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Current Situation and Prospect of Arc Additive Manufacturing Technology

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Abstract: *Arc additive manufacturing technology has the advantages of high molding efficiency, low cost and flexible molding size, so it has attracted the attention of many universities, research institutes and aerospace industries. This paper introduces the advantages and disadvantages of arc additive manufacturing technology, and summarizes the current research status of arc additive manufacturing at home and abroad from four aspects: process selection and optimization, path optimization, online monitoring and control optimization of forming process and post-processing optimization. The application status of arc additive manufacturing technology in rapid product development, personalized customization, traditional process replacement, material-structure-function integration, mold repair and so on was summarized. Arc additive manufacturing technology has great development potential and good application prospects.*

Keywords: *arc additive manufacturing, research status, application status*

1. Preface

Additive Manufacturing (AM) is also known as "physical free manufacturing" [1], "3D printing technology" [2] etc., and has attracted wide attention from universities, research institutes and aerospace industries with the concept of "Design today, product tomorrow" [3-4]. Compared with the traditional reduction manufacturing (cutting processing) technology, it is a "bottom-up" material accumulation manufacturing method [5]. It is an emerging manufacturing technology based on mathematical modeling and based on the discrete stacking principle, stacking materials layer by layer to produce solid parts. It will have a profound impact on the traditional production process, production line, factory mode and industrial chain combination. It is a representative disruptive technology in the manufacturing industry [6-7]. The biggest advantage of this technology is the high degree of flexibility of the manufacturing process, no longer rely on the traditional processing required tools, molds, etc., can quickly and accurately manufacture any shape complex parts, and to a certain extent reduce the processing process, shorten the development cycle of the product, and the more complex the shape, the higher the added value of raw materials products, the more significant the advantages of rapid and efficient molding. After nearly a century of development, additive manufacturing technology has realized the rapid manufacturing of organic materials, inorganic non-metallic materials, composite materials and metal materials products, and metal additive manufacturing is one of the most cutting-edge and promising technologies. Metal additive manufacturing technology can be divided into laser additive manufacturing, arc additive manufacturing, electron beam additive manufacturing and other technologies according to the classification of heat sources, and raw materials are generally in the form of wire and powder. Compared with other metal additive manufacturing processes, arc additive manufacturing has the advantages of high deposition efficiency (600-1200cm3/h, about 5-10 times that of laser cladding), high material utilization rate (close to 100%), low equipment and material manufacturing costs, especially for the overall additive manufacturing of large complex components. This paper reviews the current research status of arc additive manufacturing technology at home and abroad, analyzes the main problems existing in the current research, and puts forward suggestions for the development direction of arc additive manufacturing technology in the future.

2. Arc additive manufacturing technology

Wire Arc Additive Manufacture (WAAM) is a kind of arc or plasma arc as a heat source to melt the metal welding wire, under the control of the program or software using layer by layer cladding principle.

ISSN 2616-5767 Vol.6, Issue 12: 7-15, DOI: 10.25236/AJETS.2023.061202

Based on the 3D digital model, the advanced digital manufacturing technology of 3D metal blanks close to the product shape and size requirements is produced by the wire-surface system [8-10]. The parts formed by arc additive manufacturing technology are composed of all-weld metal, with uniform chemical composition and high density. The free molding environment has almost no limit on the size of the parts, and the molding efficiency can reach several Kg/h. Compared with the traditional casting, forging technology and other additive manufacturing technology has a certain advanced nature, compared with the forging and casting process, it does not need molds, the overall manufacturing cycle is short, the degree of flexibility is high, can achieve digital, intelligent and parallel manufacturing, and the strength is higher than the overall forging parts, and the toughness is better. At the same time, in the process of stacking layer by layer, the parts will be heated several times, and undergo multiple quenching and normalization, which can eliminate the problems of difficult quenching, macro segregation, strength and toughness anisotropy in large castings. Arc additive manufacturing technology also has many shortcomings, such as: the accumulation of heat input during the stacking process leads to the shape and boundary of the part is difficult to control. This will restrict the surface quality, dimensional accuracy and mechanical properties of WAAM parts. Compared with three additive manufacturing technologies, Powder bed pre-laying powder selective melting (powder-bed), simultaneous powder-powder feeding (blowout-powder), and high-energy beam wire molten deposition (Hi.Dep.Wire-fed), the advantages and disadvantages are shown in Figure 1 [11-13].

