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Multi-wire directed energy deposition-arc of aluminum alloys: process control, applications and challenges

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Highlights:

- Establishes 3D collaborative process control system for multi-wire DED-arc of aluminum alloys.
- Details *in-situ* alloying method and engineering applications of multi-wire DED-arc aluminum alloys.
- Identifies core challenges and development prospects for multi-wire DED-arc precision equipment.

Abstract: The global manufacturing industry is undergoing a transformation towards lightweight and high-performance development, and aluminum alloys have become the dominant material for key components of high-end equipment. The conventional single-wire directed energy deposition-arc (single-wire DED-arc) suffers from inherent limitations, including excessive heat input and fixed compositions of commercial welding wires. While multi-wire directed energy deposition-arc (multi-wire DED-arc) technology presents significant advantages, its development still faces numerous challenges. This paper reviews the research status and engineering progress of multi-wire DED-arc technology for aluminum alloys, analyzes the synergistic regulation mechanism of three core process dimensions (wire feeding rate regulation, current-voltage synergistic control, and inter-wire geometric parameter optimization), and summarizes its applications in the automotive, rail transit, and aerospace fields. It further identifies the core advantages and key bottlenecks of this technology, establishes a unified theoretical framework for multi-wire DED-arc aluminum alloy forming, and can provide a valuable reference for future research in this field and the development of dedicated precision equipment.

Keywords: multi-wire directed energy deposition-arc (multi-wire DED-arc); aluminum alloy; *in-situ* alloying; precision forming

1.Introduction

The global manufacturing industry is transforming towards lightweight, cost-effective, and complex forming. Aluminum alloys, with low density, high specific strength, excellent corrosion resistance, superior machinability, and environmental friendliness [1], have been widely used in key components such as aerospace fuselage frames, automotive transmission housings, and offshore platform supports [2].

Conventional single-wire DED-arc faces inherent limitations, including deformation induced by excessive heat input and fixed composition of commercial welding wires [3]. Multi-wire DED-arc utilizes a precision mechanical wire feeding system to achieve *in-situ* alloying of multiple elements through the collaboration of multiple process dimensions, breaking through the constraints of single commercial welding wires [4]. Multi-wire DED-arc is an advanced precision forming system that deeply integrates computer science, mechanical engineering, and materials science, and is emerging as a representative advanced equipment for intelligent manufacturing in Industry 4.0.

In recent years, domestic and international scholars have conducted extensive research on the development of multi-wire DED-arc process modes for aluminum alloys, optimization of process parameters, and defect control. Specific efforts include the targeted fabrication of Al-Mg-Si, Al-Zn-Mg-Cu, and Al-Mg series alloys, comprehensive adjustment of parameters including wire feeding rate ratio, arc matching, and heat input, as well as innovative applications of intelligent monitoring and hybrid processes. Multi-wire DED-arc technology for aluminum alloys has gradually transitioned from laboratory research to pilot-scale testing [5]. However, current research still has three major limitations. First, a unified framework has not been established for the matching logic between wire combination, process parameters, and performance requirements for different aluminum alloy systems. For example, differentiated technical solutions are required for hot cracking suppression of high-strength Al-Zn-Mg-Cu alloys and composition uniformity control of corrosion-resistant Al-Mg alloys. Second, parameter optimization is mostly limited to single-factor variables, lacking analysis of the coupling mechanism among composition, arc, thermal field, and microstructure, making it difficult to ensure the performance consistency of large-scale components. Third, the research and development (R&D) of special welding wires (such as Sc and Zr-containing microalloyed wires) and supporting processes (such as post-processing strengthening) lags behind, restricting the application of multi-wire DED-arc aluminum alloys in high-end equipment [6].

This paper summarizes the research achievements of Multi-wire DED-Arc process modes for aluminum alloys, analyzes the main methods for parameter optimization, outlines the applications of this technology in the field of high-end equipment, identifies the bottlenecks in the development of current technology and equipment, and prospects the future development direction. It is intended to provide theoretical and practical support for the R&D and upgrading of multi-wire DED-arc special precision forming equipment and the technological progress in the advanced manufacturing field.

