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Current Status of High-Strength Aluminum Alloy Arc Additive Manufacturing Technology

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Abstract: Wire Arc Additive Manufacturing (WAAM) combines the advantages of arc welding and additive manufacturing. It has the characteristics of high material utilization and low production cost. It shows significant advantages in the field of forming and manufacturing large and complex components of high-strength aluminum alloy, especially in the manufacturing of large structural parts in the aerospace field. This paper focuses on the research progress of high-strength aluminum alloy WAAM technology in recent years, including process innovation, microstructure regulation, performance optimization and industrial application progress, and summarizes and discusses the future development direction. First, the outline and research status of high-strength aluminum alloy arc additive manufacturing technology are introduced. Then, the challenges and solutions faced by the technology are analyzed, such as unstable manufacturing process, poor controllability of forming accuracy and forming quality, and easy existence of manufacturing defects such as pores and cracks. The influence and coping strategies of these problems in the manufacturing of large aerospace structural parts are discussed. Finally, the arc additive manufacturing technology of high-strength aluminum alloy was summarized, and the technical problems and development direction that need to be solved in the future application of large aerospace structural parts were prospected.

Keywords: Wire Arc Additive Manufacturing; High-Strength Aluminum Alloy; Manufacturing Defects; Aerospace; Research Status.

1. Introduction

Additive manufacturing (AM) is a manufacturing method that forms solid parts by stacking materials layer by layer [1, 2]. Compared with the traditional subtractive processing method, additive manufacturing has many significant advantages, such as the ability to directly produce parts with complex structures, improve material utilization, and reduce material manufacturing time [3]. With the rapid development of the technology, its application in aerospace, automobile, medicine and other industries has become increasingly widespread. Especially in the field of metal additive manufacturing, its technical advantages are reflected in the ability to achieve highly complex metal components that are difficult to produce by traditional manufacturing processes, such as metal prostheses and the demand for large-scale, integrated complex structural parts in the aerospace field [4]. Over the past 30 years, researchers have carried out a large number of research work in key links such as material selection, process technology, process simulation, stress and deformation control, defect detection and analysis, and subsequent processing, and have achieved rich results in both academia and industry [5].

The commonly used aluminum alloy additive manufacturing methods are powder bed fusion (PBF) and wire arc additive manufacturing (WAAM). PBF technology uses thermal energy to bond powder materials together to synthesize solid shapes, and according to the different heat sources, it is divided into Selective Laser Melting (SLM) and Electron Beam Selective Melting (EBSM)[6]. Due to the characteristics of aluminum alloy such as easy oxidation and high cost of powder material production, the research on additive manufacturing of aluminum alloy using PBF technology is greatly limited. The SLM process uses a laser to melt powder materials and then superimposes them layer by layer. It has been widely used in the fields of titanium alloys, nickel-based alloys, alloy steels and other materials. However, aluminum alloys have high thermal conductivity, reflectivity and low laser absorption rate (about 17%), which makes it extremely easy to cause laser energy loss during the production and processing process. The powder cannot be completely melted, resulting in large thermal stress, internal porosity, thermal cracks and other defects. The scope of application is very limited. At present, only AISi10Mg alloy is widely used in SLM technology [7, 8]. For large-sized, high-strength aluminum alloy complex structural parts required in the aerospace field, the forming efficiency, equipment cost and component size limitations of SLM technology make it difficult to meet the needs of large-scale production. EBSM technology uses electron beams to melt and form powder materials, and has the characteristics of high energy density, high density, low reflection, and high efficiency. However, EBSM needs to be carried out in a vacuum environment, the equipment investment is huge, and the size of the forming compartment is limited, which also makes it difficult to manufacture large aviation structural parts economically and efficiently. Compared with other technologies, WAAM technology has unique advantages in the additive manufacturing of aluminum alloys, especially in the low-cost and high-efficiency manufacturing of large-scale and integrated complex structural parts in the aerospace field, due to its relatively low equipment cost, high material utilization rate, fast forming efficiency, and the ability to manufacture super-large-size components without being restricted by the vacuum chamber.

Compared with traditional casting, WAAM has the characteristics of high heat input, fast forming speed and high nucleation density. According to the kinetic theory, its rapid non-equilibrium solidification process inhibits the diffusion of solute atoms and greatly improves the solid solubility limit.

When typical aluminum-copper alloys, aluminum-magnesium alloys and aluminum-silicon alloys are rapidly solidified, the content of Cu/Mg/Si exceeds the equilibrium eutectic point (Table 1), which induces component supercooling, realizes grain refinement and reduces segregation[9]. Therefore, WAAM construction can be optimized in traditional castings.

Table 1. Solution Limit of Aluminum Alloys (%)

Alloy	Balance the maximum solubility limit	Rapid solidification solubility limit	Equilibrium eutectic point
AI-Cu	2.53	18	17.3
AI-Si	1.78	16	11.3
AI-Mg	18.90	40	37.0
AI-Ni	<1	8	

So far, although arc additive manufacturing (WAAM) technology has been studied extensively, process and theoretical development has gradually matured, and large and complex structural parts that can match castings have been manufactured [10]. However, there are still many shortcomings in the technology modification and many problems need to be solved. Therefore, the research on high-strength aluminum alloy arc additive manufacturing (WAAM) technology faces unstable manufacturing process, poor controllability of forming accuracy and forming quality, and is prone to manufacturing defects such as pores and cracks and solutions and have become hot spots. This article discusses the overview and development status of high-strength aluminum alloy arc additive manufacturing (WAAM) technology, the current defects and solutions, and the future development direction in the aerospace field, providing reference for the improvement and application of later technology modification.

