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WIRE-ARC ADDITIVE MANUFACTURING: RECENT DEVELOPMENTS AND POTENTIAL

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Abstract: *Wire-arc additive manufacturing (WAAM) is a promising technology for producing medium and large components without traditional subtracting technologies. It is a hybrid of two manufacturing techniques: additive manufacturing and welding. The use of this technology has grown significantly due to advantages such as material and energy savings while achieving high deposition rates and low cost. However, there are some issues with microstructure homogeneity, and properties are affected due to the complexity of the arc-induced thermal cycles and metallurgical mechanisms, resulting in high residual stresses, distortion, porosity, cracks, and delamination. This article summarises the progress made in the field of wire additive manufacturing, with a focus on welding systems, tool path design software, material analysis, and control systems. It also highlights some critical aspects that must be addressed to ensure high-quality production, such as control and diagnosis mechanisms for defect monitoring, the effects of parameters and their optimisation possibilities for improving quality, ensuring process stability, and possible post-deposition heat treatments. The conclusions suggest further improvements to the wire-additive manufacturing process in terms of accuracy, reliability, and efficacy, as well as future applications of the technology and research activities.*

Keywords: Additive manufacturing, WAAM, Welding, Mechanical properties, Monitoring system

1. INTRODUCTION

Additive manufacturing (AM) uses the joining of materials to create three-dimensional structures, typically layer by layer [1]. In fact, it is one of the primary technologies in engineering that enables near-net-shape fabrication, which is thought to increase design freedom while achieving lower lead times and great potential for smart production [2]. It has mastered the production of high-end products while meeting sustainability standards by employing environmentally friendly manufacturing techniques, resulting in minimal waste and CO_2 emissions and a strong circular economy [2]. While there has been continuous progress in AM research over the years, there have also been some difficulties and problems encountered along the way, such as raw material incompatibilities, the lack of testing facilities, and the numerous defects in the AM parts [2]. Poor surface quality, flaws, and decreased corrosion resistance are some of the important problems that prevent the real-time application of AM products in some industries, but there are significant efforts to resolve these problems through research and there are also some post-processing techniques that can be used to overcome these difficulties [2]. AM technology has found great interest in applications in aerospace,

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automotive, biomedicine, energy and chemical industry, micro-nano manufacturing, marine, and aeronautics.

A fundamental AM system is made up of a motion system, a heat source, and feedstock [3]. The process parameters and material used determine the quality of parts created using AM procedures. AM can use metals and alloys, polymers, ceramics, composites, and natural materials [2]. Metal additive manufacturing is one of the most difficult modern technologies. Powder bed fusion (PBF), direct energy deposition (DED), binder jetting (BJ), and sheet lamination (SL) are the four major categories of AM technologies for metal materials [4]. The primary distinctions between these technologies are the nature of the heat source and the form of metal used. Depending on the AM technology used, the metal can take the form of powder, wire, foil, or laminate. Powder-based fusion technologies involve spreading layers of powder on a metal building plate and melting this powder with a laser or electron beam heating source. PBF techniques include direct laser metal sintering (DLMS), electron beam melting (EBM), selective laser melting (SLM), and sintering (SLS) [4]. When using a laser beam, the part must be built in an inert atmosphere, whereas when using an electron beam, the part must be built in a vacuum [5]. These processes can produce products with high geometrical accuracy, but the equipment and overall process are very expensive, and the metal powder can be hazardous to people, necessitating additional precautions and control of the working environment [4]. When metal wire is used as feedstock instead of metal powder, not only is the powder protection and recycling system eliminated, but the raw material cost is reduced significantly [4]. These are referred to as wire-based (WB) technologies. The wire-shaped material is fed into the deposition zone and melted by a heat source (laser beam, electron beam, or electric arc). A controlled atmosphere is required when using a laser or electron beam as a heat source, whereas an electric arc is shielded by the gas that covers the melted pool of metal [5]. The technology that uses an electrical arc as a heating source and a wire to feedstock is known as wire-arc additive manufacturing (WAAM). WAAM has many advantages over other AM technologies, such as the ability to produce very large parts, higher deposition rates, less expensive welding equipment, less expensive hardware systems, a wide range of standard wires, efficient material utilization, and energy savings [5,6,7]. However, when compared to other metal additive technologies, WAAM has several disadvantages, including high heat input, which can result in residual stresses, distortion, poor accuracy, and roughness, which necessitates the use of additional finishing manufacturing operations. It also cannot produce very complex parts; the low accuracy makes geometry optimization algorithms ineffective [6].

