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A review on aluminum alloys produced by wire arc additive manufacturing (WAAM): Applications, benefits, challenges and future trends

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A R T I C L E I N F O

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A B S T R A C T

Metal additive manufacturing is advancing with increasing momentum and attracting great attention. The Wire Arc Additive Manufacturing (WAAM) process, one of the metal additive manufacturing methods, involves melting a filler wire with an electric arc and depositing metal droplets layer by layer along the planned path. Aluminum alloys produced by the WAAM process have been in high demand in the industry, especially in the last decade. The WAAM process stands out as a suitable method for many industries due to its low investment cost, high deposition rates and the advantages of creating relatively complex parts. Key application areas of aluminum alloys produced using WAAM include aerospace, automotive, marine, and energy sectors, where lightweight structures, corrosion resistance, and high strength are critical. Much research has been done and innovative applications, including hybrid systems, have been developed to prevent defects such as residual stresses, cracks, porosity and delamination. This review article provides a comprehensive overview of the use of the WAAM process in aluminum alloys over the past decade. In the article, firstly, aluminum alloys, the WAAM technique and its types are introduced. In the following section, the methods used to improve mechanical properties and optimize the microstructure are examined in detail. In the next section, the difficulties encountered when using aluminum alloys in WAAM applications are discussed in detail. In the discussion section, current developments are evaluated, and in the last section, suggestions for future studies and inferences obtained from this study are presented. As a result, WAAM-CMT and hybrid systems were found to be effective in reducing defects such as porosity, distortion and residual stress. In addition, post-processing heat treatments and surface treatment methods are also crucial for improving mechanical properties. Finally, more research is needed in the areas of 7xxx series alloys, repair applications and environmental sustainability.

1. Introduction

Additive manufacturing (AM) processes introduced the manufacturing industry in the late 20th century and have become increasingly popular. AM was first applied to non-metallic materials, and it was later adapted to the production of complex and networked metal components in successive layers [1]. The American Society for Testing and Materials (ASTM) has divided AM processes into seven main categories as shown in Fig. 1. AM enables geometrically complex parts to be produced layer by layer based on three-dimensional data created by scanning physical objects or using design software [2]. AM holds great potential in producing complex geometries close to clear shapes, having emerged as an alternative for the manufacturing industry. The AM technique is not based on removing material from a block as in the traditional machining processes. Rather, it aims to produce components directly by adding materials [3]. Compared with traditional manufacturing methods, AM has unique advantages such as lower cost, higher efficiency, and reduced time to market of different shaped

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geometries [4–6].

In recent years, there has been increased interest in customizable fabrication of metal components in AM processes. In particular, to meet the demands of different industrial sectors, various AM processes have been developed in material deposition. For this reason, AM processes for the production of metal components are classified as wire-fed, powder-bed and powder-fed [8,9]. In powder-based AM techniques, laser and electron beams are generally used as heat sources [10]. Even though the powder-based AM process has higher resolution and better-forming accuracy, it does not have the ability of certain materials to directly produce functional parts with high structural integrity that can be used in operational systems. Moreover, although it yields near-full-density parts, achieving complete density often requires costly post-processing steps such as hot isostatic pressing (HIP) [1]. Among metal AM methods, wire + arc additive manufacturing (WAAM) is based on melting the filler wire using arc as the heat source and depositing it layer by layer along the planned path [11]. WAAM works by combining arc welding, wire feeding and robotic motion systems. With its high deposition rate, WAAM is classified as directed energy deposition (DED) according to ISO/ASTM 52900 [12]. It has attracted remarkable attention in the manufacturing industry due to its high deposition rate, production of large and closest-to-net-shape metallic parts, and low production cost [12–14]. Due to these advantages, WAAM is a critical technology applied in the aviation, automobile, military and defense industries [15]. When powder-based AM and WAAM processes are compared, WAAM stands out with higher deposition rates, equipment flexibility, and lower production costs [10,16]. WAAM is applied to many structural alloy systems such as titanium, steel, nickel, and aluminum alloys. Among these, aluminum alloys are particularly important due to their low density, high specific strength, good thermal and electrical conductivity, and excellent corrosion resistance [17–19]. Because of their lightweight nature, aluminum alloys are also widely used in the nuclear, automobile, shipbuilding, high-speed rail, and aviation sectors [20,21]. The traditional method used in the production of aluminum alloy components is based on extraction processes from a solid alloy block. However, this procedure is expensive, takes a long time to produce and wastes a lot of materials [22]. Therefore, there has been a trend toward metal additive manufacturing, which is an economical method, especially to produce prototype metal components. The WAAM process has attracted the attention of the manufacturing industry due to its ability to produce large, customized parts at lower cost and higher deposition rates than other AM methods [23,24].

This review aims to fill the existing gap by deeply examining the literature on the production of aluminum alloys by WAAM, which has gained much popularity in recent years. Although the WAAM offers various advantages i.e., high deposition rates and cost-effective large-scale production, it still poses certain challenges such as porosity, microstructural instabilities, and mechanical property fluctuations remaining unresolved and requiring further studies. This review study aims to collect the current knowledge on WAAM applications in aluminum alloys, identify gaps in this field and provide guidance for future research. For this aim, the authors of this review paper studied papers in the literature using the "Google Scholar" database to obtain the latest developments in the use of the WAAM process to produce aluminum alloys. The "WAAM", "Aluminum alloy" and "Additive manufacturing" were used as keywords in the research. Given that substantial advancements have been made in WAAM over the past decade, this review focuses on studies published within the last ten years. Fig. 2 presents the distribution of resources used in the study by years, while Fig. 3 illustrates the types of resources utilized. Finally, Fig. 4 outlines the structure of the current paper, summarizing the main sections and their contents.

2. Aluminum alloys

Aluminum alloys are widely used in aviation, automobile and marine applications thanks to their lightness, low cost, high specific strength, good formability and excellent corrosion resistance [25–27]. Fig. 5 shows the distribution of aluminum used in the world by sector. Aluminum alloys are divided into two according to their composition, process properties and microstructure. The first is cast aluminum alloys, the alloying element content is in the range of 10%–12%. The second is wrought aluminum alloys, the alloying element content is in the range of 1%–2%, but sometimes it can reach up to 6%–8% [28].

Aluminum alloys play a crucial role in WAAM applications due to their lightweight, corrosion resistance, and high specific strength. Nonetheless, the deposition process can lead to problems like porosity, residual stresses and hot cracking phenomena affecting in turn WAAM implementations for these alloys. The present section gives a summary of the aluminum alloy series and their applicability to WAAM, process challenges along with solution discussed in literature.

2.1. 1xxx alloy

The 1xxx alloy is 99% pure commercial aluminum. Although 1xxx aluminum alloys have excellent ductility and high corrosion resistance, their mechanical strength is low and cannot be heat treated. Due to their good forming properties, 1xxx alloys are used in foils and strips for packaging purposes, tank and pipe manufacturing, chemical equipment, bent hollow products and various sheet metal works [30]. Most work on 1xxx, which is from the aluminum series, has focused on aluminum alloy (AA) 1100 (99%+ Al) [31]. AA1100 is preferred to produce fuel tanks, cowls and oil tanks of aircraft due to its corrosion resistance and economic weight, in cases where the strength factor is not important. In addition, the AA1100 is resistant to chemical attack and weathering. In addition, AA1100 is a material with low cost, good solderability and deep drawing sensitivity [30]. The best results in this alloy are obtained when it is in a hard temper [32]. Their use in WAAM is limited to applications where strength is not critical, such as chemical equipment and packaging foils. However, the limited heat-treatability of 1xxx alloys restricts their use in structural WAAM applications.

2.2. 2xxx alloy

The 2xxx (Cu–Al, Cu–Al–Mg) series aluminum alloys, which have high strength, lightness, corrosion resistance and low density, are widely preferred in the aviation, automotive, space, high-speed railway vehicles and ship industries [33–35]. Heat treatment, rolling and interlayer cold working can be applied to 2xxx aluminum alloys, thus improving their mechanical properties [36,37]. The production of high-strength aluminum alloy structures using the WAAM technique attracts the attention of researchers [3]. 2219 aluminum alloy meets the features of lightness and high performance, as well as low cost and efficiency, in the aviation industry. 2219 aluminum alloy is very suitable for WAAM due

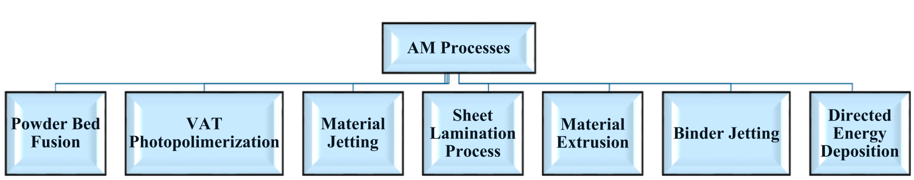

Fig. 1. Classification of additive manufacturing processes according to ASTM standard [7].

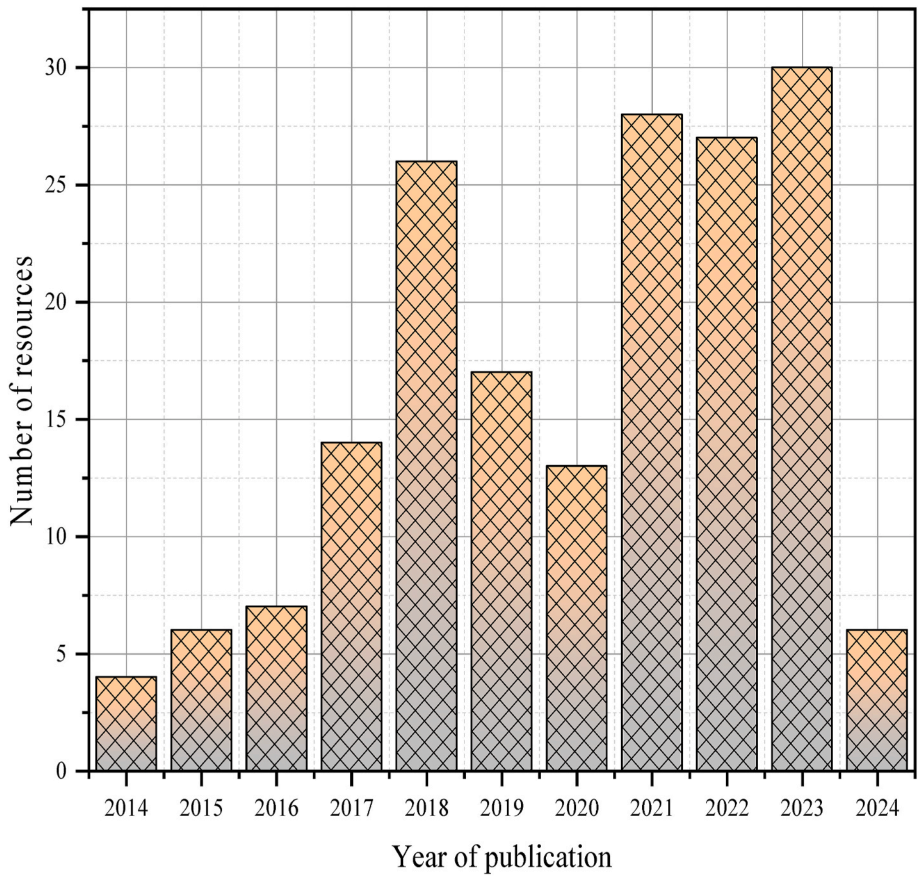

Fig. 2. Distribution of examined resources by years

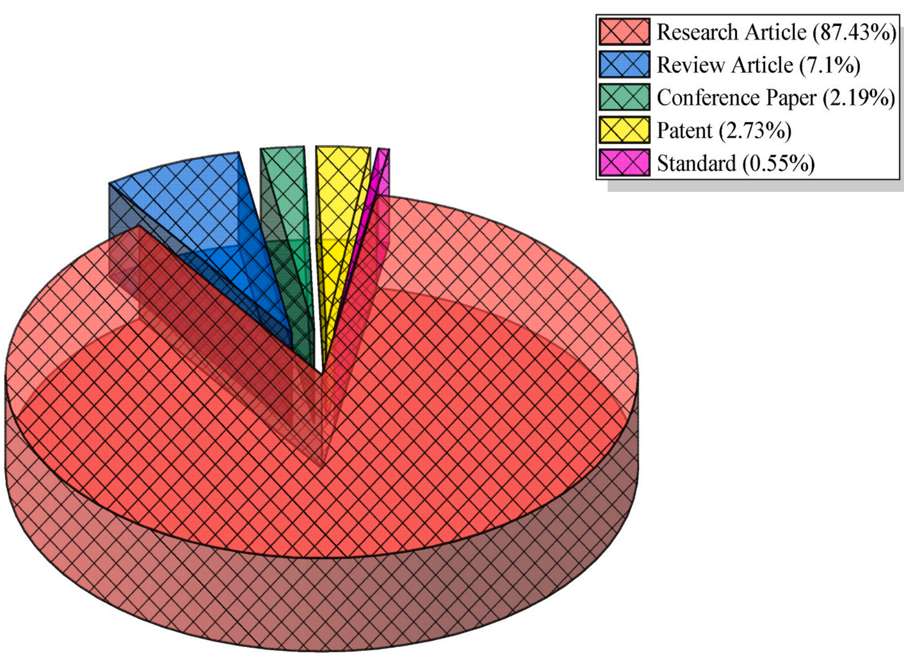

Fig. 3. Distribution of document types utilized in the study

to its very good weldability [38]. Since 2219 aluminum alloy is precipitation hardened Al–Cu, heat treatment is generally used as a strengthening method. To increase strength, solution treatment + artificial aging (T6) methods are commonly applied [39].

2024 aluminum alloy, one of the 2xxx series high-strength aluminum alloys, is an Al–Cu–Mg aluminum alloy widely used in air screws in spacecraft. 2024 aluminum alloy hardens as it ages. Heat treatment is applied to improve the mechanical properties of this alloy. In order to reach the highest strength during the traditional production of forged 2024 parts, the solution process + stretching + aging process should be

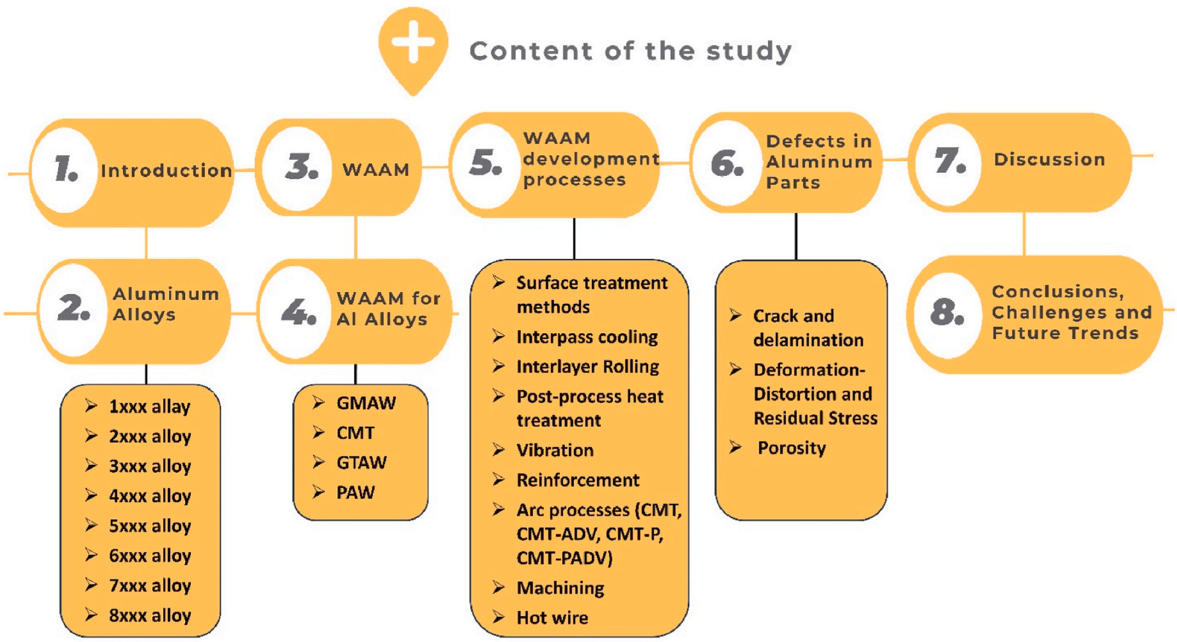

Fig. 4. The framework of the current paper

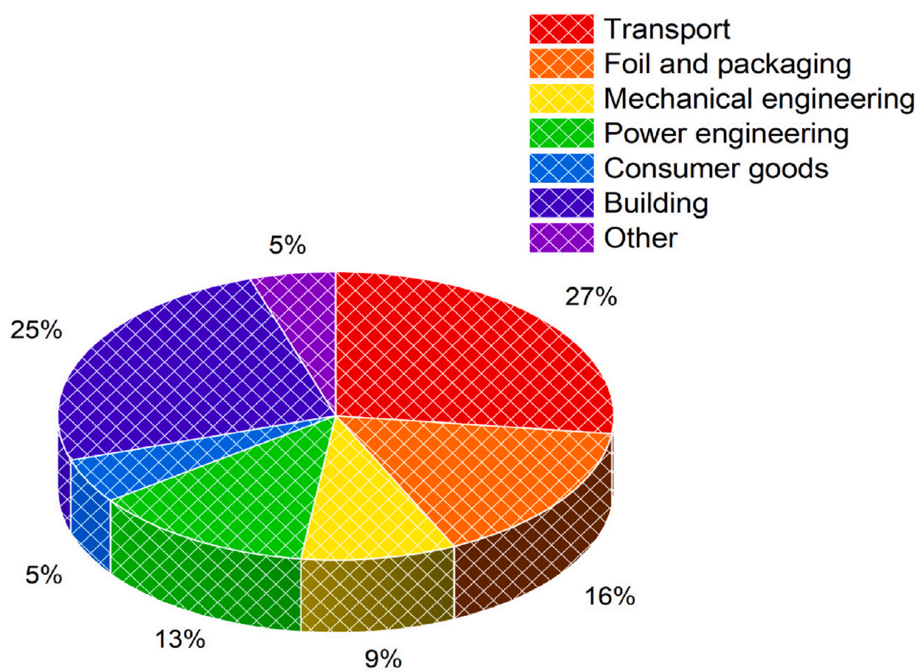

Fig. 5. Chart of world aluminum consumption by sectors [29].

carried out systematically [40]. Since there is no aluminum wire containing the elemental composition of Al–Cu–Mg aluminum alloy, it cannot be produced directly by the arc additive manufacturing process using a single wire [3]. There are some studies in the literature on the use of Al–Cu–Mg aluminum alloy in WAAM. For instance, Qi et al. [34] developed a double wire + arc additive manufacturing system. They produced Al–Cu–Mg components with different compositions by using ER2319 and ER5087 wires and adjusting the wire feeding speeds. Fan et al. [41] manufactured a new high-strength Al–Cu–Mg alloy using ER2319 and ER5183 wires using the cold metal transfer process. Gu et al. [42] obtained Al–Cu–Mg alloy using tandem double wire and pulsed GMAW arc.