2. Core forming mechanism and equipment regulation system for multi-wire DED-arc

The primary challenge for achieving high-performance precision forming of aluminum alloys via multi-wire DED-arc lies in the strong coupling characteristics of multiple process parameters in terms of mechanical execution and arc physics. Minor fluctuations in process parameters are amplified through the transmission process of arc behavior and microstructural evolution in the molten pool, which directly affecting the forming quality and mechanical properties of the fabricated components [7]. Three core aspects, namely dynamic regulation of wire feeding rate and composition, synergistic energy control of current and voltage, and optimization of inter-wire geometric parameters, constitute the complete process control framework for multi-wire DED-arc aluminum alloy forming. This framework addresses the challenge of strong coupling of multiple parameters, achieves the goal of high-performance precision forming of components, and provides theoretical basis and data support for the R&D and upgrading of multi-wire DED-arc special precision equipment.

2.1. Wire feeding rate: the mechanical execution benchmark for composition regulation

Wire feeding rate plays a dual role in material filling and composition regulation in the multi-wire DED-arc process. It directly determines the deposition efficiency and forming dimensions of components, and serves as the mechanical execution basis for *in-situ* alloying of multiple elements. Through the regulation of wire feeding rate, multi-wire DED-arc technology breaks through the limitations of fixed composition of commercial welding wires in conventional single-wire DED-arc, and its control accuracy directly defines the core design indicators of the multi-channel collaborative wire feeding mechanical system [8].

Wang *et al.* [9] fabricated Al-Zn-Mg-Cu high-strength aluminum alloys using a tungsten inert gas (TIG) heat source with a three-wire co-melting mode. Through theoretical calculations and precise optimization of wire feeding rate (Figure 1), by tuning these parameters, the alloy composition ratio was controlled with high accuracy, and the composition error met the design expectation, which is mainly attributed to the effective regulation of multi-element composition via wire feeding speed. Rely on the TIG multi-wire co-melting system shown in composition regulation method has universal applicability in the dual-wire process mode. The target composition ratio of Al-Mg-Cu alloys can be adjusted by modifying the feeding speed ratio of ER2319 and ER5356 welding wires. This work demonstrates that wire feeding rate can achieve static precise control of fixed alloy compositions, laying a quantitative foundation for the batch preparation of homogeneous high-performance aluminum alloy components, and directly verifies that wire feeding rate is the core mechanical carrier for realizing *in-situ* alloying composition design.

On this basis, the dynamic adjustable characteristic of wire feeding rate further expands the composition regulation capability of multi-wire DED-arc, enabling the continuous and controllable preparation of functionally graded materials with gradient composition changes.

Gu *et al.* [10] continuously adjusted the feeding speed of Al-Cu and Al-Mg welding wires to achieve continuous variation in the composition gradient of Al-Mg-Cu alloys. Based on extensive experimental data, a correlation model between alloy cracking susceptibility and wire feeding speed was established, providing a quantitative basis for crack defect control of functionally graded material components and laying an experimental foundation for the R&D of intelligent wire feeding systems with dynamic variable parameter regulation capability.

The above two studies respectively confirm the dual regulation capabilities of wire feeding rate from two complementary dimensions: static precise control of homogeneous components and dynamic continuous regulation of gradient components. This dual capability is unique to multi-wire DED-arc technology compared with single-wire DED-arc, and it is precisely the mechanical execution nature of wire feeding rate that makes flexible and customizable *in-situ* alloying possible.

The precise control of wire feeding rate not only provides core support for alloy composition design, but also defines the basic process boundary for the synergistic energy control of current and voltage, as well as the optimization of inter-wire geometric parameters. It is the primary prerequisite for the collaborative regulation of the three core aspects.