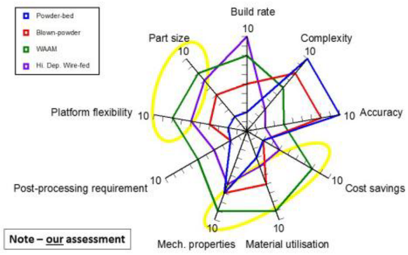


Figure 1: Comparison of advantages and disadvantages of several process methods [13-15]

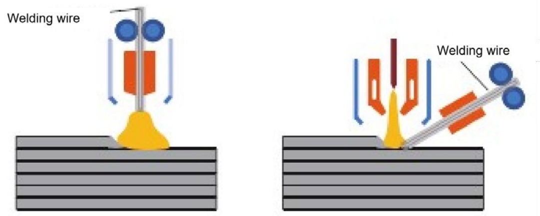
3. Arc additive manufacturing technology research status

The prototype of arc additive manufacturing technology can be traced back to 1925, when Baker[14] et al. of Westinghouse Electric in the UK first used arc as a heat source to create 3D printed metal objects by layer-by-layer deposition. In the course of nearly 30 years of development, forming control and performance control are two important indicators of arc additive manufacturing process. However, in the process of arc additive manufacturing, materials often have strong physical and chemical changes and complex physical and metallurgical processes, accompanied by complex deformation processes, and the above processes have many influencing factors. In recent years, major universities and research institutions at home and abroad in the arc additive manufacturing research mainly focused on process selection and optimization, path optimization, molding process online monitoring and control optimization, post-processing optimization and other factors, to accurately grasp the material - process - organization - performance relationship of arc additive manufacturing process, to achieve active and effective control of shape.

3.1 Arc additive manufacturing technology process selection and optimization

Different from laser and electron beam, arc additive manufacturing molten pool is large, and the existence of cold raw materials, arc force and other disturbance factors in the forming process makes the molten pool become an unstable system, but the prerequisite for WAAM to print good shape workpieces is that the forming process must make the molten pool system have stable repeatability. Therefore, the selection of the process and the optimization of the process parameters are the core of WAAM to prepare the workpiece with good shape. From the perspective of process selection, WAAM technology has two forms, as shown in Figure 2-a, coaxial wire feeding based on Melted Inert Gas Arc Welding (MIG) [15]. The process method is melted inert gas arc welding (MIG). Or Cold Metal Welding (CMT); FIG. 2-b) shows the form of paraxial wire feeding based on plasma Arc (Piasma ARC.PA), where the plasma Arc can also be replaced by Tungsten Inert Gas Arc Welding (TIG).

ISSN 2616-5767 Vol.6, Issue 12: 7-15, DOI: 10.25236/AJETS.2023.061202



a) fusion arc coaxial wire feeding *b) plasma arc side-axis wire feeding*

Figure 2: WAAM schematic diagram

From the perspective of process optimization, the initial stage is mainly through the test method, aiming at different welding wire material systems, matching different welding methods, screening out the key welding parameters that affect the forming of parts (such as: Welding speed, wire diameter, wire feed speed, dry elongation, interlayer temperature, current, voltage, gas type and flow rate, etc., the matching relationship between WAAM forming quality and key welding parameters was established. In recent years, in order to ensure that the shape, size and performance of the workpiece in the WAAM process can meet the relevant requirements and be controllable, some scholars have established a regression equation model using the relationship between the process parameters and the weld size, so as to predict the shape of the additive forming part and select the best process parameters.

In the study on the selection and optimization of arc additive manufacturing process based on TIG or PA process heat source, Qu Yang et al. [16] adopted TIG welding for arc additive manufacturing of stainless steel, and analyzed and solved the problem of wire sticking during TIG welding of WAAM by optimizing welding current, printing speed, wire feed speed and other process parameters. The molded parts have the advantages of better surface quality, compactness and high dimensional accuracy. S Jhavar[17] uses the micro-beam plasma arc fuse process instead of the laser additive manufacturing process to produce small parts, and gets a more regular and smooth weld pass shape. The wall thickness can reach 2.45mm when machining the straight wall, the maximum deposition rate is 42 g/h, and there are no cracks, pores and inclusions between the sedimentary layers. It is found that the microbeam plasma arc process has smaller heat input, and smaller columnar crystals can be deposited per unit length, and the workpiece performance is greatly improved. Ouyang et al. from Southern Methodist University in the United States formed 5356 aluminum alloy structural parts by surfacing with variable polarity argon tungsten arc welding process. The research results showed that arc length, substrate preheating temperature and interlayer temperature were the key controls affecting dimensional accuracy and surface accuracy of the formed parts, that is, optimizing process parameters. The shape of the workpiece is controlled by controlling the heat input in the additive process.