2.3. 3xxx alloy

3xxx series aluminum alloy offers certain advantages thanks to the Al–Mn component it contains. These alloys provide higher strength compared to pure aluminum and are distinguished by properties such as resistance to high temperatures, formability and good corrosion resistance. Due to these properties, it is widely used in tubes, fins, packaging containers, cookware and the automobile industry [43].

The corrosion resistance of the 3xxx series aluminum alloy is affected from presence of cathodic intermetallic particles (e.g., $Al_6(Mn,Fe)$ or $Al_{12}(Mn,Fe)_3Si$) [44].

On the other hand, there is no study in the literature yet on the use of

3xxx series aluminum alloys in WAAM applications. In the literature, there is no study related with 3xxx series aluminum alloys in WAAM applications and therefore research into the potential applicability of 3xxx series aluminum alloys to this range may be important.

2.4. 4xxx alloy

4xxx series (Al–Si) aluminum alloys are widely used in the automotive, marine, military and aerospace industries because they have properties such as excellent casting properties, weldability, light weight, thermal conductivity and corrosion resistance [45–48]. The tribological properties of Al–Si alloys are affected by the shape and distribution of silicon particles. These alloys are frequently preferred in engineering applications, internal combustion engine pistons and plain bearings due to their superior tribological properties [49–51].

In recent years, the good thermal conductivity and corrosion resistance of Al–Si alloys, their low tendency to produce cracks and their good weldability have increased interest in the production of these alloys by the AM process [26,52]. There are many studies on the use of Al–Si alloys with WAAM. Haselhuhn et al. [53] used a GMAW (Gas Metal Arc Welding) based 3D printer to produce 1100, 4043, 4943, 4047 and 5356 aluminum parts and evaluated the mechanical properties of these alloys using tensile and compression tests along with microstructural analysis. In their studies, they stated that 4000 series alloys performed better than other alloys in terms of strength and porosity.

Langelandsvik et al. [54] compared the microstructural and mechanical properties of eutectic Al–Si alloys produced by WAAM and two different casting methods (steel mold casting and sand mold casting). They emphasized that WAAM material exhibits superior mechanical properties compared to casting methods, but WAAM is a slower method than casting methods. For this reason, they stated that WAAM can be preferred in cases where high mechanical properties are required, or casting mold designs are very complex.

2.5. 5xxx alloy

5xxx series aluminum alloys (Al–Mg) are widely used in marine, automotive, aerospace and other industrial sectors due to their properties such as high corrosion resistance, good toughness, relatively high strength and excellent weldability [55]. These alloys have high cold workability and can be easily welded when the Mg content is more than 3%. They are often used as rolled products and are common in the production of rods, pipes and wires. They also have an important place in the construction field as they are suitable for processes such as drop forgings and open-die forgings [56].

The production of Al–Mg alloys by additive manufacturing is attracting more and more attention thanks to its design freedom, material cost and time saving advantages. Research on the use of 5xxx series alloys, especially 5083, 5183, 5087 and 5356 alloys, in WAAM processes focuses on the tensile properties of the materials, microstructural defects and anisotropic mechanical behaviors resulting from the process [55].

Since Al–Mg alloys cannot be subjected to heat treatment, it cannot be applied to improve mechanical properties after deposition. This requires that the mechanical properties of Al–Mg alloys produced by the WAAM process directly depend on the process parameters.

2.6. 6xxx alloy

6xxx series (Al–Mg–Si) aluminum alloys are widely used in industrial applications with their medium to high strength, good formability and toughness, heat treatability, and better weldability than high-strength alloys [57,58]. These alloys are frequently preferred in extruded profiles and rolled sheets in the automotive industry.

The majority of products manufactured from the 6xxx series are initially subjected to hot forming (e.g., extrusion or rolling) and often the final product is cold formed. In the literature, it is seen that the most used aluminum alloy from the 6xxx series is 6061. AA6061 is widely used in marine, aviation and automotive applications thanks to its advantages such as high corrosion resistance, good strength and low cost [59].

AA6061 is seen as a good option for high deposition rate processes such as WAAM for structural applications [60]. However, in addition to the strength advantages provided by this alloy, hot cracking stands out as a disadvantage. In order for 6xxx alloys to be used in WAAM, the hot cracking tendency must be overcome. One of the measures taken to prevent hot cracking is grain thinning [61].

2.7. 7xxx alloy

Aluminum alloys of the 7xxx series (Al–Zn–Mg) are commonly utilized in the aerospace industry for both the fuselage as well as for the stressed elements due to their unique property calls involving high specific strength and hardness, high toughness, high specific strength, and good machining and welding characteristics. The mechanical properties of them can be enhanced through heat treatment, and after this operation, the yield strength can be over 500 MPa. It offers some of the highest strength-to-weight ratios of all other aluminum alloys [62,63]. However, 7xxx series alloys are susceptible to hot cracking due to process parameters such as large thermal stresses and solidification shrinkage [64]. With the challenges involved in casting large-scale Al–Zn–Mg–Cu aluminum alloy, researchers are looking into the feasibility of this alloy in WAAM applications [11].

2.8. 8xxx alloy

8011 aluminum alloy is one of 8xxx aluminum alloys and contains Fe–Si as the dominant alloying element and is mostly employed as an aluminum foil alloy. Since this alloy has deep drawing performance and low earing rate properties, it is preferred in leak-proof packaging of cosmetics and beverage bottles [65].

8030 (Al-0.3~0.8% Fe-0.15~0.3% Cu), a newly developed aluminum alloy, has good resistance to yield strength and high thermal stability. This alloy is used in electrical applications thanks to its high electrical conductivity [66,67].

Table 1 gives the chemical compositions (weight%) of some aluminum alloys commonly used in WAAM. In Table 2, the properties and usage areas of aluminum alloy series are listed.

3. Wire arc additive manufacturing (WAAM)

The origin of the WAAM process begins with Ralph [75] applying for a patent in 1925 with the idea of creating superimposed metal deposits using metal wire as raw material and electric arc as a heat source in order to produce metal ornaments. In the same year, Eschholz [76] determined various parameters for single-layer metal deposition in order to obtain different types of decorations. In 1930, Shockey [77] filed a new patent application to recover the worn brake drum by depositing molten metal on top of the original brake drum. In 1971, Ujiie [78] patented the technique of producing a circular cross-section pressure vessel by depositing weld metal. For aluminum and other lightweight alloys, this approach has created new opportunities for producing structural components that offer high strength-to-weight ratios.

In 1983, Kussmaul [79] used shape welding in the manufacture of high-quality structural steel components, producing products with a deposition rate of 80 kg/h and a total weight of 79 tons. In 1993, Prinz and Weiss [80] changed CNC technology and patented the layer-by-layer metal deposition method by combining welding and milling (shape deposition manufacturing). This development has increased the applicability of WAAM, especially in the production of high strength Al–Zn–Mg–Cu alloys. Between 1994 and 1999 Cranfield

Table 1
Chemical composition of some aluminum alloys and welding wires used in WAAM.

Type	Si	Fe	Cu	Mn	Mg	Zn	V	Ti	Zr	Cr	Ni	Be	Al	Ref
2219	0.20	0.30	5.8–6.8	0.20–0.40	0.20	0.01	0.05–0.15	0.10–0.20	0.05–0.15				Bal	[68]
2024	0.5	0.5	4.4	0.6	1.5			0.20					Bal	[3]
4043	5	0.8	0.3	0.05	0.05	0.1		0.2	0	0			Bal	[69]
4047	11–13	≤0.6	≤0.3	≤0.15	≤0.1	≤0.2		≤0.15					Bal	[70]
5083	0.076	0.13	0.032	0.63	4.34	0.035		0.055		0.064	0.003		94.6	[71]
5087	0.06	0.11	0.005	0.75	4.8	0.05		0.02	0.13	0.08		0.0003	Bal	[72]
5183	0.4	0.4	0.1	0.5–1	4.3–5.2	0.25		0.15		0.05–0.25		0.0003	Bal	[25]
5356	0.25	0.4	0.1	0.05–0.2	5.0	0.1							Bal	[73]
6061	0.4–0.8	0.7	0.15–0.4	0.15	0.8–1.2	0.25		0.15		0.04–0.35			Bal	[74]
7075			1.47		2.10	5.72		0.02					Bal	[14]

Table 2
The properties and usage areas of aluminum alloy series.

Al series	Main alloying elements	Heat treatment condition	Weldability	Main properties	Fields of use
1xxx	Pure Al (≥99.00%)	Non-heat treatable	Mostly weldable by friction welding and fusion welding	Low strength, good ductility, conductivity and corrosion resistance	Aluminum foil, electrical and chemical industries
2xxx	Al–Cu/Al–Cu–Mg	Heat treatable	Mostly weldable in friction welding	High strength and fracture resistance, light weight, low density and corrosion resistance	Aircraft components, fittings, space shuttle, cryogenic tanks
3xxx	Al–Mn	Non-heat treatable	Mostly weldable by friction welding and fusion welding	Low strength, resistance to high temperatures, good plasticity, excellent corrosion resistance	Packaging containers, sheets, tubes
4xxx	Al–Si	Non-heat treatable	Mostly weldable by friction welding and fusion welding	Medium mechanical strength, high wear resistance and corrosion resistance, low melting point, light weight	Filler materials for welding and brazing, automotive industry, architectural products
5xxx	Al–Mg	Non-heat treatable	Mostly weldable by friction welding and fusion welding	Relatively high strength, high corrosion resistance, good toughness	Aluminum sheets for automotive, construction, marine, aerospace industries
6xxx	Al–Mg–Si	Heat treatable	Mostly weldable by friction welding and fusion welding	Medium to high strength, good toughness and formability, high ductility, excellent corrosion resistance	Automotive industry products, rolled sheets, extruded parts, decorative products
7xxx	Al–Zn–Mg/ Al–Zn–Mg–Cu	Heat treatable	Mostly weldable by friction welding and fusion welding	Very high strength, poor corrosion resistance, high toughness	Aerospace industry components, molding
8xxx	Other elements	Sometimes heat treatable, sometimes not heat treatable	can be welded by friction welding and fusion welding	Good fatigue resistance, good toughness properties	Electrical cables, products requiring high temperatures, bearing and connecting rod
9xxx	Spare alloys	–	–	–	–

University developed shaped metal deposition (SMD) technology to produce engine hulls for Rolls Royce [81].

Cranfield University has initiated a research project called Rapid Production of Large Aerospace Components (RAPOLAC) to develop WAAM based on cold wire fed gas tungsten arc welding and rapidly produce large aerospace components [82]. Until the project was approved, WAAM technology attracted great attention due to its forming efficiency and cost advantages.

Although studies on WAAM technology have increased recently, it actually dates back almost 100 years. WAAM was previously known by different names such as shape welding (SW), shape melting (SM), rapid prototyping (RP), shape metal deposition (SMD), solid free-form manufacturing (SFF) and 3D welding [83].

Processing of aluminum alloys with WAAM technology stands out as a potential solution especially in the aerospace and automotive sectors [11]. Traditional casting and machining methods present various difficulties in the production of high-performance materials such as Al–Cu–Mg and Al–Zn–Mg–Cu alloys. For example, low performance in casting and high buy-to-fly ratio makes large-scale production of these materials difficult. Therefore, the production of Al alloys with WAAM attracts attention in the industry by offering advantages such as energy saving, reduced material waste and the ability to produce more complex geometries.

Implementation of the WAAM process consists of three main stages. These are: i) Product design and software systems: At this stage, the design of the products to be created is made by software systems. A 3D model of the product is created using CAD (Computer-Aided Design) software and the necessary production planning is made. ii) Metal deposition with WAAM systems: In WAAM, aluminum alloys such as Al–Cu and Al–Zn are commonly used, and the electric arc melts and deposits these alloys layer by layer. In this process, metal wire or powder is used as raw material and melted with a heat source such as an electric arc to create the desired shape. iii) Post-treatment: In aluminum alloys, heat treatment and surface treatments are needed to ensure microstructural stability and optimize mechanical properties. Figs. 6 and 7 show the schematic view of the WAAM process and its flow, respectively. Especially in Al alloys, the creation of paths that direct the movement of the accumulation head plays a critical role in increasing mechanical strength.

One of the most important processes in WAAM is the creation of paths that direct the movement of the deposition head to fill 2D layers that represent the cross-sectional geometry of a component. In AM path planning, when a 3D model is sliced, a stack of 2D closed contours is created. There may be one or more closed contours or polygons for each slice. Commonly used tool path patterns are [82]: i) Raster tool path: Raster tool path, which has a simple structure, fills the layers with linear transitions. It is advantageous in terms of applicability and calculation speed. ii) Zigzag tool path: Layers are filled in zigzag movements, resulting in a more homogeneous material distribution. iii) Spiral tool path: It is a pattern frequently used in CNC machines and fills the layers

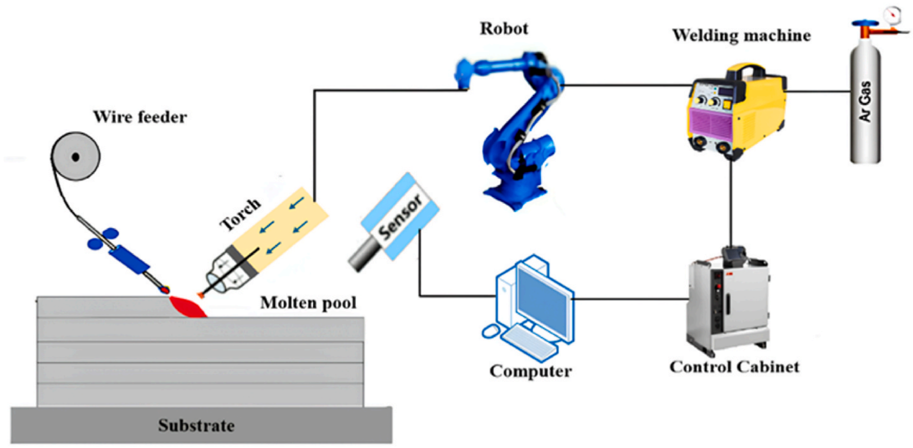

Fig. 6. Schematic view of the WAAM process

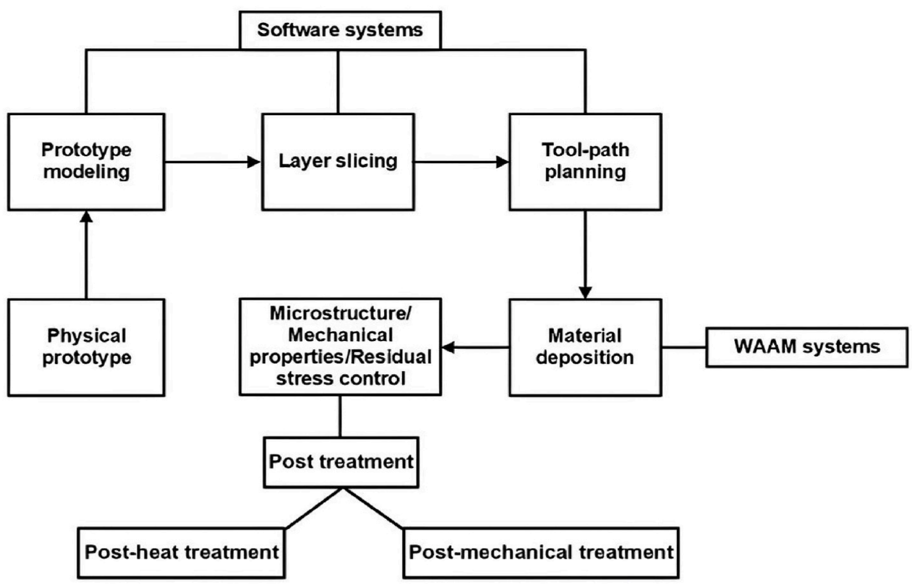

Fig. 7. Workflow diagram of the WAAM process (Reprinted from Ref. [84] with permission from Elsevier)

by following a spiral path. This tool path ensures more controlled material distribution and minimizes internal stresses.