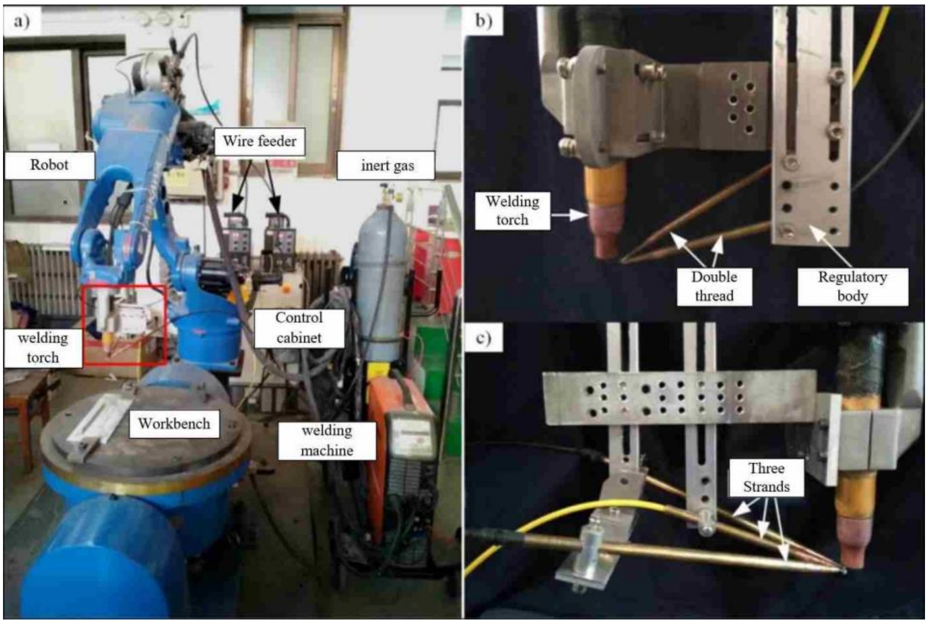

Figure 1. Multi-wire addition manufacturing system based on TIG: **(a)** system; **(b)** double-wire device; **(c)** three-wire fixture [9].

2.2. Current-voltage synergy: the core control dimension of arc energy

Current and voltage are the dominant parameters determining the arc energy input in the multi-wire DED-arc process. Their synergistic regulation directly governs the arc energy density, droplet transfer mode, molten pool flow behavior, and final forming quality. They are the main optimization directions for mitigating inter-wire arc interference and achieving high-efficiency forming with low heat input, as well as the core theoretical basis for the R&D of intelligent digital welding power sources adapted to the multi-wire DED-arc process.

The primary task of current parameter regulation is to achieve energy distribution and waveform optimization for the multi-wire system, which directly affect the stability of droplet transfer and heat input level. Zhang *et al.* [11] fabricated Q345 low carbon steel single-wall samples using a bypass-coupled three-wire indirect DED-arc process. Calculation results showed that the deposition rate of this process reached 13.3 kg/h. The bypass system reduced the heat input during the additive manufacturing process by adjusting the current, eliminating forming defects in the fabricated samples. Wang *et al.* [12] demonstrated that regulating the current waveform of the multi-wire system, such as adopting a bimodal and base current mode, can decouple the heat input from the metal filling rate, improve the stability of droplet transfer, and enhance the weld forming quality. This provides an important theoretical basis and technical approach for high-efficiency additive manufacturing of high-strength aluminum alloys with low heat input (Figure 2). Li *et al.* [13] pointed out that the current controls the energy input into the arc, and its value and matching mode will alter the molten pool morphology, wire melting behavior, and metallurgical reaction process of alloying elements. Excessive current or current mismatched with the wire feeding rate is prone to cause molten pool instability, alloy element segregation, and poor forming quality. This illustrates the importance of matching the current parameters of the multi-wire system with the wire feeding rate, and also puts forward core design requirements for the synchronous collaborative control of multi-channel welding power sources.

The primary role of the voltage parameter is to maintain the stability of the arc length of each wire in the multi-wire system and to prevent mutual arc interference between wires, which is also a key control indicator for the stable operation of multi-wire DED-arc equipment. When multiple wires work simultaneously, an arc voltage deviation of 1–2 V in a single wire can cause mutual arc interference, leading to severe molten pool fluctuations and destabilization of the forming process. Yu *et al.* [14] indicated in their research on DED-arc of 5356 aluminum alloy that stabilizing the arc voltage in the range of 17–18 V is the core process basis for obtaining appropriate heat input and ensuring the forming quality of components. The research results provide a quantitative reference for the precise closed-loop control of arc voltage in multi-wire DED-arc multi-wire systems, as well as data support for the design of real-time arc voltage feedback control systems for welding power sources.