2. Overview of Arc Additive Manufacturing Technology for High-Strength Aluminum Alloys

Wire Arc Additive Manufacturing (WAAM) technology is an additive manufacturing process based on traditional arc welding processes. It uses metal wire as the raw material and an electric arc as the heat source. Under the high-temperature action of the arc, the wire is melted, and through thermal deposition, aluminum alloy is gradually stacked layer by layer along a preset trajectory to form the desired three-dimensional structure[11]. The typical WAAM process is illustrated in Figure 1. Aluminum alloy arc additive manufacturing technologies are primarily classified into Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), Plasma Arc Welding (PAW), and Cold Metal Transfer (CMT), among others[12]. The principle of WAAM technology is shown in Figure 2[13], and the main characteristics of each process are listed in Table 2.

Aluminum alloy WAAM technology demonstrates significant application potential in aerospace and automotive manufacturing, primarily due to its notable technical and economic advantages. Compared to traditional subtractive manufacturing, WAAM can increase material utilization to over 90%, thereby reducing raw material waste. It also shortens manufacturing cycles by 40%–60% and lowers production costs by 30%–50%[14]. However, the technology currently faces challenges such as process instability, poor controllability of forming accuracy and quality, and susceptibility to defects including porosity and cracks. These technical bottlenecks in aluminum alloy arc additive manufacturing further hinder its widespread adoption in aerospace manufacturing [15].

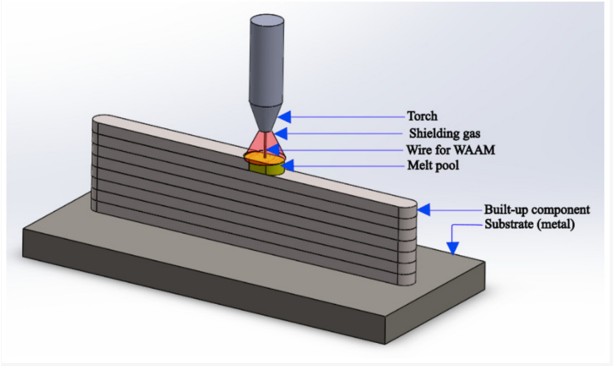


Figure 1. Arc additive manufacturing process

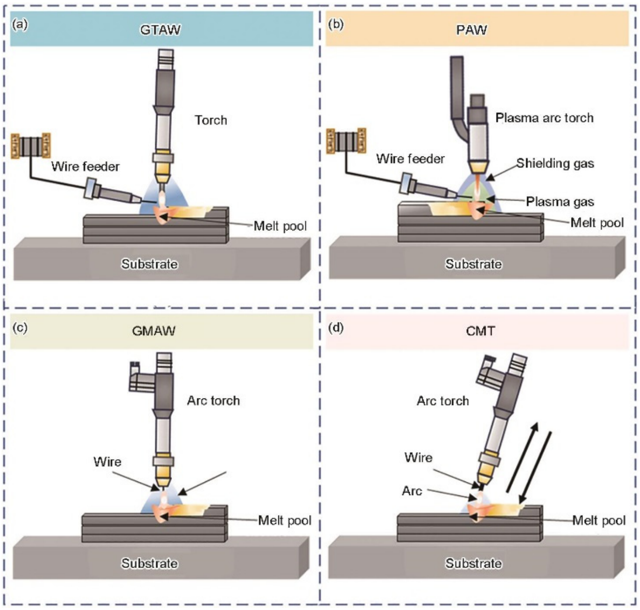


Figure 2. WAAM Technology Schematic Diagram [13]
(a) gas tungsten arc welding (GTAW) (b) plasma arc welding (PAW)
(c) gas metal arc welding (GMAW) (d) cold metal transfer (CMT)

3. Current Status of Research on Aluminum Alloy Arc Additive Manufacturing Technology

WAAM technology is essentially a continuous wire-feeding welding process. However, the high thermal conductivity and high thermal expansion coefficient of aluminum alloys, combined with non-equilibrium solidification behavior and residual stresses, readily lead to issues such as deformation, uneven shrinkage, porosity, hot cracks, and insufficient mechanical properties. These problems have hindered the development and application of arc-based additive manufacturing technology for aluminum alloys.

3.1. Porosity Defects in Molded Parts

In arc-welded aluminum alloy additive manufacturing, porosity defects typically arise from the combined effects of two mechanisms: the difference in hydrogen solubility between the liquid and solid phases of the aluminum alloy and the volume disparity between the liquid and solid phases during solidification shrinkage. During solidification of the aluminum alloy melt pool, density differences between liquid and solid phases induce solidification shrinkage. This, combined with insufficient liquid supply to the inter-dendritic shrinkage-resistant arms, creates volume discrepancies between liquid and solid phases, ultimately forming shrinkage porosity.