As presented in Fig. 8, many models have been developed to generate tool paths. Each pattern has its own advantages and uses, so choosing the most appropriate toolpath pattern for a particular application can significantly impact production quality and efficiency.

In recent years, the WAAM process has been extensively investigated. Traditional manufacturing processes have disadvantages such as low production flexibility, complex processing process and long production cycles. WAAM overcomes these disadvantages and offers various advantages. First of all, WAAM provides faster delivery by shortening production time and offers an environmentally friendly production process with less energy consumption. Additionally, it increases production efficiency and minimizes material waste and enables the production of complex shapes and reduces production costs. In theory, it enables faster prototyping of any complex shape [86,87].

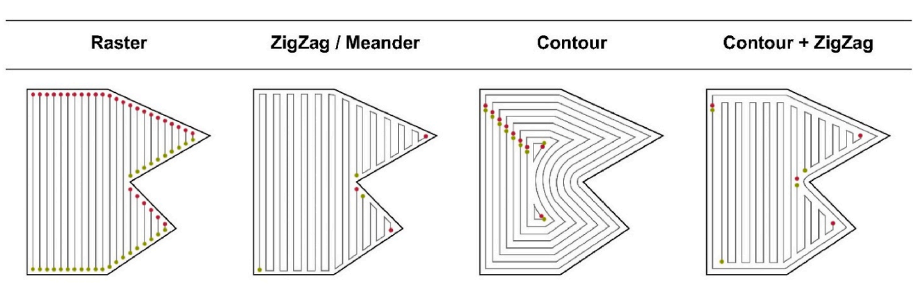

Fig. 8. Commonly used deposition strategies in WAAM [85].

Traditional manufacturing methods of aluminum alloys are generally casting, machining and forging. High-strength Al–Cu–Mg and Al–Cu alloys have been widely used in the military and aerospace industry for years and are produced by traditional methods [41]. Similarly, ultra-high strength Al–Zn–Mg–Cu aluminum alloys are also widely used in the aerospace industry. However, large-scale production of Al–Zn–Mg–Cu and Al–Cu–Mg aluminum alloys by traditional methods such as casting faces many difficulties such as low casting performance and high buy-to-fly ratio. Therefore, studies on the application of aluminum alloy in WAAM are on the rise. Out of all the methods of dealing with aluminum alloys in the aerospace and other areas, WAAM is seen as one of the most promising methods [11]. Nevertheless, it is necessary to further refine the technological process in order to counteract complications such as microstructure stability and the issue of porosity.

4. WAAM systems for aluminum alloy production

WAAM methods in the production of aluminum alloys offer several advantages in terms of material properties and process efficiency. Aluminum alloys are widely used in the aerospace and automotive sectors due to their low density, high corrosion resistance and excellent mechanical properties. However, there are some difficulties in the production of these alloys with traditional production methods (casting, machining, forging). WAAM holds great potential to overcome these challenges and there are certain methods that are frequently used in the production of aluminum alloys. These are Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW) and Plasma Arc Welding (PAW) based methods. In addition to these methods, the Cold Metal Transfer (CMT) process, which is created by modifying the GMAW process, is also widely used. A comparison of these methods is given in Table 3. As seen in Table 3, the GMAW-based WAAM method has a higher deposition rate compared to others.

4.1. WAAM process based on gas metal arc welding (GMAW)

GMAW is known as a welding and additive manufacturing process that is accomplished by creating an electric arc between a consumable wire electrode and the substrate [89]. The GMAW process is schematically shown in Fig. 9(a). The wire feeding direction is perpendicular to the substrate during deposition. This arrangement provides advantages in terms of high productivity and automation [8]. When GMAW is used, the filler wire is fed axially from the contact tip of the welding torch. When the wire touches the component, a short circuit occurs in the electric arc, which results in temperatures in excess of 10,000 °C. The wire begins to melt, and the molten material tends to corrode. Therefore, it is necessary to prevent reactions with O_2 or other corrosive components by using a gas shield. When the arc is ignited, small volumes of the component and previously deposited drops begin to melt. When the welding torch remains stationary, the size of the drop increases [90]. Wire arc additive manufacturing with GMAW is gaining attention due to its advantages of high deposition rate (more than 90% material efficiency) and high productivity [56]. GMAW also offers a high deposition rate in aluminum alloys and is notable for its suitability for automation. This method has been evaluated as a promising technique in terms of using material and energy effectively in the additive manufacturing of complex and large volume metallic components produced by aluminum alloys. However, the deterioration of surface quality on the side surfaces of the fabricated parts constitutes a significant problem for this method [91].

3D printing with GMAW is similar to single-layer, multi-pass welding, which is called multi-pass welding. In this welding process, the previously welded material is reheated, which leads to changes in the grain structure, reduction of stresses and improvement of mechanical properties [53].

Robotic gas metal arc based additive manufacturing is considered as an effective technology for the production of complex and large-sized metal components. The increase in wire feed speed in a gas metal arc can make the melt pool of thin-walled parts unstable under the influence of arc force, which may negatively affect the forming quality. Li et al. [92] developed a method that proposes to change the inclination angle between the gas metal arc torch and the substrate in order to overcome this problem and increase the stability of the melt pool. The study showed that reducing the inclination angle provides positive results.

4.2. Cold metal transfer (CMT)

In order to improve the heat input and energy density of the GMAW process, Fronius Company has developed a modified MIG welding process known as "Cold Metal Transfer" (CMT) [93]. CMT-based WAAM technology offers a flexible and fast method for the production of products with high geometric complexity. In this method, an electric arc is used as a heat source and molten metal is deposited on the surface of the substrate or pre-deposited layer. CMT provides a stable droplet transfer process that supports wire movement during the arc and short circuit phases [94]. CMT is considered one of the suitable methods for WAAM due to the controlled current waveform used to produce a uniform weld bead [95].

Due to the low melting point of aluminum alloys, the CMT exhibits some advantages such as low heat input, small deformation, high welding speed, high deposition rate and low operating cost. For these reasons, it is quite suitable for producing low melting point metals i.e., aluminum alloys [52]. There are many studies in the literature on the applications of CMT in WAAM and aluminum alloys.

In recent years, in addition to the traditional version of CMT, various droplet transfer modes have been developed, such as CMT pulsed (CMT-P), CMT-advanced (CMT-ADV) and CMT-pulsed advanced (CMT-PADV) [89,96,97]. In 'ADV' mode, the polarity of the source current is reversed in the short circuit phase. In 'PADV' mode, the polarity difference of the pulse cycle (positive polarity) and the CMT cycle (negative polarity) is defined [98]. The changes in energy input result in shorter cooling times for the CMT-ADV and CMT-PADV modes. This results in a reduction of the deposition time by approximately 22% for CMT-ADV and 33% for CMT-PADV compared to the conventional CMT process. In addition to

Table 3
Comparison of WAAM process types [88].

Feature	GTAW-based	GMAW-based			PAW-based
Energy source	GTAW	GMAW	Cold metal transfer (CMT)	Tandem GMAW	Plasma
Typical deposition rate	1–2 kg/h	3–4 kg/h	2–3 kg/h	6–8 kg/h	2–4 kg/h
Electrode	Electrode without consumables and requires a separate wire feeding process	Consumable wire electrode	Reciprocating consumable wire electrode	Two consumable wire electrodes	Electrode without consumables and requires a separate wire feeding process
Main feature	Wire and torch rotation are needed	Poor arc stability, spatter	Low heat input process with zero spatter, high process tolerance	Easy mixing to control composition for intermetallic materials manufacturing	Wire and torch rotation are needed

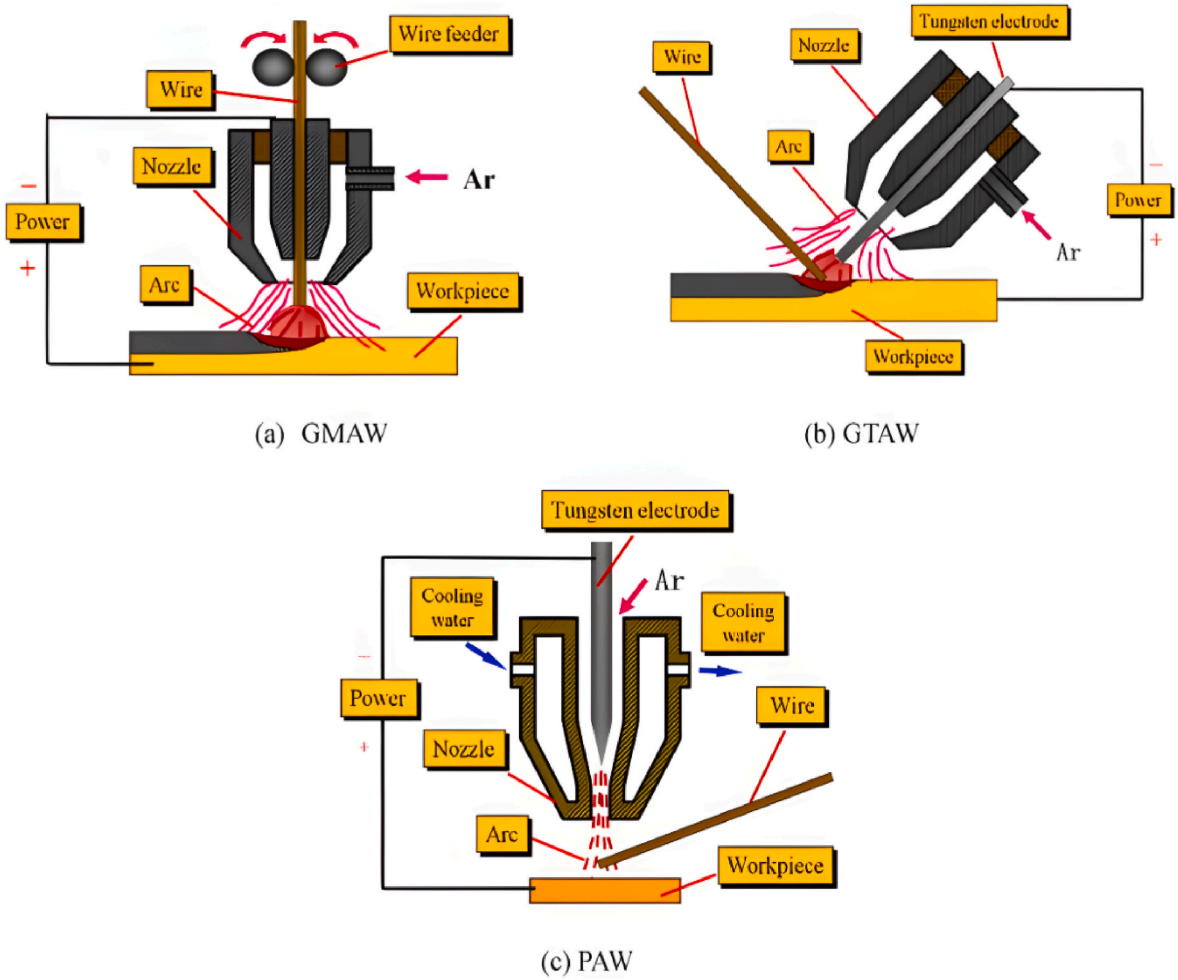

Fig. 9. Schematic representations of WAAM types [103].

the technical and material advantages, this also contributes to economic benefits [56]. The CMT-P process has higher heat input than the CMT-PADV process, thus providing larger bead shapes and greater penetration. Under deposition conditions, the CMT-PADV process is characterized by a smaller bead aspect ratio than CMT-P, and the layer width, remelting depth are smaller, and the layer height is greater [40].

4.3. Gas tungsten arc welding (GTAW)

The traditional welding setup consists of a power source, a shielding inert gas (helium, argon, etc.), a wire feeder (filler material), and a welding torch. Argon is commonly used as a shielding gas; this gas protects the deposited material from adverse effects such as oxidation and corrosion. In the GTAW based WAAM process, a tungsten electrode is used to obtain high quality welds. The schematic representation of the GTAW process is given in Fig. 9(b). This method is preferred over laser and electron beam due to its advantages such as low cost, high deposition rate, no need for a vacuum chamber, and economic application to large work volumes [1]. It also produces less spatter, and a more stable arc compared to GMAW [99].

During the GTAW process, high arc accuracy can be achieved by combining industrial welding robots and multi-sensor control systems to minimize distortion or other placement errors that may occur in industrial processes [1]. Geng et al. [100] developed a mathematical model to calculate the wire flight distance in the arc region, which is also useful in obtaining a smooth layer appearance. GTAW allows energy and material inputs to be managed as separate processes to achieve a uniform layer appearance, especially in aluminum alloys. Heat input must be kept uniform to ensure uniform layer dimensions and appearance. Adjustment of heat input does not affect arc length, and deposition rate can be controlled independently by adjusting the wire feed speed [100]. The alternating current TIG (AC-TIG) process offers many advantages in welding aluminum alloys. In particular, the ability to adjust the electrode positive (%EP) and negative (%EN) time cycle ratios makes this method useful for the purpose of oxidation removal and fusion effect enhancement. Ayarkwa et al. [15] studied the effect of TIG alternating current cycling on aluminum WAAM and reported that increasing %EP increased the pore size and number, but did not have a significant effect on the mechanical properties.

4.4. Plasma Arc Welding (PAW)

GTAW and PAW techniques work on the same underlying principles. Both employ a non-consumable tungsten electrode to strike an electric arc with the base metal along with the inert gas and without using any filler. Due to the consistency of the electric arc, there is a high level of accuracy and a near-perfect welding outcome in the case of GTAW. However, additional filler material is required for WAAM applications.

PAW is a method in which the electric arc is forced through a hole placed between the cathode and anode, thus providing high energy density and increased arc stability [83]. The PAW torch uses a tungsten electrode, but a specially designed torch cap compresses the plasma arc, increasing energy concentration and penetration depth [101]. In contrast to GMAW, heat input of PAW is more focused leading to smaller welds and lower heat input at higher travel speeds. Nevertheless, GMAW welding also has its drawbacks including complex set-up and large amounts of consumable gases [102]. The setup of PAW is displayed in Fig. 9(c).

5. Initiatives towards improving WAAM processes

5.1. Surface treatment methods

Recently, hybrid manufacturing techniques have been used to reduce plastic deformation between layers of parts obtained by additive manufacturing and to improve performance. The most common surface treatment methods include shot peening, ultrasonic impact, peening and Laser Shock Peening (LSP) [104].

LSP is a complex surface strengthening method that uses high-energy pulsed laser to generate plasma explosion on the surface of materials. Currently, research on LSP mainly focuses on SLM (Selective Laser Melting), which has been shown to improve mechanical properties and microstructure and eliminate internal defects [105–107]. These findings have also provided a promising basis for the application of LSP to the WAAM process.

Jing et al. [104] applied LSP surface treatment as a final process to 2319 aluminum alloy produced by the WAAM method. Experimental results showed that LSP improved material hardness, tensile strength and fatigue properties and eliminated internal porosity. Jing et al. [108] also applied interlayer LSP to 2319 aluminum alloy for the first time. Each layer was arranged using spiral oscillation mode and then the LSP process was applied to the top surface. It was stated that porosity was reduced, and material strength and ductility were increased as a result of the hybrid production method. Table 4 provides a summary of the studies using the WAAM process and LSP method together.

Ultrasonic Peening Treatment (UPT) was first invented by Mukhanov and Golubev in the 1950s. This method produces plastic deformation on the surface of the material by applying continuous ultrasonic pulses to the surface of the machined part. Krylov and Polischuk proposed a spherical shot between the ultrasonic transducer and the surface in 1960, which would provide high plastic deformation, but the free movement of the shot had negative effects [110]. UPT aims to improve grain size and compressive stress by producing plastic deformation on the metal surface using impact energy [111,112]. It can also reduce residual stress in welded joints and weld zones [113]. Researchers have stated that this method is promising for the cold working of metallic materials in many industries such as ship, aviation, vehicle, railway and bridge [110–112].