The synergistic matching of current and voltage requires not only precise energy and filling adaptation with the wire feeding rate, but also the suppression of arc interference in combination with the design of inter-wire geometric parameters. It is the energy center of the three-way collaborative regulation.

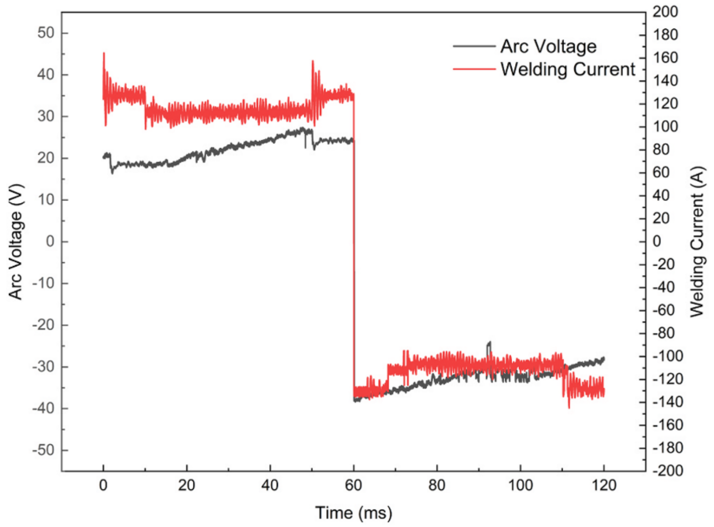

Figure 2. Arc voltage and welding current in waveform. High current creates an arc with higher energy. Waveform shows the best output in terms of arc shape, droplet transfer, and weld formation [12].

2.3. Inter-wire geometric parameters: the quantitative boundary for forming quality

Geometric parameters including inter-wire distance, wire extension length, and bead overlap spacing determine the coupling degree of multi-wire arcs, molten pool morphology, and multi-pass overlap forming quality, which are key mechanical design parameters. Minor changes in these parameters can significantly amplified through the arc coupling effect, leading to forming defects. These parameters constitute important quantitative basis for the structural design of the welding torch, robot path planning, and motion control system optimization of multi-wire DED-arc special equipment.

Bead overlap spacing is the main geometric parameter for multi-pass forming of large-scale components, which directly affects the surface flatness and internal relative density of components, and is a critical design parameter for the robot path planning system. Chai *et al.* [15] found that setting the overlap spacing to 0.689 times the single bead width can significantly improve the surface quality and relative density of multi-pass overlap forming, providing an important optimization reference for the collaborative bead forming of multi-wire additive manufacturing. Fang *et al.* [16] further confirmed in the study on cold metal transfer (CMT) based DED-arc that the optimal multi-pass overlap forming effect can be achieved at a bead overlap spacing of 0.715 times the single bead width. This paper correlates the overlap spacing directly with the single bead width and provides a universal design value, offering a clear criterion for the control of forming accuracy and surface quality of large-scale aluminum alloy components via multi-wire DED-arc, as well as a standard for the optimization of robot path planning algorithms.

Wire extension length and inter-wire arrangement matching define the main geometric boundaries for the stability of multi-wire arcs, and are also the core basis for the precision design of the multi-wire DED-arc welding torch structure. Diao *et al.* [17] comprehensively analyzed the effect of wire extension length on the welding process stability in three-wire indirect arc welding. The results showed that mismatched wire extension length between the main wire and side wires directly leads to arc dispersion and forming process instability. Under the condition of equal extension length, the arc concentration and electrical signal stability decreased continuously with the increase of extension length. Only when the extension length of both the main and side wires was controlled at 10 mm, the welding process stability and weld forming quality reached the optimal state. This study provides an experimental basis for the precise control of process parameters of three-wire indirect arc welding, and defines the stability boundary for wire arrangement and precision design of the welding torch structure in the multi-wire DED-arc multi-wire collaborative system.

The quantitative design of inter-wire geometric parameters constitutes the structural guarantee for the stable operation of the wire feeding system and the prerequisite for the stable control of current, voltage, and arc. It is the mechanical boundary defined by the three-dimensional collaborative regulation mode.

