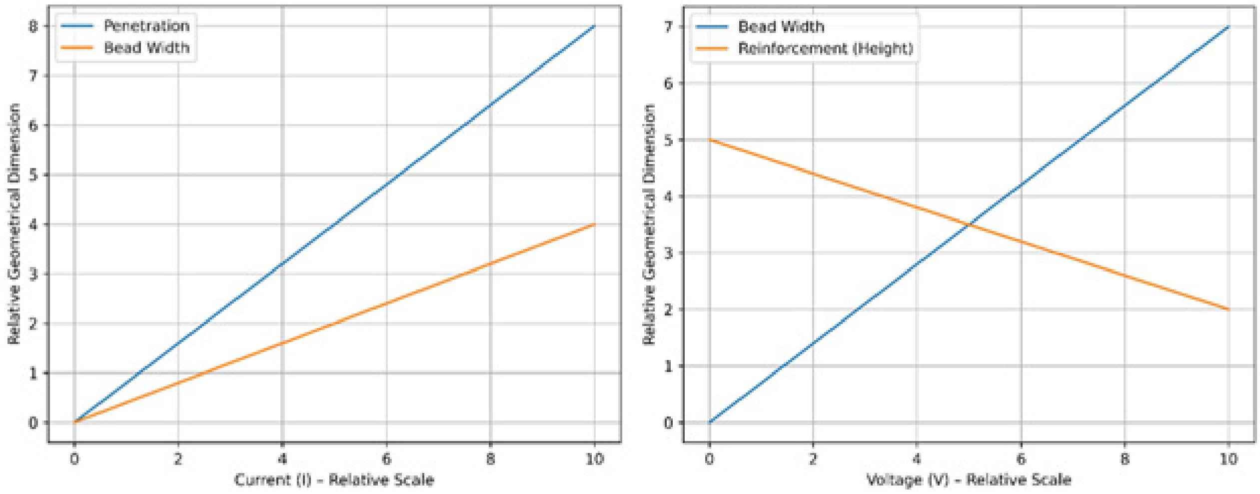

Figure 3: Effect of current (a) and voltage (b) on bead geometry.

Travel speed: Travel speed, defined as the velocity at which the torch moves along the substrate, regulates the thermal interaction time per unit length. Reductions in travel speed tend to increase the heat input per layer and arc penetration, whereas higher travel speeds promote higher cooling rates, narrower bead widths, and more refined microstructures, as experimentally observed in carbon steels [107] and aluminum alloys [108].

Studies indicate that higher torch travel speeds may enhance cooling rates and promote grain refinement, while lower speeds result in larger bead volumes and steeper thermal gradients, directly affecting the microstructure and mechanical properties of the deposited material [37,41,109]. Furthermore, the interaction between travel speed and wire feed rate is crucial in determining the height and width of the deposited layer, directly influencing surface finish and the extent of required post-processing operations [12]. The effect of torch travel speed on bead geometry is illustrated in Figure 4.

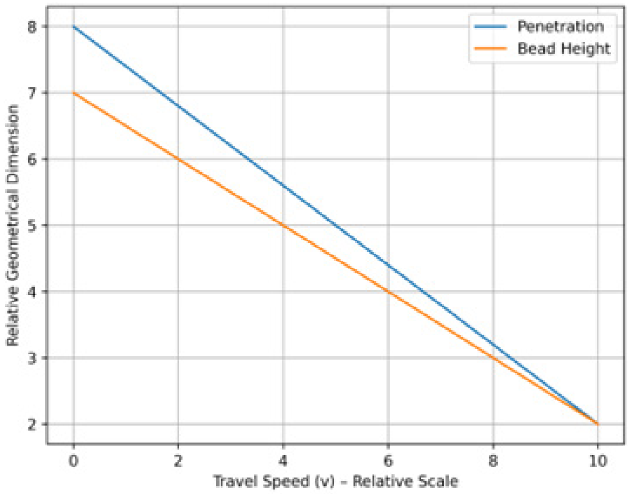

Figure 4: Effect of torch travel speed on bead geometry.

Mechanics of bead formation and deposition geometry: The formation of the bead in WAAM is influenced by the interaction between the electric arc, molten material flow, melt pool dynamics, and kinematic parameters. The bead geometry is commonly characterized by width (w), height (h), and penetration (p). These parameters are directly dependent on the combination of current, voltage, travel speed, and wire feed rate, as highlighted in both experimental studies and recent reviews [12,60,108,110-112].

