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Manufacturing status and comprehensive research of WAAM technology

Fan Bai*, Mengyang Liu and Wei Ji

School of Mechanical and Electrical Engineering, North China Institute of Aerospace Engineering, Langfang, China

* Corresponding Author

Abstract

WAAM is a layer-deposition manufacturing technology, which consists of CAD model design, layer-slicing, tool path generation, welding parameter selection, material deposition, and post-processing. In modern manufacturing, WAAM is mainly used in aerospace, military weapons, shipbuilding, and other industrial production requiring large structural parts. It uses the existing welding equipment and mechanical arm with an intelligent manufacturing system, arc as the energy output, welding wire as the manufacturing raw material, the specific requirements of materials and equipment are not high, less mechanical processing links can save a lot of money and time costs. Because WAAM technology also has production defects, although its development is approaching maturity, it is still less used than traditional manufacturing methods. This paper mainly studies the defects in WAAM production and the methods to solve the problems and summarizes the research on WAAM technology in recent years in process optimization, prediction model, heat treatment, and other aspects. And try to innovate ideas to solve the problems existing in the actual production of WAAM.

Keywords

WAAM, Process optimization, Prediction model, Post-processing.

1. Introduction

In recent years, with the continuous development of the aerospace industry, scientific research is facing new challenges, the demand for light and high strength materials (aluminum alloy, titanium alloy, etc.) is increasing year by year, according to statistics, in the next 20 years, the aerospace industry needs about 20 million tons of raw material[1].

Because light and high strength materials are difficult to process and have low material utilization rate, WAAM technology is of great concern to researchers. WAAM is based on kinematics, raw material supply, and heat source supply, essentially moving raw materials to heat and layer deposition. In most additive manufacturing systems, metals can only be used in powder form, resulting in porous and poor quality products. WAAM technology can be used as a better manufacturing process for metal alloys.

WAAM technology was proposed as early as 1925[2]. WAAM is an additive manufacturing system that combines metal welding wire as raw material, arc as a molten heat source, and manipulator kinematics. One of WAAM's advantages is the cost savings compared to traditional additive manufacturing of specific equipment and materials. Second, WAAM technology can produce large functional structural parts. Third, the deposition rate is usually 50-130g/min, which is higher than other forms of additive manufacturing technology and greatly reduces the processing cycle[3]. Fourth, compared with traditional machining and manufacturing technology, the product design has greater freedom, while solving the problem of gradient material manufacturing. Although WAAM technology has great manufacturing advantages,

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there are still some problems in actual production, such as substrate temperature difference resulting in internal residual stress deformation, dimensional accuracy control problems, and roughness problems of product components. Therefore, WAAM also needs post-processing to solve the manufacturing defects.

Given the problems existing in actual production, this paper classifies and summarizes the optimization methods of WAAM technology from three aspects of the actual process, prediction model, and hot wire processing, which solves many practical production problems of WAAM technology.

2. Study on practical process optimization of WAAM

WAAM technology based on CMT has been widely used in manufacturing large aluminum alloy components, but its poor mechanical properties in the deposition state of aluminum alloy hinder its application in the aerospace field. This part mainly discusses the solutions of WAAM to improve mechanical properties from the aspect of manufacturing technology.

Monofilament WAAM technology may cause problems such as weakened mechanical properties of products or complex cracks and pores in the manufacture of general materials, so many scholars began to explore the double filament WAAM technology (See Figure 1). Due to the limitation of commercial aluminum wire types, 2024 aluminum alloy cannot be manufactured by the traditional single-wire WAAM technology. Z. Qi et al.[3]realized the fabrication of 2024 aluminum alloy coating by double-wire WAAM technology by simultaneously feeding two wires (ER2319 and ER5087) and adjusting the wire feeding speed. L. Lu et al. used TA1 and Inconel 625 twin-wire to prepare ta1-Inconel 625 functionally graded material thin-walled component by WAAM technology. According to the measurement of the microhardness of the specimen, the fracture mode of the thin-walled component of the graded material was a brittle fracture. G. Zhang et al.[6]prepared Ti-3Al-2V alloy containing TC4 and TA1 wire by double-wire WAAM technology and studied the microstructure and mechanical properties of Ti-3Al-2V alloy. S. Shalini et al. first studied the microstructure and mechanical properties of NiTi-SS bimetal prepared by WAAM technology. Although the double-wire WAAM technology can improve the mechanical properties and structural integrity of products, it is still necessary to explore the influence of various process parameters on the products of different materials in WAAM technology.

