Wire Arc Additive Manufacturing of Aluminium Alloys using GTAW - A Review

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Abstract. Wire arc additive manufacturing (WAAM) is the most sophisticated method for creating parts by layer-by-layer material deposition. It can create large-sized components with greater rates of deposition, lower manufacturing costs, and shorter production times. Products based on WAAM have superior mechanical and metallurgical qualities, making them ideal for use in aeronautical engineering. However, because of the issues with porosity, corrosion, delamination, residual strains, and oxidation, WAAM is currently being under investigations. This review study primarily addresses the subject of industrial applications of WAAM of aluminum alloys, difficulties associated with material processing, optimization methods and mathematical modeling of WAAM.

Keywords: Wire Arc Additive Manufacturing, Aluminium Alloys, Porosity, Pulsed Gas Tungsten Arc Welding, Solidificaton Cracks

1 Introduction

1.1 Wire Arc Additive Manufacturing

The metal additive manufacturing technique known as wire arc additive manufacturing (WAAM) builds components layer by layer using an electric arc welding process[1].Another name for it is WAAM 3D printing or wire arc 3D printing. In WAAM, an electric arc welding torch receives a continuous supply of wire electrode, which is melted and deposited onto a substrate or layers that have already been deposited to form the required shape[2].Figure 1 depicts the basic schematic diagram of the WAAM process. Over time, the industrial sector has become more and more attracted to WAAM. Its ability to produce large components at low costs, high deposition rate, and high accuracy to bring the material's finish is the primary cause of its attraction. These significant benefits have made WAAM a promising method for a

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number of elements, including steel, titanium, and alloys made of magnesium and aluminum. These days, additive manufacturing (AM) is a widely utilized approach that replaces traditionally used methods that rely on raw material processing by building commodities through the deposition of material in layers[3].

1.1.1 Aluminium alloys in WAAM

One of the best processing techniques for producing huge structural pieces at a reasonable price is WAAM [4]. However, due to a lack of process knowledge, the method is not frequently employed for aluminum alloys. These alloys are corrosion resistant and lightweight, which makes them useful for various industrial applications, including shipbuilding, automobile, aerospace, and railroad construction[5]. The elements copper, silicon, magnesium and manganese are crucial for alloying. The EN AW-4000 range of alloys are often put into use, in applications of metal joining, making them a suitable alloy for AM.

1.2 Pulsed Gas Tungsten Arc Welding (PGTAW)

Pulsed GTAW commonly referred to as Pulsed TIG Welding, is a type of welding in which metals are joined by an electric arc created by a non-consumable tungsten electrode. Thin material welding and applications requiring exact control over the heat input are prominent uses for this type of welding. Moreover, the GTAW technique can provide a high-level joint.[6]

The welding current in pulsed GTAW alternates between a low current and a high peak current. The arc&heat required to melt the base metals are produced by the peak current.[7] Lower background current aids in sustaining the arc and permits a small amount of cooling the weld pool in between pulses. Welders can alter the heat input, arc shape, and weld penetration by adjusting the peak current, background current, pulse duration, and pulse frequency. The pulsing action provides several benefits in the welding process. It helps to control the heat, minimizing distortion and reducing the likelihood of burn-through on thin materials. Additionally, pulsed GTAW can be used to weld various materials, including stainless steel, Aluminium, and other non-ferrous metals.[8]

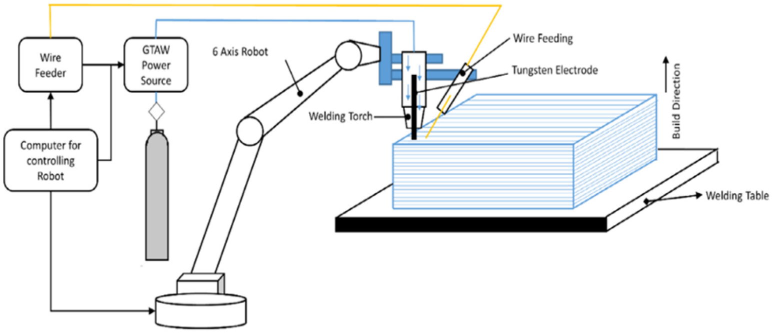

Figure 1. Basic WAAM Process **[**9**]**

2 Material Processing Challanges in WAAM

The challenges associated with processing of materials in WAAM are related to meeting the performance metrics for various characteristic properties. (Figure 2). As per the study conducted by Cunningham et al.[10] on the materials used in WAAM, the process's deposition rate is crucial for the adoption of WAAM as a large rate of deposition through DED method. As a result, this makes up the ultimate performance measure, to which the performances must be maintained. He declared that the usual deposition rates for WAAM are reported in the range of 1–10 kg/hr, depending on the material and the application.