The results show that because of the non-coaxiality of arc and wire in TIG arc additive manufacturing, the phase relationship between wire feeding direction and surfacing direction depends on the moving mechanism when the forming path is complex and varied, which often increases the complexity of forming and control system. Although the heat input of WAAM based on MIG welding is higher, the molding rate is faster, and the welding wire is used as the electrode, the arc and the wire have coaxial, there is no phase relationship between the wire feeding direction and the welding direction such as TIG arc additive molding, and the molding position is more accessible. Based on MIG/MAG, Fronius has developed Cold MetalTransfer (CMT) technology, which is different from MIG/MAG because of its ultra-low thermal input, no splash in droplet transition, arc stability and other characteristics, showing a unique advantage in the field of WAAM molding. Kazansa[18] from Clayfield University in the United Kingdom used the characteristics of CMT's small heat input to carry out technological research on carbon steel and aluminum alloy welding wires respectively.

3.2 Arc additive manufacturing technology path optimization

WAAM technology has many and complex process parameter variables, and has high requirements for path planning of workpiece with complex shape. Therefore, in order to achieve an economical, efficient and intelligent level of arc additive manufacturing, process parameters and path planning need to be co-optimized to meet the shape requirements of formed parts. In recent years, more and more research institutions at home and abroad have carried out research on arc additive manufacturing path planning. The research mainly focuses on two aspects: on the one hand, the path optimization based on the structural characteristics of the model improves the geometry and surface accuracy of the fuse; On the other hand, based on the path optimization of heat distribution in the additive process, the residual stress is reduced and the deformation is reduced.

Ding et al. [19] from the University of Wollongong, Australia, studied the arc additive manufacturing process in depth from the perspective of path planning and designed a new CAD model cutting method, which decomposed the 2-dimensional geometric figure into a series of convex polygons. Then, for each convex polygon, an optimized scanning direction is adopted, and a continuous path is generated by combining zigzag and contour mode scanning strategies. Finally, all the independent subpaths are connected to form a closed curve. This strategy can meet the design requirements of WAAM: simple implementation, minimum number of arcing/extinguishing points, high surface accuracy.

The technical team of Nanjing Inigma Process Automation Technology Co., Ltd. developed the adaptive path optimization software -IungoPNT, based on the hierarchical slicing algorithm of the STL model. The software optimized the workpiece slicing path based on the structural features of the model, and could automatically identify the features in the workpiece numerical model that needed special treatment, including the lap position, corners, thin walls, etc. Small gaps, etc., through the built-in algorithm to automatically optimize the printing sequence, filling strategy, arc, path offset, etc., greatly reduce the production of printed workpiece defects, improve the printing efficiency. Figure 3 shows the path optimization parameter interface of IungoPNT software and the material-structure-function integrated workpiece printed after path optimization.

Cranfield's research team optimized the slice path based on the heat distribution characteristics of the workpiece during the printing process. During the printing process, the deformation caused by the heat accumulation of the workpiece can be avoided through partitioning, sequence adjustment, symmetrical printing and other strategies. Figure 4 shows the large titanium alloy structural parts printed by the team based on heat distribution.