In summary, the three core aspects, namely wire feeding rate adjustment, synergistic control of current and voltage, and optimization of inter-wire geometric parameters, constitute the overall process control framework for multi-wire DED-arc aluminum alloy forming, providing important theoretical and data support for the R&D of supporting precision equipment. The optimization of the three aspects in the process has enabled the engineering application of this technology. In the future, intelligent and integrated multi-wire DED-arc equipment will further solve the challenge of multi-parameter coupling and expand its engineering application scope.

3. Engineering application practice

With a highly adaptable precision equipment system, multi-wire DED-arc technology achieves precise matching between process parameters and material properties. By leveraging the advantages of multi-wire collaborative regulation, this technology overcomes the limitations of conventional single-wire DED-arc technology. It has been applied in the customized manufacturing of key components for high-end equipment such as automotive, rail transit, and aerospace, forming technical modes adapted to different service environments. It has become an important technical method for lightweight, integrated, and high-performance manufacturing of high-end equipment.

3.1. Automotive and rail transit fields

The irreplaceable value of multi-wire DED-arc in automotive and rail transit fields stems from its unique matching with the core manufacturing demands of “medium batch, medium-to-large size, low-cost lightweighting" in this industry, which cannot be satisfied by traditional casting/forging-machining processes or laser powder bed fusion (LPBF) technology. Specifically:

Traditional casting and forging-machining processes require custom molds with high upfront investment and long production cycles (3–6 months), making them uneconomical for small-batch customized components. Moreover, complex integrated hollow structures are difficult to form, and the material utilization rate is only 30%–40% due to extensive subsequent machining [18].

LPBF technology has a low deposition rate of only 0.1–0.5 kg/h, which cannot meet the mass production requirements of medium-to-large components (dimension > 500 mm). In addition, the cost of aluminum alloy powder is 5–8 times that of welding wires, and the component size is strictly limited by the forming chamber volume.

Multi-wire DED-arc technology achieves a high deposition rate of 5–15 kg/h with a material utilization rate exceeding 90%. It eliminates the need for molds, enables rapid response to customized demands, and is particularly suitable for low-cost and rapid manufacturing of medium-to-large complex components [19,20].

Multi-wire DED-Arc technology thus provides a core technical route for the lightweight manufacturing of medium-load components. Al-Mg-Si (6xxx series) aluminum alloys, with excellent weldability and low manufacturing cost, are the main base materials for key medium-load components such as automotive transmission housings and high-speed rail bogie brackets.

To address this industry pain point, Wang *et al.*[20] demonstrated that the hot-wire GTAW-based multi-wire DED-arc technology (Figure 3), effectively compensates for the inherent low deposition rate limitation of conventional single-wire cold-wire processes. By preheating multiple filler wires using resistance heat before they enter the molten pool, this technology achieves independent decoupling control of arc energy input and material filling rate, significantly reducing the heat input to the substrate and minimizing deformation defects. It can fabricate defect-free components with compact weld beads and no visible cracks or pores, while achieving precise regulation of alloy microstructure and mechanical properties through optimization of process parameters such as preheating current, wire feeding speed and traveling speed. Compared with single-wire forming processes, it mitigates typical defects such as uneven weld bead geometry and coarse columnar grains, leading to a substantial improvement in the consistency and comprehensive mechanical properties of large-scale components. With the advantages of high deposition rate, low manufacturing cost and excellent forming capability for medium-to-large complex components, this technology can simultaneously meet the lightweight manufacturing requirements of both the automotive and rail transit sectors. To further validate the effectiveness of this approach, we also refer to the work of Fu *et al.* [22] who systematically investigated the hot-wire GTAW additive manufacturing of 2024 aluminum alloy, focusing on solving the two core bottlenecks of porosity and low deposition rate that plague conventional cold-wire WAAM of aluminum alloys. They found that the hot-wire current has a significant effect on the porosity level: when the hot-wire current reaches the optimal value of 100 A, the porosity of the deposited component is reduced by nearly 10 times from 3.19% to 0.35%, and the relative density reaches 99.6%. Meanwhile, the deposition rate is increased by 3.5 times from 86 cm^3/h to 301 cm^3/h, while the total energy input per unit volume is reduced by nearly half. Under the optimized process conditions, the fabricated 2024 aluminum alloy components exhibit excellent mechanical properties, with the transverse ultimate tensile strength (UTS) reaching 399 MPa, yield strength (YS) reaching 257 MPa, and elongation after fracture reaching 12.0%, which basically meets the performance requirements of forged parts. This research quantitatively verifies that the hot-wire assisted technology can simultaneously improve the manufacturing efficiency and forming quality of aluminum alloy WAAM components, laying a solid experimental foundation for the industrial application of multi-wire DED-arc equipment in the lightweight manufacturing of transportation equipment.