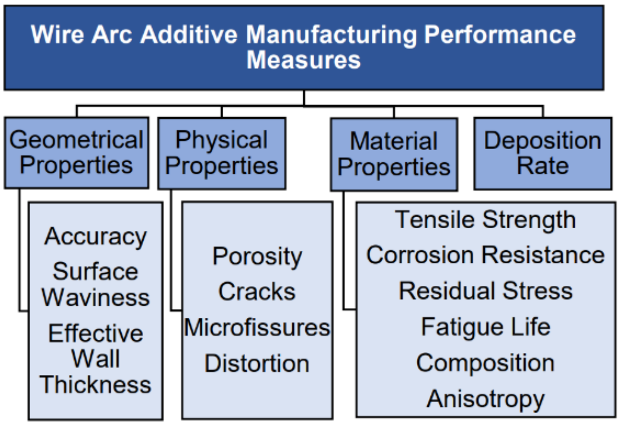

Figure 2. Performance measures in WAAM **[**10**]**

2.1 Solidification cracks

Regarding the performance metrics, Poolperm et al. [11] revealed that the development of a microstructure with large columnar grains in WAAM presents a significant challenge for solidification. In comparison to a fine axial microstructure, which is typically challenging to improvise in WAAM and other AM methods and this offers reduced strength, toughness, and corrosion resistance.

As a result of the tendency to form hot cracking at few points during WAAM and their ability to produce low quality parts, alloys that are attracted to hot cracking are generally not recommended in WAAM. Hot cracking can occur in two different ways: solidification cracking (SC), which occurs in the weld zone, and liquation cracking (LC), which occurs in the HAZ. In a mushy zone, Albannai et al.[12] examined the impact of GTAW welds on centerline solidification cracking and discovered that SC forms and spreads through the material's solidification progress at the end of the moving weld pool. In relevance to this, Agarwal etal.[13]analyzed the mechanically weak region, or mushy zone, is frequently the area which comes behind the weld pool and the ideal location for the SC, where interference takes place flanked by the shrinkage rate of the solidification progression, which was observed in his experimental study of the susceptibility to solidification cracking in high strength steels.However, during a fusion welding process, LC can be found in the partially melted zone (PMZ) of the HAZ. High stress concentrations can cause the separation of liquid stains, which in turn creates LC, because of the presence of thermal stresses and partial phase liquation in the PMZ. Consequently, Taheri et al.[14] examined the relationship between solidification and liquidation fractures in Nd:YAG laser welded GTD-111 nickel-based superalloy joints. He discovered that LC is a result of particles which melt easily, liquating in the microstructure and is mostly present in WAAM as a result of the deposited material being heated during reheating.

2.2 Porosity

Wahid et al.[15] studied the use of potential Aluminium alloys for marine applications and observed that the process parameters severely impact the porosity development. Besides, the scan speed controls porosity in a subjective way.

A problem with material integrity called porosity has an impact over the mechanical characteristics of aluminum parts made using WAAM and other techniques. According to Derekar [16], Gierth [17], Wan [18], and Biswal et al. [19], considerable proportions of pores volume ratio and pores size lower the tensile strength, and fatigue resistance of parts. This defect can be divided as pores caused by the process or by the material [20]. Regarding the process-induced flaw, two paramount reasons why aluminum parts have porosity are:

- Porosity brought by a change in volume when the aluminium solidifies. These are shrinkage pores.
- Porosity due to hydrogen entrapment which paves way for spherical pores.

This paper focuses on the second type of porosity since it is the primary cause of defects in WAAM. Additionally, alloying elements may limit the application of aluminum alloys as the input constituents in WAAM and serve as a source of development of pores [21]. The porosity spreadand evolution in aluminum alloys made by additive manufacturing under elevated temperatures were investigated by Bai et al.[22]. The author declared that because hydrogen is far more soluble in liquid aluminum, alloys made of aluminum are highly susceptible to hydrogen pores formation. This conclusion was nearly exactly the same as that reached by Lee et al. [23].