WAMM is ideal for producing parts made of various metals and alloys, particularly highly reflective metal alloys such as aluminum, copper, magnesium, titanium and nickel alloys, and steel [4, 7, 8]. The WAAM hardware system is very simple; it employs a cartesian or robotic device for positioning the welding torch, welding equipment with a shielding gas source, a wire feeding unit, and power and control units, as illustrated in Figure 1.

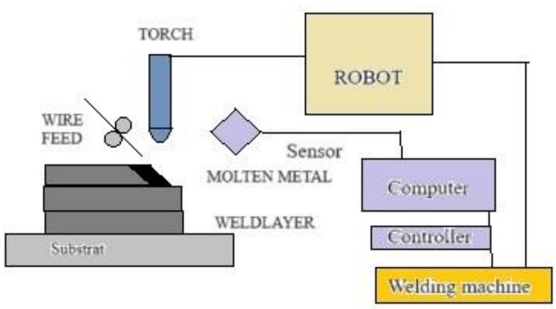

Figure 1. A schematic representation of WAAM system

When using reactive titanium alloys, an additional controlled chamber must be installed to control the production environment [5]. WAAM can be integrated into a hybrid machine that can also operate with other machine operations, making it suitable for in-between tasks [5]. The thermal cycles during the welding process have a significant impact on the microstructure and mechanical properties of

WAAM parts. Each layer is heated and cooled, resulting in multiple fusion, solidification, phase transformation, and highly non-linear dissipation. Another important factor influencing microstructure, defects, geometrical accuracy, and mechanical properties is heat accumulation [7].
The WAAM technology is very popular in research, and some of the findings in many articles suggest that the process can be used in production, owing to the favorable mechanical properties obtained. This review focuses on some aspects of welding processes and equipment, as well as material analysis and control systems. Additionally, potential optimization approaches for increasing product quality are discussed, and some ideas and recommendations for additional process enhancements are outlined.

2. WIRE-ARC ADDITIVE MANUFACTURING

Wire-arc additive manufacturing technology has been studied since the 1990s [3]. It employs standard welding equipment such as a power source, torch, and wire feeding system. Robotic or computer numerically controlled (CNC) systems can be used to control movement patterns [3]. It is critical to provide tools and guidelines for the process planning phase, particularly for the tool path, which must correspond to the shape and dimensions of the part [5]. The high deposition rate with minimal geometry constraints is ideal for the rapid production of large components as well as gradual manufacturing [5, 8]. The WAAM filler material is like the one for welding, therefore there is an available palette of materials that can be used for fabricating parts with this technology. The CNC machine or robot directs the torch along the deposition path, allowing metal layers to accumulate and form the desired shape. Using different arc welding machines and operating units, various hardware systems, each with its own set of characteristics and utility, have been developed [4]. Figure 2 depicts an example of a robotized WAAM setup [2].

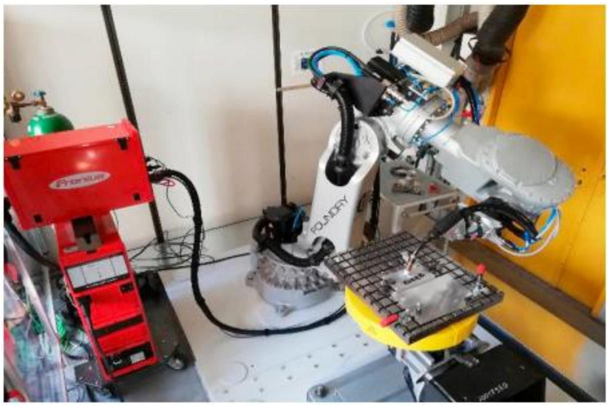

Figure 2. WAAM system with Fronius welding source
Source: Robot-Based Wire Arc Additive Manufacturing System with Context-Sensitive Multivariate Monitoring Framework. Procedia Manufacturing 2020