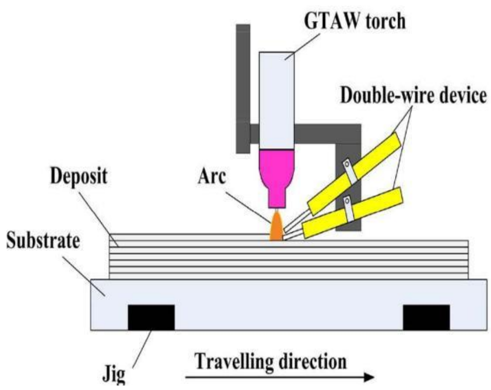

Figure 1: The double filament WAAM technology

The welding parameters in the WAAM process have an obvious influence on product quality and performance. Some scholars studied the welding process parameters (deposition current, pulse frequency, pulse welding power source wire feed speed, inert gas pressure, the waiting time between the layers (temperature) between the layers, etc.) process parameters optimization and optimization of WAAM technology products, the effect of current impact on products mainly for depositing current strong high-temperature impact. Hardy E et al. proposed that deposition current affects the molten pool temperature in the GTAW process, and WAAM based on GTAW will affect the size of structural parts due to the effect of deposition current. The deposition current will affect the fusibility of the previous sedimentary layer, and then affect the mechanical properties and fusion integrity of the deposited material[9][10]. ZHOU et al.[11]studied the effect of deposition rate on microstructure and properties of 2319 aluminum alloy during the arc additive process. With the increase in deposition rate, the θ' phase increases first and then decreases, but grain boundary segregation cannot be improved. The strength and elongation of grain boundary are 273.5mpa and 12.8%, respectively. BAI et al.[12]prepared 2319 aluminum alloy samples by arc additive method and optimized the process parameters. The results show that the strength of the deposited samples increases with the increase of the height of the sedimentary layer. Zhang Rui et al.[13]studied the influence of argon-helium mixture on the WAAM process. When the proportion of helium is low, the sample's upper surface flatness is high. The surface roughness increases first and then decreases with the increase of the helium ratio. P.J. Jiang [14]studied 5356 aluminum alloy and obtained the effects of WAAM technology on deposition current, pulse power frequency, and wire feeding speed on deposition quality, and optimized the best process parameters for arc additive of the material. In addition, conditions for partially driving welding should also be considered, such as obtaining substrate cathode cleaning to remove the oxide surface layer in welded aluminum alloy, and arc drift should be prevented[15]. Arc drift may be improved by changing the arc injection Angle. Wu Q et al.[16]show that when the wire feeding Angle is set to 60°, geometrically consistent deposition can be achieved in any direction of movement, which provides a possible solution to this problem. Geng et al.[17]also developed mathematical models to ensure that line spacing can be updated with Angle changes to achieve consistent deposition.

In addition to the optimization of process parameters affecting the quality of structural parts, interlayer temperature or cooling method is also a key factor determining the performance of large thick layer components. B. Wu et al.[18]studied WAAM technology of titanium alloy and accurately measured interlayer temperature with a high-speed camera, which was used to monitor arc stability and metal transfer behavior, and obtained the specific influencing factors of deposition height and cooling rate on product structure. When Denlinger et al.[19] studied the ti-Ni alloy processed by WAAM technology, it was concluded that the thermal physical properties and interlayer temperature during the processing were the direct causes affecting the residual stress and deformation of the component. A. Hogar[20] et al., in their WAAM study of AA5183, pointed out that the deposition of multilayer film would produce some cracks in the welding metal during subsequent reheating in addition to the usual pores. In the mathematical model analysis method of N. Hoye et al.[21], the influence of interlayer temperature on structural parts is far less than that of deposition current, but the interlayer temperature is closely related to the grain size and cracking sensitivity of organizational materials[22], so the interlayer temperature has a great influence on the quality and mechanical properties of components. C. Shen et al.[23]proposed an innovative arc wire additive manufacturing process for manufacturing 30%Fe3Al composite walls with volume fraction. Experimental tests show that interlayer temperature is the key to preventing stress-induced cracks.

