Research Status of 3D Printing Parts Material and Structure Design for Equipment Service Environment

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Abstract. As the requirements for component performance in extreme service environments, such as aerospace and defense equipment, become increasingly stringent, the limitations of traditional manufacturing processes in complex structure integration and performance optimization have become more apparent. 3D printing technology, with its high design flexibility, capability to manufacture complex structures, and compatibility with multiple materials, offers new approaches for developing components for equipment operating in extreme environments like high temperatures, high pressures, and corrosive conditions. However, it still faces challenges in material compatibility, interface bonding strength, and process stability. This paper systematically reviews the progress of research on 3D printed materials and structural design for equipment service environments, focusing on performance breakthroughs in high-performance metals and alloys, smart-responsive polymers, and ceramic matrix composites. It also analyzes the advantages of biomimetic topology optimization and lattice structure design in lightweighting, impact resistance, and multifunctional integration, and summarizes practical application cases of this technology in aerospace, biomedicine, and defense. The study shows that although 3D printing significantly enhances the environmental adaptability of components through multi-material composites and computation-driven design, its large-scale application is still limited by issues such as insufficient interface bonding strength, high process costs, and lagging detection technologies.

Keywords: 3D printing, Bionic topology, Material innovation

1 Introduction

3D printing technology, with its high design flexibility and short manufacturing cycle, is gradually penetrating into advanced manufacturing fields such as aerospace and military equipment. However, the special nature of service environments imposes higher demands on component structure design and material properties. For example, aviation engine components must withstand high temperatures and pressures, while naval equipment needs to resist corrosion and dynamic impacts; traditional structures and single materials struggle to meet these requirements. Traditional casting or machining cannot seamlessly integrate metal and ceramic gradient structures in a single component,

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whereas 3D printing can achieve this through multi-nozzle or powder bed technology [1]. Traditional cutting methods cannot produce the intricate internal topologies of biomimetic honeycombs or porous bones, but 3D printing can build lightweight lattices layer by layer [2]. In recent years, research on 3D printing technology for service environments has focused on three main areas: material innovation, structural optimization, and process adaptability. As extreme service conditions (such as high temperatures, high pressures, and corrosion) increasingly stringent demands on component performance, researchers have improved the functional adaptability and reliability of 3D printed components through multi-material composites, biomimetic topology optimization, and cross-disciplinary technology integration. This paper systematically reviews the research progress from three dimensions: material design, structural optimization, and practical applications, analyzes technical bottlenecks, and looks forward to future breakthroughs.

2 Material Innovation

2.1 High Performance Metals and Alloys

Entering the 21st century, breakthroughs in metal 3D printing first included high-strength metals such as titanium alloys and aluminum alloys, opening the door to industrial applications. After 2010, material innovation entered a period of rapid growth: ceramics, carbon fiber composites, flexible photopolymer resins, conductive polymers, and even biocompatible materials (such as bio-inks) emerged one after another, completely breaking through the material boundaries of traditional 3D printing.

In the field of metal materials, breakthroughs in high-temperature resistance, corrosion resistance, and high strength are reshaping the landscape of advanced manufacturing. The Supe team's nano-copper alloy (porosity 10.56%) [3], with a 30% reduction in corrosion rate, marks the transition from "formative manufacturing" to "functional manufacturing" in metal printing. However, the 8% elongation shortcoming highlights a common challenge in current metal additive manufacturing. The Martin team's research on high-strength aluminum alloys demonstrates another dimension of breakthrough: achieving a tensile strength of 500MPa through laser parameter control [1], with a 40% process gain essentially due to the synergistic optimization of melt pool dynamics and alloy element distribution. However, surface defects with Ra> 10μm precisely expose the contradiction between microstructure control and macroscopic morphology accuracy in current metal additive manufacturing. In this light, current metal additive research exhibits three significant characteristics: first, material development has shifted from single-performance breakthroughs to service environment adaptation, such as the multi-objective balance of "strength-temperature resistance-weight reduction" required for aerospace engine components; second, process innovation is trending towards "extreme manufacturing"; and third, quality control is transitioning from empirical trial-and-error to digitally driven methods.