2.3 Residual stress and distortion

Controlling residual stress and distortion resulting from deformation mismatch between various deposit and substrate regions after uneven heating and cooling is a major challenge when using WAAM to construct large-scale structures [24]. Build distortion and brittle fracture are the potential consequences of residual stress [25], and they may result in collapsed WAAM components. Heat treatment, which typically involves evenly heating a component to introduce plastic deformation and relax residual stress, is an effective way to relieve residual stress, according to investigations on multi-pass welds by FEAmethods conducted by Cho et al.[26]. However, this approach could negatively impact mechanical qualities and is costly and challenging to implement on large components.

The development of high pressure rolling as an adaptable and affordable method for lowering residual stresses in welds has taken place [27]. Kurkin etal.[28] carried out the preliminary research on this kind of residual stress mitigation technique in Russia. Even in thick weld joints, post-weld rolling has been shown to be an effectiveway to reduce residual stresses [29], and this effectiveness is directly correlated with the rolling load.

On WAAM Ti-6Al-4V components, interlayer rolling using flat and profiled rollers was studied by Colegrove et al. [30] and Martina et al. [31]. The distortion for both kinds of rollers reduced as the rolling load increased. According to several observations based on WAAM of steel components [32], the distortion cannot be totally removed. This is partly explained by the fact that there is no side restraint when the WAAM wall rolls, which leads to a huge amount of transverse deformation. Honnige et al. [33] examined the impact of inter-layer rolling on intersections for complex structures using an inverted roller (a roller with a convex surface). They found that while such a roller can enhance the microstructure, it has no effect on residual stress spread right at intersections because the rolling was dominated by the thermal impact of WAAM deposition.

2.4 Lack of fusion

One major obstacle to the use of AM technologies is the lack of fusion defects and their uncontrollable nature [34]. As a result, asubstantial amount of experimental information regarding the prevention or reduction of absence of fusion defects in various groups of alloys has been published in literatures. Through experiments, it was discovered that elevating the weld process power for titanium alloys, aluminum alloys, and stainless-steel alloys decreased

Table 1. Common defects in WAAM and their possible causes

Type of defect	Possible Causes	Prevention or Reduction
Pores	• Improper process parameters • Improper inter-pass layer temperature • Bad wire quality • Insufficient alloy composition • High cooling rate	• Low process pulse frequency • High inter-pass layer temperature • High heat input • High wire surface quality • Hot wire feeding
Lack of fusion	• Low energy and heat input • Improper torch angle • Improper joint edge preparation • Inappropriate weld position • Insufficient filler wire material	• Sufficient energy and heat input • Appropriate weld position • A compatible weld speed with wire feed speed • Sufficient filler wire material
Cracks	• Unweldable alloy • Alloy with high solidification range • High heat input • Large HAZ size • Large mushy zone size	• Weldable alloy • Low thermal and mechanical stress • Low heat input • Small HAZ size • Small mushy zone
Residual stress and distortion	• Insufficient weld process parameters • Complex thermal cycle • Extreme heat input • Inappropriate preheating temperature	• Proper weld proces parameters • Controlling thermal cycle • Appropriate heat treatment

the number of fusion defects in the produced parts [35,36]. Mukherjee and DebRoy[37]studied about mitigation of absence of fusion defects and stated that providing elevated heat input per unit length paved way for expanded liquid pool size and brought down the lack of fusion defects. According to Jovanovic et al.[38], using a high welding speed will result in less energy input,in a welded joint. Furthermore, the author indicated the poor welding position, erroneous torch inclination, and sparse weld joint forming are all significant factors to the absence of fusion. Other factors like exact melt pool dynamics, appropriate process parameters, and enough shielding gas are highly efficient in curbing the shortage of fusion errors which was stated by Ghaffari et al. [39] In another study, Jin et al. [40] concluded that when the WAAM process is used, precise and appropriate control of heat input and thermal history,appropriate shielding gas, high-quality feedstock, and clean substrate surfaces are helpful to reduce lack of fusion defects in stainless steel. Table 1 depicts the common defects in WAAM, their possible causes and prevention methods.

3 Optimization Techniques and Mathematical Modelling of WAAM

Various techniques such as response surface method, factorial design, Taguchi method[42],Analysis of Variance (ANOVA), Artificial Neural Network or the combination of two different techniques[43] have been used to predict the bead geometry (bead height and width) based on deposition parameters. Sarathchandra et al.[44] used response surface method (RSM) to investigate the effect of welding current, standoff height and weld speed over the bead width and height, penetration and dilution. In his study on effect of process parameters on bead geometry and microstructure, ANOVA was utilized by Dinovitzer et al. [45] to understand the impact of wire feed, argon flow, travel speed, and current on the microstructure of Hastelloy X, and the shape and roughness of the beads. Karmuhilan etal.[46] modelled the ANN for predicting bead geometry based on input parameters. The forward ANN model was created for bead geometry prediction based on the input parameters while reverse ANN model was developed to predict input parameters based on desired bead geometry. Almeida and Williams[47] utilized least square regression analysis to find out the required values of process parameters for the targeted wall width, while Nagesh and Datta[48] utilized back-propagation neural network to find the relationship between process parameter and bead geometry as shown in Figure 3.