Figure 3: Material-structure-function integrated workpiece

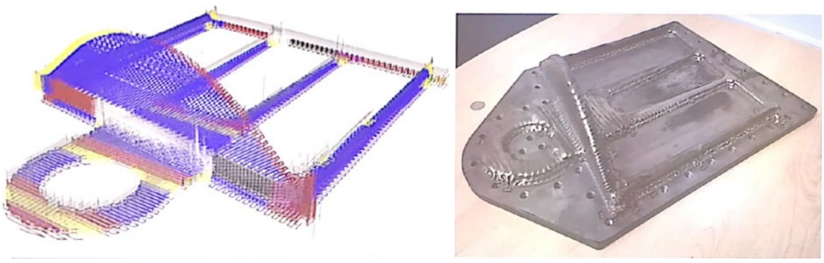


Figure 4: Large titanium alloy structural parts

3.3 Arc additive manufacturing technology molding process monitoring and control optimization

Because arc additive manufacturing technology needs to use arc welding technology, it can not avoid the problems of large heating radius, low heat flux and high heat source intensity to a certain extent. In recent years, in some studies at this stage, the monitoring, feedback and control of arc additive manufacturing process are mainly reflected in the following two aspects: real-time monitoring and control based on the process parameters of additive process; Appearance monitoring and control based on vision system. Domestic research on real-time monitoring and control of arc additive manufacturing process parameters is rarely reported. Cranfield University abroad developed a set of low-frequency monitoring and real-time data recording system and high-frequency arc monitoring and data recording system, as shown in Figure 5. Among them, the low-frequency system monitoring information mainly includes: robot end position, current, voltage, wire feed speed, height, adjustable monitoring frequency, up to 20 Hertz, for the printing process layer height compensation. The high-frequency system monitoring information mainly includes: current, voltage, wire feed speed, temperature information, the highest frequency of 20,000 Hertz for monitoring the droplet transition and process parameter stability.

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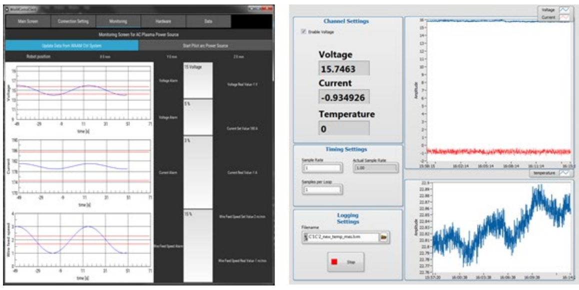


Figure 5: Low frequency and high frequency arc detection and data recording system

In some researches at present, the application of laser vision sensing system in arc additive manufacturing technology is becoming more and more mature at home and abroad. As shown in Figure 6, Tufts University in the United States used two sets of light-sensitive structures and infrared cameras to monitor the size of the surfacing layer and the temperature of the forming part in the additive manufacturing process, and took welding speed and wire feed speed as control variables to realize real-time closed-loop control of the forming size in the molding process [20-21].

Hu Xiaodong from Xi 'an Jiaotong University used passive visual sensing to carry out online detection of melt pool in PAW stacking process, and designed a fuzzy PID controller to control melt width by adjusting welding current [22]. Xu Jianning from Nanchang University designed a fuzzy control system for the deposition layer height based on welding voltage feedback [23] in the additive manufacturing of TIG fusion welding, which can adjust the deposition process parameters in real time and control the deposition size.

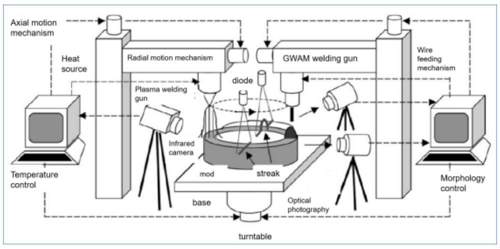


Figure 6: WAAM forming and monitoring control system schematic diagram

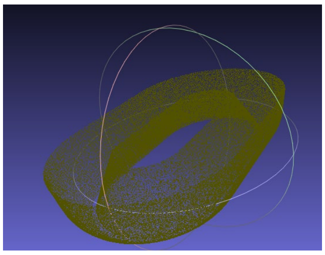


Figure 7: Mold point cloud data model

The technical team of Nanjing Inigma Industrial Automation Technology Co., Ltd. combined reverse reconstruction technology with robot vision technology to research and develop the IungoCAM system, which combined with dynamic planning algorithm, scanned the semi-finished workpiece in the printing process, collected its point cloud data for reverse reconstruction. Defect analysis (size deviation, collapse, accumulation, etc.) is carried out on the reverse-reconstructed model. Through dynamic layer-by-layer slicing and intelligent defect compensation program, the shape, size and quality of each layer of the workpiece in the printing process are detected to realize dynamic automatic correction in the printing process. Figure 7 is the workpiece point cloud data model obtained from the shooting and calculation of the IungoCAM system.