2.2 Polymer Materials

Polymer materials have long dominated the 3D printing material market due to their low cost, high strength, and strong formability. Commonly used materials include ABS, PC, and PA. Among these, ABS is widely used for desktop printing due to its excellent overall performance (such as strength and impact resistance). PC, on the other hand, is suitable for manufacturing complex industrial parts because of its high heat resistance and mechanical strength. In recent years, PA has been enhanced with the addition of PVA to improve its flexural strength and wear resistance, further expanding its applications in automotive and aerospace industries.

Research on polymer materials is evolving towards functional-responsive properties. Zaldivar et al. analyzed the mechanical properties of ULTEM® 9085 under different printing directions. The tensile strength in the [4],0° direction was 85 MPa, but it decreased to 63 MPa in the 45° direction due to weakened interlayer bonding. Awasthi et al. proposed a self-healing elastomerbased on TPU/GECO [5], with a recovery rate exceeding 90% under dynamic loads. However, after long-term exposure to ultraviolet light, the strength retention rate dropped by 20%, indicating that environmental stability still needs improvement. Therefore, current research has two key directions for advancement: on one hand, multi-scale modeling techniques are advancing from macromechanical analysis to molecular dynamics simulation; on the other hand, functionalization studies are trending towards multi-field coupling from single responses. However, it is important to note that the contradiction between material performance enhancement and processing feasibility always exists. For example, when introducing reinforcing phases, the balance between rheological properties and interfacial bonding strength must be maintained, which requires researchers to establish a cross-scale collaborative design methodology. Future breakthroughs may focus on the development of biomimetic multi-material systems, achieving leapfrog development in artificial material performance by mimicking the gradient structure and multifunctional integration characteristics of natural materials.

2.3 Ceramic Matrix Composites

Ceramic composites have become an important research direction in advanced materials by achieving synergistic optimization of mechanics and functionality through biomimetic design. In recent years, material design strategies inspired by biological gradient structures have demonstrated unique advantages in cross-scale regulation. Especially bamboo, a natural composite material that has evolved over hundreds of millions of years, features a gradient distribution of vascular bundles. Through hierarchical design that balances rigidity and flexibility, it achieves high specific strength while also providing energy dissipation functions, offering an excellent biomimetic prototype for the multifunctional collaborative design of artificial composites.

In the field of gradient structure preparation technology, additive manufacturing techniques represented by dual-nozzle 3D printing have broken through the interlayer bonding bottleneck of traditional processes. Li et al. innovatively introduced the gradient characteristics of bamboo vascular bundles into ceramic matrix composites [6], successfully preparing biomimetic composites with a flexural strength of 108.6 MPa and excellent electromagnetic wave absorption performance (reflective loss-24.3 dB, effective bandwidth 3.89 GHz) by precisely controlling the spatial arrangement of carbon fibers and the distribution in the SiC matrix. This study not only validates the unique advantages of gradient structures in force-electric functional coupling but also establishes a complete technical path from biological prototype analysis to controllable preparation of artificial materials, providing a new paradigm for the design of multifunctional integrated composites.

It is worth noting that current research on biomimetic composites has formed two major breakthrough directions: first, achieving breakthroughs in the intrinsic properties of materials through multi-scale structural biomimicry; second, utilizing advanced manufacturing technologies to achieve multifunctional integration that traditional materials cannot match, such as the simultaneous realization of mechanical load-bearing and electromagnetic attenuation functions through fiber topology arrangement in this study. These advancements have significantly propelled the dual demand for "lightweight and high-strength multifunctional response" materials in cutting-edge fields like aerospace and electronic packaging.

3 Structure optimization

Early 3D printed structure design primarily focused on simple geometric replication, constrained by traditional manufacturing processes. After 2015, biomimetic and computation-driven design became mainstream. Structural design shifted from traditional geometric replication to biomimetic topology optimization and multi-scale computation, significantly enhancing the functional adaptability of components. In recent years, new methods such as algorithm-driven lightweight design and stress adaptive optimization have further expanded the dimensions of structural optimization [7, 8].

3.1 Bionic Topology Optimization

3D printing technology has gradually developed since Charles Hull invented stereolithography (SLA) in 1986, initially used mainly for prototyping. After the 2000s, with the maturation of technologies such as fused deposition modeling (FDM) and selective laser sintering (SLS), 3D printing began to be applied to the manufacturing of complex structures. However, at this time, design still relied heavily on human experience, lacking systematic optimization. Topology optimization techniques, by allocating materials, achieve structural lightweighting and performance enhancement, gradually evolving from an engineering aid tool into a core driving force in design. For example, in the automotive and aerospace industries during the 2010s, attempts were made to combine topology optimization with 3D printing to manufacture high-strength, lightweight components. The core of biomimetic topology optimization lies in mimicking the principles of structural optimization found in nature, which has a positive impact on 3D printing.

