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A Review on challenges and opportunities in wire arc additive manufacturing of aluminium alloys: Specific context of 7xxx series alloys

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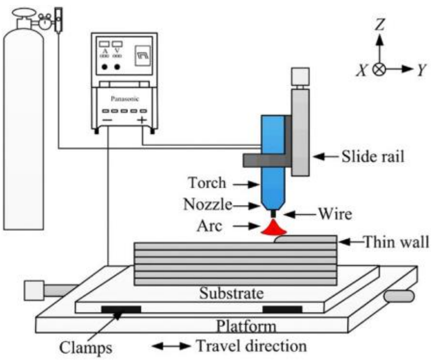

Highlights:

- Wire Arc Additive Manufacturing (WAAM) is a promising and cost-effective method for producing aluminum alloy components, particularly in the aviation and aerospace industries.
- Despite its advantages, WAAM for Al 7xxx alloys faces challenges such as zinc evaporation, hydrogen formation, oxidation, delamination, porosity, hot cracking, and complex thermal cycles, all of which can affect component quality.
- This study aims to address WAAM-related challenges by implementing Gas Metal Arc Welding techniques while also exploring further research opportunities to enhance the manufacturing process.

Abstract

Wire arc additive manufacturing (WAAM) has emerged as a promising and cost-effective method for producing components made from aluminum alloys, particularly in industries like aviation and aerospace. This process enables the fabrication of high-performance parts while minimizing manufacturing complexities. The demand for aluminum 7xxx series alloys is significant in these sectors due to their outstanding material properties. Efficient production methods, such as WAAM, are essential for utilizing these high-demand materials effectively. Despite the advantages of the WAAM process, challenges remain, particularly when layer-by-layer deposition of Al 7xxx (Al-Zn-Mg) alloys is considered. The high heat density generated during the arcing process can lead to issues such as zinc evaporation, hydrogen formation, and oxidation of the alloys. Additionally, the WAAM technique faces hurdles like delamination, porosity, hot cracking, and complex thermal cycles, all of which can adversely affect the performance of the components produced. This study aims to tackle the challenges associated with the WAAM process by employing Gas Metal Arc Welding techniques, while also exploring opportunities for further research in this area.

Keywords: WAAM; Additive manufacturing; CMT; Al-Zn-Mg alloys; Structural integrity; Low heat input

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1. Introduction

Due to their extensive application in load-bearing parts, aluminum alloys from the 7xxx series are among the most critical structural materials used in the aviation, aerospace, and automotive sectors. These alloys primarily contain zinc as the main alloying element, complemented by carefully balanced amounts of copper and magnesium. Among them, the 7068 alloy stands out as the strongest aluminum alloy available [1]. The 7xxx series components, such as aircraft frames, spars, stringers, wing skins, landing gears, etc., meet specific requirements like high specific strength, high specific stiffness, high toughness, and excellent processing and welding performance [2]. Manufacturing of such components with optimum performance is highly demanded in the industries mentioned above, which is customarily accomplished by adopting the recently developed process of additive (layer-by-layer deposition) manufacturing (AM) techniques. Additive manufacturing minimizes the overall quantity of aircraft components by allowing the design and production of parts with intricate geometries, which supports the integration of multiple parts into a single unit [2], [3]. Part consolidation offers several advantages, including reduced production costs, decreased risk of component failure, a higher strength-to-weight ratio, lighter components, and more efficient material usage despite increased part complexity [2]. Hence, a large number of AMed components have been adopted in the aviation, aerospace, and automobile industries [3], [4]. Considering the tremendous demand for Al 7xxx series alloys, wire-arc additive manufacturing (WAAM), a recently developed promising and economical technique, could be an alternative approach to metal additive manufacturing. **Figure 1** depicts the schematics of WAAM.

Mechanical and metallurgical properties of WAAMed components are quite good and well-suited for the aforementioned industries. Nevertheless, the WAAM process continues to be studied to address issues such as porosity, corrosion, delamination, residual stress, and oxidation [6], [7] for Al alloys. Conventional AM techniques like Selective Laser Melting (SLM) are not very successful for Al 7xxx alloys due to challenges like easy oxidation, high reflectivity to lasers, vaporization of Zn at high-density beams, and an unstable weld puddle [2], [8]. Due to the same issues of easy oxidation and Zn vaporization at high heat density, only a few reports have been published on WAAM of Al-Zn-Mg (7xxx series) alloys so far [9]. Traditionally, the welding of Al 7xxx components is done with Al 2xxx and Al 5xxx series welding wires [2], [8], as Al 7xxx series welding wires are not available or commercialized because of the Zn evaporation problem [9].

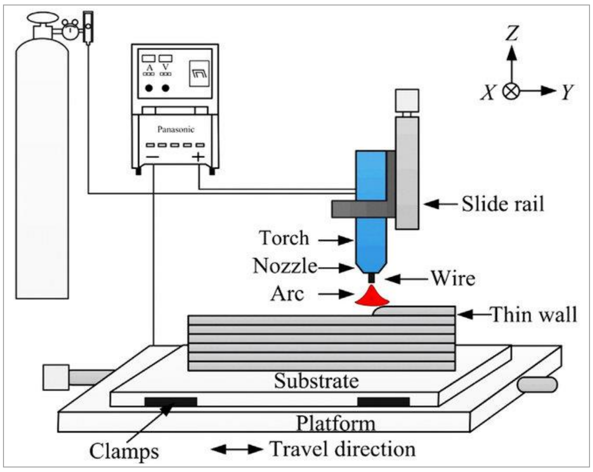

Figure 1. Schematic of WAAM process [5]

1.1. Welding Process Parameters

With regards to WAAM, the major welding parameters include welding current, welding voltage, WFS, and TS, as these parameters significantly affects the overall properties of the WAAMed built [10].

1.1.1. Welding Current

The welding current is a crucial factor as it affects the extent of heat dispersion, the configuration of the weld, and the volume of electrode used [11]. The penetration depth of the weld will increase in direct relation to the applied current, leading to an improved welded joint [12], [13]. Since the strength of the welded joint is dependent on the penetration depth, as this depth increases, the strength of the joint also escalates [12].

1.1.2. Welding Voltage

The voltage difference created between the workpiece and the tip of the welding wire is referred to as the arc voltage [14]. The depth of penetration is affected by the arc voltage and to attain the optimal penetration depth, it is essential to adjust the arc voltage to the predefined settings. Penetration reaches its maximum at a specific arc voltage and starts to decline if the arc voltage is increased beyond this optimal threshold [12].

1.1.3. Travel Speed (TS)

Travel speed (TS) is the speed at which the welding flame moves over the workpiece. Higher TS reduces heat input, resulting in narrower welds and lower penetration, while lower speed increases heat input, leading to wider welds and potential distortion. In the WAAM process, the weld bead size and weld penetration are both impacted by TS [14]. The TS needs to be slowed down to achieve the desired increase in the layer of material that is deposited [12].

1.1.4. Wire Feed Speed (WFS)

Wire Feed Speed (WFS) refers to the rate at which the filler wire is supplied to the welding arc. It plays a crucial role in determining the deposition rate, the amount of heat introduced, and the stability of the welding arc. Increasing the WFS boosts the deposition rate, allowing for quicker buildup. However, it can also raise the heat input, potentially altering the thermal cycle and contributing to residual stresses in the welded component [15].

