Review on Wire Arc Additive Manufacturing of Stainless Steels

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***Abstract*- Wire Arc Additive Manufacturing (WAAM) is an advanced process uses an electric arc and wire feedstock to build components layer by layer deposition by 3D printing technique. This review focuses on WAAM studies involving AISI 321 stainless steel, a titanium stabilized alloy known for its corrosion and heat resistance. Several experiments have been carried out on key process parameters like current, wire feed rate, travel speed, heat input, microstructure and defect formation in WAAM process. The parameters promote dense, uniform deposits with stable austenitic microstructures. Overall, literature findings indicate that WAAM offers strong potential for producing reliable AISI 321 components for aerospace and industrial applications.**

***Keywords*—Stainless Steel, 3D Printing, Titanium Stabilized Alloy, Wire Arc Additive Manufacturing**

I. INTRODUCTION

Additive Manufacturing (AM) has emerged as a revolutionary technology for fabricating complex metallic components with high material efficiency and design flexibility. Among various AM techniques, Wire Arc Additive Manufacturing (WAAM) has gained significant attention due to its high deposition rate, cost-effectiveness, and capability to produce large-scale metal parts. WAAM belongs to the Direct Energy Deposition (DED) family of AM processes and employs an electric arc as a heat source to melt and deposit metal wire feedstock layer by layer to build near net shape components. The process integrates the principles of Gas Metal Arc Welding (GMAW) with robotic motion control, enabling accurate layer stacking and efficient material utilization.

AISI 321 stainless steel, a titanium stabilized austenitic stainless steel, is widely used in aerospace, petrochemical, and thermal processing industries due to its excellent resistance to intergranular corrosion and oxidation at elevated temperatures. The addition of titanium in AISI 321 prevents chromium carbide precipitation during welding or high temperature exposure, thereby improving its weldability and mechanical stability. Ebrahim Harati et al. (2024) reviewed the use of metal-cored wire (MCW) in additive manufacturing with focus on penetration behavior and silicon control. The modified MCW showed reduced silicon island formation and improved surface cleanliness. Mechanical testing confirmed no negative effect on strength or toughness. Overall, MCW provided a more uniform penetration profile, minimizing lack of fusion defects and improving build quality on austenitic stainless steels.

Applying WAAM to AISI 321 components offers the potential to reduce production costs and lead times while maintaining the alloy's desired microstructural and mechanical properties. Antoine Queguineur et al. (2023) reviewed key process parameters such as wire feed speed, travel speed, and interpass temperature influencing WAAM builds. Their findings emphasized that heat input strongly affects layer geometry, ferrite austenite balance, and microstructural refinement. Wire chemistry also played a major role, where optimized composition improved hardness and structural consistency. The review highlighted that parameter control and material design are essential for enhancing WAAM processed stainless steels. However, process parameters such as wire feed rate, welding current, travel speed and interlayer temperature significantly influence the thermal history, microstructure and final properties of the built component. Therefore, from the understanding on review of AISI 321 Stainless steels the above parameters follow the relationship between WAAM process conditions that results in microstructural behavior of these stainless steels. (Ref.1-3).

II. TYPES OF WIRE ARC ADDITIVE MANUFACTURING PROCESS

Wire Arc Additive Manufacturing (WAAM) is a type of Directed Energy Deposition (DED) process that uses an electric arc as the heat source and a metallic wire as the feedstock to build components layer by layer deposition is referred below in Figure 1. It is known for its high deposition rate, cost effectiveness and ability to produce large scale metallic parts. It is based on the arc generation method, WAAM can be classified into several types. They are Gas Tungsten Arc based WAAM (GTAW-WAAM), Gas Metal Arc-based WAAM (GMAW-WAAM), Plasma Arc based WAAM (PAW-WAAM), Cold Metal Transfer based WAAM (CMT-WAAM), and advanced systems such as Tandem and Twin Wire WAAM.

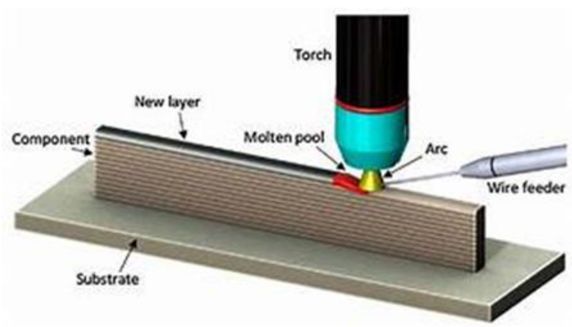

Fig. 1 A Schematic diagram of Wire Arc Additive Manufacturing Process.