3. Research on prediction model of WAAM technology

In the WAALM process, three-dimensional metal structures are constructed by depositing welded metal beads layer by layer. Standard filament-base welding processes include GMAW and GTAW. The arc can be used as a heat source to provide high deposition rates using high-energy inputs, which result in significant deformation and residual stresses in the product

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components. To find the optimal control strategy of residual stress and deformation, finite element simulation is usually used. The idea that finite element analysis can be used to predict residual stress and deformation in additive manufacturing was put forward as early as 2001[24][25]. The most commonly used finite element simulation method is to use a sequential coupled transient finite element model with a moving heat source and combine element generation to simulate material increase[26][27][28][29]. A. Mss et al.[30]used the finite element method to predict the dilution of deposition in micro-plasma transfer arc additive manufacturing (MPTAAM) and concluded that the maximum temperature profile and the image processing method can measure the width and height of the melt pool and deposition geometry from 3D-FES with good accuracy. This method can also predict the temperature in arc additive. S.H. Nikam et al.[31] used 3D-FES to analyze the temperature distribution and thermal cycle in the deposition process of MPTAAM multilayer metals. They found that an increase in deposition height increased the maximum temperature of the thermal cycle due to heat transfer of the deposition layer before and after deposition, resulting in thermal deformation and residual stress of the matrix material. S. Shrestha et al.[32] established a three-dimensional model of hot fluid in the electron beam melting process. They studied the influence law of the scanning speed of a mechanical arm on surface roughness: the increase of surface roughness increases with the increase of scanning speed. J. Ding et al. [33]studied the stress evolution law during the thermal cycle of the WAAM process by using the transient thermodynamic finite element model. The results show that the peak temperature during the thermal cycle of the WAAM process determines the residual stress at this point. Based on this finding, an effective "engineered" finite element model can save 99% of the computational time compared to traditional transient thermodynamic methods. With the increasing demand for large components in aerospace, the finite element prediction model needs a lot of computational costs, so scholars gradually focus on theoretical modeling to predict the performance of WAALM process products as soon as possible.

4. Post-processing study

In summary, the WAAM results of improving process parameters above show that process parameter optimization has no obvious effect on improving performance. To meet the requirements of lightweight and high straight-strength materials, most deposited aluminum parts require additional processes to improve their mechanical properties. Researchers at Cranfield University[34]introduced WAAM's high pressure sandwich rolling technique to improve the strength of already built components. J. Gu et al.[35]proved that the assisted high-pressure sandwich rolling process reduced the grain size, residual stress, and deformation of finished aluminum alloy components, and eliminated the porosity in aluminum alloy. FANG et al.[36]used the layer-by-layer hammering method in the deposition process of 2319 aluminum alloy to improve the mechanical properties of deposited samples. The results show that during compressive stress loading, the microstructure of the sample presents highly refined grains, which further deforms the recrystallized grains and leads to the increase of dislocation density. Thus, the ultimate tensile strength of the 2319 aluminum alloy prepared by the interlayer hammer method is improved, and the problems of grain boundary segregation and uneven microstructure of the deposited sample are improved.

Rolling and hammering processes are not suitable for geometrically complex components, such as members with small curvature or slender cantilevered structures. Cyclic heating and cooling of subsequent layers proved to be a very significant method to improve the microstructure and mechanical properties of deposited components. C.R. Cunningham et al. [37]fabricated 2319 aluminum alloy components using an arc additive system and then heat-treated them to improve their strength grade. B.V. Pere et al.[38][39]obtained homogeneous $\alpha+\beta$

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microstructure by changing the microstructure of titanium alloy by controlling the thermal cycle profile and solidification path.

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