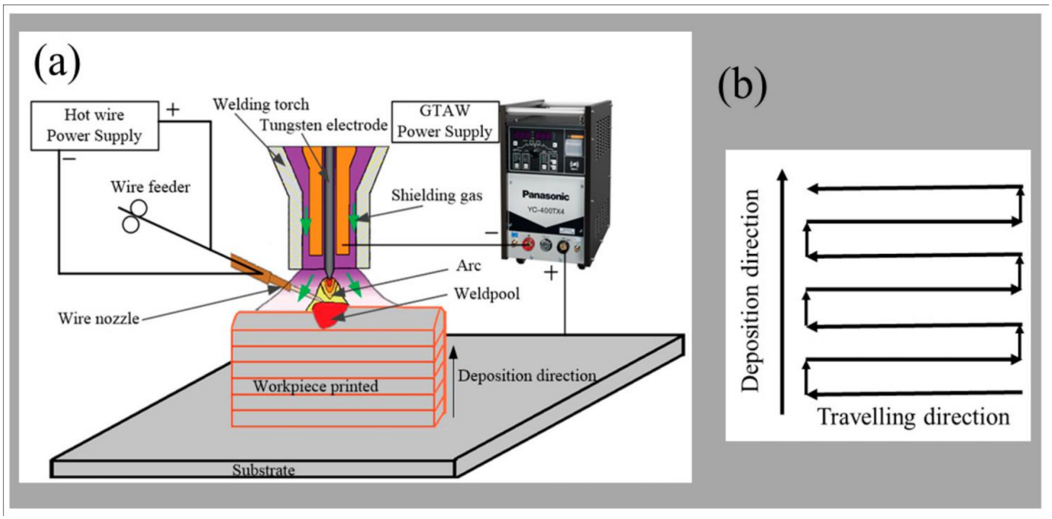

Figure 3. Schematic diagram of arc additive manufacturing by hot-wire GTAW. **(a)** The system of the hot-wire GTAW system; **(b)** a direction schematic of travelling and deposition [20].

3.2. Aerospace field

In the aerospace field, multi-wire DED-arc technology provides an integrated solution for the integrated precision manufacturing of high-strength load-bearing components. As shown in (Figure 4a) Multi-wire DED-arc can directly form 2.5 m scale large wing ribs without molds, which completely breaks through the size limitation of LPBF technology.

