Assessing the pros and cons of wire-arc additive manufacturing for material production

Rakesh Kumar Singh | K. Venkadeshwaran | Bhanu Pratap Singh | Ganesh Kumar Kantak

Abstract A promising new method for mass-producing metal components and structures for a range of industries, including shipbuilding, automotive, aviation, and other technical sectors, is wire arc additive manufacturing (WAAM). Additive manufacturing (AM) called 3D printing, is a disruptive manufacturing technique that starts with digital design data and manufactures products layer by layer. WAAM has been utilized to create parts from a variety of materials, such as alloy wires based on aluminium (Al), titanium (Ti) and nickel. This review article focuses on the most important facets of the WAAM process, including the technology utilized, the drawbacks encountered, the steps taken during and after the process, the tools used to monitor the process, the gases involved, and the materials. The comparison of WAAM with other additive manufacturing technologies is also emphasized in the article. Moreover, it compares and analyses several WAAM techniques, including plasma arc welding (PAW), gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) in terms of material deposition rate, the method GMAW have higher material deposition rate when compared to other approach. Material manufacturing using WAAM has great potential. The accuracy of the manufacturing and smoothness of WAAM-made parts can be enhanced in the future to better suit tight-tolerance uses.

Keywords: WAAM, Additive manufacturing, 3D printing, GMAW, PAW, GTAW

1. Introduction

One of the most important developed manufacturing processes in today’s world is metal additive manufacturing (MAM). The component in the net near form is manufactured with assistance from MAM (Kumar et al 2021). The most cutting-edge manufacturing technology of the twenty-first century is regarded as AM. It combines advanced global technologies, such as metallurgical engineering, digital modeling, machining, and material processing (Hannibal 2020). Aerospace, automotive, and biomedical engineering sectors uses this manufacturing technology to produce parts (Armstrong et al 2022). One of the large-scale MAM methods is WAAM. A WAAM technique develops a component using an idea of the method for welding. To create the net-like shape of the component, welding filler wire is diminished and layers were added one after the other, building up the accumulation (Barath and Manikandan 2022). The remarkable ability to fabricate metal straight from 3D models has been made possible by WAAM. When compared to alternative methods, WAAM’s unique production efficiency is higher, for large-scale or wall construction sections, since it uses a welding arc to melt metal wire into specific shapes (Zhao et al 2020). The primary determinants impacting the choice of additive manufacturing (AM) method which include an achievable complexity and resolution, deposition rate, and component dimensions (Jiménez et al 2019). Moreover, contrasted to conventional production methods, AM offers far greater design freedom for the object and makes a load-optimized design. Using wire as a deposition medium and an arc of electricity as a tool, WAAM is a promising area of AM technology. This procedure falls under DED (direct energy deposition) producing, it also produces cladding with lasers, among other things (Treutler and Wesling 2021). AM referred to 3D-Printing is a developing technology with numerous global applications based on its benchmark characteristics of reducing material waste and supply chain management (Vafadar et al 2021). The opportunity to experiment with design freedom and the conceptual application of methods like topology optimization has a significant impact on material conservation, which lowers component weight and improves the manufacturing ability of complicated components that require subcomponents (Kawalkar et al 2022). The broad potential uses of WAAM technology in various production industries have led to a significant increase in research and development of its underlying concepts. Nevertheless, a number of problems exist that prevent WAAM from widely incorporated into all of our manufacturing sectors (Xia et al 2020). The purpose of this study is to
evaluate the pros and cons of WAAM in material manufacturing. The various categories of AM techniques are depicted in Figure 1.