Table 2. Comparison of WAAM Processing Techniques

Process name	Tungsten gas shielded welding (GTAW)	Gas shielded metal arc welding (GMAW)	Plasma arc welding(PAW)	Cold metal transition welding (CMT)
Deposition rate(kg/h)	1~2	3~4	2~4	2~3
Heat source	GTAW	GMAW	Plasma	GMAW
Electrode	It does not consume electrodes and requires a separate wire feeding mechanism	Consumable electrode	It does not consume electrodes and requires a separate wire feeding mechanism	Reciprocating self-consuming electrode
Main features	Side-shaft wire feeding	The arc stability is poor and there is splashing	Side-shaft wire feeding	Consume electrodes; Low heat input, no splashing, and high process tolerance

Porosity defects compromise the static and dynamic mechanical properties of WAAM components made from high-strength aluminum alloys. Examples include reduced dimensional accuracy, poor controllability of forming quality, and a sharp decrease in fatigue life. Wei et al.[16] investigated the severe impact of porosity defects on WAAM components of high-strength aluminum alloys. As stress concentration points, porosities prematurely initiate microcracks and lead to early fracture, thereby reducing tensile strength and (especially) elongation of specimens, while significantly diminishing component fatigue life. To address porosity defects, researchers found that optimizing process parameters (current, scan rate, reducing heat input, optimizing heat source and droplet transition forms, and controlling interlayer temperature) can effectively control porosity quantity. Li Quan et al.[17] identified a dual-threshold window for pore suppression through heat input and droplet transition regulation. At low heat inputs, pore nucleation is dominated by growth, with increased heat input leading to higher micro-pore counts and larger sizes. At high heat inputs, pore escape dominates, reducing micro-pore counts. At heat inputs as low as 230.5 J/mm or as high as 439.5 J/mm, the porosity rate remained below 0.2%, demonstrating the effectiveness of optimizing the heat source and droplet transition patterns. Yu Runzhen et al. [18] synergistically controlled the WAAM process parameters, rotary friction speed, and aging temperature of 7075 aluminum alloy to suppress porosity formation. Research indicates that excessively high shielding gas flow induces turbulence, weakening protection and exacerbating porosity.

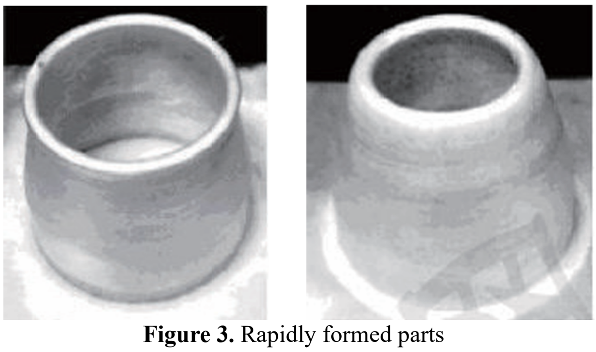


Figure 3. Rapidly formed parts

Increasing the negative polarity modulus enhances cathode atomization, removes oxide layers, and reduces [H] content in the molten pool, thereby lowering porosity—validating optimized process parameters. Ouyang et al. [19] reduced porosity below 0.5% by proportionally adjusting optimized process parameters. This process achieved a tensile strength of 286 MPa and an elongation of 12.5%. Figure 3 shows the rapidly formed component.

3.2. Residual Stresses and Deformation in Formed Parts

Due to the high heat input during welding, aluminum alloy arc additive manufacturing components experience significant thermal gradients during repeated melting and cooling cycles. Under repeated thermal expansion and contraction, residual stresses develop in the aluminum alloy components, leading to deformation and dimensional inaccuracies. This causes bending and distortion in the aluminum alloy, adversely affecting component lifespan and fatigue strength[20]. Jia Jinlong et al.[21] developed a sequential thermal-mechanical coupling model based on the temperature function method. This approach employs segmented temperature functions (1-segment/3-segment/5-segment), significantly reducing mechanical analysis time by 63% to 91%. It simultaneously controls residual stresses and substrate deformation errors within 20%, markedly enhancing simulation efficiency for large-scale WAAM components. Geng Ruwei et al.[22] established a thermo-elastic-plastic model for Al-2319 alloy, revealing that increased current and reduced substrate feed rate elevate the molten pool temperature gradient, leading to higher residual stresses. The maximum longitudinal stress occurs at the center of the deposited layer and exhibits a positive correlation with the temperature gradient. Cao Shufen et al.[23] investigated dual-pulse MIG welding, finding it reduces peak residual stresses. Huang et al.[24] demonstrated that lacking a thermo-mechanical coupled 3D finite element framework underestimates peak residual stresses by 30–50% and overall deformation by 2–3 times, leading to dimensional deviations, cracks, and fatigue hazards. To address this issue, researchers employ simulation to predict stress evolution patterns, guiding process parameter design. Thermomechanically coupled simulation methods are used to mitigate residual stress generation. Du Zelin et al.[25] validated through finite element simulations of varying process parameters that reducing heat input effectively controls residual stress and deformation to a certain extent, providing a theoretical basis for process parameter optimization. Shen Libiao et al.[26] investigated the complex influence of welding residual stresses on fatigue behavior. Their research confirmed that the residual stress field generated by welding exerts a significant and non-negligible effect on the fatigue crack initiation and propagation rates of high-strength aluminum alloy structures.