Tian et al. [111] applied the UPT process to welded joints in their studies where they joined 6061 aluminum alloy with ER4043 filler material using the CMT-WAAM method. The results showed that porosity decreased, and wear resistance increased after UPT. Wang et al. [112] stated that UTS and YS values increased but EL values decreased in their studies where they joined 2219 aluminum alloy and ER2319 welding wire using the CMT-WAAM method. They also observed that dislocation density and Kernel Average Misorientation (KAM) values increased after UPT.

Shot peening is a common surface modification process that aims to improve fatigue crack resistance by creating high-pressure residual stresses on the surface of the material and nearby areas. It is frequently preferred in the industry because it is easy to use, low-cost and reliable [114]. It is generally used to reduce the tensile residual stresses in welded joints [115]. There are no studies in the literature on the use of this method in aluminum alloys produced by WAAM.

The hammering method creates plastic deformation in the material, allowing the production of high-density fine-grained aluminum alloy components with WAAM technology. High hammering times could be required for insufficient hammering force and large plastic deformation during the interlayer peening process. To overcome these problems, Niu et al. [116] examined Al–Mg alloy samples using synchronous hammering-assisted WAAM technology and obtained 33.97% plastic deformation. As a result of the study, they stated that pores decreased and UTS and YS values increased. Zhou et al. [117] studied 5052 aluminum alloy sheet and 5B06 filler wire using interlayer peening hybrid WAAM technology and observed improvement in mechanical properties and an increase in microhardness. Fang et al. [118] developed a pneumatic hammering device that changed the interlayer deformation, internal microstructure and properties during WAAM process of 2319 aluminum alloy. As a result, 50.8% deformation, yield strength from 148.4 MPa to 240.9 MPa and ultimate tensile strength from 288.6 MPa to 334.6 MPa were observed in the samples. Zhou et al. [119] studied the annealing treatment influence on the microstructure and mechanical properties of 5B06 aluminum alloy samples obtained by employing the interlayer hammering hybrid WAAM technology. They observed that with increasing annealing temperature the strength of the samples reduced while the plasticity improved and then reduced. Also, the best tensile properties were obtained in the annealing treatment at 180 °C with 366 MPa UTS and 29.2% EL.

The integration of surface treatment methods with WAAM technology can provide significant improvements in the manufacturing process. LSP and UPT can be effective in improving mechanical properties and can help eliminate internal defects. Nevertheless, practical challenges such as the feasibility of these strategies and the equipment needed must be considered.

Limited information can be found in the conclusive literature concerning the use of WAAM in SP and Hammer Peening methods. However, further research on these methods in WAAM technology can reveal the potential benefits of them. In particular, studies on the role of SP in WAAM applications and the practical applicability of Hammer Peening can increase the effectiveness and industrial usability In particular, studies on the role of SP in WAAM applications and the practical applicability of Hammer Peening can increase the effectiveness and industrial validity of these methods. of these methods.

To conclude, surface treatment methods when applied in conjunction with WAAM technology can enhance the functionality of the components. However, considering the ease of application and the constraints posed by each individual technique, there is a need for more detailed rounds of research and development.

Table 4
Summary of studies using LSP surface treatment.

Material	Condition	YS (MPa)	UTS (MPa)	EL (%)	Hardness	Ref
2319	Before LSP	83.9	228.21	13.91	76.8 ± 2.5HV	[104]
	After LSP	210.72	259.52	8.37	100HV	
2319	AB	94.3 ± 1.3	203.7 ± 7.1	7.7 ± 0.3	75.1 ± 7.1 $HV_{0,1}$ 76.8 ± 2.8 $HV_{0.1}$	[108]
	IL-LSP	112.3 ± 1.7	244.7 ± 5.7	9.8 ± 1.3	97.0 $HV_{0,1}$ 85.0 $HV_{0.1}$	
2319	Before LSP	103.7	247.7	12.3	75HV	[20]
	After LSP	178.3	240.3	6.0	110HV	
2319	AB	106.4 ± 0.38	268.6 ± 1.01	13.4 ± 2.58	–	[109]
	T6	233.9 ± 1.21	364.6 ± 2.71	7.2 ± 1.02		
	HPTM	322.9 ± 7.02	412.2 ± 2.41	4.7 ± 0.15		
	DLSP	195.2 ± 9.26	275.4 ± 5.07	6.48 ± 0.79		

(as-build (AB) and interlayer-LSP treated (IL-LSP) hybrid post-treatment method (HPTM), direct directed laser shock peening (DLSP)).

5.2. Interpass cooling

Interpass cooling has recently been developed and evaluated by researchers at the University of Wollongong in Australia. Fig. 10 shows a schematic representation of a WAAM system with forced interpass cooling. In WAAM, compressed gases such as CO_2, Ar and N_2 can play an important role in achieving improved microstructures and mechanical properties. In this developed system, a moving gas nozzle is used to provide CO_2, Ar or N_2 gases before or after each layer is deposited, providing a strong cooling. Rapid cooling allows the layer temperature and thermal cycling to be controlled at specific intervals for the desired properties [88].

Ren et al. [121] produced Al-6.3 Mg alloy by WAAM and CMT-ADV method and provided heat transfer by controlling the intermediate transition temperature. Intermediate transition temperatures were selected as 200 °C, 160 °C, 120 °C and 80 °C. Intermediate temperature was controlled by waiting time between layer deposits. Natural convective and conductive cooling methods were used during waiting time and no protective gas was applied. In the studies conducted, microstructure, surface oxidation, porosity, mechanical properties and fracture morphology were evaluated. As a result of the study, it was observed that dendrites disappeared, the accumulation of harmful precipitated phases [$\beta(Mg_2Al_3)$ and $(FeMn)Al_6$] decreased and the microstructure became more homogeneous with the decrease in the intermediary temperature in WAAM process. Additionally, it was determined that UTS (Ultimate Tensile Strength), YS (Yield Strength) and EL (Elongation) values increased.

Derekar et al. [122] investigated the effect of interlayer temperature change on the parts prepared using 5356 aluminum filler wire and the DC pulsed GMAW-WAAM process. In their study, it was determined that in the samples with varying transition temperatures, the sample produced with higher interlayer temperature showed 10.41% less porosity than the sample produced with lower transition temperatures.

Interpass cooling stands out as an important strategy to provide microstructural homogeneity and improve mechanical properties in WAAM processes. Studies show how this method can improve material quality and play a critical role in process optimization. It is stated that cooling rate and application timing are effective on the shrinkage of dendrite structures and the improvement of precipitation properties. In this context, optimizing interpass cooling strategies can be effective in improving both microstructure and mechanical properties. However, excessive application of cooling methods can increase thermal stresses within the material and thus potential cracking risks. Therefore, detailed modeling and optimization of cooling methods are required.

5.3. Interlayer rolling

Interlayer rolling is the process of applying load at room temperature between each deposition pass to impart local plastic deformation to the deposited material [40]. This method greatly reduces distortions and residual stresses, reduces grain size, and improves mechanical properties [123]. Fig. 11 shows a schematic representation of rolling applied in the WAAM method.

Hönnige et al. [12] used two different rolling methods to investigate the residual stress and distortion in 2319 aluminum alloy walls produced by WAAM. In their study, they stated that vertical interpass rolling changes the residual stress in aluminum WAAM and can eliminate distortions. They showed that side rolling applied after the deposition process is effective in controlling the residual stress and distortions of aluminum parts. Gu et al. [123] produced flat wall specimens using different wires (AA2319 and AA5087) and applied rolling between each layer. They stated that the applied different rolling loads of 15 kN, 30 kN and 45 kN reduced the amount of porosity in both alloys. In addition, Gu et al. [125] investigated the effect of interlayer rolling and heat treatment on micropores in WAAM Al–Cu6.3 and Al–Mg4.5 alloys. They observed that the number, size, volume and roundness of micropores in both alloys decreased as the rolling loads increased as a result of interlayer rolling. A summary of the studies conducted on rolling applications in WAAM is given in Table 5.

Interlayer rolling is a feasible technique for enhancing the mechanical properties and microstructure quality of structures fabricated using WAAM techniques. Investigations reveal that the rolling process contributes to the increase of mechanical properties owing to reorganization of pores and grains inside the given material. For example, it has been demonstrated that vertical interpass rolling is beneficial to residual stress reduction in aluminum alloys, while side rolling applications can likewise help in distortion control. It has been noted that with the increase of rolling loads the number and size of micropores decrease. Nevertheless, certain detailed performing characteristics of rolling and elaboration of processing modes are essential for achieving the desirable outcomes. A meticulous design of the rolling approach can enhance the mechanical properties to an optimum level.

5.4. Post-process heat treatment

Heat treatment methods used in WAAM are applied to reduce the residual stress of the deposits, to make phase transformation suitable, to increase the strength of the parts and to control the hardness. Some points should be taken into consideration in the selection of the heat treatment method: the material used, the type of AM technique, the environmental conditions and the type of the feature to be improved. Otherwise, if the heat treatment process is applied incorrectly, grain

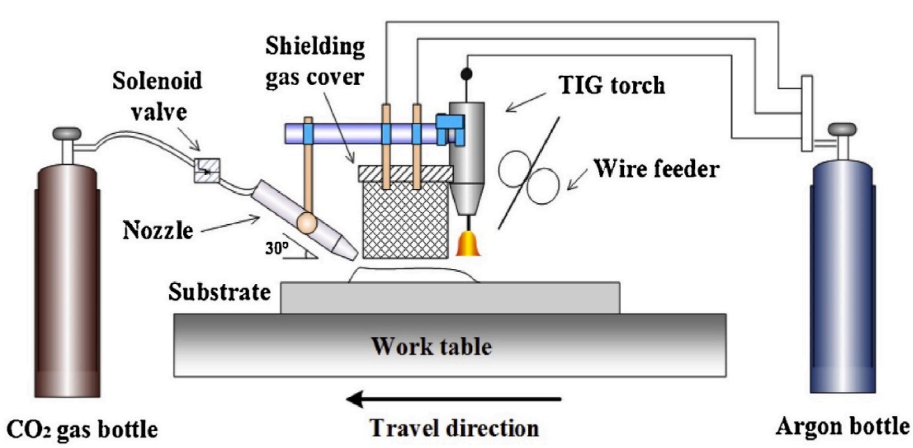

Fig. 10. Schematic representation of WAAM system with forced interpass cooling (Reprinted from Ref. [120] with permission from Elsevier)

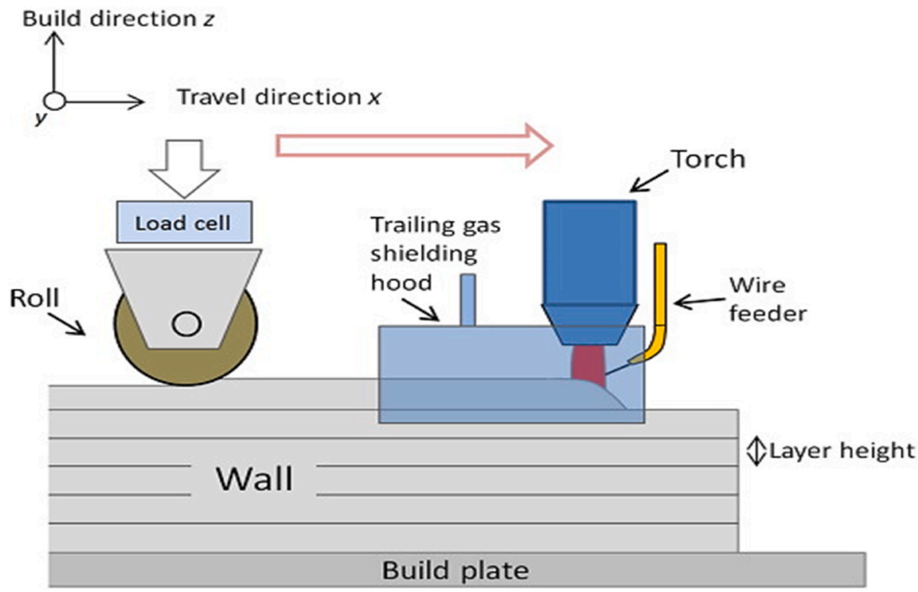

Fig. 11. Schematic view of the rolling used in WAAM [124].

Table 5
Summary of studies using rolling process in WAAM process.

Material	Condition	Arc welding	YS (MPa)	UTS (MPa)	EL (%)	Hardness	Ref.
AA2219	As-Built (V)	CMT-PA	128 ± 2	262 ± 4	15.8 ± 0.3	68.3HV	[39]
	(H)		133 ± 5	264 ± 2	18.6 ± 1.5		
	RL:15 kN (V)		142 ± 4	270 ± 7	14.6 ± 0.4	77.4HV	
	(H)		146 ± 3	271 ± 9	15 ± 1.4		
	RL:30 kN (V)		188 ± 4	286 ± 3	12 ± 0.6	90.1HV	
	(H)		195 ± 2	293 ± 6	13.2 ± 0.2		
	RL:45 kN (V)		241 ± 2	312 ± 8	7.4 ± 0.6	102.3HV	
	(H)		249 ± 1	323 ± 9	8.6 ± 0.4		
ER5087	As-Built	CMT-P	142	291	22.4	76.6 HV	[126]
	RL:15 kN		170	301	21.6	87.9 HV	
	RL:30 kN		200	320	20.9	97.3 HV	
	RL:45 kN		240	344	20.1	107.2 HV	
AA2024	As-deposited(H)	CMT-PADV	204 ± 2	324 ± 5	7.7 ± 1.4	103 ± 7 $HV_{0.1}$	[40]
	(V)		186 ± 12	267 ± 1	2.4 ± 0.1		
	As-deposited(H)	CMT-P	178 ± 9	260 ± 10	2.9 ± 0.4	100 ± 11 $HV_{0.1}$	
	(V)		163 ± 12	210 ± 16	1.4 ± 0.5		
	As rolled(H)	CMT-PADV	308 ± 7	394 ± 7	7.3 ± 1.0	128 ± 5 $HV_{0.1}$	
	(V)		273 ± 16	280 ± 22	0.5 ± 0.2		
	As rolled(H)	CMT-P	221 ± 6	328 ± 4	12.4 ± 0.2	105 ± 3 $HV_{0.1}$	
	(V)		210 ± 5	313 ± 4	6.2 ± 0.8		
	Rolled&heat treated(H)	CMT-PADV	283 ± 10	467 ± 5	22.6 ± 2.0	141 ± 6 $HV_{0.1}$	
	(V)		284 ± 2	411 ± 35	6.0 ± 2.0		
	Rolled&heat treated(H)	CMT-P	301 ± 1	468 ± 10	20.6 ± 2.0	142 ± 6 $HV_{0.1}$	
	(V)		290 ± 6	444 ± 4	9.8 ± 0.7		

coarsening may occur in the material and the possibility of cracking increases. There are many studies on heat treatment applications in WAAM. Some of these studies are summarized below:

Wang et al. [127] prepared Al–Cu alloy cast samples using in-situ rolled WAAM technology. They investigated the effect of T6 heat treatment on porosity, microstructure and mechanical properties. The deposited batch was solution treated at 535 °C for 90 min, then quenched with water and aged at 175 °C for 3 h. After T6 treatment, the number density of pores decreased by 4 times, and UTS and YS values increased due to precipitation strengthening.

Guo et al. [2] produced a crack-free Al–Zn–Mg–Cu-Sc thin-wall component by CMT method using 7B55-Sc filler wire and applied T6 heat treatment. For this, it was heated at 470 °C for 2 h for solution treatment and then immersed in water for rapid cooling followed by aging process at 120 °C for 24 h. The secondary $Al_3(Sc, Zr)$ phases precipitated during the T6 treatment aided in preventing the coarsening of microstructure and further enhanced the thermal resistance of the alloy.

Arana et al. [128] investigated the effect of heat treatment on mechanical properties for different AA2319 WAAM geometries. They stated that low aging temperature and time were not suitable for obtaining high mechanical properties and low anisotropy using four different heat treatments, and 26 h aging at 190 °C gave better results. Fig. 12 shows the microstructure and phase analysis resulting from heat treatments on the flat wall geometry.

Chi et al. [129] with WAAM-processed AA6061 samples and underwent a standard T6 heat treatment as well. The samples were done Aging at 160 °C for 18 h after solution treatment at 530 °C for 2 h and water quenching. Observations were made that the heat treatment raised the strength which was attributed to precipitation hardening thanks to Mg_2Si.

