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Review of Metal 3D Printing Technology Applications in the Aerospace Field

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Abstract. Nowadays, aerospace components are increasingly moving towards larger size, lighter weight, and multi-functional integration. Among manufacturing technologies, 3D printing technology has become a commonly used intelligent method in the aerospace field, enabling the integrated forming of complex components through layer-by-layer material deposition. This paper introduces the principles, characteristics, and aerospace applications of Selective Laser Melting (SLM), Laser Melting Deposition (LMD), Electron Beam Selective Melting (EBSM), and Wire and Arc Additive Manufacturing (WAAM). SLM, due to its high forming accuracy and densification, is preferred for precision components with complex internal flow channels and lattice structures. LMD demonstrates significant process flexibility and advantages in component remanufacturing, functionally graded materials, and rapid medium-scale component formation. EBSM, utilizing a high-vacuum environment and powder preheating, effectively controls thermal stress, supporting low-stress forming of large, high-performance titanium alloy components. WAAM provides high deposition rates and cost-efficiency, suitable for rapid near-net shaping of meter-scale extra-large structural components. Combined with typical cases, the advantages of this technology in manufacturing are analyzed. Future development directions such as material development and production line construction are prospected.

Keywords: 3D Printing Technology, Aerospace Components, Selective Laser Melting, Laser Melting Deposition

1. Introduction

With the rapid development of aerospace equipment towards larger size, lighter weight, and multi-functional integration, traditional manufacturing modes such as casting, forging, and machining increasingly reveal bottleneck problems like low material utilization, lengthy process flows, and high mold costs when dealing with the forming of complex special-shaped structures [1,2]. Against this background, additive manufacturing (AM), also known as 3D printing, as a revolutionary manufacturing technology based on the discrete-stacking forming concept, is demonstrating strong technical vitality and broad application prospects.

The core of additive manufacturing lies in breaking through the physical constraints of traditional subtractive or equal-material manufacturing. The process starts with a precise three-dimensional digital model (CAD), which is discretized into a series of thin-layer slice data through specialized

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software. The manufacturing system, based on this data, layer-by-layer and selectively directs high-energy beam sources (such as laser, electron beam, or electric arc) to act on materials like metal powder or photosensitive resin, achieving selective melting, sintering, curing, or bonding of the material, ultimately accumulating layer by layer into a three-dimensional solid part [3]. This "bottom-up" manufacturing method is essentially a mold-free, near-net-shape digital manufacturing process.

The article systematically reviews the process principles of Selective Laser Melting (SLM), Laser Melting Deposition (LMD), Electron Beam Selective Melting (EBSM), and Wire and Arc Additive Manufacturing (WAAM) technologies via a literature review based on the China National Knowledge Infrastructure (CNKI) platform. This is achieved by searching keywords such as "3D printing technology," "aerospace components," "selective laser melting," and "laser melting deposition," and filtering results for the years 2019 to 2025. It analyzes the current application status of these technologies in aerospace components and prospects their future development trends.

2. Principles and characteristics of metal 3D printing technology

2.1. Selective Laser Melting technology (SLM)

As shown in Figure 1, this technology is carried out in a chamber filled with inert gas. A fine layer of metal powder is spread by a powder spreading device, and a high-power laser beam, typically with a power of 200-1000 watts, selectively scans and melts the powder layer according to the sliced data of the 3D model [4]. The core advantage of this technology lies in its ability to manufacture dense entities with relative densities as high as 99.5% or more, with mechanical properties approaching or even exceeding those of traditional forgings. SLM is very suitable for manufacturing small- to medium-sized components with complex and precise features and is widely used in aerospace, precision molds, and other fields. However, the limitations are also apparent: The build volume is limited, making it unsuitable for manufacturing oversized components; the need for support structures to resist thermal stress and support overhanging parts makes post-processing removal of supports relatively cumbersome; additionally, high equipment costs and metal powder prices result in relatively high per-part costs.

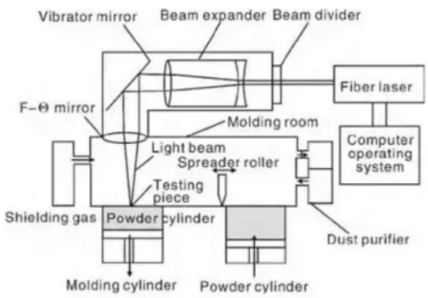

Figure 1. Schematic diagram of Selective Laser Melting technology [4]

2.2. Electron Beam Selective Melting (EBSM)

Electron Beam Selective Melting is similar in principle to SLM, as both are powder-bed-based selective melting technologies, but the energy source is replaced by a high-energy electron beam (see Figure 2). This process must be carried out in a high vacuum environment, which brings two unique advantages: 1) It perfectly avoids oxidation of metals at high temperatures, making it

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particularly suitable for processing reactive metals like titanium and tantalum; 2) The entire powder bed can be preheated to a high temperature, which greatly reduces the residual stress generated during the forming process, effectively suppressing crack formation.