2.1 Welding processes

There are six types of arc welding-based AM: gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), cold metal transfer (CMT), plasma arc welding (PAW), laser additive manufacturing (LAM) and electron beam welding (EBW) technology [4, 2]. The metal solidified during WAAM has a large column grain microstructure, which is useful for high-creep resistance applications [2].
In GMAW additive manufacturing (GMAW-AM) an electric arc forms between the continuous electrode and workpiece on the substrate surface. A robotic path that the torch follows is created from a CAD model at the beginning of the process [9]. A stable path generation and simple programming procedure are established due to the torch and wire being in a coaxial position with one another [4]. The electrode is a continuous wire that is supplied to the arc via a feeding mechanism. It melts and deposits in a defined pattern with relative movement of the torch and the worktable [10]. Inert gas is

used to shield the weld pool from the atmosphere, preventing any reactions or environmental contamination. The product is taking shape because of the overlapping weld layers creating bonds when they solidify. Shape, size, density, mechanical characteristics, and quality define each layer of welds that are deposited on the substrate. This process's high heat input causes the layers' geometry to become uneven, which negatively impacts the layers' shape and quality of the product [11]. Compared to the other three WAAM technologies, GMAW-AM has higher deposition rates, ranging from 3 to 4 kg/h [4]. However, the rates can be further increased by combining two GMAW processes or by using a pulse GMAW technique. In these situations, more external cooling atmosphere is required due to the higher heat. To increase the material utilization rate, GMAW and GTAW torches can also be combined [4]. There are process modifications with more potential because of the arc's poor stability in GMAW-AM. This applies to the modified GMAW process known as cold metal transfer additive manufacturing (CMT-AM), which depends on a regulated dip transfer mechanism [3]. Its superior arc stability, low heat input that results in less distortion, nearly zero spatters, and high process tolerance make it extremely promising [3]. CMT-AM is a high-resolution system for creating three-dimensional near-net-shaped objects that work with a robot system and simulation software [8]. Modeling software, material feeding via cord, data connection lines, soldering power, and activator operation make up this economical prototyping method [8]. The high-frequency alternation of forward wire and retraction sets apart the various CMT-based WAAM systems, some of which use CNC machines for the 3D path of the tool [8]. The advanced current dynamic creates the liquid droplet at the top of the wire, which is then unbundled at low pressure to produce a solid solder, stable arc, low heat input, and no spatter [8].

High-quality welds are produced by GTAW welding, also known as tungsten inert gas (TIG) welding, which forms an electric arc between the non-consumable tungsten electrode, the workpiece, and the filler metal. Because it is a splatter-free process that produces very little slag, it can be used for welding in all positions without the need for additional cleaning procedures. In GTAW-AM technology, GTAW is utilized as a heat source. The substrate surface is covered in melted metal as the filler wire is inserted into the arc from the torch's side. It is easier to control GTAW-AM because it has a lower heat input than GMAW-AM and because changes in heat input do not alter the arc length or the rate of deposition [11]. Numerous scholars have examined how control factors affect output metrics like deposition breadth and height [2, 11]. Their results indicate that the width and height of the deposition decrease with increasing tilt angle [2]. Anisotropy in terms of elongation at break is evident in tensile tests conducted on additively manufactured parts but yield and ultimate strength show uniformity in both directions [2]. Studies on the use of nanoparticle-enhanced aluminium wire in GTAW-AM have also been conducted; the findings indicate that the printed layers have larger metal grains [2].

While the GTAW and PAW processes are similar, the PAW process concentrates the arc more, improving stability, increasing heat transfer efficiency, and producing fast welding [6]. The majority of industrial metals, such as titanium and its alloys, nickel and its alloys, and stainless steel, can be welded using PAW. It requires less heat and is easier to control the feeding rate than the GTAW and GMAW-AM [2]. Although PAW-AM is more expensive than GMAW and GTAW-AM processes, it produces a final product with fewer defects and more consistent results. The wire fed in GTAW-AM and PAW-AM is not coaxial, which can cause variations when there is a direction change and cause the arc length to vary [6]. To make the process application possible, the robot system's rotary axis must be used to orient wire feeding and maintain it in the same direction as the welding [6]. Additionally, electron beam welding (EBW) and laser additive manufacturing (LAM) can be used to fabricate large individual components with reduced internal stress. These are additive manufacturing techniques based on high-energy-density (HED) welding [2]. Custom-built devices that use the EBW and LW processes with a separate wired procedure make up the majority of research employing these technologies [2]. Additional wire feeds and working chambers are included in the apparatus. A key component of Industry 4.0 is additive manufacturing based on laser beam welding, which makes extensive use of sensors for process control [2]. The most common issue that researchers are attempting to solve is geometry inaccuracy. Numerous factors have been taken into account, such as trace height and width, breadth, depth, geometrical responses, and dilution. The findings of these studies indicate that there is an influence on the width but no relationship between the laser power and the trace height [2]. There are benefits and drawbacks to employing these methods. These methods have the advantage of having a narrow heat-affected zone, low heat input, high solidification rates, reduced distortion, deep penetration, excellent energy transfer efficiency, and lower consumable costs. The primary drawbacks are increased initial investment costs and the challenge of enhancing the fusion zone properties using filler metal. The use of additive manufacturing technologies based on fusion welding is restricted due to the production of extremely columnar grains with anisotropic characteristics [2]. Friction stir additive manufacturing (FSAM), ultrasonic additive manufacturing (UAM), and additive friction stir deposition (AFSD) are examples of solid-state welding-based additive manufacturing techniques that offer a metal a deformation processing path. Material addition and bonding are achieved through extreme temperatures and severe plastic deformation. One of the most innovative solid-state additive manufacturing (AM) technologies, FSAM is based on the FSW principle and has the potential to overcome limitations, especially in the case of light alloy additive manufacturing [2].