Guo et al. [11] prepared ultra-high strength Al–Zn–Mg–Cu-Sc

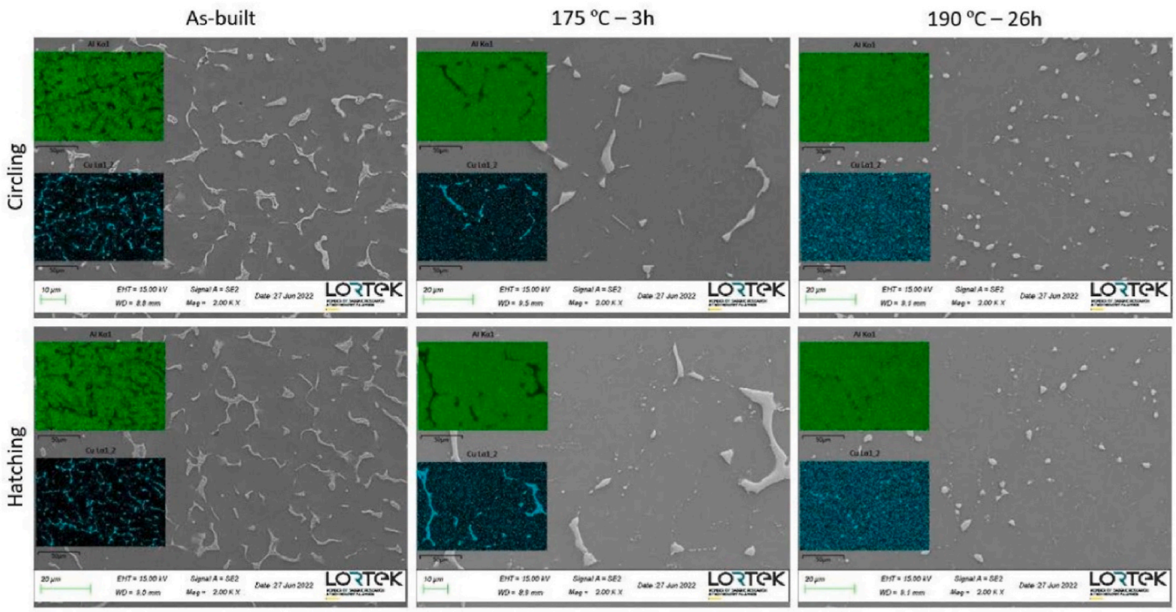

Fig. 12. Microstructure and phase analysis of the heat treated sample [128].

aluminum alloy by CMT using 7A55-Sc alloy wire. In T6 heat treatment, it was solution treated at 470 °C, quenched in water at 60 °C, and artificially aged at 120 °C for 24 h. After T6 heat treatment, the distribution of alloy elements became homogeneous.

Klein et al. [130] produced Al–Zn–Mg–Cu aluminum alloy samples using CMT-AC arc welding. The samples were solution treated at 470 °C for 5 h and then aged at 120 °C and 160 °C for 24 h. As a result, it was determined that the mechanical properties of the heat treated samples were improved.

Qi et al. [131] fabricated 2024 aluminum alloy thin-wall components by simultaneously feeding ER2319 and ER5087 wires by GTAW-based WAAM. To improve the properties of the samples, they

Table 6
Summary of post-deposition heat treated WAAM aluminum alloys.

Material	Arc welding	Condition	YS (MPa)	UTS (MPa)	EL(%)	Hardness	Ref.
Nanotreated AA6061 deposits	GTAW	As-built longitudinal	89.2 ± 0.7	189.1 ± 3.4	21.8 ± 1.7	51-54HV	[129]
		As-built Transverse	93.9 ± 0.8	190.4 ± 4.5	16.0 ± 3.1		
		Heat-treated (T6) longitudinal	306.5 ± 1.4	365.4 ± 4.1	8.7 ± 0.3	131-136HV	
		Heat-treated (T6) transverse	301.6 ± 1.5	361.3 ± 4.7	8.5 ± 1.4		
Al-7.3Zn-2.1Mg-1.6Cu-0.23Sc-0.18Zr	CMT	As-deposited	293	337	3.5	-	[11]
		Heat-treated(T6)	488	554	1.7		
Al–Zn–Mg–Cu	CMT	As-deposited(L)	197.4 ± 8.5	292.2 ± 4.4	3.2 ± 0.7	-	[130]
		As-deposited(T)	207.8 ± 0.2	278.0 ± 2.8	2.2 ± 0.1		
		HT (470 °C - T6- 120 °C)(L)	269.9 ± 9.8	413.4 ± 20.2	11.6 ± 3.7		
		HT (470 °C - T6- 120 °C)(T)	277.7 ± 6.0	403.7 ± 18.7	9.4 ± 1.8		
		HT (470 °C - T6-160 °C)(L)	339.4 ± 13.2	477.0 ± 16.2	7.9 ± 1.1		
		HT (470 °C - T6-160 °C)(T)	339.8 ± 8.8	431.2 ± 23.4	3.9 ± 0.7		
AA2024	VP-GTAW	As-deposited	177	284	6	92-98HV	[131]
		503 °C solution treatment + T4	330	497	16	133-143HV	
7B55-Sc	CMT	As-deposited(H)	305 ± 8	358 ± 8	4.8 ± 0.6	–	[2]
		As-deposited(V)	299 ± 7	346 ± 10	3.8 ± 0.5		
		T6(H)	542 ± 6	618 ± 4	5.7 ± 0.7		
		T6(V)	536 ± 8	611 ± 5	4.3 ± 0.7		
ER205A	CMT-WAAM	As-deposited(H)	103.2	249.7	11.2	65HV	[133]
		As-deposited(V)	102.8	236.6	7.8		
		T6(H)	459.5	510.2	11.8	173.3HV	
		T6(V)	463.6	510.6	8.6		
AlCu4.3-Mg1.5	CMT	As-deposited(H)	185	293	12	106.8HV	[132]
		As-deposited(V)	185	245	4		
		HT(H)	399	485	9	161.4 HV	
		HT(V)	383	430	2		
AA2319	WAAM + in-situ rolled	As-deposited	152.7 ± 7.2	279.6 ± 14.2	15.3 ± 1.9	70.9 ± 4.7HV	[127]
		Solution treatment	196.3 ± 8.8	362.7 ± 9.7	26.4 ± 2.5	87.7 ± 6.9HV	
		Heat-treated(T6)	356.6 ± 17. 1	454.4 ± 23.8	14.4 ± 0.2	141.6 ± 2.7HV	
AA2196	WAAM	As-deposited	187	262	1.5	103HV	[134]
		Heat-treated(T6)	286	376	7.2	138HV	
Al-6.2Zn-2.2 Mg	GMAW	As-deposited(H)	208	324	9.66	113HV	[135]
		As-deposited(V)	188	299	8.98		
		HT(H)	346	402	5.57	150HV	
		HT(V)	340	389	4.18		

were heated at 485 °C for 90 min, 498 °C, and 503 °C, and water quenched. Solution and natural aging treatments improved the microhardness and tensile properties.

Gu et al. [132] produced AlCu4.3Mg1.5 alloy using CMT-WAAM. They reported that microhardness increased by 51% after T6 heat treatment.

Table 6 contains a brief summary of studies using post-deposition heat treatment on WAAM aluminum alloy.

Heat treatment procedures are crucial for enhancing material quality and performance in WAAM. The improved mechanical properties and reduced porosity in T6 heat treated aluminum alloy samples further indicate that this method is effective. It was presented that the heat treatment parameters such as solution temperature and aging time are playing important roles on microstructures and mechanical properties. The improvement of properties with increasing solution treatment temperature indicates that heat treatment strategies should be optimized. However, if the heat treatment process is not carefully controlled, problems such as grain coarsening and cracking may occur in the material. A detailed examination of heat treatment methods and parameters can provide higher performance and durable materials in WAAM applications.

5.5. Vibration

Various vibration techniques have been used to reduce defects in WAAM aluminum alloys. The following are summaries of these studies:

Zhang et al. [136] developed workpiece vibration to enhance WAAM with variable polarity CMT arc. They studied the effects of workpiece vibration on defects, mechanical properties and microstructures in Al–Mg alloy. It was reported that vibration homogenizes grain distribution and greatly improves grain size, increases tensile strength but negatively affects elongation and anisotropy. It was observed that UTS in both longitudinal and transverse directions increased as vibration acceleration increased. It was also found that workpiece vibration reduced porosity from 6.66% to 1.52% and reduced pore size. Fig. 13 (a) shows the mechanical properties in different tensile directions and Fig. 13 (b) indicates the anisotropic percentage of mechanical properties.

Zhang et al. [137] used low-frequency vibration of rigid platforms in addition to CMT arc welding to overcome the problems encountered in WAAM aluminum alloys. They investigated the effects of different vibration frequencies on mechanical properties and microstructure. The increase in vibration frequency did not lead to a significant increase in tensile strength, but it increased the elongation. Vibration reduced the size and density of pores on the fracture surface. It was determined that as the vibration frequency increased, the grain size of the deposited layers became finer and decreased by 19.1% compared to the non-vibrated sample.

Ultrasonic vibration has many advantages such as mechanical effect, cavitation and acoustic streaming. Considering these advantages, researchers have introduced ultrasonic vibration into the arc welding process [138]. For example; Zhang et al. [139] applied ultrasonic vibration to the WAAM process to produce aluminum alloy components. They used ER4043 Al alloy wire and AA6061 as substrate material. They observed that when ultrasonic amplitude increased, weld width increased, but when the amplitude exceeded the tolerable UTS value, the weld cracked without completely spreading. They also stated that the most important effects on the average grain size were welding speed and ultrasonic amplitude parameter.

Wang et al. [6] investigated the ultrasonic-assisted (UA) WAAM process for AA7075 metal matrix nanocomposite with TiB_2 nanoparticles. During deposition, they lowered an ultrasonic probe into the molten pool and swept it behind the arc to study mechanical properties and microstructures. As a result, it was found that ultrasonic vibration reduced the porosity and improved the solidification structure. In addition, it was determined that the mechanical properties were improved in the tensile and microhardness tests performed on UA-WAAM samples. Fig. 14 shows the mechanical properties of non-UA and UA samples, and Fig. 15 shows the schematic representation of the UA-WAAM process.

Vibration methods to be added into WAAM processes, combining with light metals e.g., aluminum alloys showed improvements in porosity reduction and grain size refining. In aerospace and automotive sectors, these methods have great potential for the production of stronger and more durable components. However, further experimental and theoretical research is needed to fully understand the effects of vibration parameters and to optimize the process.

5.6. Reinforcement with powder particles

It has been established through some studies that composite materials consist of metal or ceramic powders that have been properly added to the alloys' base metal to enhance the microstructure and mechanical characteristics of the alloys. In this regard, ceramic powder in aluminum alloys plays the role of a pegging dislocation and sub-grain boundary in the aluminum matrix and inhibits dislocation and grain boundary movement. It also promotes grain nucleation by providing recrystallization, prevents grain growth and increases the recrystallization temperature [140]. Some of the studies conducted on this subject are summarized below:

Jin et al. [141] deposited AA2219 and TiCps composites using the WAAM method. They investigated the effect of TiCps amount on microstructure development and mechanical properties. The addition of 5 μm TiCps reduced the free energy of the system, allowing the

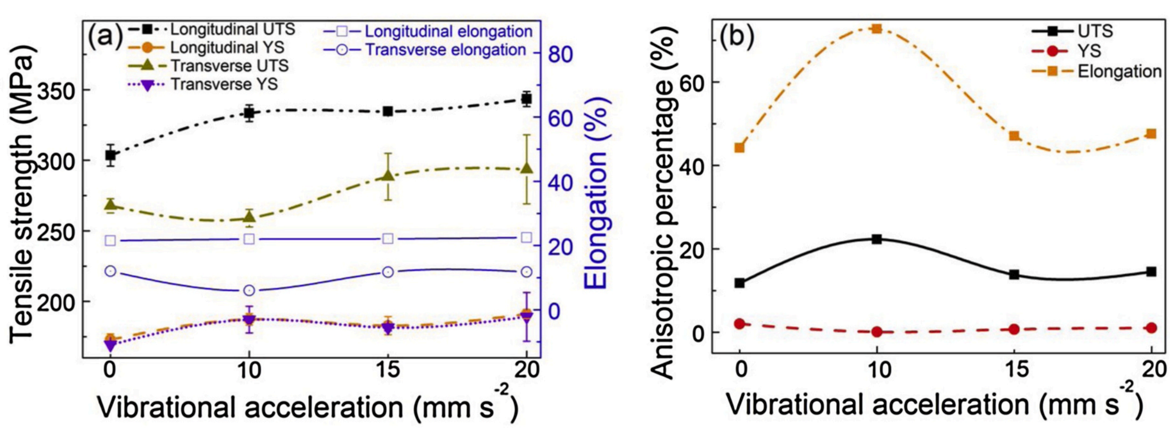

Fig. 13. (a) Mechanical properties in different tensile directions; (b) Anisotropic percentage of mechanical properties (Reprinted from Ref. [136] with permission from Elsevier)

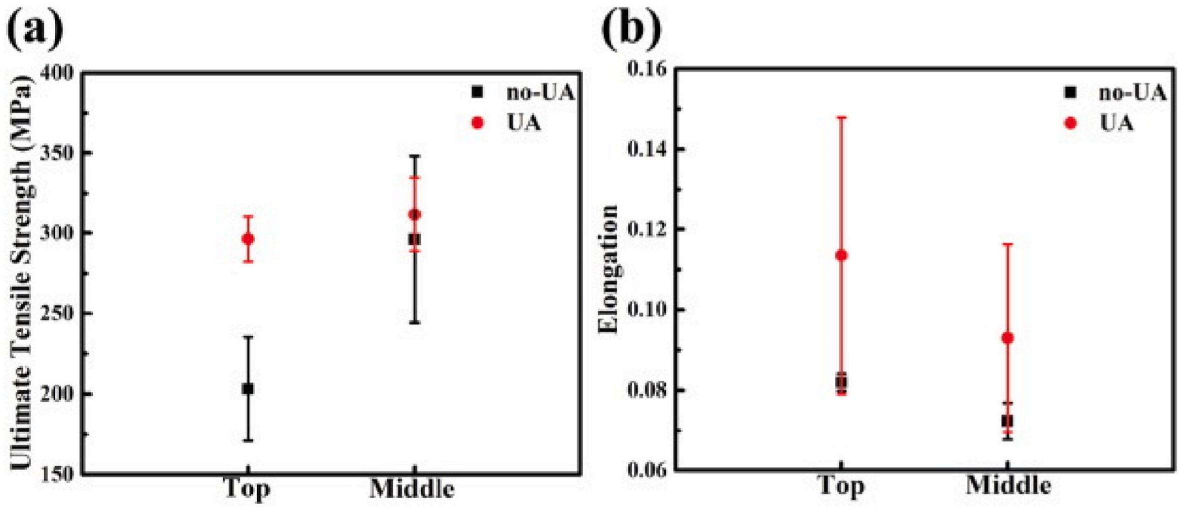

Fig. 14. Mechanical properties of the middle and upper regions of the non-UA and UA samples (a) Tensile strength (b) Elongation [6].

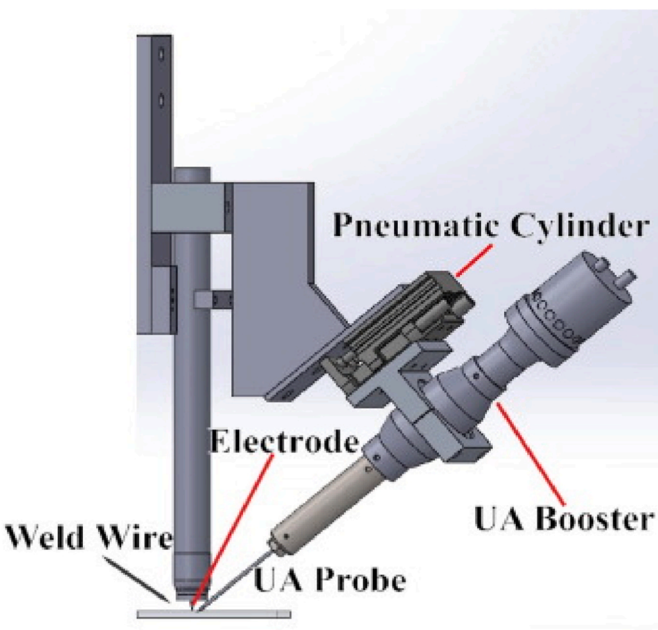

Fig. 15. Illustration of UA-WAAM process [6].

nucleation and growth of grains on the TiCps surface. Thus, the grain size reached a minimum value of 18.4 μm and columnar defects were eliminated. It was stated that the strength increased by 141 MPa and the elongation increased by 4.0% compared to the sample without TiCps.

Song et al. [140] fabricated thin-walled aluminum alloy samples in the WAAM system using double-pulse melting electrode inert gas-shielded welding (DP-MIG). They used ER2319 aluminum alloy wire and an appropriate amount of B_4C powder as feedstock. They investigated the effects of adding B_4C powder on microstructure, phase change and mechanical properties. As a result, it was observed that the grain size of the layer with B_4C powder was reduced and this reduction improved the mechanical properties. Compared with the production without B_4C powder, microhardness increased by 12.53%, horizontal tensile strength by 23.98%, horizontal elongation by 37.27%, vertical tensile strength by 26.44% and vertical elongation by 42.95%. Fig. 16 shows the powder-fed system used.

Mclean et al. [64] investigated the effect of adding titanium diboride (TiB_2) particles to AA2319 produced by CMT-WAAM on microstructure and mechanical properties under low and high heat input conditions. They stated that the grain size was reduced under high and low heat input conditions with the addition of TiB_2, with a reduction of 22% in the case of high heat input and 17% in the case of low heat input.