EBSM has extremely fast scanning speeds and high melting efficiency, making it particularly suitable for manufacturing titanium alloy and nickel-based superalloy components widely used in the aerospace field. Its disadvantages are that the vacuum system leads to high equipment costs and maintenance complexity; due to the relatively larger focal spot of the electron beam and the phenomenon of powder pre-sintering, the minimum feature size and surface accuracy it can print are usually not as good as SLM.

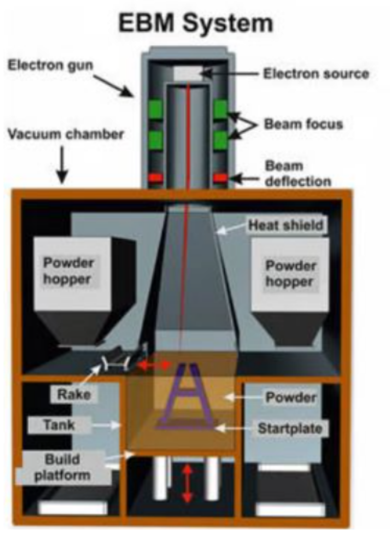

Figure 2. Schematic diagram of electron beam selective melting

2.3. Laser Melting Deposition technology (LMD)

Laser Melting Deposition technology, sometimes referred to as Laser Engineered Net Shaping (LENS) technology, involves a process similar to precision laser welding. As shown in Figure 3, it is achieved through a processing head that integrates a laser head and a nozzle. A high-power laser beam forms a melt pool on the substrate surface, while metal powder is simultaneously injected into the melt pool by a stream of inert gas, instantly melting and solidifying to form a cladding layer. By building up layer by layer, a three-dimensional solid or coating is eventually formed [5]. The greatest characteristic of LMD is its flexibility. It can manufacture new parts on a flat substrate and is even more adept at adding features, repairing, and surface strengthening on existing parts. It supports mixed printing of multiple materials and even the preparation of graded materials, allowing the local composition to be changed by switching powders during the manufacturing process. Its build rate is significantly higher than SLM, but due to the free solidification of the melt pool, the resulting parts have poor surface roughness and low dimensional accuracy, usually requiring subsequent machining to meet usage requirements; thus, it is better suited for near-net shaping.

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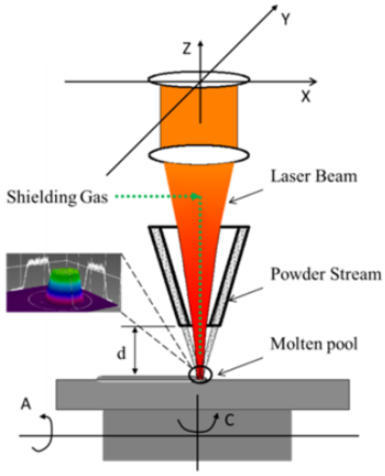

Figure 3. Schematic diagram of Laser Melting Deposition technology

2.4. Wire and Arc Additive Manufacturing (WAAM)

Wire and Arc Additive Manufacturing uses standard arc welding processes such as MIG, TIG, or plasma arc as the heat source and metal wire as the raw material. The arc melts the wire, and through the movement of a robotic arm, large metal components are built up bead by bead, layer by layer. The most prominent advantages of WAAM are its extremely high deposition rate and very low material and equipment costs. It offers unparalleled economy in manufacturing meter-scale or even larger metal parts, making it very suitable for the rapid manufacturing of aerospace large frames, ship propeller prototypes, or large molds (see Figure 4) [6]. The cost is very low forming accuracy and extremely poor surface quality. Due to the concentrated and substantial heat input of the arc, parts experience significant heat accumulation, leading to pronounced macroscopic thermal deformation. The microstructure is usually relatively coarse, and the overall performance exhibits significant anisotropy. WAAM-manufactured parts often require substantial subsequent subtractive machining to obtain the final shape and dimensions.

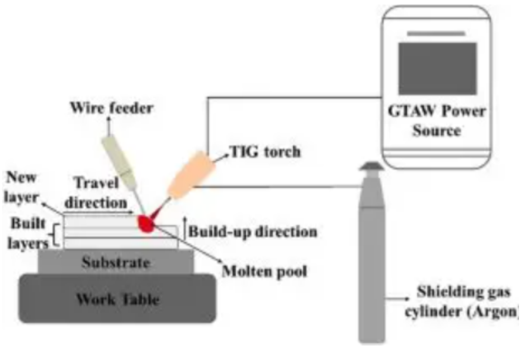

Figure 4. Schematic diagram of Wire and Arc Additive Manufacturing technology

3. Aerospace applications and technological development

3.1. Power system components

SpaceX's Raptor 3 engine (see Figure 5) incorporates multiple innovations in its design. The number of external parts is significantly reduced, adopting a more streamlined and integrated design. By

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internalizing secondary flow channels and adding regenerative cooling devices, it eliminates the mass and complexity of the heat shield while also removing the need for a fire suppression system. Compared to Raptor 1 and 2, Raptor 3 is 7% lighter and has 21% higher thrust, fully demonstrating that 3D printing technology in the aerospace field can achieve a perfect combination of lightweight and high efficiency.