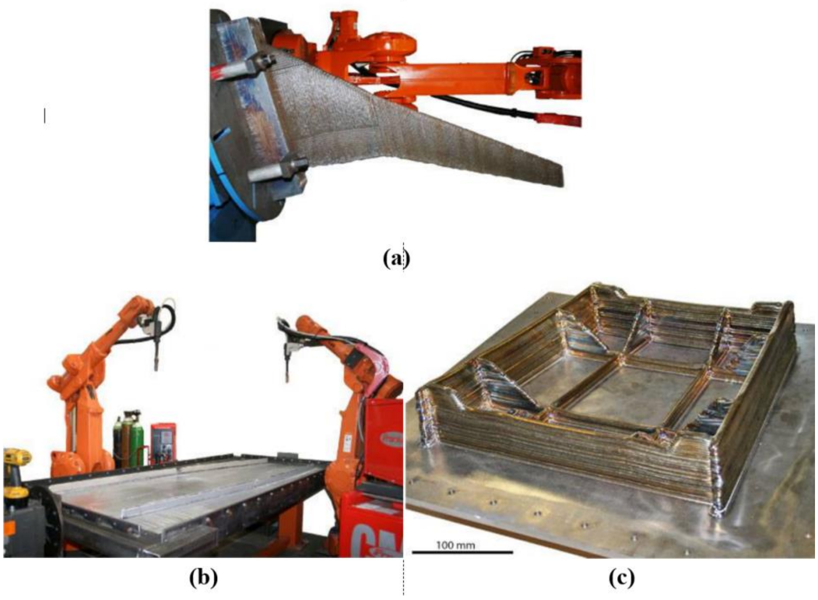

Figure 4. Typical multi-wire DED-arc formed high-strength load-bearing components for aerospace applications: **(a)** 2.5 m aluminum alloy wing rib (single-robot multi-wire DED-arc, 12 h deposition); **(b)** Al-Zn-Mg-Cu fuselage frame (*in-situ* alloying multi-wire DED-arc); **(c)** 7075 aluminum alloy wing main beam (bypass wire-feeding multi-wire DED-arc) [23].

Al-Zn-Mg-Cu (7xxx series) aluminum alloys are the main material for key load-bearing components such as aerospace fuselage frames and wing main beams. During service, these materials are required to have a UTS of over 500 MPa after heat treatment and a fatigue life of more than 10^7 cycles. However, this alloy system is susceptible to hot cracking, it is difficult to balance strength and plasticity during the additive process, and there is a lack of special welding wires in the market, making it difficult for conventional single-wire DED-arc technology to solve these industry challenges. Wang *et al.* [24] used a multi-wire DED-arc precision collaborative wire feeding system to *in-situ* fabricate Al-5.7Zn-3.4Mg-1.6Cu high-strength aluminum alloy. The as-deposited components had an average hardness of 98.6 HV, UTS of 243.9 MPa, and elongation after fracture of 5.9% (Figure 4), with mechanical properties significantly exceeding those of as-cast alloys with the same composition. This indicates that the multi-wire co-melting process can break through the category limitation of commercial 7xxx series aluminum alloy welding wires, providing a customizable printable composition space for high-strength load-bearing components in aerospace. Subsequent comprehensive reviews Meng *et al* [25] have summarized that researchers have developed bypass-coupled multi-wire gas metal arc directed energy deposition (GMA-DED) precision equipment. By controlling the interlayer temperature within the optimal range of 100–120 °C and precisely matching the droplet transfer rhythm of multiple wires with the deposition travel speed, the forming process of 7075 series aluminum alloys has been effectively stabilized. The typical as-deposited samples exhibit an average microhardness of 115–120 HV. The ultimate tensile strength in the direction perpendicular and parallel to the deposition direction is 260–270 MPa and 230–240 MPa, with corresponding elongation after fracture of 2.0%–3.0%, respectively. These results demonstrate that the multi-wire GMA-DED process significantly improves the strength and plasticity of 7075 aluminum alloys compared with the conventional GTAW-DED-arc process, as comprehensively illustrated in the tensile property comparison of different DED-arc variants.

Compared with the traditional forging-machining process, this technology increases the material utilization rate from less than 20% to more than 85%, and shortens the production cycle from 6–12 months to 1–2 months. Compared with LPBF technology, it has no limitation on the forming size of components, and fundamentally solves the industry problem of frequent hot cracking in LPBF forming of 7xxx series high-strength aluminum alloys, providing important equipment and process support for the integrated precision manufacturing of high-strength load-bearing aerospace components.

As mentioned above, through the innovation of precision equipment systems and optimization of multi-wire collaborative processes, multi-wire DED-arc technology achieves customized technical adaptation to the core requirements of different high-end equipment application scenarios. This technology addresses the balance between forming efficiency and performance of 6xxx series aluminum alloys in the lightweight manufacturing of transportation equipment, and overcomes the technical limitations of additive manufacturing for 7xxx series high-strength aluminum alloys in the aerospace field. Existing relevant research and pilot-scale achievements provide mature and replicable technical solutions for the high-performance manufacturing of key components of high-end equipment, further promote the engineering application of multi-wire DED-arc technology in the high-end equipment manufacturing field, and have significant practical significance and engineering value for the technological upgrading of the industry.

4. Core challenges in technology and equipment development

Despite the remarkable research progress and engineering breakthroughs of multi-wire DED-arc aluminum alloy technology, the stringent requirements of high-end equipment manufacturing mean that this technical mode and the R&D of precision equipment still face three major challenges.