Liu et al. [142] used an innovative powder and wire CMT process to fabricate SiCp/Al metal matrix composite samples. They studied the effects of different concentrations of SiC particles on mechanical properties, microstructure evolution and grain orientation. They reported that with the addition of SiC particles with an average grain diameter of 49.1 μm at 8 vol%, the UTS reached 325.6 ± 16 MPa and the mechanical properties were improved. They also emphasized that this method offers a new and low-cost approach for the production of Al–Mg composites.

Fan et al. [143] investigated the microstructure, mechanical properties, arc behavior and forming quality of ER4043 samples before and after interlayer coating of La_2O_3 powders by CMT-WAAM. The addition of La_2O_3 powder had positive effects on the mechanical properties of the samples. The interlayer coated nano-sized La_2O_3 powder increased the tensile strength in horizontal and vertical directions and showed that the average grain sizes decreased. They also stated that the microstructure could change from columnar crystals to thin equiaxed dendrites. Fig. 17 shows the mechanical properties of the samples.

Powder additive WAAM processes have great potential for the production of new generation lightweight and durable materials in high-performance areas such as aerospace, automotive and defense industries. However, further research is needed on powder additive amounts, ensuring homogeneous distribution and optimizing cost-effectiveness. In addition, additional studies on different alloy types and powder materials will further increase the general validity and adaptability of this method.

5.7. Arc processes

CMT is advanced GMAW as mentioned in Section 4. CMT is divided into different droplet transfer modes called Conventional CMT, CMT Pulse, CMT Advanced and CMT Pulse Advanced. The effect of different CMT arc modes and process parameters on porosity has attracted great interest in scientific research.

5.7.1. CMT

Derekar et al. [144] produced a WAAM part using an Al–Mg–Mn alloy substrate with dimensions of 200 × 125 × 20 mm^3 and ER5183 as wire. They investigated the effect of Pulsed MIG and CMT on the porosity formation of the samples. As a result of their study, Pulsed-MIG showed higher porosity than CMT. The authors also stated that Pulsed-MIG collected more hydrogen than CMT. Wei et al. [145] applied

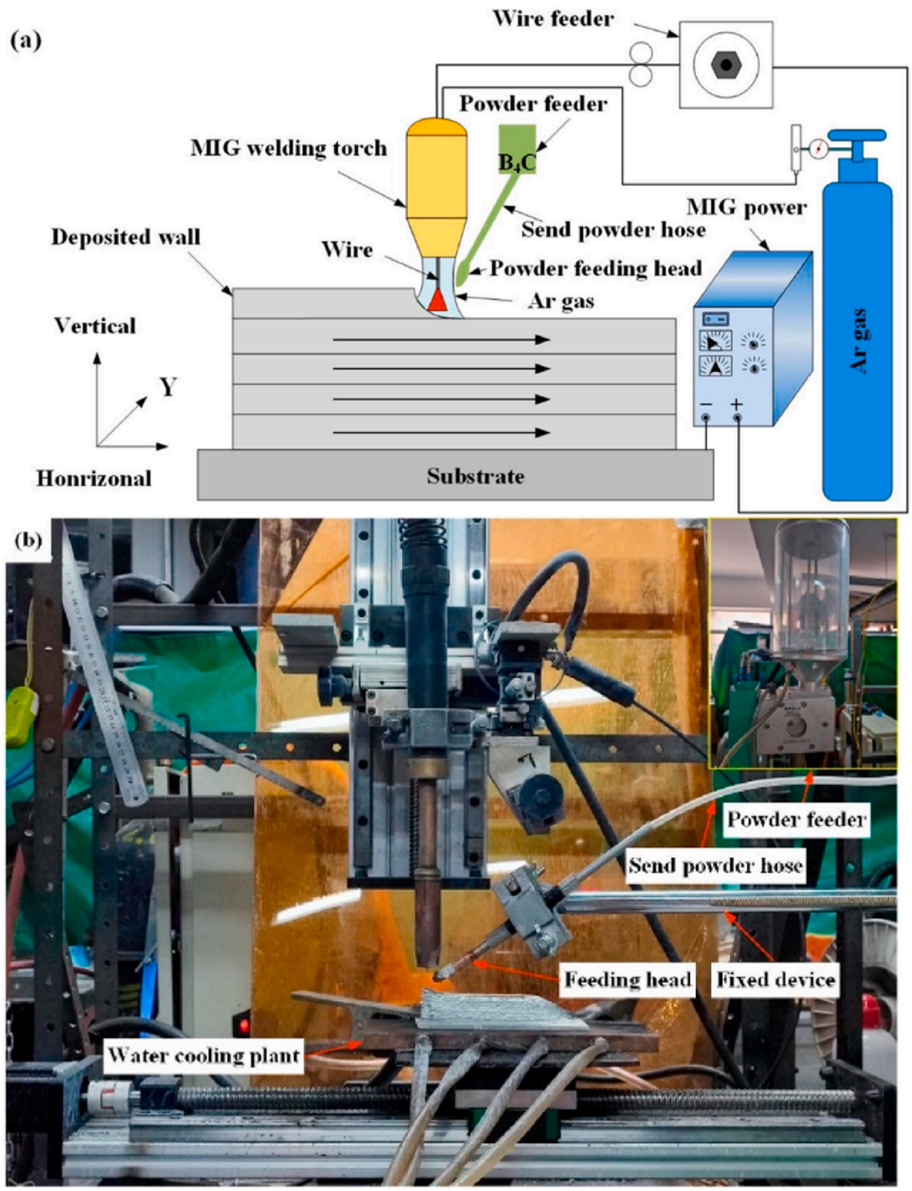

Fig. 16. DP-MIG aluminum alloy powder feeding additive manufacturing (a) Schematic representation of DP-MIG-WAAM aluminum alloy powder feeding manufacturing (b) Demonstration of the experimental equipment of the system [140].

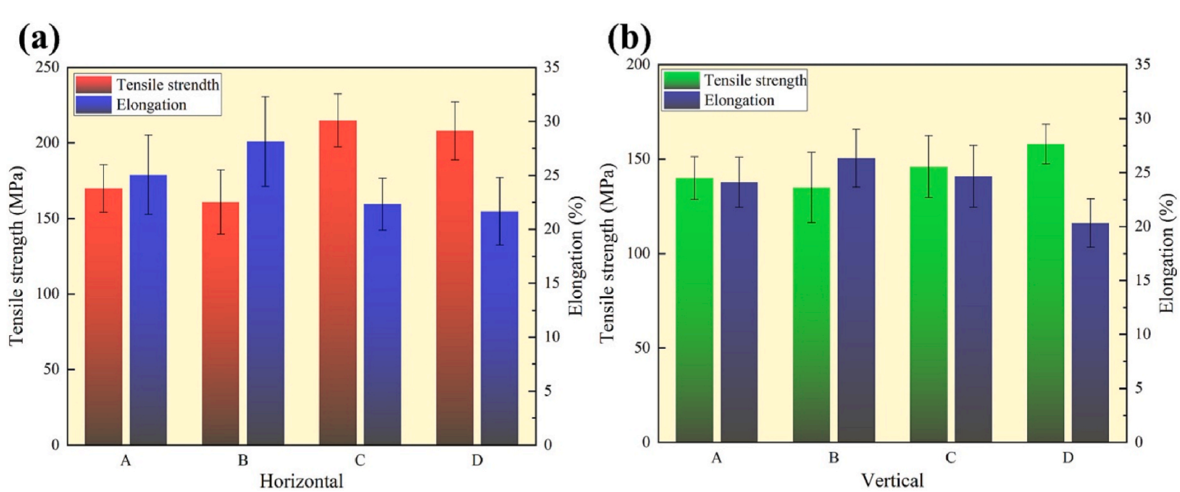

Fig. 17. Mechanical properties of additive samples for (a) horizontal direction and (b) vertical direction (Reprinted from Ref. [143] with permission from Elsevier)

arc oscillation while manufacturing an AA2319 sample with CMT-WAAM. They studied the effect of different arc oscillations on porosity, microstructure and mechanical properties. It was pointed out that arc oscillation was effective in reducing grain size and porosity ratio. Arc oscillation models are given in Fig. 18. Moreover, the tensile strength in the vertical direction was improved but it had no effect on the tensile strength in the horizontal direction.

Ortega et al. [146] compared two sets of CMT process parameters that gave different average powers for the deposition of AA4043. They observed two types of solidification defects: porosity and a small amount of hot cracking defects. It was found that the group that gave the highest average power had fewer and larger pores. Also, the group that gave the highest average power was better at spreading the deposited liquid metal droplets. Shanker et al. [147] used AA7475 sheet with a thickness of 3 mm and T7351 (solution treated + artificially aged) and UNI-ER 4043 (AlSi5) wire with a diameter of 1 mm as filler material. They compared the microstructural properties, tensile properties and hardness distribution for the two processes using CMT and GMAW methods for deposition. As a result, they observed similar microstructures in both processes. It was presented that the only difference between the dendritic structures was that the dendrite arm spacing was narrower in CMT and wider in GMAW. They also pointed out that the CMT welded samples had better mechanical properties than GMAW. Hu et al. [148] produced their samples by adding a DC magnetic field to the CMT-WAAM manufacturing process. As a result of their work, the porosity decreased and significant improvements occurred in microhardness and tensile strength at 2A excitation current.

5.7.2. CMT Advance

Nie et al. [149] investigated the microstructure, macrostructure and mechanical properties of AA4043 produced by CMT-ADV. They indicated that the mechanical properties of 4043 aluminum alloy rapid prototyping samples produced in this mode were partially good. No anisotropy was observed in mechanical properties in horizontal and vertical directions. Rauch et al. [150] produced the AA2319 WAAM block structure with an oscillatory deposition strategy using the CMT-ADV arc mode. They worked on the effect of the resulting structure on porosity, microstructure, microhardness and mechanical properties. As a result, it was highlighted that the average area porosity percentage formed in all regions of the block structure was similar to the thin wall structure produced by CMT-PADV due to the slow cooling rate provided by the increase in the exposure time of liquid aluminum to air. The authors also observed a coarse microstructure in the AA2319 block structure obtained by WAAM with the oscillatory strategy due to slow cooling.

5.7.3. CMT pulse

Cong et al. [16] investigated the pore distribution, microstructure and microhardness parameters for thin wall and block structures of WAAM Al-6.3%Cu alloy using CMT-P and CMT-ADV processes. They stated that the number of pores in the block structure was less than that in the thin wall structure. When the CMT-P process was compared with the CMT-ADV process, they stated that the porosity was less with the CMT-ADV process. Vishnukumar et al. [94] deposited AA5052 substrate with dimensions of 160 × 150 × 5 mm and ER4043 filler wire with a diameter of 1.2 mm using CMT and CMT-P modes. It was pointed out that the microstructure consisted of course and equiaxed dendrites in the CMT mode, while it consisted of fine equiaxed dendrites in the CMT-P mode.

5.7.4. CMT Pulse Advance

Arana et al. [151] used the WAAM process based on CMT-PADV arc welding technology with nanomodified AA2024 wire. They added TiC nanoparticles to the wire in their study. Researchers obtained the flat wall sample produced with structural defects, approximately 1% reduced porosity and fine equiaxed grain structure. It was stated that pores with diameters smaller than 100 μm were obtained with the CMT-PADV welding process and circular deposition strategy. Fang et al. [89] used four different welding arc modes, namely CMT, CMT-P, CMT-ADV and CMT-PADV, to deposit AA2219. They investigated the porosity, microstructure, mechanical properties and pore size distribution in different arc modes in detail. It was demonstrated that the best tensile strength in the CMT-PADV mode, and the large-sized AA2219 parts with very good properties can be deposited quickly with appropriate control and monitoring of process parameters in the CMT-PADV mode. Also, researchers noted that the largest number of small gas pores is formed in the conventional CMT mode. Cong et al. [97] investigated the porosity and weld bead geometry of 2219 (Temper 851) high strength aluminum alloy welds formed with ER2319 wire obtained with different CMT arc modes. They mentioned the formation of a narrow finger-shaped geometry and the presence of numerous gas pores in the upper and lower parts of the welds when the conventional CMT process was used. When the CMT-ADV process was used, a finger-shaped geometry with less melting depth was obtained. Appropriate heat input is important to reduce porosity. They also emphasized that porosity was largely eliminated when the CMT-PADV process was used. Table 7 summarizes the studies conducted using the CMT-WAAM processes.

In summary, CMT arc processes are advanced versions of GMAW technology and are implemented in four main modes: Conventional CMT, CMT Pulse, CMT Advanced and CMT Pulse Advanced. Each mode has its own advantages and disadvantages.

CMT generally has the potential to reduce porosity and provide quality weld beads. CMT Pulse and CMT Pulse Advance are also efficient in obtaining finer grain structure and lower rates of porosity. CMT Advanced and CMT Pulse Advance offer high tensile strength and mechanical properties, allowing for rapid deposition of large-sized parts.

CMT Pulse and CMT Pulse Advance modes are, however, more expensive and operationally complicated. Furthermore, detailed process parameters must be carefully controlled to ensure optimum performance of them. In conventional CMT and CMT Advanced modes, porosity can

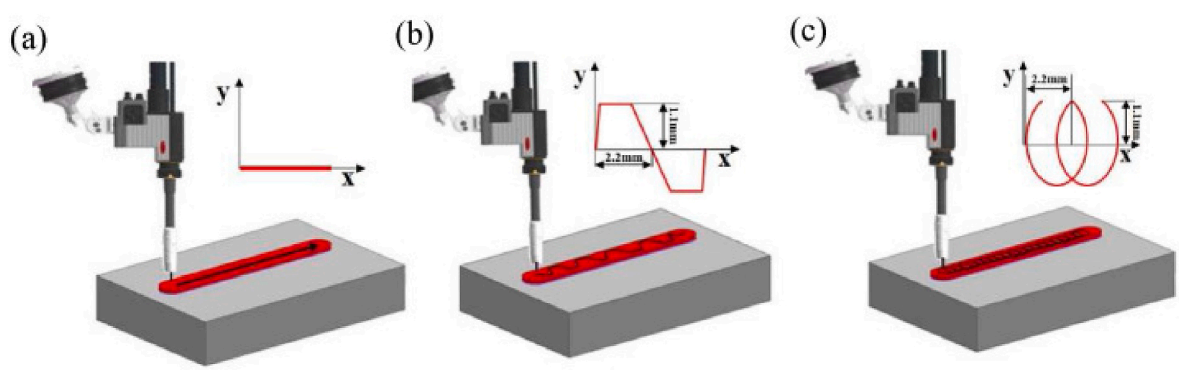

Fig. 18. Schematic view of models with (a) no oscillation, (b) asymmetric trapezoidal oscillation, (c) spiral oscillation [145].

Table 7
Summary of studies using CMT-WAAM processes.