2.2 WAAM monitoring systems

WAAM technology has numerous potential applications in a variety of industries due to the many benefits it offers. This has led to a significant increase in interest in topics for the future development of WAAM in academic research and industry over the last decade. There are some challenges to fully implementing the technology, which can be attributed to a lack of process monitoring and closed-loop control over the entire process [10]. As a result, implementing process monitoring and feedback control is one of the most significant advancements that can be made [10]. Because the main challenges remain manufacturing precision, quality assurance, and automation level, various solutions for improving quality with the improvement of monitoring systems are proposed. Vision, spectral, acoustic, and thermal sensing are all used, and they all have different roles in the monitoring process. Visual sensors are used for surface monitoring, while spectral and acoustic sensors are used for internal changes in the metal [10].

A great deal of research has been done on feedback control systems in the last few years. Newly developed devices use feedback signal systems to measure the distance between the nozzle and the top of the surface to control the height of the layers. Additionally, neural self-learning PSD controllers for bead width measurement and adaptive controllers that maintain this distance constant through wire-speed adjustments are available [10]. If the wire feed is constant, the robotic movements in WAAM processes should decelerate at sharp corners, which leads to over-fill. The adaptive control system, which adjusts the wire feed based on the dynamic constraints of various sections, can be used to accomplish this. The bead can be observed using a thermal camera and laser scanner, and a closed-loop control can be put in place [4,10]. Most of the research on WAAM controlling systems indicates that this process is still in the early stages of development and that control systems and additional study are necessary to bring it closer to commercialization.

3. CONCLUSION

The manufacturing sector has changed as a result of additive manufacturing's (AM) use of layer-by-layer deposition to produce structures with nearly net shape and little material waste. However, by combining additive manufacturing (AM) with different welding techniques, it is possible to overcome the dimensional constraints of the parts produced through AM. This article aims to give a summary of the current state of welding-based additive manufacturing (AM) and the underlying principles of the WAAM technology. There is a great deal of research on arc-welding-based AM techniques in comparison to other techniques, like the beam welding AM technique, and a broad range of concepts used in AM with arc-welding filler metals. With fusion welding-based AM, only simple structures can be produced. The production of high-quality metal parts can be facilitated by the hybridization of beam welding-based AM with arc to enhance process capabilities. This concept has many promising prospects, so it is expected that more research will be done in the future for the application of different welding techniques and materials in the additive manufacturing process. Research opportunities for the advancement of the WAAM process include the development of new materials, fabrication in different patterns, management of grain structure, and phase transformations for a wide range of alloys. Numerous benefits stems from the FSAM process, including efficient structural design, favorable microstructures and mechanical qualities, and environmentally friendly procedures. Further research on FSW-based AM is required to create innovative techniques that get around the drawbacks of fusion welding. Additional findings from this review include the following: GMAW-AM has a higher rate of deposition than the other basic welding technologies; CMT welding is a GMAW modification suitable for large stainless steel products; GTAW and PAW techniques are suitable for small to medium parts with medium to high mechanical properties; LBW-AM requires less energy and provides effective control over the weld pool and surface quality; FSW-AM has the potential to consume a small amount of material with low emissions, waste, and energy. This article's informational goal also includes providing details on the state of development and monitoring and control systems at this moment. The monitoring systems are designed to record process signals on the possible occurrence of a defect, while the control system controls the bead geometry and heat input. The monitoring and control system's goal is to improve process stability, accuracy, quality, and application of online defect diagnosis.

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