Technology development and application analysis of additive manufacturing technology in the aeronautics and astronautics field

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Abstract. Additive manufacturing (AM) is a new digital and environmentally friendly manufacturing technology developed in the past 30 years. It has the advantages of saving energy consumption, saving material consumption, rapid manufacturing of products with complex structures and the ability to produce small batches of personalized products. It is in line with the development trend of aerospace equipment, which is increasingly integrated, complicated, lightweight, and integrated structure and function. This paper mainly introduces four kinds of additive manufacturing methods that are commonly used or have application prospects in the aerospace field. They are laser additive manufacturing technology (LAM), Wire arc additive manufacturing technology (WAAM) which is the most commonly utilized AM technology at present and has the characteristics of high melting efficiency, simple equipment and a relatively low-cost electron beam additive manufacturing technology (EBM) and friction additive manufacturing technology (FAM) which can obtain better components in the terms of mechanical properties. WAAM This article elaborates on the current problems and prospects of the possible development direction of additive manufacturing technology in the aerospace field in the future.

Keywords: additive manufacturing, aeronautics and astronautics, intelligent manufacturing

1 Introduction

As a high-tech-intensive industry, the aerospace manufacturing industry is a typical representative of the high-end equipment manufacturing industry. Currently, the mainstream manufacturing technology in the aerospace industry is still equal to material manufacturing or subtractive manufacturing technology. However, typical aerospace component products are becoming increasingly complex, new high-performance materials are constantly emerging, part structures are constantly becoming more complex, and part performance is constantly optimizing. Traditional

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parts manufacturing and traditional machining technology are gradually difficult to meet the needs of some working environments.

Additive Manufacturing (AM), compared with the traditional manufacturing method, is an innovative, not yet fully utilized advanced manufacturing technology. The process of cutting complex 3D part models into 2D models with a specific thickness reduces dimensionality. Materials were added layer by layer using 2D slices for stacking till the 3D part was accomplished. Additive manufacturing is a good choice for processing complex, porous, and repaired parts due to its high processing flexibility. Different from the traditional cutting or subtractive manufacturing method. This technology is a highly integrated system with multiple disciplines and directions, including design, simulation, processing, forming technique, forming software, online monitoring of forming processes, and intelligent closed-loop control. The classification is generally classified according to the type of heat source, the state of raw materials, and the forming method. According to the type of heat source, it can be divided into LAM, EBM, WAAM and FAM. To summarize briefly: LAM has high power density, high speed, and low heat input; EBM has the advantages of high power, large power adjustment range, an energy utilization rate of more than 90 %, convenient adjustment of spotlight lens, fast scanning frequency, and free of metal reflection; WAAM has high forming efficiency and relatively low processing cost but has the need of subsequent procedure; Additive manufacturing has the characteristics of intelligence, lightweight, customization, complex forming, no need for molds, and material saving.

Compared with traditional manufacturing technology, this technology is non-contact machining and is not constrained by cutting tools and part structures. It can achieve the manufacturing of complex parts such as thin-walled and enclosed cavities [1]. According to the authoritative development report “Wohlers Report”, aerospace is the most promising field for breakthroughs in additive manufacturing technology research and industrial applications. Additive manufacturing has developed into a key core technology for enhancing aerospace design and manufacturing capabilities, and its application scope has expanded from the component level (printing of components for aircraft, satellites, high-speed aircraft, and manned spacecraft) to the whole machine level (printing of engines, drones, and nano satellites). The aerospace field mainly benefits from the significant advantages of AM technology in the field of lightweight high-performance materials and integrated structural forming.

To sum up, additive manufacturing technology has important research significance and practical application value in aerospace. This article aims to provide a concise analysis of the research progress of AM technology in the aeronautics and astronautics sector. The subsequent structure of the paper is as follows. Based on the research background in the aerospace field, Chapter 2 provides a review and analysis of additive manufacturing technology from four categories: LAM, WAAM, EBM, and FAM. Chapter 3 discusses the obstacles and technical prospects in the aeronautics and astronautics field. Chapter 4 summarizes the full text.

2 Research status

2.1 Laser additive manufacturing

Laser additive manufacturing (LAM) is an AM technology based on laser as the heat producer and metal powder as the raw material. There are currently two typical types of near-net forming manufacturing processes. One type is the laser melting deposition AM technology with synchronous powder feeding and layer-by-layer deposition as the main technical features. This technology has great advantages in the efficient manufacturing of near-net-shape blanks for large metal structural parts. However, laser melting deposition parts usually have lower dimensional accuracy and poor surface quality, and generally require subsequent mechanical processing or electrophysical/chemical processing to meet the specification accuracy and surface tolerance standards of the component. The other type is the selective laser melting AM technology (SLM) with the main technical features of powder bed powder spreading and selective melting. It spreads powder layer by layer through a powder bed, selectively melting pre-laid metal powder thin layers (usually tens of micrometres in thickness) using high-energy laser beams, and forming complex shaped components through layer-by-layer melting and stacking. The precision net forming of small and medium-sized complex components is its main development and application direction.