Year	Energy source	Materials	Process parameters	Found observations	Ref
2021	CMT CMT-P	AA5052	**Parameters for CMT:** Arc current:66 Amps Arc voltage: 11.8 V Welding speed:450 mm/min Heat input:93 J/mm Deposition rate: 0.71 kg/h **Parameters for CMT-P:** Arc current:58 Amps Arc voltage: 15.8 V Welding speed:500 mm/min Heat input:98 J/mm Deposition rate: 0.51 kg/h	-The corrosion rate of the samples ranged from 0.18 mm/year to 0.21 mm/year. - The WAAM process has potential for repair in marine applications.	[94]
2020	CMT CMT-ADV CMP-PADV	AlMg5Mn	**Parameters for CMT:** Welding speed: between 0.3 and 0.6 m/min Buildup time:320 min **Parameters for CMT-ADV:** Welding speed: between 0.3 and 0.6 m/min Buildup time:250 min **Parameters for CMT-PADV:** Welding speed: between 0.3 and 0.6 m/min Buildup time:215 min	- There is a relationship between energy input and microstructure in terms of grain size and porosity. The lowest energy per unit length was realized in the CMT-PADV process with a value of 1.44 kJ/cm. In other words, the finest grain structure is in CMT-PAV and porosity is reduced to 0.06%. -The hardness value was measured in the range of 81.4 HV1 for CMT and 85 HV1 for CMT-PADV. The arc mode has little effect on hardness. Hardness increased slightly as a result of reduced energy input.	[56]
2022	CMT- P	Al–Mg–Si	Mean wire feed rate:3.5 m/min Deposition rate:0.64 kg/h Current:82/102 A Mean voltage:9.3 V Travel speed:12 mm s^{-1} Energy input per unit length:64 J/mm	- The isotropic yield strength is about 265 MPa, which is quite high for extruded and heat-treated material. - CMT + Pulse mode gave the best results in terms of porosity, cracks and surface quality.	[61]
2015	Conventional CMT CMT-P CMT-ADV CMT-PADV	Al-6.3% Cu	**Parameters for the single layer deposits** **Parameters for conventional CMT:** WFS = 7.5 m/min, TS = 0.5–1.0 m/min, HI = 165.8–331.6 J/mm **Parameters for CMT-P:** WFS = 7.5 m/min, TS = 0.5–1.0 m/min, HI = 183.4–366.8 J/mm **Parameters for CMT-ADV:** WFS = 7.5 m/min, TS = 0.4–0.8 m/min, HI = 170.8–341.6 J/mm **Parameters for CMT-PADV:** WFS = 7.5 m/min, TS = 0.4–0.5 m/min, HI = 135.4–169.3 J/mm **Parameters for multilayer wall additive manufacture** **Parameters for CMT-P:** WFS = 5–6 m/min, TS = 0.8–1.0 m/min, layer number 14 or 20 HI = 137.1–189.1 J/mm **Parameters for CMT-ADV:** WFS = 6–7.5 m/min, TS = 0.5–0.8 m/min, layer number 10 HI = 135.7–273.4 J/mm **Parameters for CMT-PADV:** WFS = 6–7.5 m/min, TS = 0.4–0.6 m/min, layer number 10 or	- Porosity was observed to be very much affected by different arc modes in the CMT process. - Among the other four arc modes, the CMT-PADV mode was found to be the most suitable for WAAM of aluminum alloys. - With the CMT-PADV process, porosity was removed and fine equiaxed grains were obtained.	[96]

(continued on next page)

Table 7 (*continued*)

Year	Energy source	Materials	Process parameters	Found observations	Ref
			14 HI = 112.2–168.4 J/mm		
2017	CMT-P CMT-ADV	Al-6.3% Cu	**Parameters for CMT-P:** **P0**-thin wall-WFS = 6 m/min, TS = 0.8 m/min, HI = 189.1J/mm **P1**-block-WFS = 7.5 m/min, TS = 0.6 m/min, HI = 305.7J/mm **P2**-block-WFS = 7.5 m/min, TS = 0.5 m/min, HI = 366.8J/mm **Parameters for CMT-ADV:** **A0**-thin wall-WFS = 6 m/min, TS = 0.8 m/min, HI = 137.5J/mm **A1**-block-WFS = 7.5 m/min, TS = 0.6 m/min, HI = 227.8J/mm **A2**-block-WFS = 7.5 m/min, TS = 0.5 m/min, HI = 273.4J/mm	- When CMT-ADV and CMT-P processes are compared; porosity is reduced with CMT-ADV process. - The microhardness value of the thin-walled specimens is higher at the lower parts and decreases towards the upper parts. The hardness value of the block specimens was found to vary approximately in the range of 72–77 HV.	[16]
2018	Pure CMT CMT-P VP-CMT	Al–6Mg	**Parameters for CMT:** Scanning speed: 7 mm s^{-1} Wire filling speed: 6 m/min Heat Input:250 J/mm **Parameters for CMT-P:** Scanning speed: 11.05 mm s^{-1} Wire filling speed: 9 m/min Heat Input:250 J/mm **Parameters for VP-CMT:** Scanning speed: 7.56; 9.86; 6.13 mm s^{-1} Wire filling speed: 7 m/min Heat Input:250; 110; 143.5; 177J/mm	- Parts produced in VP-CMT arc mode have a maximum UTS of 333 MPa. - The CMT arc mode with variable polarity can refine the grain size, which is an important factor in improving mechanical performance.	[10]
2018	CMT CMT-ADV CMT-P CMT-PADV	AA2219	**Parameters for CMT:** WFS = 6 m/min, TS = 0.5 m/min, HI = (220.9 J/mm) **Parameters for CMT-ADV:** WFS = 6 m/min, TS = 0.5 m/min, HI = (194.0 J/mm) **Parameters for CMT-P:** WFS = 5 m/min, TS = 0.5 m/min, HI = (231.8 J/mm) **Parameters for CMT-PADV:** WFS = 7 m/min, TS = 0.5 m/min, HI = (130.1 J/mm)	- The best tensile strength was obtained in CMT-PADV mode. The tensile strength reached 283 MPa in the horizontal direction.	[89]

(Wire Feed Speed (WFS), Heat Input (HI), Travel Speed (TS)).

be an issue, especially in processes with low average powers.

Process complexity and cost can pose significant challenges, especially in advanced modes. Detailed process settings are required to optimize the effects on porosity and microstructure.

CMT Pulse and CMT Pulse Advance modes are recommended to minimize porosity and achieve high mechanical properties. Careful optimization of process parameters is critical to obtaining the best results. In addition, the use of new materials and nanomodification techniques can improve quality and performance.

5.8. *Machining of WAAM parts*

Deposition by droplet transfer at high temperature results in low geometric accuracy and rough surfaces in WAAM processes. Conventional post-processing methods (milling, turning, etc.) are used in WAAM to obtain net shape. Post-processing has a significant effect on the corrosion resistance, creep life, and other mechanical properties of the part by improving the surface quality [152]. A hybrid system integrating WAAM, and high-speed milling can help increase geometric accuracy and improve the production of complex structures [153]. A visual showing the steps of the hybrid WAAM process combining welding-based process and milling is shown in Fig. 19.

There are various studies that run the machining procedure after parts are produced with WAAM. For example, Li et al. [155] stated that regardless of which additive manufacturing system is chosen, it is still difficult to produce components with similar geometric accuracy and surface quality to traditional subtractive manufacturing due to the stair-stepping effect and fluidity of molten metal. To overcome these drawbacks, researchers proposed hybrid manufacturing, which combines additive and subtractive processes, as a solution. In hybrid manufacturing, additive and subtractive processes are applied alternately in each or several layers; thus, first, a blank part close to the net shape is produced, and then the desired geometric accuracy and surface quality are achieved. In the study, they investigated the effectiveness of hybrid WAAM and milling processes in the production of hardened panels used in sectors i.e., aviation, aerospace and automotive. They investigated the effects of deposition parameters such as wire feed speed and feed rate and milling parameters such as spindle speed and tool feed rate on surface quality, material usage and productivity. They stated that maximum performance can only be achieved by harmoniously optimizing deposition and milling parameters. Optimization showed that high feed rate, wire feed rate according to target width, high spindle

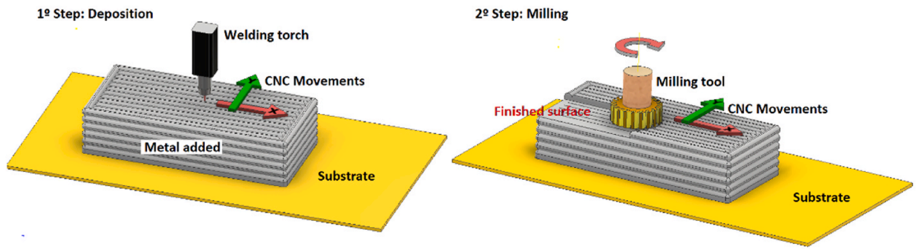

Fig. 19. Hybrid WAAM/Milling experimental setup [154].

speed and moderate tool feed rate are required to create a good balance between surface quality, material usage and productivity. Using these parameters, material consumption can be reduced, and productivity can be increased without loss of accuracy in the production of panels compared to traditional methods.

Zhang et al. [153] studied the effect of milling thickness on the deposition accuracy of Al5Si aluminum alloy thin wall in a hybrid robotic WAAM-milling manufacturing system. They reported that when the milling thickness was between 0.4 and 1.2 mm, hybrid manufacturing reduced the surface roughness by 22.9% and the machining tolerance by 31.6%, but when the milling thickness was 1.6 mm, the surface roughness increased by 71.5% and the machining tolerance by 22.5%.

Zhang et al. [156] compared the deposited Al5Si aluminum alloy with AZ31B magnesium alloy using hybrid wire arc additive milling method. When the optimum process parameters were used, the surface roughness of the magnesium sample was found to be 146.1 μm, which was 90% higher than that of the aluminum sample. The anisotropy in tensile strength and elongation was determined to be 32% and 56% in the magnesium sample, respectively, which were 6 and 3.3 times higher than that of the aluminum sample.

Ma et al. [157] used three strategies to control the uniformity of the deposited layers to produce large and high thin-walled structures by combining a robotic additive and subtractive manufacturing system: 1) deposition by texturing, 2) arc ignition and arc quenching control, and 3) local measurement milling. They used ER4043 aluminum alloy with a diameter of 1.2 mm in their experiments. When these strategies were combined, the differences in the layer heights of the weld beads were controlled within the allowable error limits, thus demonstrating that large and high thin-walled structures can be successfully produced without frequent milling.

As a result, it has been observed that parts produced with WAAM exhibit low geometric accuracy and rough surface properties due to high temperature droplet transfer. For this reason, traditional methods such as milling and turning are applied to improve the surface quality after the processes. Such processes improve the mechanical properties, corrosion resistance and creep life of the part.

Hybrid manufacturing systems (such as WAAM and high-speed milling) are effective in increasing geometric accuracy and surface quality. Hybrid manufacturing provides the desired geometric accuracy and surface quality by using additive and subtractive processes alternately in each layer. This method is especially preferred for the production of hardened panels in the aviation, aerospace and automotive sectors.

Optimum machining and deposition parameters (such as wire feed speed, spindle speed, tool feed rate) have significant effects on surface quality and productivity. Hybrid manufacturing improves surface roughness and tolerance, while also reducing material consumption and increasing productivity. However, optimum parameters should be determined carefully.

So, it is recommended that hybrid manufacturing techniques be used to improve the surface quality and geometric accuracy of parts obtained with WAAM. This can be achieved by optimizing the manufacturing process and adjusting the parameters, accordingly, thus achieving maximum performance and efficiency.

5.9. *Hot wire*

In order to reduce porosity and improve the deposition rate in the WAAM process, Fu et al. [158] have developed the hot wire arc additive manufacturing (HWAAM) method. This method differs from WAAM in that it has a new hot wire auxiliary device module used to obtain resistance heat based on the resistance of the wire. (a) System equipment and (b) Schematic representation of the system are given in Fig. 20. While alternating current is used as the welding power source, direct current is preferred for hot wire welding.

Four different thin-walled AA2024 components were produced using HWAAM with different hot wire current parameters, and the microstructures, porosity formation mechanisms and mechanical properties of these samples were analyzed. The studies showed that the use of hot wire greatly reduced porosity and improved mechanical properties. The maximum tensile strength was measured as 399 MPa, yield strength as 257 MPa and elongation ratio as 12.0% [158].

Fu et al. [159] used HWAAM method to produce AA7055 alloy and applied three-stage solution and aging heat treatments to improve the mechanical properties. Grain structures, precipitates, defects and mechanical properties of both as deposited and heat-treated samples were investigated. In the samples after heat treatment, UTS was 563 $\pm$ 7 MPa, YS was 434 $\pm$ 6 MPa and EL was 10.0 $\pm$ 1.2% and very little anisotropy was observed. Porosity was 0.18% in the as-deposited samples and 0.26% in the heat-treated samples.

Wang et al. [160] studied the ultrasound-assisted hot wire arc additive manufacturing (UA-HWAAM) process for TiB2 nanoparticle-reinforced AA7075 metal matrix nanocomposite in detail. While higher tensile strength and more uniform strain distribution were obtained in tensile tests in UA samples, pores and nanoparticle clusters were observed on the fracture surface in the normal HWAAM sample, which resulted in poor mechanical performance. The hot wire system showed that nanoparticles greatly reduced the porosity during the GTA-based WAAM process. The increase in feed rate directly reduces the melt pool size and peak temperature, contributing to the reduction of porosity and the improvement of grain structure.

Xu et al. [161] investigated the manufacturing of low-angle bars and especially the manufacturing of bars with 0° horizontal angle by pulsed hot wire arc additive manufacturing (PHWAAM). PHWAAM is a GTAW-based method and provides lower heat input compared to PWAAM. In their research, they produced highly curved bars and stated that PHWAAM has more advantages in manufacturing highly angled bars and cage structures than GMAW.

When we briefly evaluate the use of hot wire for the improvement of parts produced with WAAM, it is determined that HWAAM was developed in response to the challenges of WAAM technology, such as reducing porosity and improving deposition rate. HWAAM significantly reduces porosity and material defects by increasing mechanical properties with the heating technology based on the resistance of the wire. Especially in aluminum alloys such as AA2024 and AA7055, higher strength and elongation rates are obtained after heat treatment. The ultrasound-assisted HWAAM (UA-HWAAM) method provides

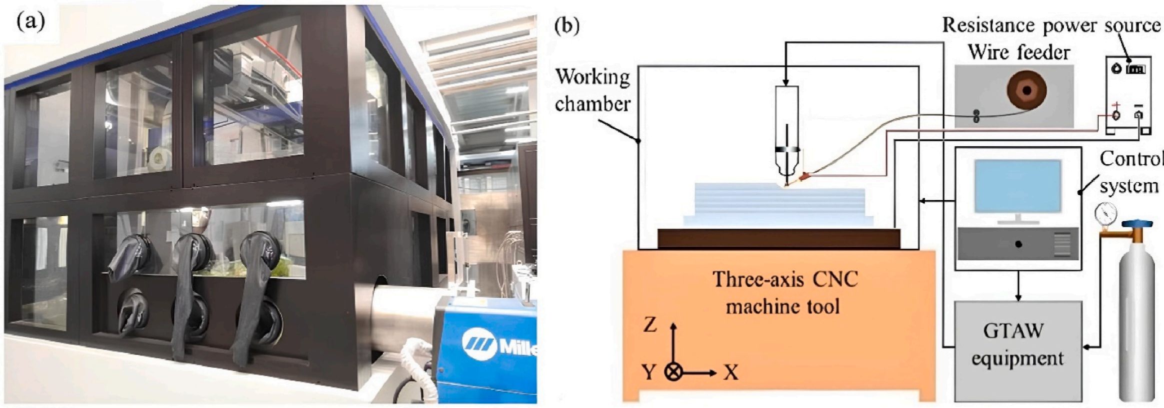

Fig. 20. (a) system equipment (b) schematic view of the system [158].

mechanical performance improvements such as higher tensile strength and uniform strain distribution.

PHWAAM method offers advantages in the production of complex geometries such as multi-angle rod and lattice structures. However, there are technical challenges such as control of heat input and nanoparticle distribution. Research shows that optimization of process parameters is critical to improve material performance and production efficiency.

In general, HWAAM and its derivatives offer superior mechanical properties and surface quality compared to traditional WAAM, providing additional advantages for the production of complex structures. However, the process needs to be optimized and controlled for a wider range of applications.

6. Defects in aluminum parts produced with WAAM

WAAM aluminum samples usually contain various metallurgical defects, such as pores, slag, and cracks, which adversely affect their mechanical properties. Their microstructure usually consists of coarse columnar grains and shows an anisotropy tendency [162]. The main defects encountered in WAAM aluminum samples are explained in the sub-sections.

6.1. *Crack and delamination*

Cracks and delamination are caused by the thermal and material properties of the deposited material. Delamination is defined as the separation of layers that are bonded together and is usually caused by the incomplete or partial melting of the underlying layer while a new layer is being deposited [163]. Delamination cannot be eliminated by post-processing methods. He et al. [164] used friction stir processing (FSP) to prevent anisotropy caused by delamination. The macro and microstructures of the samples before and after the FSP process are shown in Fig. 21. It is stated that delamination can be eliminated by the FSP process. Methods such as heating the substrate before the deposition process are suggested to prevent cracking and delamination.

Aluminum alloys could be subject to hot cracking due to the low melting phases formed at the grain boundaries during the WAAM process [165]. Klein et al. [166] investigated the microstructure and mechanical properties of WAAM processing in high strength 7xxx (AlZn5.5MgCu) alloy and stated that hot cracking can be prevented by intrinsic heat-treatment (IHT). Chi et al. [167] prevented hot cracking by adding TiC nanoparticles to AA2024 alloy. Hot cracking can be generally divided into two types: solidification and liquidus cracking [168]. Solidus cracking, which is frequently seen in WAAM aluminum

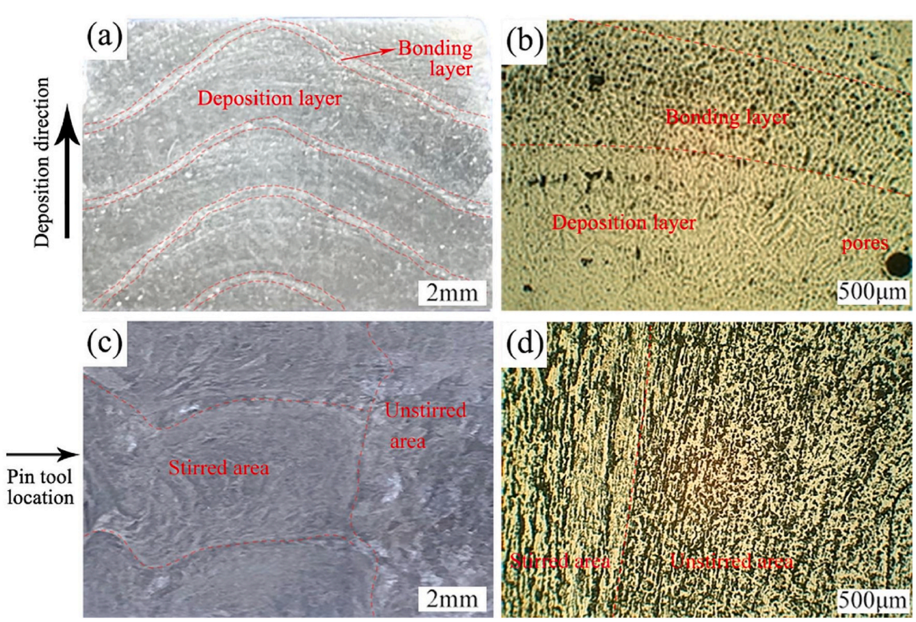

Fig. 21. Macrostructure and microstructure of the obtained samples (a) As-deposited x100, (b) As-deposited x400, (c) FSP treated x100, (d) FSP treated x400 (Reprinted from Ref. [164] with permission from Elsevier)

alloys, is a common defect that occurs due to insufficient fluid supply during the fusion process in high strength aluminum alloys [42]. Xu et al. [168] investigated the cracking mechanism of Al–Cu alloys in the WAAM process and studied the microstructure, grain size transition, eutectic structure development, crack sensitivity and solute segregation. They observed cracks with a length of 6–9 cm and a depth of 5–7 cm at the bottom of the samples. The following measures can be taken in order to prevent the occurrence of crack defects: (1) Optimizing the wire compositions, (2) Employing nanoparticle modification, (3) Preheating the substrate, (4) Reducing the deposition cooling rate.