The literature demonstrates that:

Current and voltage modify the melt pool shape by altering surface forces and penetration into the substrate [12]. Travel speed regulates the thermal residence time and, consequently, influences the energy deposited per unit length - directly affecting bead width and height [41]. These combined parameter effects are frequently modeled using empirical correlations and mass conservation models, which relate arc characteristics and energy input to the final geometric features [41]. Inadequate control of these parameters may lead to defects such as porosity, overheating, layer height variation, and residual thermal stresses, compromising both structural integrity and geometric accuracy of the component [12,37,91].

Persistent technical challenges, defects, thermal control, and mechanical properties

Despite its clear benefits-such as high deposition rates, low material waste, and reduced operational cost compared to other metal additive manufacturing technologies-Wire Arc Additive Manufacturing (WAAM) still faces substantial technical challenges that limit its full industrial adoption and the final quality of manufactured components [82,92]. One of the most frequently cited challenges in the literature is defect control during deposition, which directly impacts the mechanical integrity of the parts. Defects such as porosity, lack of fusion, spatter, and irregularities in the deposited bead geometry may arise due to inadequate parameterization (such as wire feed rate, travel speed, and heat input), surface contamination, or arc instabilities. These defects negatively affect density, tensile strength, and fatigue performance of fabricated components [37,41,46,52,57,91,95,97,113,114] . Figure 5 illustrates the most common irregularities observed in deposited materials.

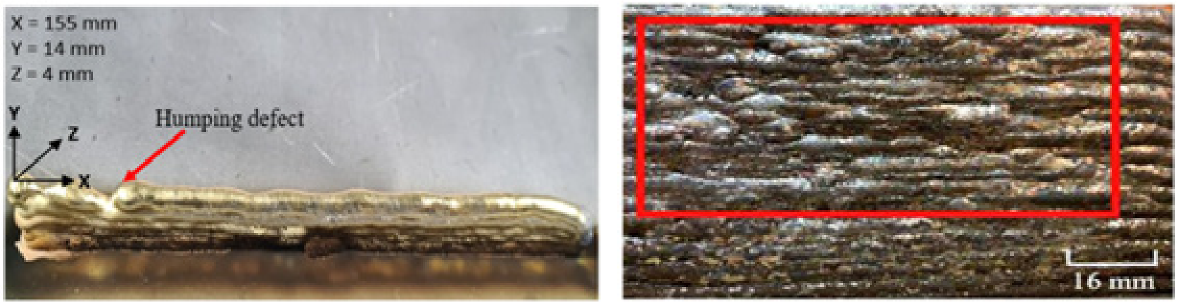

Figure 5: Surface structure of walls produced using different interpass times [37].

Thermal management represents another central technical challenge: the layer-by-layer nature of Wire Arc Additive Manufacturing (WAAM) imposes repeated heating and cooling cycles, leading to heat accumulation, steep thermal gradients, and microstructural heterogeneity throughout the component. This behavior may result in geometric distortion, high residual stresses, and anisotropy in mechanical properties between different orientations (e.g., build direction versus deposition plane) [91,115]. Microstructural and mechanical anisotropy is particularly pronounced in WAAM-fabricated components due to preferential grain growth along the deposition direction and the specific thermal history experienced by each layer. This leads to measurable differences in strength and ductility between orientations, posing challenges for critical structural applications that require uniform mechanical behavior [12,57,115-117].

The integration of multiple materials within the same metallic component-an emerging trend in advanced research and applications-also presents substantial technical challenges. The deposition of dissimilar materials can induce thermal mismatch, formation of brittle intermetallic phases, delamination, and elevated residual stresses, requiring tailored material transition strategies and compositional gradients [92,118]. In addition, aspects related to process control and real-time monitoring are still under development. The complexity of coupled physical phenomena (thermal, metallurgical, and fluid-dynamic) makes it difficult to autonomously predict and adjust parameters, hindering full industrialization of the process with assured repeatability and compliance with robust quality standards [119].

Finally, although WAAM can produce components with satisfactory mechanical strength in many cases, post-deposition heat treatments, microstructure control strategies, and standardized certification procedures remain necessary to ensure that large-scale industrial components meet regulatory requirements in sectors such as aerospace, automotive, and energy [37].

Knowledge gaps limiting full industrial application, process standardization, and component qualification methods

Proposed directions and emerging research trends for future developments: Wire Arc Additive Manufacturing (WAAM) continues to evolve rapidly, and the literature highlights several promising research directions that may help overcome current technical limitations and expand the industrial applicability of the technology. Among the main research fronts are material innovation, advanced monitoring and control strategies, predictive modeling, and process standardization.