In recent decades, owing to the tremendous development of high-speed scanning galvanometer and multi-laser collaborative scanning technology, the maximum size of formable components using this technology has also increased. Whether it is the laser melting deposition AM technology for efficient manufacturing of large metal structural components with near net shape blanks or the laser selective melting AM technology for high-precision net forming of small and medium-sized complex precision components, both provide new solutions for high-quality, short process and near net shape rapid manufacturing of complex structural integrated metal components in the aerospace field, with broad development and application prospects [2]. Countries represented by Germany, the United States, and others are leading the world in the research and development of core optical components such as high-power lasers and high-speed scanning galvanometers, new powder materials, and original process technology.

Ti alloys are commonly utilized in aerospace, biomedical, and other areas for their excellent specific strength, corrosion resistance, temperature resistance, and biocompatibility in aerospace applications. In 2014, Edwards et al. conducted research to assess the fatigue properties of SLM-generated Ti–6Al–4V specimens. According to his study, high tensile residual stresses, porosity and surface condition are the main contributors to the poor fatigue behavior of the SLM-generated TC4. Edwards drew the following conclusions. First, post-process hot isostatic pressing and stress relieving can be used to eliminate the first factors generated by the SLM of TC4. Second, the three factors mentioned above contributed to the samples in this study's fatigue performance being over three-quarters lower than that of wrought materials. Third, eliminating porosity and residual stress can further enhance the characteristics of the specimen. Fourth, it was found that anisotropy has a substantial impact on fatigue performance. The author believed that more testing should be done to better access the fatigue properties in the LAM process [3].

However, there is currently no fully mature technology for laser additive manufacturing to process fully dense and complex titanium-based components. Pores, cracks, and surface spheroidization are common machining defects found in components during the forming process [4]. The mechanical properties of TC4 alloy obtained by LAM exhibit significant anisotropy and have an impact on the elongation of tensile specimens. There is a minor decrease in the tensile strength of the inclined orientation compared to the scanning orientation, but its yield strength, elongation, and cross-sectional shrinkage are higher than those in the scanning direction and additive height direction. The fatigue performance of TC4 alloy manufactured by additive manufacturing in harsh service environments is different from that of traditional TC4 alloy. At the same maximum stress level, the fatigue life of additive specimens under high cycle stress testing is lower than that of forgings.

2.2 Wire arc additive manufacturing

Wire arc additive manufacturing (WAAM) technology is the most commonly utilized metal AM technology which employs an arc as the heat producer to melt metal wires for deposition and forming. WAAM technology has benefits such as high material utilisation, high depositing efficiency, low manufacturing cost, and large forming size, making it a highly advantageous additive manufacturing technology for manufacturing large titanium alloy components. The control of the arc additive manufacturing process mainly involves the selection and control of additive heat source, additive parameters, protective gas, cladding wire, motion system, and additive substrate. The processes that can be used for additive manufacturing include gas metal arc welding (GMAW), plasma arc welding (PAW), or gas tungsten arc welding (GTAW).

The study by Williams et al. shows that when the WFS/TS ratio is 30, the process of adding TC4 titanium alloy by the PAW method is relatively stable. Reducing heat input can accelerate the cooling rate in the molten pool, and effectively inhibit the growth of coarse columnar crystals. Moreover, lower heat input can reduce the solubility of harmful gases and reduce the formation of porosity [5].

Xiong et al. designed a visual sensing system consisting of a pick-up head, which extracts layer width in real-time through various parameters. They also designed an indistinct controller to maintain the expected layer width by changing the arc current. The stability of layer depth and width has been greatly improved [6].

A new tool path generation strategy that suits relevant requirements was proposed by Ding et al. after studying tool path planning for arc wire additive manufacturing [7]. This algorithm first decomposes two-dimensional slices into a set of convex polygons according to their geometric shape, and then draws a contour pattern and fills a zigzag path for each convex polygon, connecting them to form a closed curve. This method can reduce the number of tool path passes and ultimately connect all sub-paths together to form a single connection path. This method can reduce the number of tool path paths and path elements. This strategy combines the advantages of zigzag and contour prop path generation strategies. Compared to existing hybrid path planning methods, the proposed path planning strategy significantly reduces the surface roughness and changes of parts manufactured.

Wu et al. conducted research on the influence of heat accumulation on the constancy of Ti6-Al-4V arc and metal transfer behavior during the manufacturing process of tungsten wire arc additive under local gas protection [8]. The study found that due to reasons such as the decrease in cooling speed, the geometric shape of the first few layers of the melt head will differ a little, resulting in a slight change in the space between the electrode and the remaining melt pool. The shape of the bead is shown in Fig.1.