Figure 5. Structural evolution of the SpaceX Raptor engine

NASA, through the project LCUSP and its successor project RAMPT (Rapid Analysis and Manufacturing of Propulsion Technology), systematically broke through the technical bottlenecks of additive manufacturing for aerospace engine thrust chambers [7]. During the LCUSP phase, the additive manufacturing copper alloy GRCop-84 (Cu-8at.%Cr-4at.%Nb) was developed, combining high thermal conductivity, excellent high-temperature creep resistance, and strength (see Figure 6). As it also needs to withstand pressure from the combustion chamber and coolant, there are certain requirements for the structural strength of the thrust chamber body [8,9]. The RAMPT phase further optimized it into GRCop-42 (Cu-4at.%Cr-2at.%Nb), which increased thermal conductivity by 15% while maintaining equivalent strength. In process reliability verification, the GRCop-84 and C18150 chromium-zirconium thrust chamber bodies integrally formed using Selective Laser Melting (SLM) technology passed hot-fire test assessments of 2365 seconds and 1443 seconds respectively, without failure, confirming the long-term service reliability of additively manufactured copper alloys under extreme thermomechanical loads [8,10].

Figure 6. GRCop-84 thrust chamber

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Figure 7. SLM-formed GRCop-84 thrust chamber

In July 2021, China's Deep Blue Aerospace successfully completed a vertical takeoff and vertical landing free flight test for the first time using a self-developed "Thunder-5" (LT-5) liquid rocket engine manufactured with 3D printing technology (see Figure 8). This engine was printed using nickel-based superalloy powder, with a maximum size of 0.6×0.6×0.6 m. Utilizing its excellent properties such as high strength, ductility, fracture resistance, and low variability, it broke through the bottlenecks of low production efficiency, complex process routes, and long production cycles associated with traditional rocket engine manufacturing methods.

Figure 8. LT-5 liquid rocket engine

3.2. Aircraft frame structures

In May 2020, the Aerospace Materials and Process Research Institute of the China Academy of Launch Vehicle Technology (CALT), part of the China Aerospace Science and Technology Corporation (CASC), utilized 3D printing technology by adopting Huashu GaoKe's Continuous Additive Manufacturing Solution (CAMS) HT1001P for processing. Chief Designer Li Dong and others manufactured 50 interstage separation device protection plates with good physical and chemical properties, which were spliced together, forming an important component on the Long March 5 launch vehicle. Each component measured approximately 370 mm × 100 mm × 125 mm, and the printing time was only 48 hours.

Meanwhile, the research team from the Fifth Academy of China Aerospace Science and Technology Corporation (CASC Academy 5) significantly suppressed the deformation tendency and metallurgical defects of titanium alloy frame-beam structures through a multi-strategy collaborative control method, successfully achieving the integrated, high-precision forming of the main beam structure. This technology system was validated in the development of the new-generation crewed spacecraft test vessel. The return capsule heat shield base frame structure, designed by CASC Academy 5, utilized metal 3D printing technology to achieve goals such as lightweighting, reduced production costs, and shortened production cycles.

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Figure 9. Interstage separation device protection plate

Figure 10. Return capsule heat shield base frame structure

4. Conclusion

Metal 3D printing technology, due to its technical characteristics of layer-by-layer stacking and mold-free forming, demonstrates significant advantages in the manufacturing of aerospace components, playing an irreplaceable role especially in achieving structural lightweighting, functional integration, and manufacturing efficiency. This paper systematically elaborated on the process principles and application characteristics of SLM, LMD, EBSM, and WAAM metal 3D printing technologies. Combined with practical cases in the aerospace field, both domestic and international, such as the SpaceX Raptor engine, NASA's GRCOP thrust chamber, the Long March 5 interstage separation device protection plate, and the return capsule heat shield base structure in China, it fully verified the great potential of this technology in enhancing performance, shortening cycles, and reducing costs. Metal 3D printing has become an important technical support promoting the innovative development of aerospace equipment.

However, this technology is still mainly in the "auxiliary manufacturing" stage of development and has not yet become a mature manufacturing method for mainstream load-bearing structures in aerospace. Current applications are mostly concentrated on prototype trial production, non-critical components, or the manufacturing of complex features difficult to achieve by traditional processes. Reliability, consistency, and cost-effectiveness still face severe challenges. Especially regarding the anisotropy of material properties, internal defect control, process stability, and long-term service reliability, there are still obvious shortcomings, making mass production in high-safety fields like aerospace still difficult. Based on this, this paper summarizes several future development directions.

In the future, efforts should continue to promote the development of new metal materials suitable for extreme service environments (such as ultra-high temperature, strong corrosion, and high load), especially high-performance copper alloys, nickel-based superalloys, titanium alloys, etc.; further develop large-size component manufacturing technologies and explore hybrid manufacturing modes combined with other manufacturing processes to achieve integrated "printing-machining-inspection"

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production lines; and establish additive manufacturing material, process, inspection, and acceptance standard systems applicable to the aerospace field.

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