1.2. Al 7xxx Series Alloy

Unlike single-pass welding, WAAM utilizes layer-by-layer material deposition. Therefore, heat input during WAAM is subjected to complex thermal cycles [6], [8], i.e., rapid heating above the melting temperature, quick solidification, and repeated re-heating and re-cooling cycles in deposits. In this regard, the heat input acts as a low-temperature heat treatment for the previously deposited layers [8], [16], [17], affecting pore growth and microstructure, especially in age-hardenable Al-Zn-Mg (7xxx) alloys [6]. In the context of these issues, for WAAM of Al-Zn-Mg alloys, a low-heat-input method is preferable [18]. This can be achieved by the Gas Metal Arc Welding (GMAW)-based Cold Metal Transfer (CMT) process, with its arc variation modes [6], [8], [19], for fabricating WAAMed deposits of Al-Zn-Mg alloys. Given the non-availability of Al-Zn-Mg alloy welding wires [9], custom welding wires will be drawn from extruded Al-Zn-Mg alloy rods. These wires can be used with the CMT process and arc modes for depositing Al-Zn-Mg alloy. Thus, systematic research on the highly demanded yet under-investigated Al-Zn-Mg alloy in WAAM-CMT is required to address its mechanical properties, metallurgical properties, stress corrosion cracking resistance, and porosity defects (**Table 1**). Such investigation would enhance understanding of the behaviour and associated mechanisms of Al-Zn-Mg WAAMed deposits for potential commercial applications in the aviation, aerospace, and automobile industries [20].

Table 1. Types and applications of 7xxx series Aluminium Alloy [21]

	Alloy Designation		Charactersitics
	AA	UACJ	
7xxx Al-Zn-Mg	7075	75S	Typical high-strength alloy for use in aircraft manufacture.
	7178	A78S	The strongest aluminum alloy.
	7003	ZK60 K73	An extrusion alloy for welded structures. Better extrusion properties than AA7204.
	7204	ZK141 K70 ZK147 K70Y	Alloys for welded structures. The strength at the welded part recovered almost to the same level as that of the raw material by natural aging.
	7046	ZK55 ZK170	Even stronger than AA7204. Welding and hollow extrusion are possible.
	7050	ZG62 ZC88	High-strength aluminium alloys.

2. AM of 7xxx series Aluminum Alloys: SLM, L-PBF, and WAAM

2.1. Selective Laser Melting (SLM)

The Fraunhofer Laser Technology Institute in Germany carried out the first research on the SLM technique as an additive manufacturing method for aluminum alloys in 1995 [22]. Aluminum powder was melted using a laser source to fabricate components; however, it has been noted that aluminum alloys tend to oxidize easily and exhibit high laser reflectivity, which makes selective laser melting additive manufacturing (SLM-AM) more difficult. Later, in 2011, Bartkowiak *et al.* [23] conducted research on SLM-AM for high-strength aluminum alloys using Al-Cu and Al-Zn powder with a low-power fiber laser. From this point onward, research on AM using SLM for high-strength aluminum alloys has increasingly attracted industrial attention [2]. In 2016, Kaufmann *et al.* [24] produced high-density Al 7075 alloy through the SLM process and examined the influence of preheating temperature. Nonetheless, the preheating temperature did not have a notable positive impact on minimizing hot cracks in the additive manufactured deposit. Also in 2016, Sistiaga *et al.* [25] investigated SLM for Al 7075 alloy by adding 4 wt% silicon to the Al 7075 powder, which improved the hardness of the deposit after T6 treatment. Additionally, it was reported that the inclusion of suitable alloying elements could reduce hot cracking and improve mechanical properties [25]. In 2017, Martin *et al.* [26] studied ultra-high-strength Al 7050 alloys using SLM AM followed by T6 treatment, which enhanced the tensile properties of the as-formed Al 7050 deposit. Zhou *et al.* [27] investigated the incorporation of Si and TiB2 into SLM-produced 7xxx series Al-Zn-Mg-Cu alloy. The findings indicate that the solidification cracks have been eradicated through this dual incorporation, resulting in a significantly refined microstructure. The resulting mechanical properties exhibit high Ultimate Tensile Strength (UTS) (556 ± 12 MPa) and Yield Strength (YS) (455 ± 4.3 MPa). It is hoped that this innovative method will facilitate the processing of critical engineering materials, such as the challenging-to-weld Al-Zn-Mg-Cu alloys, via SLM technology.

Tan *et al.* [28] proposed a novel approach to enhance the selective laser melting (SLM) of 7075 aluminum alloy, which is known for being difficult to process because of its high strength, poor weldability, and wide freezing range. Their technique combined substrate modification with inoculation treatment to produce dense, crack-free alloys with superior strength. By incorporating 1 wt% titanium submicron particles into the alloy powder, they attained grain refinement, which improved resistance to cracking. The modification of the substrate using thermal insulation materials, such as vermiculite, further diminished cooling rates and thermal gradients, thus reducing thermal stresses within the melt pool. This approach resulted in SLM-fabricated 7075 alloys exhibiting fine equiaxed microstructures and mechanical properties that rival those of wrought materials. Furthermore, it paves the way for SLM processing of other alloys with low processability, broadening the industrial relevance of SLM technology. The densification behaviours of 7075, 7075-AS, TI-7075, and TI-7075-AS fabricated and longitudinal EBSD-inverse pole figure (EBSD-IPF) maps of 7075, 7075-AS, TI-7075, and TI-7075-AS samples fabricated with E = 83 J/mm^3 are shown in **Figure 2** and **Figure 3**, respectively.