Gas Tungsten Arc-based WAAM (GTAW-WAAM), also known as TIG-WAAM, a non-consumable tungsten electrode generates the arc while the wire is fed externally. It offers excellent control over heat input, producing high-quality, clean deposits with minimal spatter, making it ideal for reactive materials such as titanium and stainless steels. However, it has a relatively low deposition rate, limiting productivity. Gas Metal Arc-based WAAM (GMAW-WAAM) or MIG-WAAM, uses a consumable wire electrode that acts as both the filler and arc source. This method provides high deposition rates up to 10 kg/hr and is cost effective, but the higher heat input can lead to distortion and residual stresses. It is widely used for large steel and stainless steel structures.

The Plasma Arc based WAAM (PAW-WAAM) employs a constricted arc between a non-consumable tungsten electrode and the workpiece, creating a high-energy plasma jet that melts the wire. It offers better arc stability and deeper penetration than TIG, with moderate deposition rates and good control, although it requires a more complex setup. Cold Metal Transfer-based WAAM (CMT-WAAM) is a modified GMAW process developed to minimize heat input by synchronizing wire feeding with the current waveform. This results in low spatter, reduced distortion, and excellent surface finish, making it suitable for aluminum and stainless-steel thin components, though it requires specialized equipment.

Finally, tandem and Twin-Wire WAAM systems use two arcs or two wires simultaneously to achieve very high deposition rates and enable the combination of different materials. Tandem WAAM employs sequential arcs for improved efficiency, while Twin-Wire WAAM feeds two wires into a single molten pool, allowing alloy customization and graded structures. These advanced variants are especially useful for large steel components and functionally graded materials. Parankush Koul et al. (2025) reviewed the potential of Wire Arc Additive Manufacturing (WAAM) as a cost-effective high-deposition technique suitable for stainless steels such as AISI 321. The review emphasized WAAM advantages including rapid prototyping, customization, and reduced production cost. However, challenges such as residual stresses, surface roughness, and anisotropic properties were identified. Recent advancements in CMT, real-time monitoring, AI control and hybrid processing were highlighted as key enablers for improving WAAM-processed AISI 321 components.

The GTAW-WAAM provides superior quality with low deposition rates, GMAW-WAAM ensures high productivity, PAW-WAAM balances precision and penetration, CMT-WAAM minimizes heat input and distortion, and Tandem or Twin Wire WAAM maximizes deposition rate and material flexibility. Together, these WAAM variants make the process adaptable for a wide range of materials and industrial applications, from aerospace titanium components to large scale steel structures. Huijing Zhang et al. (2024) reviewed micro-control deposition trajectory technology in WAAM and reported improved melting stability and droplet transfer. The method reduced defects and enhanced fusion uniformity with finer microstructures. Mechanical properties such as strength and elongation were significantly improved. The review suggested further advancements in molten pool modeling and precision robotic control for optimized WAAM performance (Ref.4,5).

III. LITERATURE REVIEW

Ebrahim Harati et al. (2024) investigated the application of metal cored wire (MCW) in additive manufacturing, with particular emphasis on penetration behavior and silicon control. The study compared deposits produced using solid wire, standard MCW, and a modified MCW under both Spray Arc and Cold Metal Transfer (CMT) modes. Results indicated that the modified MCW effectively reduced silicon island formation by relocating silicate inclusions from the deposit toe to the surface, thereby improving overall cleanliness. Mechanical characterization, including tensile and Charpy V-notch tests conducted under both as-deposited and post weld heat-treated (PWHT) conditions (at 570 °C for 2 hours), demonstrated that the wire modification did not adversely affect mechanical performance. Furthermore, the use of MCW resulted in a more uniform penetration profile compared to solid wire, minimizing the risk of lack of fusion between layers and enhancing the structural integrity and quality of the additively manufactured components.

Antoine Queguineur et al. (2023) studied the effects of wire feed speed (WFS), travel speed (TS), interpass temperature (IT) and duplex stainless steel (DSS) wire chemistry on the geometrical, microstructural, and mechanical properties of WAAM. Using G2205 and G2209 wires, the study found that heat input (HI) strongly influenced layer thickness, ferrite content and microstructure. Increased WFS enhanced deposition rate and layer height, while higher TS reduced them. The G2205 wire, with higher nickel content, achieved a more balanced austenite–ferrite ratio and higher hardness. Ferrite content and hardness were positively correlated with HI, where excessive heat caused coarser microstructures. The maximum deposition rate reached 3.54 kg/hr, with higher values in thicker builds. The study emphasized that process optimization and wire composition are crucial for improving WAAM-fabricated DSS components and suggested future work on modeling, corrosion behavior, and industrial applications.