A priority research area is the development of advanced materials. The fabrication of multi-material structures by WAAM still faces significant challenges due to the formation of brittle intermetallic phases and thermal incompatibility between dissimilar alloys. Progress in the development of optimized wire compositions and functionally graded materials may mitigate detrimental segregation and enable more reliable bonding between distinct materials, particularly for applications requiring combined property performance (e.g., simultaneous wear resistance and ductility). This advancement is especially relevant for renewable energy, naval, and aerospace systems, where bimetallic or graded structures can provide unique functional advantages [92]. Figure 6 illustrates different deposition strategies employed in recent studies for the fabrication of bimetallic structures.

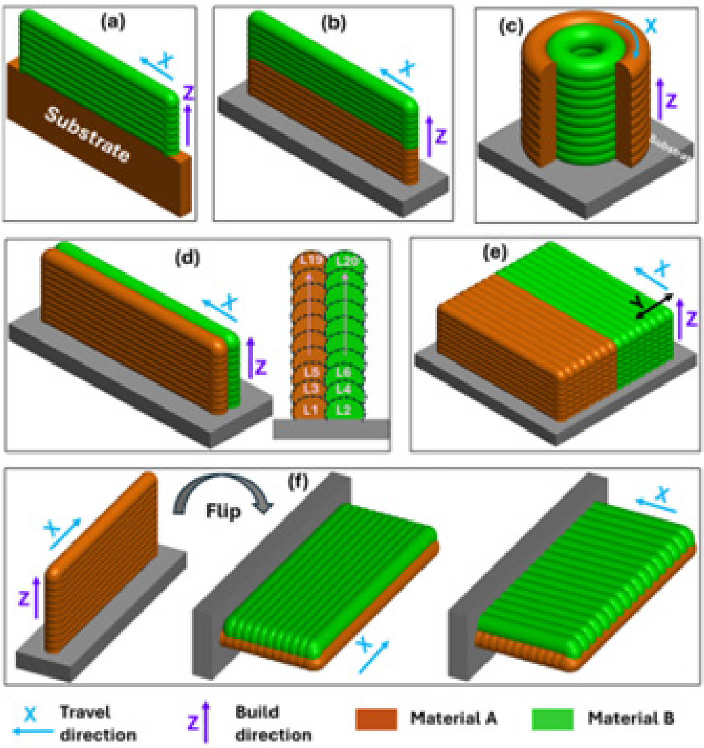

Figure 6: Deposition strategies for bimetallic structures. (a) Material deposited onto the substrate; (b) Material deposited over a layer of another material; (c) Radial bimetallic structure; (d) Interlaced multilayer structure along the Z direction; (e) Interlaced multilayer structure along the X and Y directions; and (f) Material deposited on the lateral surface of another material [92].

Another emerging direction is real-time process monitoring and control. Most Wire Arc Additive Manufacturing (WAAM) systems still operate in open-loop mode, limiting the ability to detect and correct defects during part fabrication. Advances in integrated sensors, computer vision, laser scanning systems, and thermal sensors can provide immediate feedback on deposited bead geometry, arc stability, and local thermal conditions. This enables dynamic parameter adjustments, improving repeatability and reducing defect formation [120-125].

Predictive modeling and simulation also stand out as essential research directions. Thermo-metallurgical simulation methods-including finite element modeling, computational heat flow simulations, and microstructure modeling-are important tools to anticipate thermal evolution and microstructural development during deposition. Recent literature emphasizes the need for robust models capable of capturing the complex interaction between process parameters and defect formation. Overcoming this challenge would allow faster and more targeted process optimization [126-133]. Within methodological innovation, the application of collaborative robotics and coordinated motion control for deposition on complex geometries is another promising research line. Emerging studies explore multi-robot systems and control algorithms that adjust torch orientation according to build direction, reducing adverse effects such as uncontrolled overheating and defects in overhangs or inclined surfaces-features that remain difficult to manufacture using conventional WAAM approaches [134-138].

Finally, process standardization and the development of robust databases are considered fundamental for WAAM's industrial evolution. The lack of widely accepted technical standards hampers comparison between studies, part certification, and adoption in high-demand sectors such as aerospace and biomedical engineering. The literature recommends establishing harmonized guidelines for material qualification, monitoring procedures, parameter reporting, and defect acceptance criteria, facilitating integration of WAAM into mature production chains [92,139,140].

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