Compared to traditional 3D printing methods, optimizing material distribution through biomimetic algorithms can achieve lightweighting while meeting mechanical performance requirements, thus balancing structure and performance. Qin et al. designed an elastic biomimetic web based on spider web topology [9], which increases strength by 40% and reduces density by 30% under distributed loads, but the anisotropy increases the risk of local stress concentration by 15%. Yang Fanghong et al. developed a multi-tube energy-absorbing structure [2], enhancing toughness through UV-cured heterogeneous interfaces, achieving an energy absorption density of 44.6 J/g, which is 48% higher than that of traditional honeycomb structures. Chen et al. proposed a reverse elastic deformation design method [10], using asymptotic numerical methods to calculate the material's resting state, improving deformation compensation efficiency by 5-8 times under complex service conditions, providing a new paradigm for topology optimization under dynamic loads.

The combination of bionic topology optimization and 3D printing marks the leap from "tool manufacturing" to "intelligent design system". Its core value lies in transforming the evolutionary wisdom of nature into engineering practice, realizing innovation, and providing solutions with high efficiency, environmental protection and innovation for many fields.

3.2 Lattice Interlayer Optimization

The lattice structure excels in lightweighting and energy absorption. Yang Fanghong et al. improved the impact resistance of the lattice structure by 1.5 times, but stress concentration led to a 20% decrease in fatigue life [8]. Kang et al. prepared porous PCL/HA composite scaffolds by combining negative Poisson's ratio structures with conventional lattice designs[11], which increased the Young's modulus, yield stress, and energy absorption by 98.64%,99.27%, and 98.61%, respectively, while maintaining a porosity>90%. This provides new insights into the mechanical-function co-design of biomimetic structures in the biomedical field. Gulino et al. achieved a fracture toughness of 1.5 kN/m in metal-composite joints by 3D printing roughened aluminum-based surfaces on [12], although interface defect detection technology is not yet mature. Recent studies have also explored integrated functional-structural design. Li et al. embedded electromagnetic wave-absorbing lattices into carbon fiber/SiC composite materials [3], achieving synergistic optimization of mechanical properties and stealth functions, reducing radar cross-section (RCS) by 12 dBsm, thus providing a new paradigm for manufacturing stealth fighter components.

4 Practical Application Cases

The turning point from laboratory validation to engineering application of 3D printing technology occurred in the aerospace field. In 2014, the U.S. Navy used the "shipboard printing" project to repair the landing gear of the Harrier fighter, achieving rapid battlefield response for the first time. In 2022, Sinha et al. used SLM technology to manufacture aviation turbine blades[13] , increasing high-temperature creep life by 20%. In the biomedical field, O'Hara et al. achieved the printing of 0.5 mm microvascular models in 2016[14], reducing the design cycle by 80%, which has promoted the development of personalized medicine

The application of 3D printing technology in aerospace, biomedical and other fields has gradually shifted from prototype verification to functional product production, but it still faces challenges of standardization and cost.

4.1 Aerospace Field

3D printing technology has gained popularity in the aerospace field due to its unique advantages

It has found widespread application. The aerospace industry has extremely high requirements for material properties, structural complexity, and production efficiency. 3D printing technology constructs three-dimensional objects by adding materials layer by layer, capable of producing complex shapes and high-precision components, meeting the stringent demands of this field. From rocket engines to satellite structures, 3D printing is redefining the boundaries of aerospace manufacturing, bringing revolutionary changes to this domain.

Sinha et al. used selective laser melting (SLM) technology to manufacture for aviation turbine blades[13], optimizing the microstructure to increase high-temperature creep life by 20%, significantly enhancing the reliability and durability of engines under extreme operating conditions. Li et al. developed a carbon fiber reinforced SiC composite satellite bracket with a specific strength of 130.6 MPa/(g/cm^3), achieving a 40% weight reduction while effectively addressing the challenge of thermal deformation control for high-stiffness satellite structural components in orbit [6]. Wang et al. proposed a lightweight design method based on skin-frame structures, reducing material usage by 30% through sparse optimization algorithms [15], and verified its cost-effectiveness in powder bed and extrusion printers. This innovative approach not only overcomes the limitations of traditional topology optimization in adapting to manufacturing processes but also provides a quantitative evaluation tool for the manufacturability design of spacecraft structural components through lifecycle cost modeling. These research findings systematically address the long-standing issue of balancing lightweighting and reliability in aerospace equipment from multiple dimensions, providing key technological support for the development of next-generation high-thrust ratio aviation engines and low-cost space launch systems.