3.3. Microstructure and Mechanical Properties of Formed Parts

During part processing, the coupled effects of solidification-cooling-deformation-aging result in grain size, precipitation phases, residual stresses, toughness, and anisotropy. If microstructure control is lost, insufficient part strength may lead to deformation and reduced dimensional accuracy. Wang Qianrui et al.[27] optimized welding parameters and heat-affected zone temperature control. They found that elevated temperatures caused grain coarsening and a sharp drop in hardness within 6 mm. Localized homogenized heating simulated a homogeneous thermal field, resulting in grain refinement, hardness recovery, and excellent overall post-weld mechanical properties. Zhang Dong et al.[28] fabricated 2319 high-strength aluminum alloy additive components using CMT technology and analyzed their microstructure and mechanical properties. The study demonstrated that introducing arc oscillation significantly improved component forming quality, resulting in more uniform internal microstructure, reduced grain size distribution variation, and decreased texture strength. Additionally, the material exhibited a low porosity of 0.42%, with tensile strength and elongation exceeding other comparison samples, demonstrating superior comprehensive mechanical properties. Yan Junpei et al.[29] prepared 2024 high-strength aluminum alloy using the CMT+P mode, revealing its microstructural evolution patterns. The study indicated that columnar grains transformed into equiaxed fine grains (≈8 μm), the θ/S phase changed from a continuous layered structure at grain boundaries to a dispersed discontinuous distribution, and porosity decreased significantly. Yield strength increased by approximately 15%, elongation rose by about 4, peak residual stress decreased by ≈30%, warpage was <0.8 mm, and overall fatigue and mechanical properties were significantly improved. He et al.[30] fabricated 2024 aluminum alloy additive components using laser and CMT-P technologies. Findings revealed that in terms of microstructure, the laser zone in specimens predominantly featured fine equiaxed grains (average size 14.8 μm) with no significant texture, while the arc zone consisted of columnar grains (average size 32.3 μm) exhibiting pronounced texture. Controlling process parameters significantly improves the forming quality and microstructural uniformity of high-strength 2024 aluminum alloy, thereby enhancing its comprehensive mechanical properties. Hao Shuai et al.[31] employed Cold Metal Transfer (CMT) technology to fabricate Al-Zn-Mg-Cu alloy using 7B55 aluminum alloy wire as raw material, analyzing the effects of heat treatment on microstructure and mechanical properties. The study revealed that during heating and artificial aging, high-density, nanoscale GP zones, η′ phase, and secondary $Al_3(Sc,Zr)$ particles formed within the grains. These precipitates significantly enhanced the tensile properties of the material.

3.4. Additional Auxiliary Processes for Formed Parts

However, traditional methods for wire arc additive manufacturing (WAAM) of high-strength aluminum alloys often suffer from issues such as low forming accuracy, high porosity, and significant residual stresses, leading to degraded mechanical properties. Beyond optimizing welding heat input and employing pulsed/reversed polarity current techniques, universities and research institutions worldwide have introduced auxiliary processes into WAAM systems. These include multi-field assistance (laser, ultrasonic impact); rolling, interlayer hammering, shot peening, friction stir welding; particle modification (altering material systems); aging treatment; cryogenic rolling; etc. These approaches systematically reduce porosity formation, control residual stresses and deformation, and enhance the forming quality and comprehensive mechanical properties of high-strength aluminum alloy components.

Multi-field assistance (laser-arc hybrid, ultrasonic field, and electromagnetic field assistance) can also effectively control porosity formation. Ultrasonic pulse (USP) treatment is another contact-based strengthening method that utilizes stress-hardened layers, primarily aiming to refine grain size and close porosity. Tian et al.[32] applied USP between layers in aluminum alloy WAAM, demonstrating that USP controls porosity size and quantity reduction while refining grains, confirming the effectiveness of interlayer USP application. Wu et al.[33] introduced ultrasonic impact between layers of aluminum alloy WAAM to reduce porosity while simultaneously enhancing tensile strength and yield strength. Yang et al.[34] employed ultrasonic rolling (impact energy 6 J) to prepare gradient nanolayers on 7075-T6 surfaces, inducing residual compressive stresses of –124 MPa. Studies indicate that rational roll-forming process design prevents crack formation and significantly improves surface roughness and that residual stress introduction enhances the pitting and stress corrosion resistance of 7075 aluminum alloy. Jing et al.[35] pioneered interlayer LSP application on 2319 aluminum alloy. Layers were arranged in a spiral oscillation pattern, followed by LSP application to the top surface. Post-processing, interlayer LSP-treated samples exhibited a 73.9% reduction in pore count and an 87.4% decrease in total pore area, alongside enhanced material strength and ductility. Jing et al.[36] applied LSP surface treatment as a finishing process to WAAM-produced 2319 aluminum alloy. Experimental results demonstrated that LSP enhanced material hardness, tensile strength, and fatigue properties while eliminating internal porosity. Sun Rujian et al.[37] applied 6 J laser shock pulses after each deposition layer, resulting in residual tensile stress shifting from +120 MPa to −180 MPa (introducing a 0.8 mm deep compressive stress layer) and reducing overall warpage by 62%. Jiang et al.[38] proposed coating the surface of 7150 aluminum alloy with 0.4–0.6 mm of high-temperature inorganic adhesive and aluminum foil, then adjusting the surface/core cooling curve difference during quenching to eliminate surface compressive stress concentration. Results demonstrated a residual stress reduction exceeding 90%, a 15% increase in elongation, and discontinuous distribution of grain boundary precipitates, achieving both strength and stress corrosion resistance. Sun Rujian et al.[39] applied LSP technology to WAAM 2319 aluminum alloy, reducing the average grain size from 68.86 μm to 34.32 μm—a 50.2% decrease, as shown in Figure 4. Microhardness increased from 67.8 HV to 100.6 HV, with residual compressive stress influencing a depth of 0.65 mm, thereby improving internal residual stress distribution within the component.