Mohamed Dekis et al. (2025) reviewed the potential of Wire Arc Additive Manufacturing (WAAM) for steel components, emphasizing its advantages such as design flexibility, high deposition rates, and material efficiency. Despite these benefits, the study identified key challenges including porosity, lack of fusion and residual stresses, which critically affect part quality. The authors highlighted that effective process control and appropriate post processing treatments are essential to mitigate these defects. A comprehensive understanding of heat transfer, material behavior and defect formation mechanisms was deemed vital for optimizing process performance. Recent advancements, such as hybrid manufacturing, in situ monitoring, and the use of advanced materials, have significantly improved process reliability and component integrity. The study concluded that ongoing research should focus on refining process parameters, enhancing microstructural control, and expanding the range of materials and geometries applicable to WAAM for industrial applications.

Parankush Koul et al. (2025) highlighted the potential of Wire Arc Additive Manufacturing (WAAM) as a cost effective, high-deposition rate technique for metal components using conventional welding equipment. The process enables rapid prototyping and the production of complex, customized parts with reduced production costs and shorter lead times compared to other additive manufacturing methods. Despite these advantages, the study noted persistent challenges such as thermal-induced residual stresses, poor surface finish, geometrical inaccuracies and anisotropic mechanical properties resulting from layer-wise solidification. Current research aims to overcome these limitations through innovations in Cold Metal Transfer (CMT) technology, adaptive path planning, real-time monitoring using artificial intelligence (AI), hybrid processing, and advanced simulation tools for improved process control and predictability. Furthermore, ongoing efforts in standardization, quality assurance, and the integration of multi-material and sustainable manufacturing approaches, supported by robotic automation, are expected to enhance WAAM's industrial scalability and establish it as a key technology for next-generation metal manufacturing.

Huijing Zhang et al. (2024) investigated the development and effects of micro-control deposition trajectory technology in Wire Arc Additive Manufacturing (WAAM) for thin-walled components. This technique disperses arc force and ensures uniform heating, leading to a more consistent melting depth and enhanced molten pool stirring compared to conventional deposition methods. Unlike typical short circuit droplet transfer, the micro-control approach facilitates stable droplet transition, thereby minimizing arc instability and spatter formation. The resulting deposits were free from visible defects and displayed a uniform fusion line. As the swing speed increased, the microstructure evolved from ferrite and austenite to vermicular ferrite and austenite, indicating improved microstructural refinement. Mechanical testing demonstrated that micro-control thin-walled components exhibited higher tensile strength and elongation, maintaining a ductile fracture mechanism with significantly fewer porosity defects. The study concluded that future work should focus on analyzing molten pool flow, temperature, and stress behavior, as well as enhancing control precision through advanced electromagnetic and robotic micro-control techniques.

Cheng Huang et al. (2022) investigated the mechanical properties and microstructure of Wire Arc Additive Manufactured (WAAM) steel plates produced using ER70S-6 (normal-strength) and ER110S-G (high-strength) wires. A total of 137 tensile specimens with varying thicknesses and orientations were tested, supported by 3D laser scanning, digital image correlation (DIC), optical microscopy (OM), and electron backscatter diffraction (EBSD) analyses. Results showed that WAAM steels exhibited good ductility and comparable Young's modulus, satisfying Eurocode 3 standards, though tensile and yield strengths were lower than conventional welds due to slower cooling rates. The as built samples showed slight anisotropy and lower strength than machined specimens, while deposition strategy had little effect. Microstructural observations revealed ferritic pearlitic structures in normal strength steels and ferrite bainite martensite in high-strength steels. EBSD confirmed a weak crystallographic texture, consistent with the near isotropic mechanical behavior of WAAM components.

