Proceedings of CONF-FMCE 2025 Symposium: AI and Machine Learning Applications in Infrastructure Engineering
DOI: 10.54254/2755-2721/2025.MH25251

# *Metal Additive Manufacturing Technology in Rocket Engines and Future Prospects*

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***Abstract.*** Against the backdrop of the aerospace industry's escalating demand for lightweight, high-strength components with complex geometries, traditional manufacturing methods such as forging and casting face inherent limitations in material efficiency and design flexibility. Metal additive manufacturing (MAM), a flagship of digital manufacturing, leverages high-energy beam technologies like laser powder bed fusion to enable layer-by-layer fused deposition, thus overcoming bottlenecks in fabricating intricate aerospace parts —from rocket engine cooling channels to turbine blades with internal lattice structures. This technological paradigm shift is particularly pronounced in the commercial spaceflight sector, where advancements such as SpaceX's reusable rocket programs and China's burgeoning commercial launch vehicle initiatives have harnessed MAM to reduce production cycles by 40% and achieve up to 30% weight reduction in critical components. As a result, MAM has emerged as a pivotal technology to balance cost-effectiveness and performance in next-generation aerospace systems. This paper systematically reviews the technical characteristics, application advancements, and existing challenges of MAM, while contextualizing its technological development pathway and future directions through engineering practices in U.S. and Chinese rocket engine programs.

***Keywords:*** Metal additive manufacturing, Rocket, Engine, Technical challenge

## 1. Introduction

Metal Additive Manufacturing(MAM) is a digital model-driven advanced forming technology that utilizes high-energy beam heat sources (such as laser beam/electron beam/electric arc) to fuse and deposit metal powders or wires layer by layer. Guided by precision control systems, this technology enables three-dimensional directional material accumulation, ultimately achieving integral forming of complex-structured metal components [1]. This technology deeply integrates interdisciplinary technologies such as digital twin, intelligent control and precision machinery, which is regarded as a key technology direction to promote the transformation of manufacturing industry to intelligent and flexible, and has an important strategic value in aerospace, biomedical and other high-end manufacturing fields. However, the technology still faces critical bottlenecks, including pore defects, thermal stress-induced deformation, and high temperature alloy performance generation difference, the future depends on the optimization of multi-physical field coupling process, the research and development of new high entropy alloy and the construction of the whole process standard system,

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to promote metal additive manufacturing from prototype manufacturing towards the mass production of aerospace power system, which fits the strategic demand of repeatable vehicle and space nuclear power equipment for multi-functional integrated components.

## 2. Metal additive manufacturing technology features

Metal additive manufacturing technology can be systematically categorized into two major technological systems based on the material accumulation mechanism: solid-phase forming and melt forming. Specifically, melt molding technology forms two branches of powder bed fusion (PBF) and directed energy deposition (DED) according to the material delivery method, and its secondary classification standard involves the synergistic combination of material morphology (powder/wire) and energy source type (laser/electron beam/arc), and the different process paths correspond to the multiscale molding mechanism from the cold processing to the combination of high-energy beam metallurgy [2]. Additive manufacturing exhibits remarkable advantages over traditional material reduction processes: it can break through geometric constraints, support topology optimization and functional gradient design, and enhance the potential of product performance through structural innovation. By adopting a mold-free manufacturing strategy and integrating intelligent support technology, it significantly compresses the product development iteration cycle. It can realize near - net - shaping technology based on precise material deposition control, with the material utilization rate reaching more than 90% and the machining allowance significantly reduced; and it can eliminate traditional assembly interfaces through multi - scale structural monolithic forming technology to achieve lightweight design of components on the premise of ensuring structural integrity [3,4].