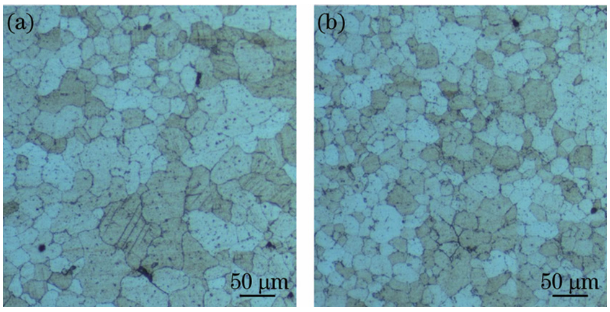
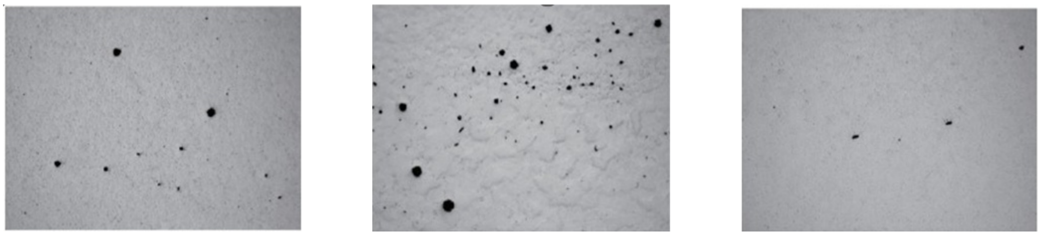


Figure 4. Grain microstructure (a) Before LSP; (b) After LSP

During rolling, hydrogen molecules in the pores of aluminum alloys produced by arc-fed wire additive manufacturing decompose into hydrogen atoms that diffuse into the alloy. These hydrogen atoms may redistribute into dislocations or interstitial lattice sites, accumulating at the surface as they move with dislocations. The surface oxide layer fractures due to elastic deformation, facilitating hydrogen atom escape[40]. Zhang et al.[41] investigated the effects on 2219 aluminum alloy without rolling-assisted processes. Their study revealed that without rolling introduction, the as-deposited microstructure of 2219 alloy exhibited coarse grain structure, numerous defects, and susceptibility to non-uniform deformation, resulting in significantly lower comprehensive mechanical properties compared to conventionally rolled or forged products. Gao et al.[42] investigated that without rolling, the high thermal gradients and contraction stresses induced by laser ultra-rapid cooling cannot be subsequently "relaxed" by energy or mechanical means. This results in high residual stresses and numerous microcracks in the formed parts, significantly reducing their fatigue life. To address this issue, researchers employed rolling, interlayer hammering, shot peening, and friction stir welding to effectively eliminate porosity in arc-fed wire additive manufacturing aluminum alloy parts, remove casting defects, reduce residual stresses, and improve microstructure and mechanical properties. GU et al.[43] observed that small-sized porosity essentially closed when rolling force increased to 15 kN; at 45 kN, large-sized porosity collapsed and closed, leaving only trace amounts of micro-pores. This demonstrates that increased rolling load significantly reduces porosity defects (see Figure 5), validating the effectiveness of rolling. Hönnige J R et al.[44] introduced a synchronous rolling device into arc-based additive manufacturing, confirming that this process significantly reduces residual stresses (localizing the affected zone) while achieving grain refinement. Gu Jianglong et al.[45] demonstrated through interlayer rolling and post-heat treatment experiments that rolling force exhibits a strong negative correlation with pore count. As rolling force increases, porosity decreases significantly while material hardness and strength simultaneously improve. Gou et al.[46] discovered that three-dimensional ultrasonic shot peening achieves dual-phase synergistic refinement (precipitation of β phase followed by secondary α phase) in CMT-added TC4 titanium alloy, activating grain boundary slip and rotation, resulting in substantial improvements in mechanical properties. Dai et al.[47] employed wire arc additive manufacturing (WAAM) with interlayer friction stir processing (FSP) to fabricate 2319 alloy with a gradient microstructure, achieving plastic deformation exceeding 70%. Results demonstrated that the hybrid additive manufacturing technique effectively eliminated coarse columnar grains in WAAM. Grain refinement reached 87.1%, with dynamic recrystallization exceeding 62%. This enhanced the material's mechanical properties, achieving a yield strength of 162.9 MPa (↑48.1%) and elongation of 15% (↑15.4%) compared to WAAM, demonstrating synergistic strength-ductility improvement and validating the effectiveness of the hybrid additive manufacturing technique. Zhou et al.[48] investigated 5052 aluminum alloy plates with 5B06 filler wire using interlayer shot peening combined with WAAM. They observed improved mechanical properties and increased microhardness, validating the effectiveness of interlayer shot peening. Fang et al.[49] developed a pneumatic hammering device that modified interlayer deformation, internal microstructure, and properties of 2319 aluminum alloy during the WAAM process. Results showed a deformation rate of 50.8%, yield strength ranging from 148.4 MPa to 240.9 MPa, and ultimate tensile strength from 288.6 MPa to 334.6 MPa, demonstrating enhanced microstructure and mechanical properties as illustrated in Figure 6. Zhou et al.[50] investigated the effect of annealing treatment on the microstructure and mechanical properties of 5B06 aluminum alloy specimens prepared by interlayer hammering hybrid WAAM. They found that specimen strength decreased with increasing annealing temperature, while plasticity initially increased before decreasing. Furthermore, optimal tensile properties were achieved at 180°C annealing with 366 MPa UTS and 29.2% EL. Dai et al.[51] proposed a friction stir processing (FSP) technique combined with friction stir welding (FSW), achieving dynamic recrystallization and grain refinement through intense mechanical grain fragmentation and plastic deformation induced by thermal effects. Results showed that after two cycles of FSP treatment, grain size was refined to 2.57 μm, with complete elimination of porosity and cracks. Following three cycles of FSP treatment, comprehensive mechanical properties significantly improved: tensile strength reached 402.6 MPa (↑49.3%), and elongation reached 11.27% (↑290%).