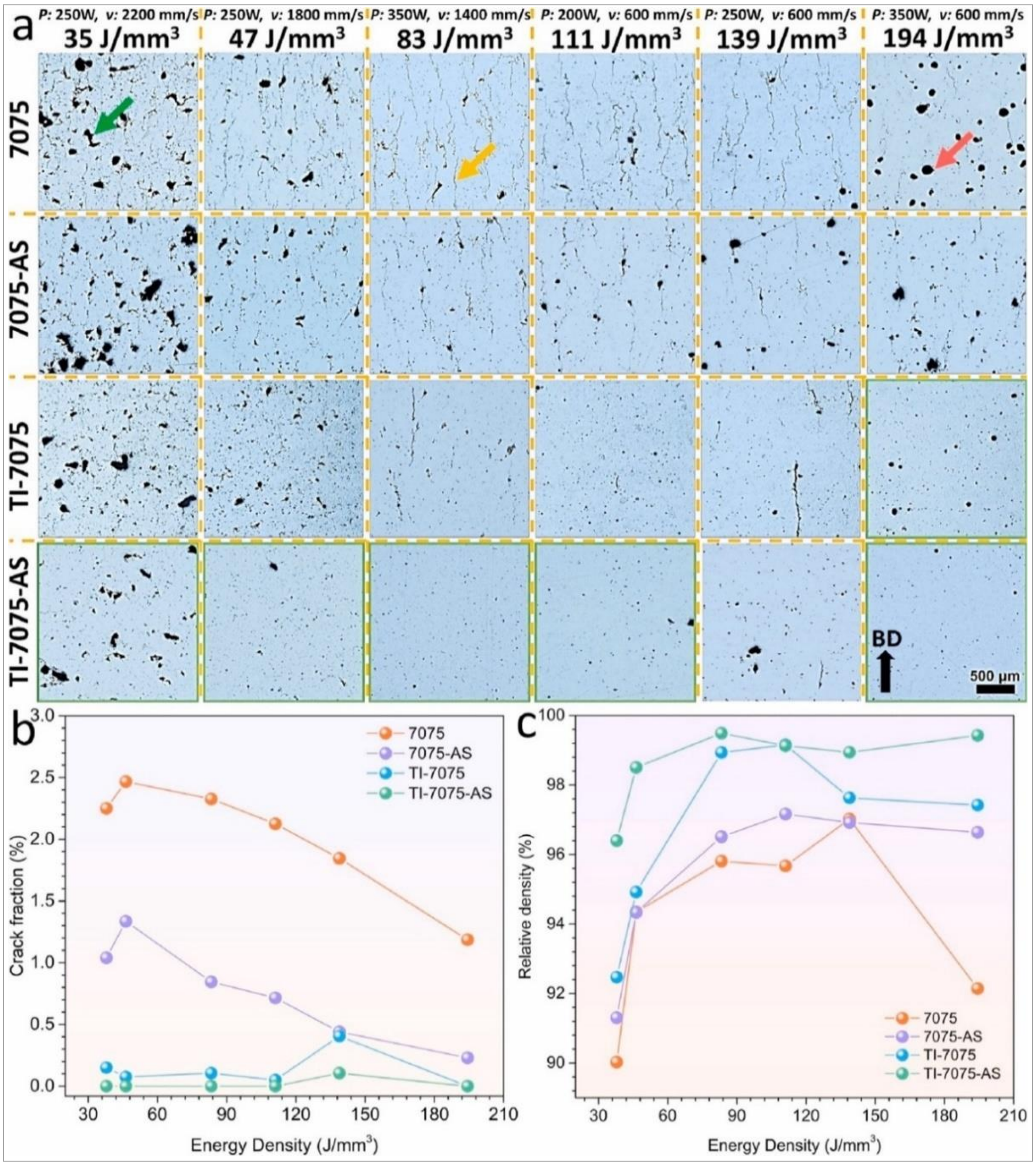

Figure 2. Densification characteristics of 7075, 7075-AS, TI-7075, and TI-7075-AS samples are illustrated through: (a) longitudinal micrographs of each sample, along with the trends in; (b) crack fraction; and (c) overall sample density in relation to laser energy density. In (a), cracks, lack-of-fusion pores, and keyhole pores are indicated by yellow, red, and green arrows, respectively. Samples that exhibit no cracks are enclosed in green frames in (a). Please note that standard deviation error bars, which are typically 12% of the mean values, have been excluded from (b) and (c) to minimize data clutter [28]

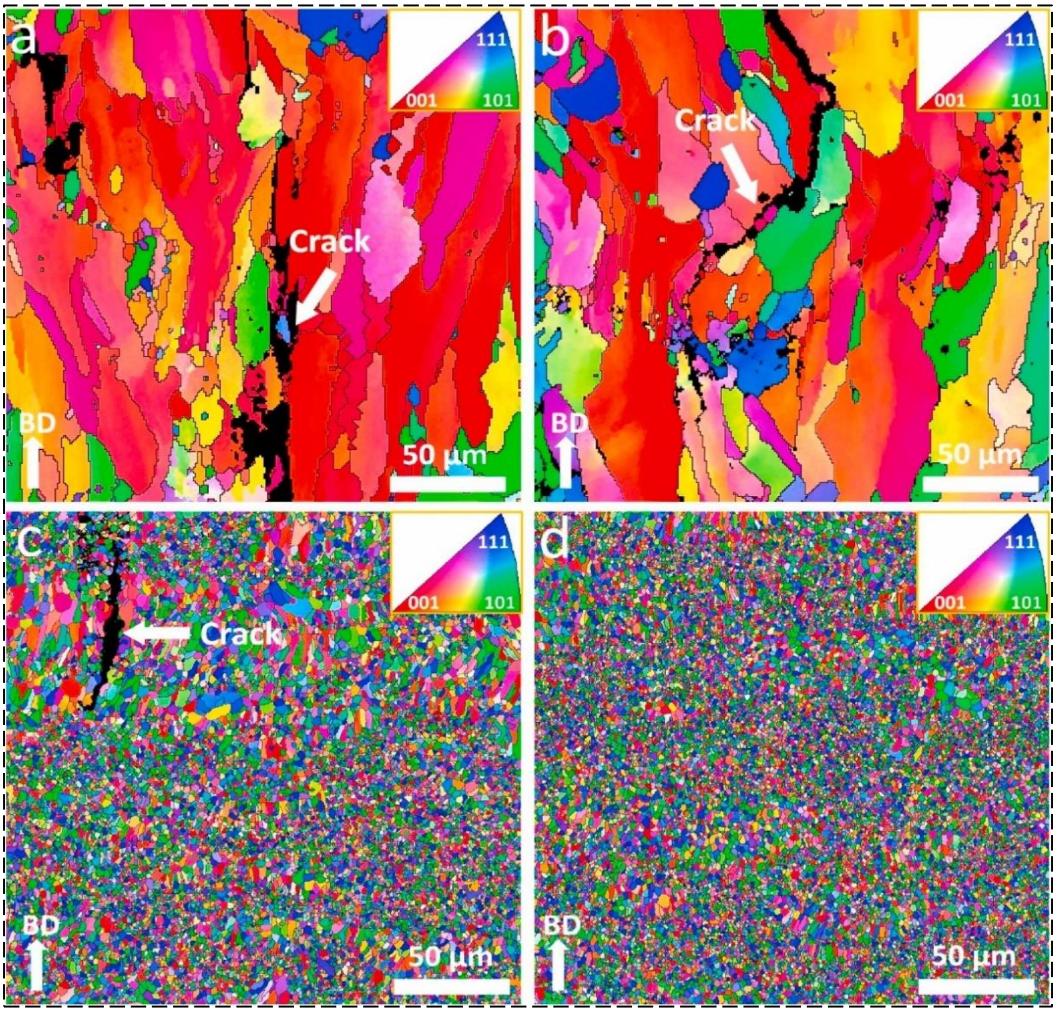

Figure 3. Longitudinal EBSD inverse pole figure (IPF) maps are shown for the following samples produced with an energy density of 83 J/mm³: (a) 7075; (b) 7075-AS; (c) TI-7075; and (d) TI-7075-AS. The maps illustrate crystal orientations along the build direction, with the IPF color code indicating the grain orientations [28]

Sistiaga *et al.* [25] added 4 wt.% silicon to 7075 aluminum alloy, which enhanced its printability. The resulting material reached a density of 98.9%; however, the yield strength remained suboptimal—about 279 MPa in the as-printed state and approximately 338 MPa after undergoing heat treatment. This shortfall is likely due to microcracks and pores in the microstructure. Subsequently, Martin *et al*. [26] applied an electrostatic self-assembly technique to incorporate nanometer-scale ZrH_2 particles into 7075 alloy powder. The alloy produced showed tensile strength between 383 and 417 MPa in the T6 condition, with elongation ranging from 3.8% to 5.4%. The release of hydrogen gas from the decomposition of ZrH_2 is suggested as a possible factor contributing to the reduced mechanical performance.

2.2. Laser-Powder Bed Fusion (L-PBF)

The 7xxx series aluminum-zinc alloys are renowned for their superior mechanical strength and are extensively utilized in the aerospace sector. However, these alloys often encounter hot cracking issues during the laser powder bed fusion (L-PBF) process. Numerous studies have explored the impact of processing parameters on defect formation in L-PBF-fabricated 7075 alloy components. The addition of silicon has been found to mitigate microcrack formation in these parts. For instance, Sistiaga *et al.* [25] reported that incorporating 4 wt% silicon particles into 7075 powder effectively prevented microcrack development. This enhancement in processability was linked to a decrease in melt pool viscosity due to the silicon. Furthermore, the study identified the formation of a new eutectic phase and significant grain refinement, both of which contributed to reducing crack initiation and growth. Aversa *et al.* [29] investigated a 7075 alloy combined with a printable AlSi10Mg alloy in a 50:50 ratio, while Otani *et al.* [30], [31] examined a 7075 alloy with an additional 5 wt% of silicon. Their findings also validated that the inclusion of silicon prevents hot cracking and results in fine primary aluminum grains. However, blending two or more powders may lead to an uneven distribution of elements, resulting in anisotropic mechanical properties within the fabricated parts.