First, the basic theoretical framework is incomplete. At present, the analysis of the coupling mechanism across the entire chain of composition-arc-thermal field-microstructure-properties is insufficient. Parameter optimization is mostly carried out through single-factor or double-factor experiments, lacking an overall quantitative regulation framework. The matching logic among process, equipment, and performance for various aluminum alloy systems has not been unified, which is not conducive to the modular and universal design of special equipment.

Second, the core equipment and integrated technology need to be improved. Key components such as high-precision collaborative wire feeding systems and multi-channel intelligent welding power sources have insufficient control accuracy, poor long-term operation stability, and weak compatibility with multiple systems. The multi-parameter on-line monitoring and intelligent closed-loop regulation technologies for the forming process is not yet mature, which makes it difficult to ensure the performance consistency of large-scale components and restricts the industrialization promotion of the equipment.

Third, the full-chain engineering application mode is not well established. The R&D and industrialization of special welding wires suitable for the multi-wire DED-arc process are progressing slowly, making it difficult to fully exploit the technical advantages of multi-wire *in-situ* alloying. The supporting post-processing processes, performance testing standards, and industry specifications are not yet complete, hindering the large-scale application of this technology in the high-end equipment field.

5. Development direction and outlook

To meet the development needs of high-end equipment manufacturing, multi-wire DED-arc technology will focus on precision, intelligence, specialization, and standardization, with breakthroughs mainly in the following four aspects:

First, strengthen the research on multi-field coupling basic theory, to establish a global quantitative correlation model covering wire combination, process parameters, equipment control, and component performance, as well as a standardized process-equipment matching database, providing a theoretical basis for the universal and modular design of special equipment.

Second, tackle the key technologies of core precision components, develop key components such as high-precision multi-channel collaborative wire feeding systems and multi-channel intelligent welding power sources, optimize the compatibility between multiple systems, and improve the long-term operation stability and control accuracy of the equipment.

Third, promote the intelligent upgrading of equipment, integrate multi-sensor on-line monitoring technology, develop an intelligent control system for real-time defect identification and adaptive parameter regulation, and combine digital twin technology to form a full life cycle management and control mode, realizing intelligent closed-loop control of the entire forming process.

Fourth, improve the full-chain technical mode for engineering application, accelerate the R&D and industrialization of special welding wire systems, formulate industry performance evaluation standards and specifications, establish a complete technical system covering materials, equipment, processes, testing, and applications, and promote the large-scale application of this technology in the high-end equipment field.

6. Conclusion

This paper reviews the research status and engineering progress of multi-wire DED-arc technology for aluminum alloys, analyzes the internal synergistic relationships among the three core process aspects, namely wire feeding rate adjustment, synergistic control of current and voltage, and optimization of inter-wire geometric parameters, and clarifies its core advantages over conventional single-wire DED-arc in terms of flexible composition adjustment via *in-situ* alloying and high-efficiency forming with low heat input. Combined with existing research achievements in the field, it sorts out its application adaptability in automotive, rail transit, and aerospace fields, and identifies the main bottlenecks of the current technology in terms of basic theory, core equipment, and engineering application mode. This paper improves the overall theoretical framework of multi-wire DED-arc aluminum alloy forming, and can provide a reference for subsequent research in the field and the R&D of special precision equipment. Meanwhile, due to the insufficient public research data on the long-term service performance of large-scale components, the analysis of some cutting-edge directions in this paper still has room for further improvement.

Data availability statement

No supplementary or additional data were generated in this study.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, I used generative AI-assisted technologies solely for non-research content purposes. Specifically, the author only used Doubao to polish English grammar, enhance sentence readability, and unify the reference format to meet the journal's specifications. No generative AI tools were used to generate research data, analyze experimental results, write core scientific arguments, or draft any substantive content of the manuscript. I remain fully responsible for the integrity, originality, and accuracy of all content in this manuscript.

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Authors' contribution

Lianxin Xu: writing—review and editing, writing—original draft, data curation, conceptualization; Liwei Wang: supervision, resources, project administration, methodology, funding acquisition; Dianlong Wang: investigation, formal analysis. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Liwei Wang holds the position of Associate Editor for *Advanced Equipment* and has not peer reviewed or made any editorial decisions for this paper.

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