During part forming, the microstructure of the formed component is non-uniform, featuring coarse, directionally grown columnar crystals and eutectic structures between dendrites. This results in degraded mechanical properties, particularly poor plasticity and toughness. Therefore, to improve the microstructure and mechanical properties of formed components, conventional arc-based additive manufacturing techniques require modification. Researchers have introduced nanoparticles to enhance the mechanical properties of formed parts. Li Gan et al.[52] added 1 wt% nano-TiO_2 particles, utilizing an aluminothermic reduction reaction to dissolve titanium into the aluminum matrix. The high shape constraint factor (Q-value) of titanium was leveraged to refine the grain structure. Results demonstrated a bimodal grain size distribution (equiaxed grains at melt pool edges + fine columnar grains internally), eliminating cracks. Printed specimens achieved 99.97% density, with room-temperature tensile strength comparable to forged 2219 aluminum and a 40% improvement in high-temperature strength retention at 315°C. The heat-treated specimens exhibited an excellent combination of strength and plasticity across the 25–315°C range, validating the effectiveness of the nanoparticles. Liu et al.[53] proposed a strategy of adding TiC nanoparticles to AA2024 welding wire in DED-A and investigated the mechanism for improving microstructure and mechanical properties. The study revealed that TiC nanoparticle addition significantly refined the average grain size of the deposited composite from 65.4 μm to 16.4 μm, primarily by promoting heterogeneous nucleation and inhibiting grain growth. Correspondingly, the material's mechanical properties were comprehensively enhanced: tensile strength, yield strength, and elongation in the horizontal direction reached 304 MPa, 174 MPa, and 9.5%, respectively, representing increases of 75%, 70%, and 164% compared to the unmodified AA2024. Properties in the vertical direction also improved synchronously, reaching 287 MPa, 165 MPa, and 9.9%. Lü Qizhao et al.[54] proposed adding 1–3 wt.% TiC to Al6061 and investigated its effects on microstructure and properties. The study revealed that at a TiC content of 3%, the average grain size decreased from 45.5 μm to 25.3 μm, achieving a refinement rate of 44.4%; tensile strength and yield strength increased from 148.5 MPa and 118.0 MPa to 178.1 MPa and 157.3 MPa, representing improvements of 19.9% and 33.3%, respectively; and average microhardness rose from 50.5 HV to 65.2 HV, an increase of 29.1%, significantly enhancing the material's overall mechanical properties. He Pengfei et al.[55] simultaneously introduced micron-sized WC particles during the deposition of 2024 aluminum alloy, finding that this effectively suppressed columnar grain growth and resulted in a uniformly refined equiaxed grain structure.



a) Not rolled or heat-treated during deposition

b) Post-deposition heat treatment

c) After deposition, undergo 15 kN interlayer rolling treatment

d) After deposition, undergo 30 kN interlayer rolling treatment

e) After deposition, undergo 45 kN interlayer rolling treatment

f) After deposition, undergo 45 kN interlayer rolling treatment and heat treatment.

Figure 5. Changes in pore size of 2319 aluminum alloy after different interlayer rolling and heat treatment[43]

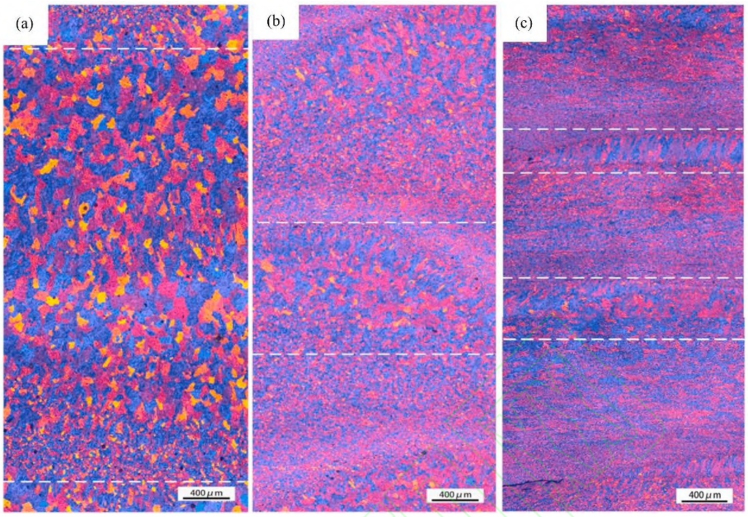


Figure 6. Microstructures of formed parts at different strain rates [49] (a) 0%, (b) 21.8%, (c) 50.8%

After parts undergo arc-based additive manufacturing, their microstructure exists in a supersaturated solid solution state, presenting issues such as sparse precipitation phases, insufficient strength, and uneven hardness distribution. To overcome this bottleneck, researchers introduced artificial aging treatment to reduce residual stresses and enhance micro-deformation resistance, thereby improving the microstructure and mechanical properties of the formed components. Xie et al.[56] demonstrated that aging treatment induces ultra-high-density dislocations and deformation bands, resulting in finer grain sizes and higher strength, achieving an optimal balance between high strength and high plasticity. Zheng et al.[57] investigated that during aging treatment, residual stresses in Ti-Cu arc-additive parts decrease. Due to the presence of precipitation hardening, high yield strength is maintained without insufficient plastic relaxation occurring during the high-temperature stage.