Otani and Sasaki [31] investigated the influence of adding up to 16 wt% silicon to pre-alloyed 7075 aluminum to understand its effects on processing behavior, microstructure development, and mechanical performance. They found that, under optimal processing conditions, increasing the silicon content reduced defects such as voids and hot cracking, which in turn improved the relative density. Notably, adding 5 wt% silicon completely eliminated hot cracking and resulted in a yield strength of 360 MPa, ultimate tensile strength of 537 MPa, and 9.7% elongation before failure. However, they also noted that higher silicon content led to increased brittleness. These findings suggest that this alloy system holds strong potential for fabricating lightweight components using L-PBF, and further exploration of silicon additions could enhance performance even more.n In a related study, Martin *et al.* [26] introduced hydrogen-stabilized zirconium nanoparticles into 7075 alloy powder, which facilitated the formation of evenly distributed Al_3Zr intermetallic compounds. During solidification, these compounds acted as nucleation sites for primary aluminum, resulting in a fine, equiaxed grain structure that helped suppress microcrack formation. Following T6 heat treatment, the alloy achieved yield strengths between 325 and 373 MPa and ultimate tensile strengths ranging from 383 to 417 MPa, with elongation values between 3.8% and 5.4%, comparable to conventionally processed 7075 alloys.

Qi *et al.* [32] explored the effect of different melt pool geometries, goblet, semicircular, and a hybrid of the two, on the behavior of the 7050 alloy. These shapes correspond to keyhole, conduction, and transition welding modes, respectively. Their results showed that in keyhole mode, crack formation was reduced due to altered thermal gradients and solidification rates from the edge to the center of the melt pool. However, they also cautioned that increasing heat input to modify melt pool shapes can cause the evaporation of alloying elements such as zinc, leading to chemical inconsistencies. This approach to tailoring melt pool geometry could also be extended to other alloy systems. Kaufmann *et al.* [24] attempted to reduce hot cracking in 7075 alloy by preheating the build plate to 200 °C. However, their results showed no significant improvement in reducing hot crack formation. Mehta *et al.* [33] Mehta et al. [33] investigated the creation of a tailored 7017 aluminum alloy designed specifically for the powder bed fusion-laser beam (PBF-LB) additive manufacturing technique. This alloy was developed by adding 3 wt% zirconium (Zr) and 0.5 wt% titanium carbide (TiC) powders to standard pre-alloyed 7017 aluminum, which effectively prevented solidification cracks during production and achieved a high relative density of 99.8%. The resulting alloy demonstrated a notably higher Young's modulus, surpassing 80 GPa compared to the typical 70–75 GPa found in conventional aluminum alloys, making it particularly suitable for applications requiring enhanced stiffness. The microstructure of the printed alloy contained particles from the added powders as well as primary precipitates or inclusions formed during the PBF-LB process. Following a heat treatment similar to the T6 process but adapted for PBF-LB, the microstructure evolved to include Zr nanoparticles and precipitates based on Fe or Mg/Zn. This treatment increased the yield strength by 75%, from 254 MPa to 444 MPa, although ductility decreased from roughly 20% to about 9%. Using in-situ tensile tests combined with synchrotron X-ray computed tomography (SXCT) and ex-situ tensile tests with fracture analysis, it was found that fractures in both as-printed and heat-treated samples were primarily initiated by defects formed during printing. Nonetheless, crack growth was hindered by deflections caused by decohesion around Zr-containing inclusions or precipitates within the aluminum matrix, which helped improve ductility despite the presence of printing-related defects.

2.3. Wire Arc Additive Manufacturing (WAAM)

Gierth *et al.* [6] reported research on the $AlMg_5Mn$ alloy using the WAAM technique with energy-reduced GMAW-CMT. Various CMT arc mode variations were used in the study. They reported that the CMT-PADV arc mode is preferable for the WAAM of Al alloys due to its minimal surface irregularities, highest material utilization, lowest heat energy per unit length, and reduced porosity defects, along with improved tensile properties. In 2019, Su C. *et al.* [34] investigated the metallurgical and mechanical properties of Al-Mg alloys fabricated by WAAM using the CMT technique. They suggested that the deposit width could be controlled using the wire feed rate and travel speed ratio. They also observed porosity and cracks in the interlayer regions of the deposit. In 2020, G. Liu *et al.* [35] reported research on the Al2219 alloy using WAAM. Low heat input deposition was achieved using a double-electrode gas metal arc approach. The coupled arc included the main arc (GMA torch – substrate) and a bypass arc (GTA torch – GMA wire). The final deposit showed an interlayer microstructure with cellular and dendritic structures, which was influenced by heat input. The study also discussed porosity and eutectic phase distribution. J. Gu *et al.* [19], [36], [37], in 2016 and 2020, reported various studies on WAAMed Al alloys. Porosity and hot crack-like defects are commonly formed in WAAM components. Their investigations suggested that post-processing heat treatments and interlayer cold rolling could significantly reduce these porosity and hot crack defects; however, such post-processing adds costs to WAAMed components.

In 2021, Tawfik *et al.* [8] conducted comprehensive studies on the WAAM of aluminum alloys. They reported that WAAM of Al 6xxx and 7xxx series alloys is more challenging than that of Al 2xxx, 4xxx, and 5xxx series alloys due to defects and an unstable melt puddle. An important investigation in June 2021 on the Al-Zn-Mg (Al 7xxx series) alloy using GMAW-WAAM was reported by Sen Li *et al.* [9]. Homemade Al-Zn-Mg welding wires fabricated from Al-Zn-Mg alloy stock were used in the study. High arc temperatures led to Zn evaporation, significantly reducing its wt% in the final deposit. Zn evaporation and H_2 formation in the weld pool were identified as major causes of porosity in the deposit. T6 heat treatment significantly reduced the Al-Zn-Mg second phase particles, and the overall properties of the deposit improved after T6 treatment. Yuan *et al.* [38] employed Gas Tungsten Arc Welding with Alternating Current (GTAW-AC) as the heat source to deposit 7050 aluminum alloy layers. During the deposition process, each layer was reinforced with 2, 4, and 6 wt% titanium nitride (TiN) particles. The inclusion of TiN particles enhanced the mechanical properties, with the deposits achieving a tensile strength of approximately 207 MPa. Notably, the specimen fabricated with 6 wt% TiN particles exhibited the highest tensile strength of 286.5 MPa in the horizontal orientation. The microstructural analysis revealed the presence of α-Al, η-($MgZn_2$), S (Al_2CuMg), θ (Al_2Cu), and $TiAl_3$ phases in the coated specimens. Furthermore, the average grain size decreased significantly from 459 µm in the as-deposited condition to 104 µm in the sample with 6 wt% TiN particles. This refinement in grain structure contributed to enhanced mechanical performance of the deposits as the proportion of powder particles increased.

Daniel *et al.* [39] developed WAAM specimens using 7075 aluminum alloy reinforced with titanium carbide (TiC) nanoparticles, employing a GTAW-AC heat source. Following the deposition process, the samples underwent heat treatment to achieve the T73 temper condition. The ultimate tensile strength (UTS) was initially recorded at 377 MPa in the as-deposited state and increased to 462 MPa after heat treatment—closely approaching the UTS of the 7075-T7351 aluminum alloy plate, which is 468 MPa. The incorporation of TiC nanoparticles facilitated the formation of crack-free deposits with an equiaxed grain structure. Additionally, the heat treatment contributed to a more uniform distribution of the secondary phase, thereby enhancing the mechanical properties of the alloy. In a separate study, Guo *et al.* [40] employed a GTAW heat source to fabricate WAAM components from 7055 aluminum alloy. After deposition, the samples were subjected to solution heat treatment at 460 °C, 465 °C, and 470 °C, followed by artificial aging at 120 °C for up to 110 hours. Hardness measurements were conducted at aging intervals of 6, 11, 65, and 110 hours. Regardless of the solution treatment temperature, all samples reached their peak hardness after 65 hours of aging. The hardness values for samples solution treated at 470 °C, 465 °C, and 460 °C and aged for 65 hours were 205.8 HV, 192.7 HV, and 191.2 HV, respectively, indicating superior hardness at the highest treatment temperature (470 °C). The ultimate tensile strengths (UTS) measured were 226 MPa for as-deposited samples, 385 MPa for those only solution treated at 470 °C, and 562 MPa for samples that also underwent 65 hours of aging. Microstructural examination revealed Al_3Fe and T-(AlZnMgCu) phases in the as-deposited condition, while the aged samples exhibited nanoscale η′ phases that contributed to improved mechanical strength. However, the WAAM process still faces issues such as porosity, cracking, uneven microstructures, distortion, and residual stress. The WAAM process presents challenges like porosity, cracks, inhomogeneous microstructure, distortion, and residual stresses. These defects are closely related to thermal distortion caused by accumulated heat [6], [10], [15] in steady weld pools due to inappropriate process parameters [23].