## 3. Metal additive manufacturing technology for rocket engines in China and the U.S.

Rocket engine metal parts additive manufacturing is mainly used in the engine casing, nozzle expansion section shells, etc.The research on additive manufacturing of rocket engine metal components demonstrates a dual-track evolutionary path: one is through the overall forming technology will rocket bearing shell and complex external functional structure integrated manufacturing, breaking through the traditional split processing mode, to reach the process of process intensification and to improve the manufacturing efficiency and reliability of the structure; the second is to ensure the mechanical properties of the The second is to break through the traditional process constraints under the premise of ensuring the mechanical properties, and realize the functional weight reduction design for the needs of aerospace power system.

### 3.1. USA

Leading U.S. aerospace power companies have achieved significant engineering validation of metal additive manufacturing in key rocket engine components. Northrop Grumman's Orbital ATK successfully employed laser powder bed fusion (LPBF) additive manufacturing technology to successfully realize the monolithic manufacturing of a certain type of solid rocket engine nozzle. Rigorous hot-fire testing under full operational conditions confirmed that the additively manufactured nozzle met structural integrity and ablation resistance requirements. This achievement demonstrated the feasibility of integrating flow channel topology optimization and cooling channel fabrication, validating LPBF's engineering applicability for manufacturing critical load-bearing aerospace components [5,6]. The National Aeronautics and Space Administration (NASA) made

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substantial progress in the field of metal additive manufacturing of liquid rocket motor nozzles, which used the laser directed energy deposition (DED) process to successfully prepare 1.016-meter class and 2.41-meter class oversized integral regenerative cooling nozzle. Test data show that the molding accuracy is controlled within ±0.5mm, and the structural bearing and thermal protection performance verification under high-pressure combustion environment confirms that the technology can effectively realize the gradient composite structure that is difficult to process by traditional processes [7]. Lockheed Martin introduced an innovative application of LPBF in the RL-10C-X upper stage engine, enabling the integrated manufacturing of heterogeneous materials for key thrust chamber components, including the injector, combustion chamber, and regenerative cooling nozzle. Inconel 625 high-temperature alloy was selected for the injector and nozzle to ensure oxidation resistance, while the combustion chamber utilized C-18200 chrome-copper alloy for enhanced heat transfer. LPBF process breaks through the traditional manufacturing constraints and completes the optimized design of the topology of the thrust chamber and the integrated molding of the micro-channel inner runner structure. This technology enables the engine thrust chamber to achieve over 90% parts integration, reducing hundreds of assembly interfaces compared to the RL-10C-1 model, while compressing the development cycle to 1/3 of the traditional process, providing a revolutionary manufacturing solution for the reusable aerospace power system [8].

### 3.2. China

Chinese rocket engine R&D institutions have actively explored the application of metal additive manufacturing (AM) in rocket propulsion systems. The team led by Zhao Yong from the Institute of Power Technology of Aerospace Science and Industry (IPTI) adopted a multi-scale structural design approach, applying gradient array topology optimization to titanium alloy (TC4) load-bearing components for solid rocket motors. Selected zone laser melting (SLM) process was used to realize the integrated forming of bionic honeycomb-truss composite structure. Tests show that the tensile strength of the component reaches 950MPa (deviation from forging performance <5%), and the structure achieves a weight reduction of 13.6% under the premise of maintaining the reliability of the whole life cycle, and at the same time, the manufacturing cycle is shortened by 50%, which provides an innovative manufacturing paradigm for the lightweighting of the main bearing structure of the vehicle, which is also a synergistic optimization of the function and structure [9]. China Aerospace Science and Technology Group Zhao Lin Yu team for solid engine bracket additive-driven lightweight design, based on multidisciplinary synergistic optimization method to achieve composite structural innovation, the dynamic load topology optimization weight reduction rate of 34%, a new engine directly under the parts of the structural efficiency record [10]. Meanwhile, the Inner Mongolia Power Machinery Research Institute broke through the large size thin-walled ignition device shell forming technology bottlenecks, the use of selective laser melting (SLM) process manufactured chrome-nickel alloy shell successfully passed the 15MPa high-pressure ignition test, compared with the traditional manufacturing program to reduce the machining sequence by 70%, shorten the development cycle by 60%, verified the additive manufacturing in the engine fireworks complex components of the fast-response manufacturing technology Advantage [5].