Parts processed under cryogenic conditions exhibit coarse grain structures and pronounced anisotropy. To address this issue, researchers introduced cryogenic rolling technology to refine grain size, increase dislocation density, and enhance mechanical properties. Ji et al. [58] prepared components with a layer height of 0.5 mm using FRAM, performing multiple rolling passes at both room temperature and liquid nitrogen (-196°C) to promote grain rotation and dislocation proliferation. Results showed that grain size variation decreased from 15.2 µm to 4.8 µm; CR samples exhibited 2.3 times higher dislocation entanglement density than RR samples, confirming dislocation strengthening as the dominant mechanism. Yield strength increased to 328 MPa (↑12%), and elongation reached 11.2% (↑30%). Chen Chao et al. [59] investigated the microstructural and mechanical properties of aluminum alloy thin-walled components processed by WAAM and WAAM-HSF. The study revealed that both processes formed abundant columnar dendrites, but the WAAM-HSF process exhibited more pronounced grain refinement.

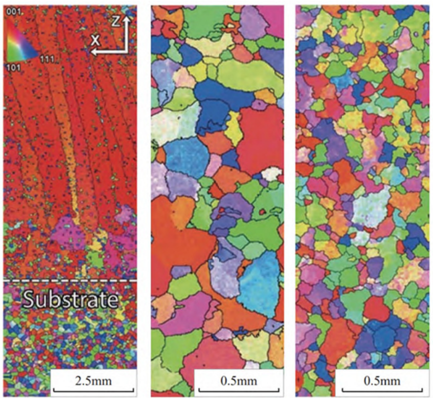


Figure 7. Effect of cold rolling on the arc deposition layer of TC4 titanium alloy

In terms of mechanical properties, WAAM-HSF components showed a 9.96 HV increase in microhardness and a 17 MPa increase in tensile strength, but the average elongation after fracture decreased by 5%. Martina F et al. investigated the microstructural effects of different additive cold rolling hybrid manufacturing processes on TC4 titanium alloy. They found that after 75 kN cold rolling, the coarse columnar microstructure underwent a substantial equiaxial transformation [60], as shown in Figure 7.

4. Engineering Applications of Aluminum Alloy Arc Additive Manufacturing

Aluminum alloy welding arc additive manufacturing (WAAM) technology, with its technical advantages of lightweighting, low cost, high efficiency, and large-scale forming capabilities, has been applied in the manufacturing of large-scale, moderately complex aerospace components. Through continuous research by scholars both domestically and internationally, this technology has been implemented in numerous practical applications. The Williams Stewart research team at Cranfield University pioneered the application of WAAM technology for aluminum alloy components. Employing CMT arc wire additive manufacturing at a deposition rate of 1.1 kg/h, they fabricated a 2.5-meter-long aluminum alloy wing rib plate for aircraft applications (Figure 8(a)). This reduced the material-to-product ratio per part from 37 to 12, saving approximately 500 kg of raw material per component [61-63]. Relativity Space in the United States employed WAAM technology utilizing a combined laser-plasma heat source to fabricate aluminum alloy fuel tanks for rockets (Figure 8(b)), which successfully passed all performance evaluations [62]. In recent years, domestic research institutions such as Huazhong University of Science and Technology and Capital Aerospace Machinery Co., Ltd. have utilized WAAM technology to prototype typical aerospace aluminum alloy structures, including brackets, cabin sections, frames, and grids. Among these, WAAM cabin sections (Fig.8(c)) demonstrate particularly significant technological advancements and have been successfully applied in aerospace equipment[64].

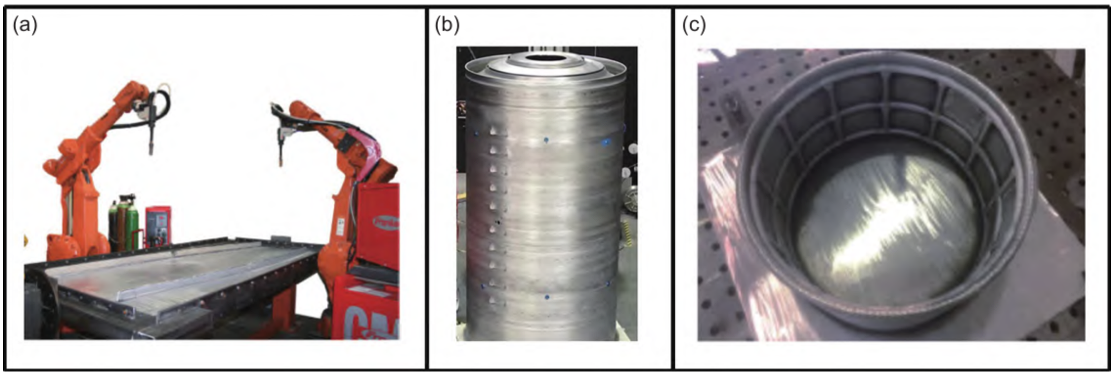


Figure 8. Aluminum parts formed by WAAM (a)aluminum wing spar[61]; (b) fuel tank[62]; (c) cabin part[64]

MAYUR Pc et al.[65] achieved additive manufacturing of aluminum alloys using pulsed GTAW technology. This process first produces near-net-shape blanks through layer-by-layer deposition, followed by machining and T6 heat treatment to ultimately yield components meeting specified mechanical properties. Figure 9 illustrates the morphological comparison of the component before and after processing.