WAAM deposits are subjected to complex thermal cycles [8], including rapid heating, cooling (solidification), and repeated re-heating and re-cooling cycles [8]. Heat input from these thermal cycles acts like a low-temperature heat treatment for the previously deposited layers [6], resulting in a non-equilibrium composition and inhomogeneous (coarse, fine, cellular, and columnar) microstructures [8]. Several researchers have contributed to the study of WAAM, with most research focusing on its industrial applicability [3], [41]. Singh *et al.* [42] investigated Al 7050 alloy using SLM-AM (not WAAM) by adding Ni to the Al powder, which led to the formation of Al3Ni intermetallics in the deposit, reducing ductility. The deposits were then post-processed using friction stir processing (FSP), which refined the Al3Ni intermetallics in the α-Al matrix. This FSP improved the deposit's strength and elongation [42]. In 2011, Suryakumar *et al.* [43] conducted research on hybrid layered manufacturing concerning weld bead modelling and process optimization. They reported that the metal wire deposition rate in WAAM is around 15–130 g/min, which is higher than conventional AM processes like SLM [7], [41].Vimal *et al.* [7] reported that, for the WAAM process, gas tungsten arc GTAW, GMAW, and CMT are the most commonly used techniques. The CMT process is an advanced version of GMAW-based WAAM, where variations in arc modes are controlled. This includes CMT pulse (CMT-P), CMT advanced (CMT-ADV), and CMT pulse advanced (CMT-PADV). These arc mode variants are effective in controlling porosity defects during WAAM deposition [6], [7]. Only limited research has been conducted on the WAAM of Al 7xxx series alloys, and there remains a significant need for further study using CMT and its variants for Al 7xxx series alloys.

Yoder *et al.* [44] investigated a deformation-driven additive manufacturing method designed to address the difficulties in producing high-strength aluminum alloys like 7075, which are typically non-weldable. Traditional beam-based additive manufacturing often suffers from hot cracking during solidification and the loss of solute elements through vaporization, resulting in mechanical properties that fall short of those found in wrought counterparts. In contrast, their approach relied on frictional heating to induce rapid plastic deformation, producing a refined, equiaxed microstructure with no surface or interfacial porosity. After undergoing proper solution treatment and aging, the printed alloy achieved yield strength, ultimate tensile strength, and elongation values of 477 MPa, 541 MPa, and 8.2%, respectively, on par with wrought AA7075-T6 and significantly better than beam-based processes. Importantly, these results were attained without the addition of new alloying elements or nanoparticles, highlighting the reliability and reproducibility of the method.

Meanwhilae, Li *et al.* [9] conducted an investigation on the microstructural characteristics and mechanical behavior of an aluminum alloy wall produced through Wire Arc Additive Manufacturing (WAAM), utilizing a specially developed Al-6.2Zn-2.2Mg welding wire and a gas welding arc as the thermal input. The study involved a comparative analysis between samples in their as-deposited form and those subjected to T6 heat treatment. In the as-deposited specimens, numerous secondary phases were identified, with compositional analysis indicating a non-uniform distribution of zinc and magnesium elements. Upon applying T6 heat treatment, there was a notable reduction in both the quantity and size of these secondary phases, facilitating the dissolution of Zn and Mg into the aluminum matrix, which in turn enhanced homogeneity and improved material performance. **Figure 4** shows the microstructure and elemental distribution before and after the T6 treatment, while **Figure 5** summarizes the changes in mechanical properties. Specifically, the ultimate tensile strength (UTS) increased from 299–324 MPa to 389–402 MPa, elongation decreased from 8.98%–9.66% to 4.18%–5.57%, and microhardness rose from 113 HV to 150 HV following the treatment.

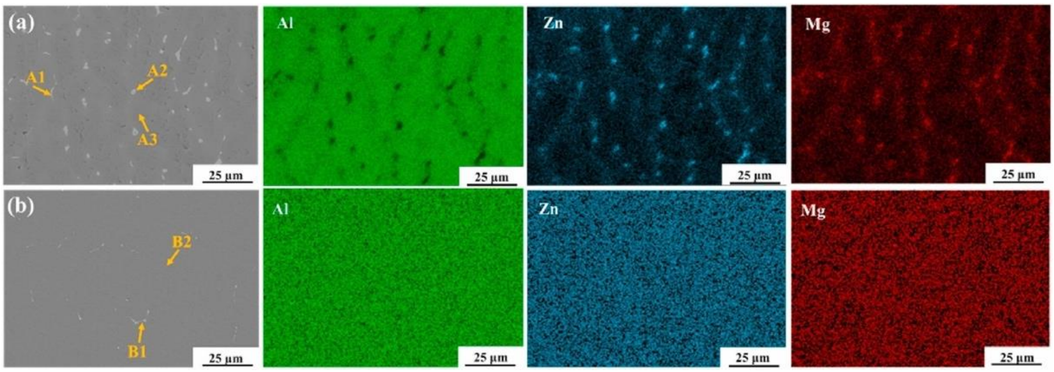

Figure 4. (a) The deposit's SEM micrograph along with its corresponding elemental mappings are shown; and (b) the SEM micrograph and elemental mappings of the deposit following the T6 heat treatment (T6 HT) are also presented [9]

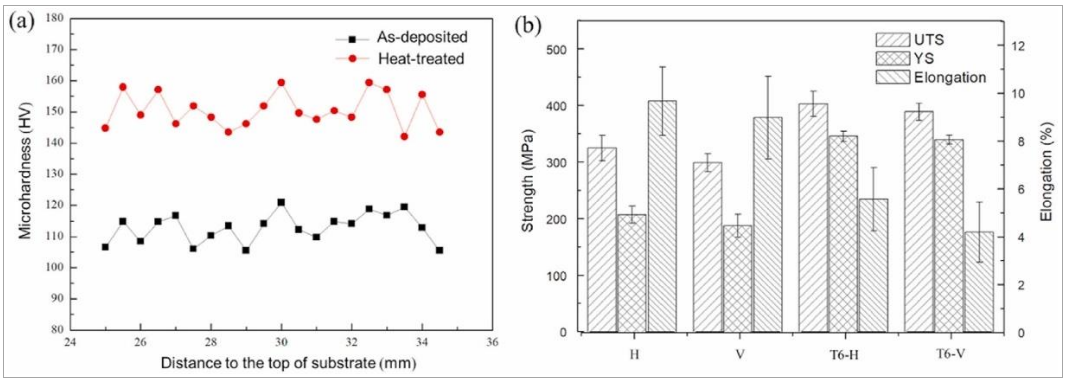

Figure 5. Mechanical properties of the deposit and the sample heat-treated under T6 conditions: (a) microhardness and; (b) tensile properties [9]

3. Technical Challenges during Fabrication of Al-7xxx Alloy

The material design of a part plays a critical role in its ability to endure harsh conditions, particularly in aerospace and aviation applications. Any failure of such parts can have severe consequences. Several types of defects occur in AMed parts of 7xxx high-strength Al alloys due to the manufacturing conditions and the alloys' properties. These include porosity [45], residual stresses and distortion [15], [46], cracks [47], an inhomogeneous microstructure, balling and satellite generation [48], oxidation, and evaporation of volatile alloying elements. The occurrence of these defects is often linked to factors such as thermal distortion caused by accumulated heat [10], unsteady weld pools resulting from inappropriate parameter selection [49], poorly designed programming strategies, environmental factors like gas pollution [50], and equipment malfunctions. Eliminating these challenges is essential for improving the quality and performance of WAAM-manufactured parts and ensuring the reliability of the components.