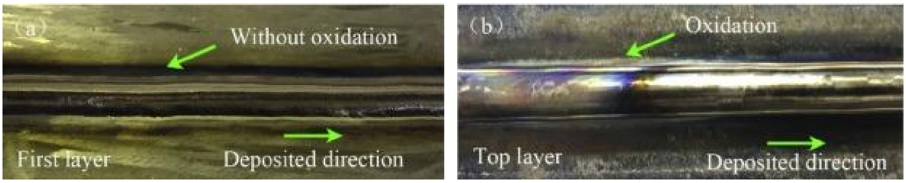


Fig. 1. The bead appearance of the layer. (a) is the first layer; (b) is the top layer [8].

Shao et al. fully explored the relationship between the nanostructure characteristics and corrosion resistance of the prepared samples [9]. Studies have shown that arc oscillation produces a large number of vacancies and interstitial ions through grain refinement in the nanostructure of the sample, which ultimately improves the corrosion stability of the TC4 alloy prepared.

Li et al. developed an intelligent image monitoring system for monitoring interlayer deposition quality in WAAM processes [10]. This system can instantly identify defects in incomplete fusion and voids after a given layer is deposited. And evaluate and verify the feasibility by detecting surface anomalies and identifying the accuracy of manufacturing components.

In 2021, Yu et al. proposed a feasible strategy to improve the current WAAM process's ability to process complex geometric structures. The team proposed a robot-based WAAM process strategy, which is suitable for processing wire-structured free-form surface parts composed of multiple support rods. The contents of the strategy optimization include: studying the optimal welding parameters, and modeling the welding head according to the parameters; Forming an adaptive slice model based on slice geometry and height control; The path of the overall deposition process is planned using these items in combination. The research team tested the feasibility of this strategy with two complex models manufactured [11]. The slicing mode is shown in Fig.2.

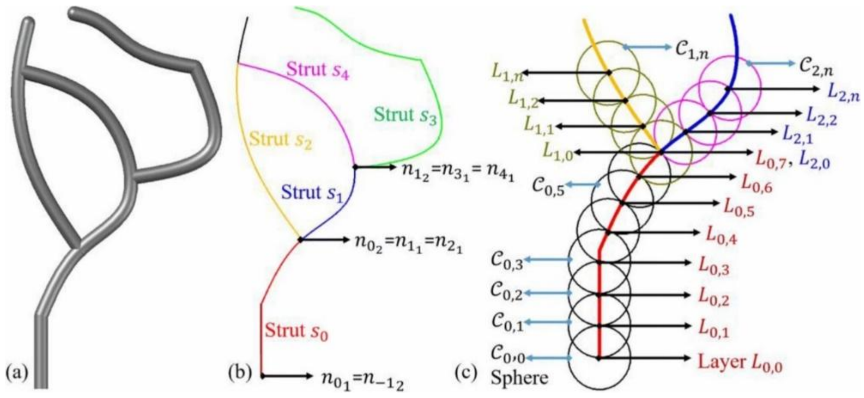


Fig. 2. Schematic diagrams of slicing methods. (a) is wire structure model; (b) is the image of isolate struts; (c) is the suggested strut slicing method [11].

2.3 Electron beam additive manufacturing

Different from the Select Laser Melting (SLM) process, EBM uses an electron beam instead of a laser beam to melt and fuse powder particles. Limited materials are generally used in EBM to reduce the optimization difficulty. Moreover, the technical process is rather slow, which also increases the cost of parts. Furthermore, in lattice/honeycomb structures, the specification and size of the components are limited. The EBM process is carried out under a vacuum, unlike the protective atmosphere in the SLM. Consequently, the oxidation of parts is normally prevented. Furthermore, any gas incorporated on the surface of the powder particles during the EBM process does not result in pore formation. However, the processing of alloys with volatile components such as Zn, Mg, etc. is not recommended [12].

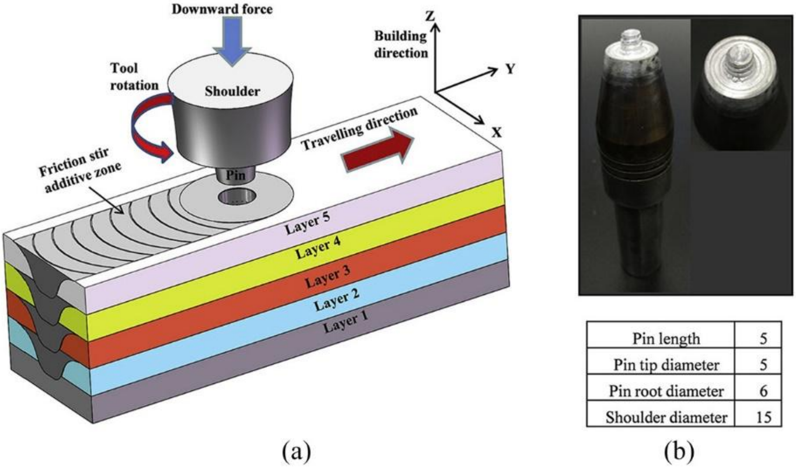
In 2021, Pistor et al. plotted the complete microstructure map of technical single-crystal additive manufacturing with the traditional material. Through extensive experimental and numerical simulations, the team investigated the relationship between process parameters, pool size and shape, and crystal fractions. Based on this, a new strategy for preparing high-fraction single crystal was derived [13].