(Srivastava et al 2023) examined into the discussion of the impact of different process parameters and how it optimized to address the difficulties in WAAM through various techniques such as alternating passes, heat treatment, inter-pass cooling, melt pool changes, as well as other methods for improvement. To pinpoint the problems and potential research areas, a number of WAAM tendencies and future facets were analyzed. (Chaturvedi et al 2021) provided an extensive overview of the cutting edge in WAAM for non-metallic substances, including its growth and progression. The paper examines and synthesizes important research findings and conclusions from literature reports about the mechanical and metallurgical behavior of materials, strategies are used, control of process parameters, optimization, and process limitations, as well as WAAM applications. The goal of (Chen et al., 2021) was to present a illustration of the WAAM technique's efficiency diagnostic and management. The research includes the creation processes of common faults, recognition methodologies, and persisting identification issues in the WAAM industrial contexts. Following it, an idea for a closed-loop quality control model based on the fusion of data from several sensors was present. (Lin et al 2021) offered a summary of the use of WAAM as the deposition technique in the 3D metallic printing for Ti alloy. To achieve microstructure optimization, enhance physiological characteristics, and remove the remaining strain from Ti elements implanted by WAAM, the paper first presents Ti alloys and the WAAM technology. The research discusses about WAAM systems utilized in Ti manufacturing. Following, it also discussed about how economically viable to use WAAM on Ti alloys. Finally, used for WAAM Ti components across various industries are shown. Navarro et al (2021) developed a new metal AM platform, GTAW was integrated on a support method. The most common issues are covered along with potential solutions, and the design and construction of a straightforward, reasonably priced, and efficient WAAM system was described. Impacts of procedure parameters on the performance of 2 cumulatively produced amalgams, plain carbon steel and Inconel. Çam (2022) suggested the three distinct methods for producing metal parts using MAM techniques. These are wire feed fusion systems, powder bed fusion systems, and powder feed fusion systems. Metal or alloy powders are the starting material in the first two of these AM techniques, while in the third approach, the starting material was the wire for filler made of alloys or metals. Suárez et al (2021) proposed a validation technique for AM as a substitute for commercial manufacturing in the creation of mid-sized aircraft components. First, for four distinct metal alloys, the best welding process and suitable parameters are chosen. Each of the four metal alloys was used in turn to create a characterization wall for mechanical and metallographic testing, bringing about the determination that material supplied by the WAAM technology was appropriate for medium-sized aeronautical component fabrication. Vimal et al (2021) explored into a comprehensive discussion of the different technologies and process developments, including inter pass cooling, weld pool oscillation as well as peening effect. They have covered the metallurgical and mechanical aspects of aluminum alloys as well as an analysis of WAAM. The review that was completed outlines several WAAM-related difficulties with aluminum alloys, along with solutions. Tripathi et al (2022) established a wire-arc AM system based on gas tungsten arc welding and fabricated a geometry utilizing low carbon amalgam steel filler wire. Hardness, toughness, and room temperature tensile assessments are carried out to assess the mechanical characteristics of a printed alloy. Pant et al (2023) investigated the main aerospace industry application sectors where WAAM has been utilized with a few instances; some simulation work and modeling that has been

Figure 1 Categories of AM technique.
done for WAAM that is pertinent to the aerospace industry, as well as existing state of the utilized WAAM substances were concentration to the aviation field. Omiyale et al (2022) examined and discussed in detail works related to the mechanical features, metallurgical features, and usage of WAAM of aluminum alloys for the automotive and aerospace industries. The goal was to determine study voids and potential paths. The purpose of the study was to present an analysis of WAAM of aluminum alloys used in the manufacturing of components for the automotive and aerospace industries.

2. WAAM process

One of the DED technologies, WAAM has gained prominence in the last ten years as an AM technique. Classical arc welding technology where WAAM originated (Tomar et al 2022). The wire is heated using an electric arc to melt for the WAAM process, after it is moved to a pool of molten metal. Afterward, it hardens at the melt pool's border, creating the portion layer after layer (Rosli et al 2021). The WAAM technique can produce large-dimensional, completely dense components with low production costs, as well as constructions that can be stretched to tens meters. It also appropriate for maintaining the repair fractured pieces and elements. Generally speaking, the metal wire's immediate cost utilized in the WAAM technique is around 15% of the weight of the powdered metal. A conventional WAAM procedure is displayed in Figure 2.