3.1. Cracking

Crack formation during additive manufacturing (AM) arises from several factors, including the presence of porosity, which serves as a starting point for cracks, as well as thermal cycles and solidification processes inherent in the manufacturing method. **Figure 6** illustrates the occurrence of cracks in AM-fabricated AL 7075. Cracking in aluminum alloys during AM can be broadly categorized into liquation cracking and solidification cracking [22]. Liquation occurs when specific parts of the microstructure melt selectively under heat exposure. This often involves second-phase particles or grain boundaries with high segregation, which melt at lower temperatures than the surrounding matrix, leading to localized melting and subsequent separation. Factors contributing to liquation cracking include a high concentration of alloying elements, the excellent thermal conductivity of heat-treatable aluminum alloys, and process parameters such as high laser power or rapid scanning speeds. In contrast, solidification cracking takes place in the final stages of solidification when insufficient liquid metal is available to fill gaps created by the shrinking solid metal, which has a lower volume than its liquid counterpart. This type of cracking is linked to a wide solidification temperature range ($\Delta T = T_{liquidus} – T_{solidus}$) and is especially common in AM of high-strength aluminum alloys, notably those in the AA2xxx series [51]. Due to the susceptibility to cracking during the rapid solidification of high-strength aluminum alloys, researchers have examined crack formation in multiple studies related to alloys such as AA2024 [52], [53], AA7050 [32], and AA7075 [24], [25], [26], aiming to minimize crack occurrence. As these alloys solidify, columnar grains grow along the thermal gradient, while shrinkage occurs at the grain boundaries, leading to the development of cracks. These solidification cracks typically initiate and propagate during the final stages of solidification, particularly along the grain boundaries [32].

Hot cracking, or solidification cracking, presents a significant challenge in WAAM of aluminum 7xxx series alloys. These cracks form during the final stages of solidification as the material struggles to accommodate internal stresses from temperature gradients. A primary cause is the wide solidification range of Al 7xxx alloys, which makes them prone to cracking. During WAAM, rapid heating and cooling contribute to forming brittle grain boundary films of low-melting phases that easily crack under thermal and residual stresses. Additionally, intense thermal cycling in WAAM generates substantial thermal stresses. Different regions of the deposited material cool and solidify at varying rates, resulting in tensile stresses that initiate and propagate cracks, particularly along grain boundaries. Furthermore, the high zinc and magnesium content in 7xxx alloys can cause segregation at grain boundaries, lowering the local melting point and worsening

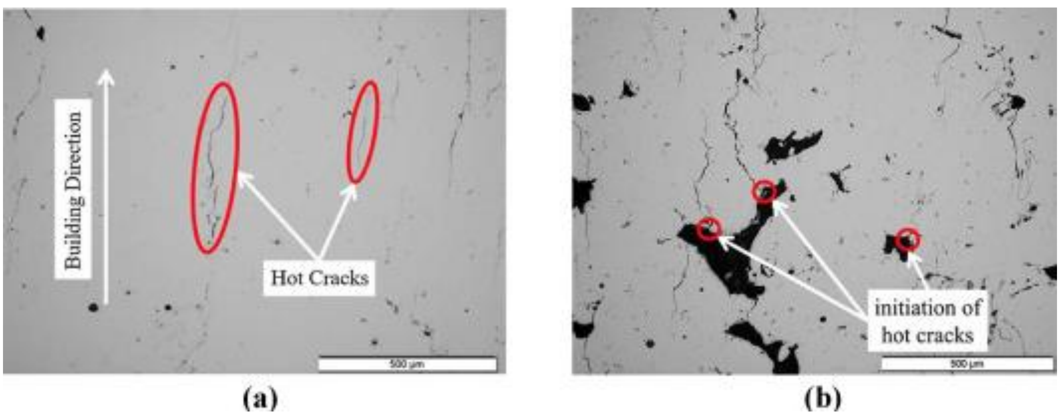

Figure 6. Cracking in AMed parts: (a) SEM microscopy of hot cracking in SLMed AA7075 with 500 W laser power and 1200 mm/s scanning speed [24]; (b) Porosity formation and hot crack initiations due to porosity of SLMed AA7075 [24]

hot cracking, especially in alloys with high zinc content like AA7075. Several strategies can be employed to alleviate hot cracking. Process optimization, such as adjusting heat input, layer height, and interlayer cooling time, can reduce temperature gradients and minimize cracking. Additionally, alloying adjustments and adding grain refiners can help refine the microstructure and reduce the likelihood of solidification cracking, enhancing overall material integrity.

3.2. Porosity

Another reason limiting the widespread commercial application of WAAM in aluminum alloys is the inherent difficulty in processing specific series like the 7xxx and 6xxx families. These series present challenges mainly because welding defects such as porosity and an unstable melt pool frequently occur during additive manufacturing (WAAM). **Figure 7** depicts the defects which are common among the AM of aluminium alloys. Porosity is the predominant obstacle associated with WAAM of aluminum alloys, as it significantly undermines the mechanical properties of the manufactured components [37], [54], [55], [56]. The presence of porosity compromises the part's strength, primarily due to damage from microcracks [57]. Additionally, it also diminishes fatigue strength by causing variations in size and shape distribution within the additively manufactured component. A primary cause of porosity is hydrogen entrapment. Molten aluminum has a high affinity for hydrogen, absorbing it from the surrounding atmosphere, especially if the shielding gas (usually argon) contains any moisture. During solidification, the absorbed hydrogen is expelled, forming gas pores within the solidified structure [58], [59]. Additionally, contaminants in the wire feedstock or shielding gas, such as moisture or impurities, can introduce hydrogen into the molten pool, further increasing the likelihood of porosity. Improper process parameters as excessive travel speed, incorrect wire feed rate, or unsuitable shielding gas flow rate can also destabilize the molten pool, resulting in poor gas shielding and enhanced porosity formation [60]. Consequently, minimizing or eliminating porosity is essential. Typically, the formation of porosity can be categorized as either raw material-induced or process-induced [61]. The wire used in WAAM typically contains surface contaminants like moisture, grease, and hydrocarbons, which are difficult to fully remove. These impurities can enter the molten pool during deposition, causing porosity in the final solidified product. For this reason, it is essential to thoroughly clean the raw wire, especially when working with aluminum alloys, to minimize pore formation. In contrast, pores that form due to the process itself are usually irregular in shape and result from poor path planning or inconsistent layer deposition. Complex deposition paths or fluctuating process parameters can lead to problems such as incomplete melting or spattering, which create voids in the material. To address these issues, strict control over the shielding gas, using high-purity argon and ensuring proper flow rates, is important to limit hydrogen contamination. Additional measures like preheating the substrate and reducing cooling rates can help lower hydrogen uptake. In certain cases, applying a vacuum treatment can further reduce gas absorption in aluminum alloys, thereby decreasing porosity in the final component.