Here, it was essential to develop a real-time monitoring and evaluation technique which would take real-time data by means of systems temperature and geometrical information of weld bead and ensures the stability and accuracy in WAAM.

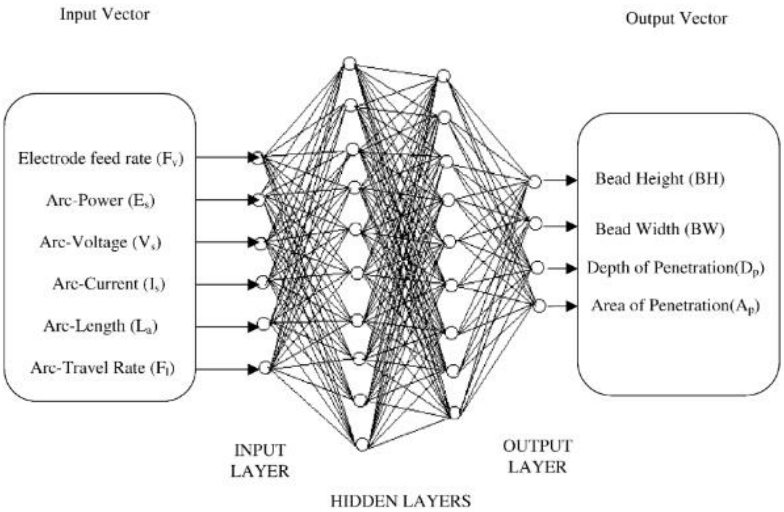

Fig. 3. Back propagation neural network used to predict bead geometry and penetration[48]

Several researches and mathematical models were proposed to understand the material properties during distortion and the impact of process parameters on the wall built through WAAM and such models and computations are still in study. Through the nonlinear numerical computations and the Goldak's double ellipsoid heat source model, Manurang et al. [49] conducted an analysis on distortion in the AM process after which, he stated that these models significantly affect the distortion in the process. Chen et al.[50] proposed a closed loop quality control model based on multi-sensor data fusion. This model offered a workable way to guarantee the effectiveness of the deposition process and the quality of WAAM parts under challenging manufacturing circumstances. This model serves as the foundation for the introduction of a brand-new method called hybrid deposition and micro-rolling (HDMR), which is a more environmentally friendly and superior product than conventional manufacturing techniques. Farias etal.[51]employed a finite element model (FEM) to analyze the influence of idle time on the inter-pass temperature(IT) of 20-layer single-bead walls produced via WAAM and used the FEM results to develop a predictive model for IT based on ANN. The ANN was used to establish a process map which proved supportive to obtain a suitable balance between productivity and part behaviour.

Montevecchi et al. [52] solved the heat transfer equations to conduct a FEA of the workpiece's thermal behavior during WAAM. He noted that the acquisition of the idle times determined by FEA breaks the significant structural disruptions, as demonstrated by the analysis of the geometry of the manufactured workpiece. An overview of air-jet impingement performances using a blend of numerical-experimental advent was presented by Hackenhaar et al. [53]. Based on the findings, he concluded that air-jet impingement limits the process's ability to raise the interlayer temperature more gradually than free convection cooling. Hejripour et al. [54] worked on the three-dimensional transient thermal models of AM parts. The simulated thermal cycles were validated using experimental data, and this allowed him to show a relationship among the phases that form in the WAAM parts and the cooling rates. The author′s findings demonstrated that in a ferrite matrix, austenite formation is greatly aided by the built layers' slow cooling rate at high temperatures.

4 Industrial applications of WAAM

4.1 WAAM in the field of aerospace

Currently, AI-Li alloys help to achieve weight savings of 8–10% and increased stiffness of up to 15%, all while satisfying the acceptance level of the remaining performance criteria. It is possible to argue that using traditional aircraft assembly techniques avoids the high conversion costs associated with using carbon resin composites.Third-generation Al-Li alloys have not yet been developed for use in high-performance military aircraft, transport aircraft, or smaller helicopters. Holdway and Bowen[55] measured the lithium depletion in aluminum-lithium alloys using X-ray diffraction techniques and stated that the aluminum industry aims to develop and provide difficult materials at competitive prices for use in various applications.