![Diagrammatic view of WAAM technique.](https://www.malque.pub/ojs/index.php/mr)

Other types of AM, such as laser metal deposition (LMD), electron beam melting (EBM), and selective laser melting (SLM), are contrasted with the WAAM technique. The comparison between the material deposition rate in the WAAM technique and alternative AM methods is shown in Figure 3.

![Contrast of WAAM with various AM techniques.](https://www.malque.pub/ojs/index.php/mr)
2.1. Types of WAAM process

The three main forms of WAAM processes can be distinguished by the kind of arc-based method for welding that utilized to disintegrate every wire supply to create a 3D object or the architectural design involves adding layers upon layers of intricate details. The three distinct kinds of welding are known as GTAW, PAW, and GMAW respectively.

Figure 4 demonstrates the flow for three categories of the WAAM procedure.

An electric arc is created in GTAW-based WAAM among the substrate material with an inert tungsten cathode to generate heat. To achieve the required shape and mechanical qualities, a filler cable comes from the back. The heat from the arc causes the filler wire to melt, depositing it on the surface of substrate. Yet, the PAW is constrained in a nozzle, GTAW is less efficient than PAW and has a different welding torch structure. Among the water-cooled nozzle and the tungsten electrode in PAW is produced. The inert gas (IG) passes via the torch’s arcing zone and becomes ionized or transforms into a plasma state. After that, the substrate receives this plasma jet transfer a tiny aperture. The intense heat from this plasma jet melts the filler wire. Furthermore, shielding gas is employed to prevent contamination of the molten pool. However, compared to GMAW and GTAW, the basic value of PAW is higher. Contrasted to other WAAM techniques, GMAW is employed because of its greater high material utilization, material deposition rate and shorter lead time.

MAG (Metal active gas) and MIG (Metal inert gas) comprise GMAW. An IG, such as helium or argon is utilized in MIG. The majority of metals utilized by MIG are non-ferrous. For shielding, MAG utilizes carbon dioxide or a combination of IGs, such as a trimix of $\text{Ar} + \text{CO}_2 + \text{O}_2$. The main application of MAG with ferrous metals. Compared to other WAAM techniques, the GMAW method has a greater material deposition rate, as seen in Figure 5.

3. Materials utilized in WAAM technology

Wires manufactured for welding applications and available in various alloys and spooled forms are the feedstock materials used in WAAM procedures. The alloys utilized in WAAM are listed in Table 1, along with their numerous uses. To produce a sound, flawless, and dependable component, one must comprehend the many process alternatives that are accessible, as well as the underlying physical procedures, feedstock substances, control of process techniques, and the treatments and causes of the various typical defects.

3.1. Steel and aluminium alloys

Despite the successful completion of fabrication trials for numerous series of Almamlgam, such as Al-Cu, and Al-Si, the value in commerce of WAAM is mainly validated for big as well as complicated constructions with thin walls, as small and simple Al alloy components can be produced at low cost using traditional machining techniques (Sowrirajan et al 2022). Even though steel is the most frequently employed material for engineering, employing WAAM to produce it is undesirable for the identical premise. The low commercial uses of WAAM in Al is a result of chaotic melt pools weld flaws that happen through the deposition procedure and make some Al alloy sequences, including Al 6xxx and 7xxx, challenging to weld. Compared to Al alloy
components machined from billet material, as-deposited produced parts have worse mechanical qualities (Pasang et al 2023). To strengthen the tensile strength and to enhance the microstructure, the majority of Al particles that are deposited to unaltered the needs of heat treatment after the procedure.