Wanwan Jin et al. (2020) highlighted Wire Arc Additive Manufacturing (WAAM) as a low cost, high efficiency method for producing large-scale stainless-steel components, offering advantages over powder bed fusion (PBF) techniques. The study emphasized that process parameters including wire feed rate, scanning speed, welding current, cooling time and interlayer temperature strongly influence dimensional accuracy, surface quality and microstructural evolution, particularly the austenite ferrite phase balance. The thermal history plays a critical role in determining microstructure, which can be optimized through parameter control, alloy modification, or post heat treatment. Key challenges such as residual stress, distortion, and defects (porosity, cracks, lack of fusion) can be mitigated by proper heat input management, shielding gas control, and material cleanliness. Mechanical properties were found to depend on process conditions, microstructure, and defect control, though anisotropy in strength and grain structure remains due to layer wise deposition. The study also noted that hybrid approaches, such as in-situ rolling, can reduce anisotropy and residual stresses. Future work should focus on fatigue and corrosion studies, numerical modeling, and process optimization to enhance deposition rates, quality, and industrial applicability of WAAM for stainless steels.

Kasireddy Usha Rani et al. (2022) successfully demonstrated the 3D metal geometry using Wire Arc Additive Manufacturing (WAAM) based on Gas Metal Arc Welding (GMAW), with a modified wood engraving machine adapted as a metal 3D printer. The study examined the influence of heat input on residual stress distribution using the deep hole drilling (DHD) method. The Results confirmed that GMAW-WAAM can produce components with good hardness and strength, suitable for complex geometries such as gears and turbine vanes. A bimetallic specimen combining mild steel (MS) and stainless steel (SS) showed defect free bonding at the interface. The SS region exhibited higher hardness (240–260 HV) than the MS region (160–180 HV), attributed to chromium diffusion across the interface. Tensile strength of the bimetallic sample was intermediate between MS and

SS, with all values slightly exceeding conventional standards. Residual stress analysis indicated compressive stresses (50–80 MPa) in MS and tensile stresses (up to 90 MPa) in SS, confirming interface stability and sound mechanical integrity of the WAAM bimetallic structure.

E.D. Weflen et al. (2021) presented a novel automated welding approach for casting repair using Wire Arc Additive Manufacturing (WAAM) with pulsed Gas Metal Arc Welding (GMAW) and robotic motion control. A standardized terraced V-groove geometry was designed to enable precise control of bead width and layer thickness, ensuring consistent simulation and quality validation. Experiments on low carbon steel identified optimal travel speed and step over distance for effectively filling casting cavities, confirming the feasibility of WAAM for production weld repairs. The study highlighted the need for further investigation into bead sidewall interactions, void formation, and cavity welding effects on layer uniformity. Although demonstrated with low carbon steel, the method shows strong potential for extending to other alloys and arc processes, enabling hybrid manufacturing applications such as non-ferrous casting repair and feature addition to existing components.

S.W. Williams et al. (2016) is identified Wire Arc Additive Manufacturing (WAAM) as a low cost, high efficiency method for large-scale stainless-steel components, offering advantages over powder bed fusion (PBF) processes. The study emphasized that process parameters such as wire feed rate, scanning speed, welding current, cooling time and interlayer temperature significantly affect dimensional accuracy, surface quality, and microstructural evolution, particularly the austenite–ferrite balance. The thermal history was found to strongly influence microstructure, which can be optimized through parameter control, alloy adjustment or post heat treatment. Challenges such as residual stresses, distortion, and defects (porosity, cracks, lack of fusion) were noted but can be mitigated by maintaining proper heat input, shielding gas and material cleanliness. The mechanical properties of WAAM components depend on process parameters, microstructure and defect control, though anisotropy in tensile strength and grain orientation persists due to layer wise deposition. The study recommended further research on fatigue and corrosion performance, numerical modeling and process optimization to enhance quality and enable industrial scale adoption of WAAM for stainless steels.

IV.CONCLUSIONS

From the reviewed literature, it is observed that Wire Arc Additive Manufacturing offers significant advantages for stainless steel components. The combination of optimized process parameters, refined microstructure and stable mechanical performance confirms that WAAM is a sustainable and industrially viable alternative to traditional manufacturing methods. WAAM has the ability to produce large-scale, corrosion-resistant and high-temperature-capable components.The optimization of process parameters such as current, wire feed rate, travel speed and interlayer temperature played a critical role in achieving uniform layer deposition and minimizing defects such as porosity and distortion. The Microstructural observations in Wire arc additive manufacturing of Austenitic stainless steel revealed a predominantly austenitic matrix with stable titanium carbides that contributed to enhanced resistance against intergranular corrosion and high-temperature degradation. Overall, the review validates the potential of WAAM in stainless steel parts for aerospace, petrochemical and high temperature applications, providing a sustainable and efficient alternative to traditional manufacturing routes. (Ref.6-10).

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