These strategies can be applied to reduce the defects observed in WAAM aluminum alloys and improve the mechanical performance of the material.

To briefly evaluate, delamination is the result of poor adhesion between material layers and cannot be fixed by post-processing methods. Although this problem can be partially overcome with techniques such as FSP, it can be difficult to provide a homogeneous solution in all areas. Further, hot cracking is caused by tensile thermal stresses developed during cooling, particularly for high strength aluminum alloys. For WAAM aluminum alloys, reducing the defect content will need diverse approaches including careful parameter optimization, application of new types of additives, and cooling rate control. Such methods can enhance the mechanical properties of components and increase the process reliability.

6.2. Deformation-distortion and residual stress

Due to the high heat input during welding, WAAM process results to residual stresses and distortions which influence the component life and structural reliability [169]. During solidification, residual stresses are generated due to localized temperature changes in the molten metal. These stresses are unevenly distributed and change with time, leading to dimensional deviations, loss of geometric tolerance, decreased fatigue performance and reduced fracture resistance [170]. Plastic strain mismatch between the weld and base metal has adverse effects on mechanical properties and usually causes residual stresses resulting in distortion [171]. Especially in thin-walled and large-scale parts, high residual stresses lead to significant distortion, which leads to geometrical errors and crack formation [172].

Residual stresses are divided into three categories: Type I (macro scale), Type II (grain scale), and Type III (atomic scale). Type I residual stress plays a critical role in macro deformations of metallic components such as distortion and springback, while Types II and III are generally neglected. Researchers have developed various methods to reduce residual stress and distortion. Thermal techniques include stress relieving, preheating, optimized path strategy, and use of heat sink during deposition [173]. Mechanical techniques include machine hammering, ultrasonic impact, global mechanical stretching, and cold rolling [12].

Zhang et al. [170] studied Al5Si alloy by using hybrid wire arc additive and milling processes alternately. They stated that the compressive stress generated during milling process reduces the residual stress on the surface and balances the initial tensile residual stress. Köhler et al. [9] analyzed the residual stresses of WAAM samples produced with Al-4047 and Al-5356 alloys by X-ray diffraction method and they found that the magnitude of the residual stress depends on the yield strength of the filler material.

In summary, the high heat input in the WAAM process leads to significant residual stresses and distortions that threaten structural integrity and shorten the life of components. These stresses cause geometric errors and crack formation, especially for large and thin-walled parts. Both thermal (i.e., stress relieving, preheating) and mechanical (i.e., hammering, cold rolling) methods have been suggested to overcome these problems. In addition, surface stresses can be balanced with compressive stresses resulting from milling using hybrid manufacturing techniques. As a result, optimization of the methods used to minimize deformation and residual stress in WAAM is critical for structural integrity and part life. These approaches increase the efficiency of the process and increase the mechanical and geometric quality standards of the final products.

6.3. Porosity

Porosity is the most common defect in WAAM aluminum alloys and has significant negative effects on mechanical properties. The main reason for this problem is the difference in solubility of hydrogen between the solid and liquid phases in aluminum alloy welds. When passing from the liquid phase to the solid phase during solidification, hydrogen becomes supersaturated and precipitates. Hydrogen bubbles are formed in the liquid phase in front of the solid-liquid interface; most of these bubbles are trapped before they can escape, and pores are formed during solidification [11].

The main sources of hydrogen in the WAAM process are moisture, grease and hydrocarbons on the surface of the filler wire. These contaminants evaporate during the arc, converting to atomic hydrogen and mixing into the molten pool [174]. Contamination and moisture in the shielding gas, hose, tubing and substrate can also cause hydrogen formation [144]. Similarly, oxygen and nitrogen have adverse effects on the mechanical properties of aluminum welds and therefore should not be used as shielding gas components in WAAM [165]. Increasing the shielding gas flow rate can cause the molten pool to solidify rapidly by forced convection, increasing porosity [175].

The solubility of hydrogen in molten pure aluminum is 0.65 ml per 100 g, while this value is 0.034 ml in solid pure aluminum [123]. Porosity can also be seen as shrinkage pores resulting from volume differences between liquid and solid phases. These pores are formed by the migration of hydrogen from the liquid phase into the voids during solidification, and their growth is usually triggered by Ostwald ripening [98]. Ayarkwa et al. [176] reported that the number of pores increases with increasing wire feed rate/wire speed ratio.

The application of alternating current or variable polarity in the WAAM process provides a great advantage for the production of aluminum parts that exhibit lower sensitivity to porosity and oxide residues due to the cathode cleaning feature of electric arcs [177]. Zhang et al. [10] emphasized that the variable polarity cold metal transfer (VP-CMT) method reduces porosity. Fang et al. [89] compared the conventional CMT, CMT-P, CMT-ADV and CMT-PADV modes in terms of porosity and stated that the CMT-PADV mode gave the lowest pore area percentage and aspect ratio, and almost no large pores were encountered. Fig. 22 shows the distribution of gas pores formed in different arc modes for AA2219 alloy produced by WAAM. Other methods of reducing porosity include workpiece vibration, ultrasonic vibration, interlayer rolling, and reducing surface roughness, which have also yielded positive results. Improving the surface gloss of the filler wire is also an effective method for controlling porosity.

So, various methods are used to reduce porosity; for example, variable polarity arcs and different welding modes (CMT, CMT-PADV) lead to less porosity formation. In addition, mechanical methods such as workpiece vibration, ultrasonic vibration, interlayer rolling are also effective to control porosity.

As a result, preventing porosity in WAAM aluminum alloys is of critical importance to increase the mechanical performance and durability of the material. In this context, optimizing process parameters and integrating various techniques will contribute to obtaining higher quality and reliable products.

7. Discussion

WAAM has a remarkable position among additive manufacturing methods by offering a high deposition rate, low production and equipment costs and high equipment flexibility in the production of large-scale parts. The ability of WAAM to reduce deposition defects and improve material properties, especially in aluminum alloys, attracts the

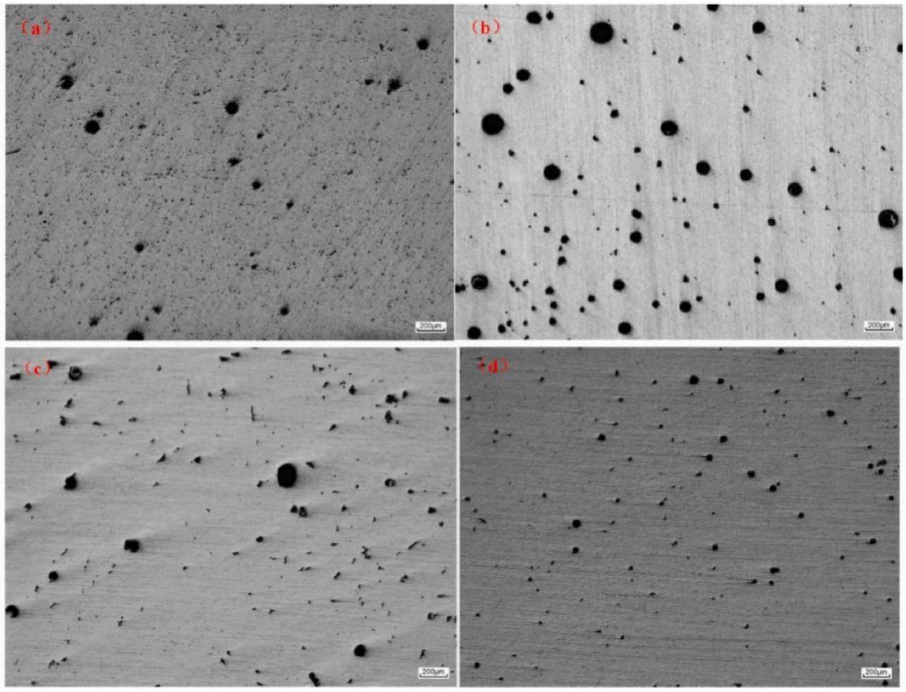

Fig. 22. Observed porosity for AA2219 produced by WAAM according to different modes: (a) CMT; (b) CMT-ADV; (c) CMT-P and (d) CMT-PADV [89].

attention of researchers and further emphasizes the potential of this process. In this context, in order for the WAAM process to be used more widely in industrial applications; homogenization of the microstructure, reduction of porosity and improvement of mechanical properties are of great importance.

Various methods developed to reduce porosity and control defects in the WAAM process are noteworthy. CMT-PADV, an advanced welding technology, has made significant contributions to reducing porosity during the deposition process. Also, interlayer rolling, low heat input, interpass cooling and FSP are used to reduce defects in the microstructure and improve material quality.

The positive effects of FSP on mechanical properties in both interlayer and post-treatment applications have been observed clearly. In the study of He et al. [178], it was stated that interlayer FSP application improved fatigue performance by reducing porosity in the AA4043 sample produced with WAAM. At the same time, it was reported that this application led to the fragmentation of the Si-rich eutectic phase and grain refinement. These findings show that FSP is an effective method for optimizing the microstructure of aluminum alloys. Similarly, it was observed by Wei et al. [179] that porosity was eliminated, and grain size was significantly reduced with interlayer FSP and subsequent T6 heat treatment of AA2024 components.

These studies show how the microstructure improvements obtained using FSP in the WAAM process can be used to improve the mechanical performance of the material. The improvements such as grain refinement, microhardness increase, and porosity elimination obtained by the FSP processes after WAAM increase the durability and longevity of the components. The study of Bai et al. [180] shows that the bilateral friction stir post-processing (B-FSP) technique is superior in eliminating porosity and improving mechanical properties compared to unilateral friction stir post-processing (U-FSP).

Optimization of processing parameters in the WAAM process is a critical factor that directly affects the quality of the manufactured components. Parameters such as voltage, nominal current, feed rate and wire feed rate determine the heat input and therefore the characteristics of the microstructure. Careful control of these parameters allows an increase the uniformity of the microstructure and to reduce of porosity and other deposition defects.

Zhou et al. [181] analyzed the effects of feed rate on mechanical properties and microstructure in the production of AA2219 alloy by WAAM. The findings showed that the size and volume fraction of equiaxed grains decreased with the increase in feed rate, which increased the UTS, YS and EL values. However, it was found that very high speeds caused a decrease in UTS. Similarly, Su et al. [182] revealed how the microstructure can be improved, and the mechanical properties can be optimized by controlling the wire feed rate and feed rate.

These results indicate that determining the optimum parameters in the WAAM process has a great impact on the microstructure and mechanical properties. Therefore, further research should focus on how to monitor and optimize these parameters more precisely and in real-time.

Advanced aluminum alloys, such as ultra-high strength Al–Zn–Mg–Cu alloys, are highly suitable for WAAM. Although there are difficulties in producing these alloys as wires, the development of new filler wires and the understanding of their effects on the microstructure offer great potential for advances in this area. Guo et al. [2] reported that the development of a new Al–Zn–Mg–Cu-Sc filler wire, called 7B55-Sc, resulted in significant improvements in hot crack resistance and tensile strength.

Optimizing the mechanical properties in the WAAM process with new-generation filler wires has the potential to expand the application areas of this technology. In the study of Jin et al. [183], it was shown that the addition of TiCnps eliminated the columnar crystals and irregular microstructural features. Such innovative approaches can further improve the performance of WAAM on aluminum alloys.

Although the use of WAAM in aluminum alloys offers significant advantages, there are still many challenges to be solved. Thus, future studies are expected to place special emphasis on the emergence of innovative filler wires, management of processing parameters with micrometric accuracy, and the fusion of various methods of manufacturing. It is believed that the use of digital technologies, in particular artificial intelligence and machine learning, for in-process control and optimization of WAAM processes will greatly enhance the scope of industrial applications of this technology. In addition to this, additional investigations are required on the utilitarian aspects of the processes related to WAAM technology. This, in particular, will include a focus on the use of green materials, or at least materials that can be recycled more efficiently, and energy saving technologies.

8. Conclusions, challenges and future trends

In this study, the use of the WAAM process in aluminum alloys has been reviewed. Significant progress has been made in the application of WAAM technology to aluminum alloys in the last decade, especially in terms of improving mechanical properties and eliminating defects encountered in production processes. The principal findings and future scope of the review article are provided below.

- The heat input applied in the WAAM process has a significant influence on the aluminum components' microstructure and mechanical properties. Due to the low heat input and wire feed stability, CMT and especially CMT-PADV technology have been distinguished as an effective and suitable method for WAAM applications. The improvements included, for example, reduced spatter and better surface finish, which facilitate the process and improve the quality of the final product. More research in the future would be to investigate these methods in greater detail on other aluminum alloys and process parameters.
- The incorporation of hybrid systems in WAAM-deposited aluminum alloys is perceived as an efficient solution in the elimination of residual stress, distortion, porosity, cracks and other inherent defects. However, the high equipment costs and requirement for more parameters are the main demerits of these systems. While interlayer rolling among hybrid methods provides an improvement in microstructure and mechanical properties, it is not suitable for complex-shaped parts. It has been stated that interpass cooling method has the potential to reduce porosity and improve mechanical properties; however, research on this subject is limited and more work is needed in this area.
- 7xxx series aluminum alloys are widely used in the aviation and aerospace industries owing to their ultra-high strength properties. However, sufficient strength values cannot be achieved in the production of these alloys by WAAM, and the production of Al–Zn–Mg–Cu alloy filler wires presents significant difficulties. Therefore, further research is recommended by WAAM to improve the machinability of alloys suitable for aviation and aerospace applications. In particular, the development of new-generation filler wires and the effects of these wires on the microstructure and mechanical properties should be comprehensively investigated.
- The issue of porosity is one of the greatest challenges facing the WAAM process. This challenge tends to change in accordance with several factors such as backing plate cleanliness, wire cleanliness, quality of surface, angle of the torch, cleanliness of shielding gas, and the parameters of welding. Prevention and minimization of porosity can be handled more efficiently through the investigation of material machinability, tool path planning regulations, and individual component characteristics. In particular, hardness, tensile strength, and fatigue performance can be increased by plastic deformation on the surface using surface treatment methods (e.g., LSP).
- In WAAM processes, surface treatment methods are essential for characterizing the mechanical properties and mitigating porosity rates. When such processes as LSP or UPT are utilized within the surface of a material, its mechanical performance improves, and risks of porosity are averted. Still, more investigation is needed on how these processes can be employed throughout the WAAM process. In particular, studies on the effectiveness of these techniques in aluminum alloys produced by WAAM need to be increased.
- WAAM technology has the potential to contribute to the circular economy and sustainable production by repairing damaged parts and using recyclable materials. However, research in this area is limited and further studies of such applications can provide significant contributions to sustainability.
- Post-process heat treatment is generally required to improve the mechanical properties of aluminum alloy parts obtained by WAAM. Heat treatments both optimize the microstructure and increase the overall strength of the material by reducing porosity. Future studies should thoroughly investigate the effects of heat treatments on mechanical properties with different parameter combinations.

In line with these conclusions, the following recommendations can be made to enhance and expand the industrial-scale applicability of WAAM technology in aluminum alloys.

- The development of new materials and filler wires should be accelerated. In particular, the development of special filler wires for high-strength aluminum alloys such as the 7xxx series will increase the usability of WAAM in critical sectors such as aerospace.
- Further research should be conducted on the optimization of process parameters and the integration of hybrid systems. The efficiency of hybrid systems should be increased, and cost-effectiveness should be ensured in production processes.
- Applications and repair efforts for environmental sustainability should be expanded. Recycling and repair applications of WAAM technology can play an important role in achieving circular economy goals.
- The use of digital technologies and artificial intelligence should be increased. The use of digital technologies and artificial intelligence algorithms in monitoring and optimizing WAAM processes will increase the efficiency of the process and improve quality.
- Optimization of heat treatment processes should be focused on. An in-depth investigation of the effects of different heat treatment parameters on aluminum alloys produced with WAAM will enable the production of parts with superior mechanical properties.

These recommendations provide a strategic roadmap to fully realize the potential of WAAM technology and increase its availability at an industrial scale in aluminum alloys.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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