![Comparison of various WAAM procedures in terms of material deposition rate.](https://www.malque.pub/ojs/index.php/mr)

**Figure 5** Comparison of various WAAM procedures in terms of material deposition rate.

<table>
<thead>
<tr>
<th>Uses</th>
<th>Automotive</th>
<th>Marine</th>
<th>Aerospace</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amalgam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel-based</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ti-based</td>
<td>-</td>
<td>-</td>
<td>(Chakraborty et al 2022)</td>
</tr>
<tr>
<td>Al-based</td>
<td>(Raut and Taiwade 2021)</td>
<td>-</td>
<td>(Muvunzi et al 2022)</td>
</tr>
</tbody>
</table>

**Table 1 Alloys utilized in the WAAM process.**

3.2. *Titanium (Ti) Compound*

As Ti amalgam have a large power to weight proportion, poor machinability, as well as high material cost, much study has been done on their possible uses in various sectors using WAAM technology. With resolution and macro roughness of around 0.6 mm, WAAM for Ti amalgam has a deposition rate among 0.76 and 3 (kg/hour). Consequently, the resulting metal layers are extremely thick, do not require the Hot Isostatic Pressing (HIPing) procedure, and the manipulator’s reach is the sole constraint on element size. Ti-6Al-4 V deposited using WAAM has superior traits to the wrought alloy regarding damage tolerance. Specifically, it can withstand large cycle loads. In terms of tensile strength and elongation, the Ti amalgam exhibits considerable anisotropy. The rolling of the component induces strains in both normal and transverse directions. In summary, the qualities of the refined material are superior to those of the wrought alloy. Research indicates that the mechanical processing of the component determines properties during the deposition process rather than by the circumstances of solidification.

3.3. *Nickel*

Nickel alloys are produced via WAAM, and several collaborations have effectively achieved the WAAM of nickel relying alloys. For AM, several popular nickel base alloys are utilized, such as Inconel 625, Hastelloy C276, or Inconel 718 (Alami et al 2023). The Inconel 718 and cold metal transfer- gas metal arc (CMT-GMA) welding procedure reaction, as well as the relationships found among the procedure variables, seam width, and build-up height. Most of the mechanical qualities of alloys made with nickel are attained by post-weld heat treatment (PWHT). Research on WAAM is one of many sources that advance our understanding of PWHT, particularly in the case of newly created amalgams. The PWHT modifies the material characteristics of a newly designed alloy made by AM (Liu et al 2021). Many welded alloys based on nickel go through further PWHT. Some research demonstrates that the PWHT factor affects the secondary stages that develop and deviate from bulk material recommendations.
4. Defects of WAAM process

Defects are important and must be examined to improve mechanical qualities. Numerous variables, including climatic conditions, thermal deformation linked to heat accumulation, inadequate programming strategies, poor parameter selection that results in instability of weld pool dynamics, and machine uncertainty, can cause defects in WAAM. Several potential flaws in WAAM can impact the quality of printed products. Typical flaws include distortion, porosity, and a lack of fusion. Avoiding harsh environments can help eliminate flaws like porosity, fractures, residual strains, and distortions. It is challenging for WAAM to produce sharp edges and intricate curves. Table 2 represents the common WAAM defects and solutions to rectify the flaws. The surface roughness was greater in WAAM-fabricated material than in SLM printed material. Typical faults discovered in WAAM-produced stainless steel items include porosity, fractures, and lack of fusion. Defective deposition occurs due to process factors, including heat input and deposition routes. Varying ejection or inadequate fusion resulting in voids or gaps in the impacted regions is more likely to occur in a complicated deposition route. Since the electric current works directly on the material processed in GMAW, it is more prone to issues with excessive heating, spattering, and porosity than PAW and GTAW-based WAAM. GMAW duplex stainless steel samples show certain gaps and an absence of fusion in the sectional view, particularly in the spaces among the bead.

Table 2 Common WAAM flaws and potential causes.