3.4 Post-processing optimization of arc additive manufacturing technology

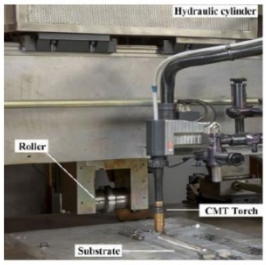
The microstructure of WAAM additive manufacturing parts is closely related to the thermal process it undergoes. The parts manufactured by WAAM technology are subjected to the reciprocating heat cycle of moving heat source, and the heat accumulation is high in the forming process. Different thermal cycle processes determine the difference of the structure and mechanical properties of the molded parts. In this

ISSN 2616-5767 Vol.6, Issue 12: 7-15, DOI: 10.25236/AJETS.2023.061202

context, the researchers proposed the use of post-treatment technology (milling, heat treatment, rolling, etc.) to improve the structure and mechanical properties of metal workpieces, so that it can better meet the needs.

Zhang Haiou and Wang Guilan et al of Huazhong University of Science and Technology proposed arc micro-casting rolling technology [24], which implemented micro-zone rolling of hot metal through extrusion arc forming at high temperature, and significantly improved the mechanical properties of materials. Song et al., Korea Science and Technology Research Center, combined GMA additive manufacturing technology with milling technology to realize the compounding of addition-reduction technology, as shown in Figure 8a). After each layer of metal is deposited, the technology adopts the cutting method to smooth the surface, ensure the molding efficiency and improve the molding accuracy . Cranfield University in the UK, the University of Manchester and Northeastern University in China have collaborated to develop the GMA Additive - RCC composite manufacturing system, as shown in Figure 8b). The system rolls the deposited sample after each layer of metal is deposited. By increasing the interlayer rolling process, this technique achieves the microstructure refinement of titanium alloy [25] and improves the residual stress of structural steel [26]. Among them, the mechanical properties of 2219, 2204 aluminum alloy manufactured by the UK Cranfiled University using WAAM technology and 2219, 2204 sheets are compared. It can be seen from Table 1[27] that after T6 heat treatment, the mechanical properties of 2219 and 2204 aluminum alloy parts manufactured by WAAM all exceed the T6 state level of forgings of the same material.

a) Additive and subtractive composite system



b) Additive rolling system

Figure 8: Additive - equal - reduced material composite manufacturing technology

Table 1 Comparative table of mechanical properties of aluminum alloy manufactured by WAAM technology and sheet metal

Materials		Yield strength /Mpa	Tensile strength /Mpa	Rate of elongation /%
WAAM2219 Aluminium alloy	Sedimentary state	130	260	15.5
	T6 state	309	455	13.65
forge 2219 Aluminium alloy	O state	76	172	18
	T6 state	290	414	10
WAAM2024 Aluminium alloy	Sedimentary state	185	287	11.4
	T6 state	407	499	8.3
forge 2014 Aluminium alloy	O state	70	185	20
	T6 state	393	476	10

4. Application status of arc additive manufacturing technology

Due to its short overall manufacturing cycle and high degree of flexibility, WAAM can realize the advantages of digital, intelligent and parallel manufacturing in the fields of automotive, military, aerospace and shipbuilding, which reflects great advantages, and has been widely used in rapid product development, personalized customization, traditional process replacement, material-structure-function integration, mold repair and other aspects. WAAM adopts continuous weld as the basic structural unit, which is suitable for the rapid prototyping of aircraft internal frame, stiffener and panel structure. At present, large overall titanium and aluminum alloy structural parts are widely used in the aerospace field. In the application research of titanium alloy WAAM technology, Cranfield University in the United Kingdom is at the forefront of the world, and has carried out extensive cooperation with the European Space Agency, Lockheed Martin Company and Bombardier Company, successfully producing aircraft warping beams and landing gear support outer wing ribs. It can also form high-complexity parts, as shown in Figure 9 [28-29]. At present, the titanium alloy deposition efficiency reaches 1~2 kg/h, the mechanical properties of the components reach the level of forging, and the maximum single-direction forming size of titanium alloy parts reaches 1.5m, which greatly shorths the processing cycle and saves