## 4. Technical challenges at this stage of metal additive manufacturing technology

The pore defects commonly found in metal additive manufacturing components are the core problem that restricts their mechanical properties, and their formation mechanism is closely related to the regulation of process parameters and raw material properties. There are two typical failure modes in process parameters: one is the keyhole effect caused by too high energy density, the low melting point elements in the melt pool vaporize to form bubbles, which are retained under the extremely fast cooling rate due to the sudden increase in melt viscosity, forming deep and narrow pores and macro deformation caused by residual stress. The second is the unfused defect caused by insufficient energy density, which is manifested as metallurgical failure between neighboring scanning tracks due to insufficient heat input, and inter - layer or inter - channel porosity is directly triggered by the reduction of the lap rate of the melt pool. In terms of raw material factors, the adsorbed gases on the surface of the powder or the impurities such as argon wrapped inside are released during the melting process, forming randomly distributed spherical closed pores. The above pore defects affect the component performance through multiple mechanisms: on the one hand, as a source of stress concentration, they trigger crack initiation, resulting in plasticity, tensile strength and other indicators of decline; on the other hand, the destruction of material continuity exacerbates mechanical properties anisotropy, significantly reducing the high week fatigue life and other dynamic load-bearing capacity, and the reliability of key components in aerospace and other fields constitutes, a serious challenge [11,12].

Metal additive manufacturing technology in high-temperature alloy molding precision control has limitations due to process characteristics. The laser beam diameter of mainstream equipment is over 50 microns, while traditional cutting processes can achieve sub-10 micron accuracy. Thermal stresses generated during layer-by-layer deposition cause non-uniform shrinkage, posing challenges to dimensional tolerance control [13]. High-temperature alloy additive parts exhibit performance variability and unique microstructural features: Interlayer porosity, grain boundary segregation, and other intrinsic defects weaken strength-toughness matching. While hot isostatic pressing and post-processing can partially mitigate these issues, they increase manufacturing costs—contradicting the near-net-shape advantages of additive manufacturing.

## 5. Conclusion

Metal Additive Manufacturing (Metal AM), a quintessential representation of digital manufacturing technology, enables integral forming of complex metal components through high-energy beam layer-by-layer fused deposition technology, providing innovative solutions for the manufacture of high-performance components in aerospace and other fields. This paper analyzes the technology characteristics, application progress, and challenges from three dimensions and draws the following conclusions. First, metal additive manufacturing demonstrates three major innovations in technical features. The first is the full-process modeling technology based on digital twin and intelligent control, which significantly improves forming accuracy and process stability. The second is the capability of multi-material heterogeneous integration, breaking through traditional process limitations. The third is the synergistic effect of topology optimization and additive manufacturing, unleashing the potential of structural innovation.

Second, China and the United States present a differentiated development pattern on the technology path. With LPBF and DED technologies as the core, the United States focuses on the engineering verification and heterogeneous material integration of core components such as injectors and regenerative cooling nozzles, and has completed the flight assessment of 1-2.5-meter components; while China has taken SLM process as the breakthrough, and has made significant progress in titanium alloy lightweight bracket, ignition device shells and other auxiliary structures, and has realized a 34% weight reduction rate and a 60% compression of the cycle. This difference not only reflects the difference between the two countries' technological foundation and industrial demand, but also reveals the different focuses of subsequent technological breakthroughs.

However, metal additive manufacturing still faces key bottlenecks: pore defects leading to mechanical property degradation, and residual stress accumulation in oversized component molding. Future research needs to focus on the optimization of multi-physics field coupling process, the development of new high-entropy alloys and the construction of the whole chain of standard systems to launch breakthroughs, in order to promote the technology from prototype manufacturing to the aerospace power system mass production transformation. With the development needs of reusable vehicle and space nuclear power equipment, metal additive manufacturing will play a more important strategic role in the manufacturing of multi-functional integrated components and extreme environment-adaptable structures.

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