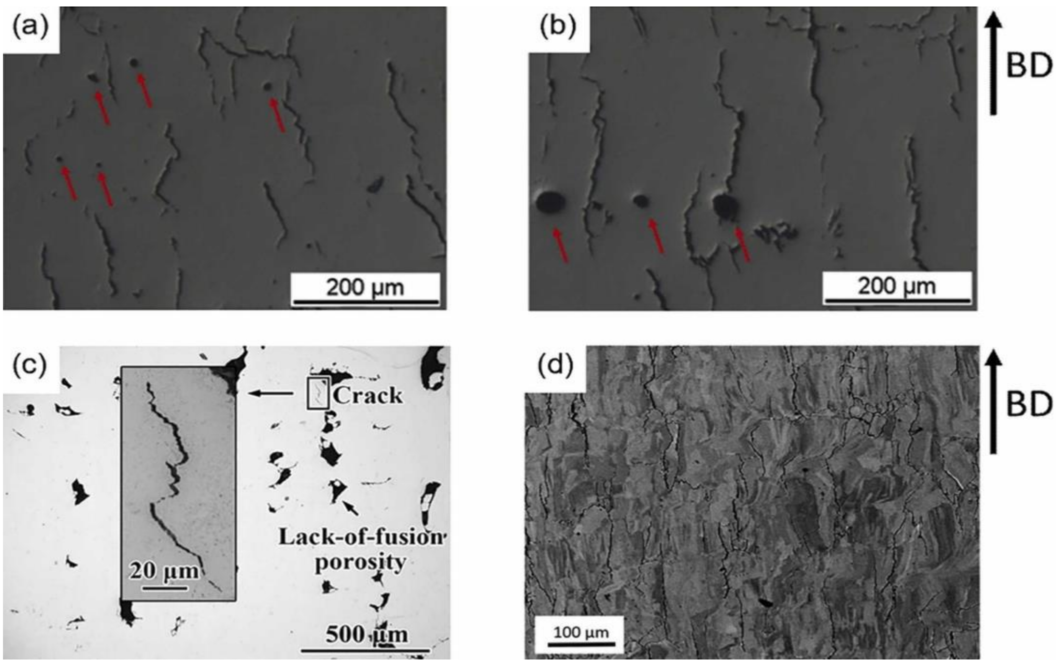

Figure 7.
Two kinds of defects in AM of aluminum alloys: (a-b) Spherical pores with different sizes [66]; (c) irregular holes due to lack of fusion and solidification cracks [67] and; (d) solidification cracks [66]

3.3. Residual Stresses and Distortion

Residual stresses are a common challenge in WAAM due to localized heating and rapid cooling cycles [62]. In aluminum 7xxx series alloys, these stresses can cause warping, cracking, and part distortion [63]. Steep thermal gradients created during rapid heating and cooling [64], [65] lead to differential expansion and contraction across layers, generating high residual stresses. Additionally, layer-by-layer deposition in WAAM leads to a cumulative buildup of these stresses, causing distortion over time, particularly in thin-walled or complex geometries [15]. The material characteristics of Al 7xxx alloys also play a role; these alloys exhibit low ductility at room temperature, making them less capable of accommodating residual stresses without cracking or warping. Mitigation strategies for residual stresses include interlayer temperature control to maintain a consistent temperature across layers, reducing thermal gradients and associated stresses. Post-process stress relief treatments, such as annealing or solution heat treatments, can also alleviate residual stresses. Optimized deposition path strategies, like zigzag patterns or adaptive path planning, can help achieve more uniform heat distribution, minimizing stress concentrations.

3.4. Anisotropy

WAAM components frequently display anisotropic mechanical characteristics, indicating that their strength and performance change based on the direction of the applied load. [9]. This issue is particularly noticeable in aluminum 7xxx series alloys. The layered deposition process in WAAM results in different cooling rates between the vertical (build) direction and the horizontal (layer) direction, promoting a columnar grain structure along the build direction [68]. This contributes to anisotropic behavior, with weaker mechanical properties in certain directions, such as the vertical compared to the hori zontal [34]. Additionally, directional solidification influenced by deposition direction and solidification rates affects the grain orientation and morphology. To mitigate anisotropy, post-process heat treatments like solution treatment followed by aging can help homogenize the grain structure. Tuning process parameters, such as heat input and travel speed, can also alter cooling rates and grain morphology, leading to more uniform mechanical properties across different directions.

3.5. Oxide Formation and Fusion Defects

Aluminum alloys, including the 7xxx series, naturally form an oxide layer when exposed to air, which can cause challenges during WAAM by impeding proper fusion between layers. This oxide layer is highly stable and reforms rapidly, even after cleaning. During WAAM, the oxide layer may not fully melt or mix with the molten pool, causing defects such as inclusions or incomplete bonding. While the CMT process uses less heat than traditional arc welding, insufficient heat input may prevent full melting of the oxide layer, leading to fusion defects. Mitigation strategies include thorough surface preparation, such as cleaning the wire and substrate before deposition, to reduce oxide layer presence. Proper inert gas shielding with appropriate flow and coverage can minimize oxide formation. Optimizing heat input to ensure full melting of the oxide layer without causing excessive heat that could lead to distortion is also essential for achieving good fusion.

3.6. Balling and Satellite Generation

Considering the principle of minimizing surface energy, liquid metal used in additive manufacturing (AM) processes can retract into a spherical form due to surface tension, especially when it has limited contact with the substrate. This tendency to form spheres is known as the balling phenomenon [69]. As a result, insufficient surface contact in aluminum alloys due to the balling phenomenon leads to uneven surfaces on the solidified layers, ultimately reducing the overall quality of the part. In additive manufacturing (AM) of high-strength aluminum alloys, balling is commonly associated with the melting and sintering stages. This effect can also be triggered by droplet splashing and poor wettability during the AM process. However, when sufficient melting occurs in the lower part of the melt pool, the occurrence of balling tends to decrease [70]. Another form of surface defect, known as satellite formation, differs from balling in terms of both its microstructure and appearance. Unlike the round shape seen in balling, satellite defects are made up of several small particles attached to the surface layer. Their formation is significantly affected by the scanning strategy and processing parameters [71]. In the study by Aboulkhair *et al.* [71], it was observed that the formation of satellites during selective laser melting (SLM) of AlSi10Mg decreased significantly when the scanning speed was set to 250 mm/s, compared to higher speeds of 500 mm/s or 750 mm/s. The pronounced presence of balling and satellite formation at a laser scanning speed of 750 mm/s for the AlSi10Mg alloy, along with the SEM image showing the oxide film morphology of SLMed AA6061, are illustrated in **Figure 8a** and **Figure 8a**, respectively.

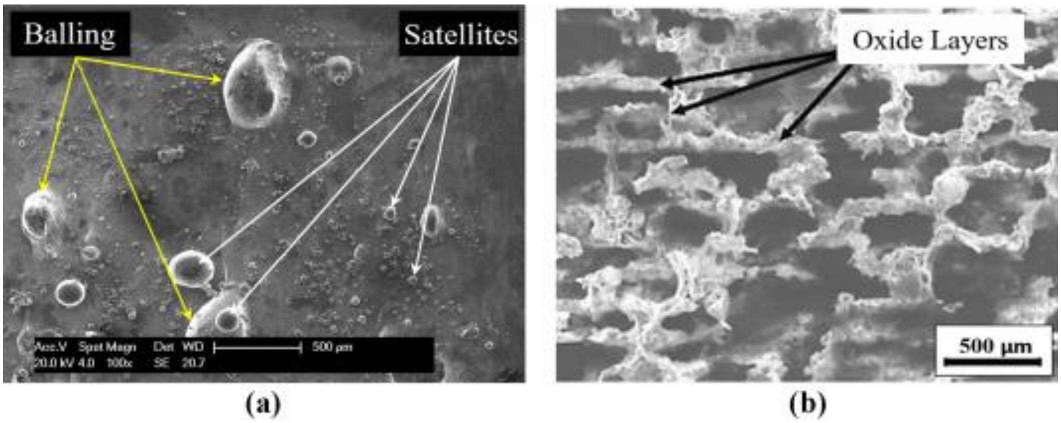

Figure 8. Surface defects of AMed parts: (a) Balling of high strength AlSi10Mg in SLM at 750 mm/s scanning speed [71]; (b) SEM image of oxide film morphology of SLMed AA6061 [72]