Lu et al. developed a dynamic temperature measurement array system suitable for the manufacturing process of electron beam additive manufacturing [14]. The follow-up temperature measurement array system is shown in Figure 3. Real-time monitoring of the temperature field distribution during the manufacturing process of electron beam fuse additives is of great significance for suppressing deformation and improving the quality of electron beam fuse additive manufacturing. The temperature measurement array system can work stably in harsh environments such as high vacuum, high temperature, high radiation, and high metal vapour during the manufacturing process of electron beam fuse feeding. It can achieve storage and reconstruction analysis of the temperature field, and display images intuitively, with strong system stability and simple operation.

In 2022, Chen et al. proposed a novel model to describe the dynamic processes of solid-liquid phase transition and heat transfer, and they verified the correctness of the model through classical benchmark simulations. Additionally, it provides more ways to have a deeper insight into the forming of the single trajectories of EBSM on the target layer bed as well as multiple trajectories to assess the impact of process parameters. The outcomes indicate that the model has significant potential for the progress of AM processes [15].

2.4 Friction additive manufacturing technology

The technical foundation for FAM is friction stir processing (FSP) and friction stir welding (FSW) technology, which is a subdiscipline of additive manufacturing. The progression schematic is shown in Fig.3. A stirring tool runs at high speed and is clamped at the top of other plates. The heat generated by the high-speed rotating friction melts the surrounding material. As the agitating tool keeps moving, plasticization continues to occur along the trajectory. Following this process, new plies are stacked repeatedly to reach the required height. Gao's experiments show that, based on its special solid processing process, the mechanical properties of the additive component can be improved compared with the traditional powder bed fusion additive manufacturing technology. The application of this AM technology presents huge potential and is likely to be rapidly promoted in the next few years [16].



Pin length	5
Pin tip diameter	5
Pin root diameter	6
Shoulder diameter	15

Fig. 3. A diagram of the multilayer FAM process [16].

3 Discussion

Complex equipment in the aerospace field often operates in extreme environments, with high requirements for equipment state and fatigue tolerance reliability. When the operating efficiency of the equipment declines beyond the range, it is necessary to repair and replace the components timely. However, due to the particularity of aerospace parts, ordering parts is likely to involve other project delays. The best way to solve the tasks in short terms is to print components instantly with additive manufacturing technology. It is an important way to increase the engineering application potential to explore the applicable scenarios of additive manufacturing, and lightweight additive manufacturing equipment, and accurately simplify the equipment construction process.

During additive manufacturing, protective gas (usually inert gas or nitrogen) is usually filled in the forming cavity, which can effectively avoid oxidation of molten pool metal during printing. However, the preparation process is also added, requiring higher sealing and pressure-bearing performance of printing equipment. Meanwhile, equipment operation requires a more stable environment and sufficient protective gas reserves. To fully leverage the advantages of additive manufacturing and adapt to the field working environment, it is important to explore the laser powder melt forming without the working condition of protective atmosphere for the application and promotion of metal laser additive manufacturing.

The fourth industrial revolution is marching towards intelligent manufacturing. In this unprecedented revolution, the integration of traditional manufacturing technology and new information technology played an important role. However, traditional manufacturing techniques alone are not sufficient for the development of advanced manufacturing systems. Cooperation from other disciplines, particularly computer science and engineering, is essential to fully unleash the benefit of additive manufacturing technologies.

4 Conclusion

The research progress of additive manufacturing technology in aeronautics and astronautics areas is summarized and analyzed in this paper. Firstly, the research background and significance of AM technology in the aeronautics and astronautics field are discussed. Then, based on the application background of the aerospace field, AM technology is introduced from four aspects: LAM, EBM, WAAM and FAM. Finally, the existing problems are discussed and the possible development direction of additive manufacturing technology in the aerospace field is prospected. The author believes that the aerospace industry is one of the main forces to promote the development and application of AM technology. Moreover, the application of additive manufacturing technology in the aerospace field has been developed from the component level to the complete machine level. It can be predicted that the development trend of AM technology is toward industrialization, intelligence and conciseness to realize the integration of material, structure, process, performance and function.

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