<table>
<thead>
<tr>
<th>Defect type</th>
<th>Prospective Reasons</th>
<th>Preventive or Decreased</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absence of Fusion</td>
<td>• Heat input and low energy</td>
<td>§ Sufficient heat input and energy</td>
</tr>
<tr>
<td></td>
<td>• Wrong angle for the torch</td>
<td>§ Use appropriate torch angle as well</td>
</tr>
<tr>
<td></td>
<td>• With enough shielding, gas</td>
<td>§ use joint procedures</td>
</tr>
<tr>
<td>Pores</td>
<td>• Inadequate substance of the alloy</td>
<td>§ Excellent quality of the wire surface</td>
</tr>
<tr>
<td></td>
<td>• Rapid cooling</td>
<td>§ Warm wire delivery</td>
</tr>
<tr>
<td></td>
<td>• Inadequate procedure parameters</td>
<td>§ low frequency of procedure pulses</td>
</tr>
<tr>
<td>Cracks</td>
<td>• Incompatible metal</td>
<td>§ Adhesive metal</td>
</tr>
<tr>
<td></td>
<td>• Gaseous hydrogen is present near the weld pool</td>
<td>§ Keep hydrogen away from the weld pool</td>
</tr>
<tr>
<td></td>
<td>• Weld pool motion that is suitable</td>
<td>§ The movable weave weld pool</td>
</tr>
</tbody>
</table>

5. Applications of WAAM process

- WAAM is well-suited for producing large-scale components with medium levels of complexity that are crafted from premium materials because of its unique characteristics. As a result, sectors like nuclear energy, automotive, molds & dies, aerospace, and defense may employ this technology.
- The aerospace and automotive sectors use optimized designs because they save weight without sacrificing the part’s functionality or efficiency.
- Topologically optimized parts become significant material waste, and need long lead times when produced using current methods.
- The aerospace industry is concentrating on producing complex-shaped parts made of Ti and nickel alloys. Because of the challenges involved in using subtractive processes to create these materials, WAAM is a cost-effective way to produce these components.
- In the nuclear firm, Ni-based alloys and stainless steels are utilized for parts that must have excellent heat and resistance to corrosion. In order to lower the cost and weight of these parts, WAAM is a suitable option to replace some less-used nickel parts with stainless steel.

WAAM has made it feasible to create metal straight from 3D models is a unique skill. Recent technical advancements in the WAAM process have been reviewed, emphasizing process flaws, applications, and defects (Singh et al 2021). A quality-based framework is presented to produce defect-free and high-quality components by combining the performance aspects of certain WAAM methods with a knowledge of material properties. As WAAM matures as an economic manufacturing process, developing a feasible WAAM architecture for metal components is an interlinked issue that includes materials science, thermo-mechanical engineering, and physical welding method development. Despite extensive research conducted in recent years in a number of areas, versatile standard WAAM technique that is equivalent to available powder-bed fusion methods has not been built. This system would need to include material analysis, programming, and process planning. The target material
properties and process parameters have a direct impact on the flaws that are created in WAAM-manufactured parts. It is crucial to build auxiliary processes or strategies to prevent the creation of flaws.

6. Final considerations

The technique WAAM has the potential to manage the AM sector, due to their better traits related to other approaches. Benefits include reduced lead time, material waste, and energy use. The WAAM technique is reviewed in this work. WAAM works with metals and alloys, making it suitable for construction, automotive, and aerospace applications. WAAM has been used to make items from aluminum, Ti, and nickel alloy wires. This article discusses the WAAM process's technological components, characteristics, and applications. The research compares WAAM to other AM methods. It analyzes and examines numerous WAAM procedures, including gas metal arc welding (GMAW), plasma arc welding (PAW), and gas tungsten arc welding (GTAW), and finds that GMAW deposits material faster. A significant issue impeding the use of WAAM is maintaining dimensional accuracy in the face of dynamic temperature conditions. As the work piece grows tall, the heat dissipation conditions worsen throughout the deposition process, causing the layer dimensions to vary. The use of WAAM in material manufacture has enormous potential. In the future, to make WAAM-produced components more suitable for applications requiring tight tolerances, researchers might enhance their accuracy and surface quality.

Ethical Considerations

Not Applicable.

Conflict of Interest

The authors declare no conflict of interest.

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