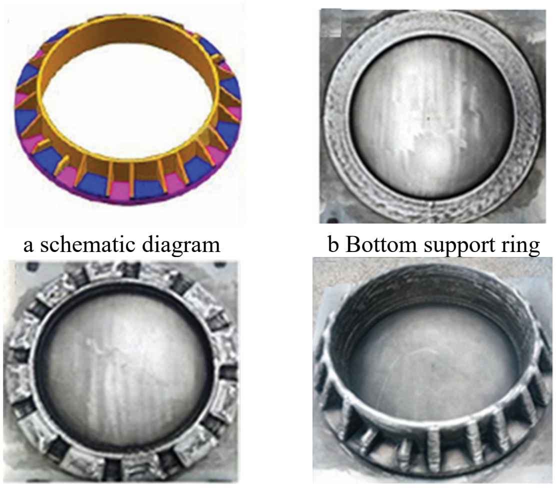
Since 2017, the Ningbo Branch of the China Academy of Ordnance Science has successively employed arc additive manufacturing technology to print complex aluminum alloy components such as artillery mounts, missile pods, and brackets. Through in-service testing and application, these components have achieved significant weight reduction while substantially shortening development cycles[66]. In 2019, Beihang University manufactured a large-scale aluminum alloy aerospace thin-walled component measuring 3000 mm × 1000 mm × 1000 mm through arc additive manufacturing combined with composite surface milling, as shown in Figure 10. This method reduced the component manufacturing cycle by 70% while keeping dimensional deviations within 7%[67].


a Additive moldings b Post-processing of finished parts

Figure 9. Pulsed GTAW Aluminum Alloy Component


Figure 10. Thin-walled aluminum alloy parts manufactured by arc additive manufacturing [67]

Gao Lianling et al. [68] employed Cold Metal Transfer (CMT) technology to additively manufacture an aluminum alloy transition end frame for launch vehicles. This component serves as a critical connection between booster modules and is classified as a large structural part. The deposition process was divided into three sequential segments: first forming the bottom support ring, then fabricating multiple annular groups distributed at equal angles and intervals, and finally depositing multiple sets of stiffener structures. Figure 11 displays the simulated results and actual additive manufacturing outcomes of this component. Figure 11a shows the overall simulation, while Figures 11b, 11c, and 11d depict the actual formed topography of the three sections from bottom to top, respectively.


a schematic diagram b Bottom support ring

c Ring Group d Integral forming

Figure 11. CMT Additive Aluminum Alloy Transition End Frame

In 2021, the team led by Academician Lu Bingheng successfully developed the world's first prototype of a high-strength aluminum alloy heavy-lift launch vehicle connecting ring with a diameter of approximately 10 meters using integrated arc deposition and removal manufacturing technology (see Figure 12). Weighing about 1 ton, the connecting ring achieved significantly reduced costs compared to traditional machining processes, with the production cycle shortened to one month [69].

Figure 12. Ø10m-class high-strength aluminum alloy heavy-lift launch vehicle connection ring prototype

5. Conclusion and Vision

Aluminum Welding Arc Additive Manufacturing (WAAM) technology has become indispensable in the aerospace sector for complex components due to its lightweight properties, low cost, high efficiency, and capability for large-scale manufacturing. Currently, WAAM technology still faces challenges in achieving effective and precise control during material processing, with certain limitations and areas requiring further breakthroughs.

1) High-strength aluminum alloy arc additive manufacturing primarily faces metallurgical defects such as porosity and hot cracks, leading to issues like insufficient mechanical properties (e.g., strength) and anisotropy in components. Additionally, this technology is constrained by challenges in residual stress and deformation control.

2) In summary, a single arc energy field cannot simultaneously meet the extremely high demands of high-strength aluminum alloys for microstructure, defect control, and performance uniformity. The manufacturing approach of integrating multiple energy fields with WAAM through auxiliary processes represents the inevitable technological direction for achieving high-performance, high-reliability, and high-consistency manufacturing of high-strength aluminum alloy components.

(1) Pores and hot cracks in aluminum alloy arc additive manufacturing processes can be mitigated by optimizing process parameters (heat input, scanning speed) and employing multi-energy field assistance (laser (LSP), ultrasonic shock).

(2) Through processes such as rolling, interlayer hammering, shot peening, and friction stirring, tensile stresses can be converted into compressive stresses. This effectively resolves residual stresses and deformation caused by high heat input during aluminum alloy arc additive manufacturing.

(3) The incorporation of nanoparticles (1 wt% TiO_2) and deep cold rolling enables grain refinement and effective control over microstructural evolution, thereby enhancing the comprehensive mechanical properties of components. This has become a critical consideration in the research process.

At present, aluminum alloy wire arc additive manufacturing (WAAM) still lacks efficient and precise control methods in material processing. The related shortcomings are difficult to overcome completely in the short term, and overall development remains in a continuous research and development phase. Future efforts should focus on developing new methods for aluminum alloy additive manufacturing and further exploring the intrinsic relationship between “process-microstructure-property” in aluminum alloy additive manufacturing. Elucidating the stress formation mechanism in aluminum alloy additive manufacturing components and proposing methods to effectively control residual stress levels and distribution will provide guidance for fabricating large, complex aluminum alloy components in aerospace applications. Within the aerospace sector, advancing through three parallel tracks—intelligent control, material genome engineering, and composite processes—is essential to overcome the bottleneck in synergistic “shape-property” regulation, propelling aerospace equipment lightweighting and efficiency into a new era.

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