According to Colegrove et al.[56] interlayer rolling reduces porosity size, which is thought to be the cause of the increase in ductility of WAAM rolled aluminum alloys. According to Chaturvedi et al.[57], polarity reversal causes turbulence to form in the melt pool, which may result in improper components being achieved.

4.2 WAAM in automobile industries

Through his study on recent developments in Aluminium alloys for the automobile industries, Miller et al.[58] stated that the scope for weight reduction is givenby the Body-In-White (BIW) with high Aluminium content.

Recent studies show the replacement of steel with Aluminium to achieve up to 50% weight saving for BIW.[59]Through his experimentations and research Rodrigues. et al.[60] concluded that, in the automobile industry, magnesium alloys are being utilized more frequently in place of aluminum to lower the total weight of components. According to Thompson et al.[61], the automotive industries are using topologically optimized structures more frequently because they minimize weight without sacrificing the part's functionality or performance. While topologically optimized components become very costly, have significant material waste, and require long lead times when produced using conventional technologies, WAAM helps to produce them.

4.3 WAAM in marine industries

Through the recent studies on Aluminium alloys by Cam and Ipekoglu[62], it was observed that the yield strength of carbon steel is about 235 MPa. Because aluminum alloys can move faster with less weight, they are utilized in a variety of transportation systems, including boats, hydrofoils, ferries, and cargo ships. They are utilized in ship hulls and superstructures for this reason. One could argue that the main uses of aluminum alloys are in the building of ships and other marine applications because of their ease of availability, comfort during the fabrication process, and stability. Alloys like Monel are appropriate for marine applications because they can withstand corrosive conditions.[63]

4.4 WAAM in biomedical industries

Aluminum alloys possess favorable properties like lightweight, corrosion resistance, and high strength-to-weight ratio. In the biomedical field, these characteristics make them potentially useful for various applications. Pradhan et al.[64] investigated the dry machining of Ti-6Al-4V alloy using SNMA120408 grade inserts and such a material is designed for orthopedic applications. Through his study on Ti-6Al-4V alloys, according to Oliveira et al. [65], Ti-based alloys are well-suited for use in aerospace and biomedical applications due to high strength, toughness, strong corrosion resistance, and ability to withstand severe temperatures without significantly losing their mechanical characteristics. The longevity, effectiveness, and dependability of common anti-wear coatings are highly dependent not only on the type of surface modification, research techniques, or experiment setup, but also onexperimental conditions, such as sliding velocity or applied load, according to Lepicka and Dahle′s[66] review of surface modification techniques used on Ti-6Al-4V alloy.

Therefore, creating uniform guidelines for biomedical alloy wear testingwhich is necessary for applications involving orthopedics like arthroplasty is advised.

4.5 WAAM in construction industries

The construction industry may become more digitally advanced, leading to more productive buildings, less wasteful use of materials, and improved worker safety. The utilization of metal AM technologies, particularly WAAM, is seen by current plans for the implementation of automated steel constructions as a chance to create a new generation of efficient steel structures with less material consumption. An integrated design strategy, integratingdesign algorithms with considerations for the WAAM manufacturing process, structural considerations, and verifications, was presented by Laghi et al. [67] to build resource-efficient structural components. Using this method, he was able to note that the creation of novel, resource-efficient structural components has expanded the application of metal AM in the construction industry. In their study on the state of AM in the construction industry, Paolini et al. [68] noted that AM provides significant design freedom and automation opportunities. Digital planning techniques can be used to make use of these advantages.

Though WAAM using aluminum alloys has potential applications in the civil engineering sector, challenges such as ensuring the structural integrity, material properties, and adherence to buildingstandards must be addressed. Regulatory compliance, material testing, and quality control are essential considerations when implementing WAAM in civil engineering projects.

5 Conclusion

WAAM typically involves steps such as material selection, wire selection, equipment setup, shielding gas, pulse parameters, travel speed and wire feed rate, pre-heating and post heating, cooling rate, and process optimization. This paper threw light on some of the common defects in WAAM like porosity, lack of fusion, and surface cracking.Such defects can be rectified by ensuring smooth wire feeding and verifying consistent shielding gas flow and coverage. This paper also addressed the applications of WAAM of Aluminium alloys using pulsed GTAW include rapid prototyping of complex aerospace components and biomedical implants.

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