3.7. Post-Processing Challenges

Post-processing is often essential to enhance both the mechanical properties and surface finish of parts produced through WAAM, particularly in Al 7xxx alloys [37]. These alloys require solution heat treatment followed by aging to reach their full-strength potential. This arises primarily from the material properties of the 7xxx series, which achieves high strength through solid solution strengthening and precipitation hardening. The WAAM process can disturb the distribution of these strengthening precipitates, making post-process heat treatment crucial for restoring full mechanical properties [73]. Additionally, WAAM parts typically have a rough surface finish due to the deposition method, often requiring further post-processing, such as machining or polishing, to meet the standards for critical applications [74]. To address these challenges, carefully designed heat treatment protocols, including specific solution treatment and aging steps, are essential to optimize strength. Hybrid manufacturing approaches that combine WAAM with subtractive techniques, such as CNC machining, can also help achieve smoother surface finishes and tighter dimensional tolerances, making the parts suitable for demanding applications [75].

4. Opportunities and Scope for Advanced Research in AM of 7xxx Series Alloys

AM is a demanding technique that attracts the attention of aviation, aerospace, automobile, and other industries owing to its unique features of time-saving, cost-saving, and better properties of AMed components [3], [6], [7], [8]. The present proposal focuses on the Al 7xxx series (Al-Zn-Mg) alloys for additive manufacturing using welding-arc techniques (WAAM), which is least investigated [2], [9]. It demands detailed investigation in the context of properties, WAAM-tailored defects, and the behavior of fabricated components under several weld thermal cycles (during layer-by-layer deposition). This research would directly impact the adoption of WAAM techniques for Al 7xxx series alloys in the aforementioned industries in the context of economic welfare, structural integrity of the critical components, and specific process capabilities for the WAAMed components with desired sound properties. As reported by B. Zhou *et al.* [2], Al 7xxx series alloys have been AMed using SLM techniques, and detailed research on Al-Zn-Mg alloys with WAAM is still lacking, which requires further investigation [9].

Based on the literature review, Sen Li *et al.* [9] investigated Al-Zn-Mg alloys using homemade welding wires, and this is the only research (recently in 2021) reported so far on WAAM of Al-Zn-Mg alloys using the GMAW process while WAAM CMT remains unattempted. Moreover, they reported the final deposit with a 44 wt% reduction of Zn owing to Zn evaporation [9], and such composition does not meet the properties of Al-Zn-Mg alloys (7xxx series) used in industries [2]. The SLM technique has certain limitations with powder-based deposition of Al-Zn-Mg alloys. Aluminum has high reflectivity for lasers, and the deposition rate of SLM is quite lower than that of WAAM techniques [2], [7], [8]. Considering the benefits of WAAM techniques over SLM techniques, it could be the candidate process for AMed components in potential industries [7], [8].

Considering the present challenges and limitations as discussed for the SLM and WAAM techniques for Al-Zn-Mg alloys, there is a need for investigations that could address those limitations and challenges. The extruded bar stock of Al 7xxx alloy could be used to draw the welding wires, which was used by Sen Li *et al.* [9] in 2021, and would be used as homemade welding wires of Al-Zn-Mg alloy of the Al 7xxx series. The low-energy or heat input approach of CMT and its arc variation modes have been proven significantly beneficial in the context of arresting defects and final component properties [6], [7], [8], [9] for the other grades of the Al-alloy series. Hence, the present project would adopt the GMAW-based CMT arc variation modes for the WAAM of Al-Zn-Mg alloy.

Considering the limitations suggested by Sen Li *et al.* [9], an appropriate composition of additional flux+metal powder could be employed to gain the required composition of the final deposit as specified or for standard Al 7xxx alloy. Using an appropriate composition of additional flux+metal powder would facilitate the absorption of Zn vapors and H_2 during the welding arc. CMT-based process parameters, gas flow rate, and Al-Zn powder would be the main controlling factors for the WAAM process. The detailed investigation would include the heat input analysis along with validation by thermocouples (to be attached to deposited layers). This could address the issue of the delamination effect and low-temperature heat treatment of the deposited layers because of several welding thermal cycles in layer-by-layer deposition. Metallurgical studies could address the phase transformation and quantification of formed defects like pores and hot cracks if they occur. Al-Zn-Mg alloys are age-hardenable, and without significant heat treatment, they cannot be placed in end applications in industries [2]. Hence, the T6 thermal cycle and modified thermal cycle [2] would be given to the WAAMed deposit. Such heat treatments are required to arrest the stress corrosion cracking (SCC) issues of Al-Zn-Mg alloys [2] and improve the SCC resistance of WAAMed Al 7xxx alloy deposits.In the present scenario, such investigations for the hardly investigated WAAM of Al-Zn-Mg alloys have not been addressed. Hence, for scientific understanding and adoption of proposed research outcomes in potential industries, highly demanded advanced research in the field must be investigated. Furthermore, the research and investigation of WAAM of Al 7xxx series alloys would need to commence to understand the mechanisms with reduction of defects to produce good quality WAAMed components for aviation, aerospace, and automobile industries, where structural integrity is the critical concern for any WAAMed components or parts.

5. Summary and Findings

Aluminum 7xxx series alloys are in high demand in aviation, aerospace, automotive, and other industries. WAAM is a viable manufacturing process for rapidly producing high-density components. However, challenges in WAAM for Al 7xxx alloys have limited its industrial adoption. This study explores these challenges and highlights research opportunities to enhance manufacturing processes and heat treatments for WAAMed components. This work aims to address existing barriers and broaden the scope for implementing WAAMed Al 7xxx alloys in critical applications.

Key Findings:

- Al 7xxx series alloys, primarily composed of Al-Zn-Mg, are vital in aerospace, aviation, and automotive industries due to their excellent strength-to-weight ratio, high toughness, and corrosion resistance.
- Among these, 7068 and 7075 alloys are particularly noteworthy for their high strength and broad application in structural components.
- Conventional techniques like Selective Laser Melting (SLM) face issues such as high reflectivity of aluminum, Zn vaporization, and porosity.
- WAAM emerges as a promising alternative but is still underexplored for Al 7xxx series alloys.
- WAAM enables complex topologies and reduces manufacturing costs but introduces challenges like porosity, residual stresses, cracking, and oxidation.
- Zinc evaporation, hydrogen-induced porosity, and the formation of unstable grain structures are significant barriers.
- Techniques like custom welding wires (e.g., Al-Zn-Mg rods) and low-heat-input processes (CMT) mitigate some defects.
- Post-process heat treatments (e.g., T6 aging) and advanced process parameters can refine microstructure and improve mechanical properties.

- Despite progress, WAAM for Al 7xxx alloys remains inadequately researched, especially in applying advanced methods like CMT with arc variations.
- Studies must address thermal cycle effects, phase transformation, and long-term material behavior under operational stresses.
- Successfully addressing these challenges can make WAAM a cornerstone in producing lightweight, strong, and durable components for critical applications in aviation and beyond.

6. Recommendations for Future Research

- Development of optimized alloys and wire compositions tailored for WAAM to overcome issues like cracking and porosity.
- Enhanced understanding of thermal management during WAAM to minimize defects and improve layer bonding.
- Exploration of hybrid approaches combining WAAM with other manufacturing or post-processing techniques for superior material properties.
- Detailed studies on the effects of varying parameters (e.g., gas flow, interlayer cooling) to achieve process stability and consistency.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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