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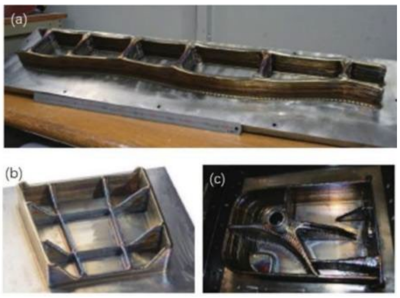
69kg of materials compared with the traditional method.



a) wing girder b) undercarriage support outer wing rib c) complex structural parts

Figure 9: Titanium alloy parts of WAAM at Cranfield University, UK

Cranfield University has also carried out a large number of aluminum alloy WAAM technology application research, trial production of many aluminum alloy parts, as shown in Figure 10, in the international leading level. Based on the flexible configuration capability for structural design, arc additive manufacturing can replace part of the traditional manufacturing process. Domestic Fushun Donggong Metallurgy uses arc additive to manufacture the development cabin shell, as shown in Figure 10, which does not require mold and greatly reduces the cost of product development cycle.

a) Sedimentary frame beam b) hemisphere

Figure 10: Aluminum alloy parts of WAAM at Cranfield University, UK

Nanjing Inigma uses 921A high-strength weldable alloy structural steel to print the submarine pressure hull, as shown in Figure 11. The traditional components are manufactured by assembling welding process. Due to the obvious changes in the coarse crystal zone of the heat affected zone under the action of welding heat cycle, the welding heat affected zone appears softening phenomenon under different heat input conditions. By using the corresponding wire for arc additive manufacturing, the tensile strength of the printed component can reach 720Mpa and the yield strength can reach 620Mpa through strict control of the heat input.

Figure 11: Submarine pressure hull

On the map of manufacturing innovation in China, arc, as one of the core technologies, is comprehensively promoting related development from aerospace, automotive electronics, military defense, and other aspects. The integrated manufacturing concept of "material - structure - function" has become an important direction of the development of intelligent manufacturing in China, and the complementarity of materials and manufacturing has become a major trend.

In 2014, Nanjing University of Science and Technology has carried out research on "material-structure-function" integrated micro-heterogeneous additive, arc control, intelligent control and other technologies. As shown in Figure 12, it has developed high-performance complex components and structure-function integrated components such as 500MPa high-strength aluminum, 1100MPa high-nitrogen steel and 1200-1600mpa ultra-strong steel. Through the micro-heterogeneous structure design of laminated Mosaic, soft and hard interweaving and heterogeneous multi-wire arc additive process, special properties and functions are obtained, which provides a new idea and a new method for the preparation of new materials and metamaterials, and provides a new vision and broad imagination space

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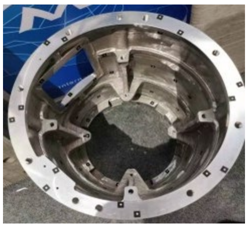
for the personalized design of structural and functional components. In addition, the emergence and development of arc additive manufacturing technology provides a new idea for mold repair and remanufacturing. Using this technology to repair and remanufacturing molds can realize the automation of repair process, improve production efficiency, and save a lot of welding materials.



a) Cabin shell

b) Heterogeneous electromagnetic emission tube

Figure 12: Arc additive manufacturing rapid trial production workpiece

5. Development direction of arc additive manufacturing technology

In the past few years, arc additive manufacturing has achieved explosive development, covering new principles of arc additive manufacturing, new processes, shape control and control principles and processes, material design, structural optimization design, equipment quality and efficiency improvement, quality testing and standards, composite additive manufacturing and other systems. Mainly :(1) The development of intelligent arc additive manufacturing equipment with software as the core; (2) Optimization of molding process and construction of process library;(3) Expand the types and scope of application of arc additive manufacturing materials; (4) The development direction of the integrated system and technology of increasing and decreasing materials is mainly. This field has become an important development direction of advanced manufacturing and has broad development prospects. The development of arc additive manufacturing in China should be based on scientific research, facing the major needs of national strategic products and strategic fields, aiming at the commanding heights of the world's advanced manufacturing technology and industrial development, and seizing the historic development opportunity of "lane change overtaking" in China, so as to provide support for the major strategic goal of becoming a world manufacturing power in 2035.

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