4.2 Biomedical Field

In recent years, 3D printing technology has garnered widespread attention and interest in the biomedical field due to its high precision, personalized customization, and capability for manufacturing complex structures. In this domain, from tissue engineering to medical devices, 3D printing technology has demonstrated tremendous potential and value. By precisely controlling material distribution and microstructure, 3D printing can create biological structures that closely resemble human tissues, offering new solutions for tissue repair and regeneration.

O 'Hara et al. optimized the design of vascular models through grid Boolean operations [14], reducing the printing cycle for 0.5 mm microvessels by 80%. Kang et al.' s PCL/HA composite stent achieved a porosity>90% and improved mechanical properties in bone tissue engineering [11], opening up new directions for personalized implant design. Zaldivar et al.'s ULTEM® 9085 orthopedic implant retained 85% of its in vivo strength [4].

4.3 Construction and Defense Fields

3D printing technology has brought an unprecedented change to the construction industry. 3D printing technology can meet diverse functional and aesthetic needs. More importantly, 3D printing buildings show significant advantages in environmental protection, energy saving and structural stability.

Wang Zhendi et al. 's overlapping n-type reinforcement scheme increased the flexural strength of 3D-printed concrete by 1.54 times, but the rebar penetration must be>70% to avoid brittle failure[16]. In the defense sector, Celik et al.' s hemp fiber-reinforced PLA composites have been used in the manufacture of removable military shelters, with their blast resistance improving by 40% compared to traditional concrete, and weight reduced by 60%[17]. Additionally, using hemp fiber-reinforced PLA composites, they improved the flexural modulus by 17% through maleic anhydride interfacial modification, providing a low-cost solution for sustainable construction formwork. Supe et al.'s copper alloy ship components exhibit excellent corrosion resistance[3].

5 Future Research Directions

5.1 Mechanical Compatibility Design of Multi-Material Gradient Interface

The insufficient interfacial bonding strength of gradient materials such as metal-ceramics and polymer-metals is the core issue constraining their engineering applications. In the future, it is necessary to combine in-situ synthesis techniques with multiscale modeling methods to explore the mechanisms of interfacial atomic diffusion and the distribution patterns of thermal stress. Developing adaptive gradient transition layer design algorithms will enhance the service reliability of composite materials. For example, we can draw on Li et al.'s biomimetic gradient structure concept[6], using topology optimization algorithms to dynamically adjust the interfacial porosity, achieving a balance between mechanical properties and functional requirements.

5.2 Material, Structure and Process Optimization Driven By Extreme Environment

A dynamic correlation model between service environment parameters (temperature, load, corrosive media, etc.) and material properties, structural design, and printing processes must be established. Combining sectional stress analysis with an automatic correction system, a closed-loop optimization framework based on digital twins should be developed. For example, in the manufacturing of high-temperature components for aviation engines, real-time monitoring of thermal stress distribution can dynamically adjust laser power and scanning paths to achieve coordinated optimization of microstructure growth and macroscopic performance.

5.3 Intelligent Manufacturing and Full Life Cycle Management

Online defect detection and intelligent repair technology are key to breaking through the bottleneck of large-scale production. By integrating high-resolution imaging (such as synchrotron CT) with machine learning algorithms, real-time identification and classification of defects like pores and cracks can be achieved; combined with in-situ repair processes (such as laser remelting or microplasma spraying), adaptive repair strategies can be developed. Additionally, it is necessary to build a comprehensive lifecycle database covering design, manufacturing, and service maintenance, promoting the standardization and traceability of 3D-printed components.

5.4 Sustainability and Environmentally Friendly Material Development

As environmental regulations become stricter, research on biobased materials (such as hemp fiber reinforced PLA and recyclable metal powders is urgently needed. It is necessary to explore low-energy printing processes and material recycling systems to reduce carbon emissions during manufacturing[17]. At the same time, develop light-degradable or biodegradable smart materials to promote the application of 3D printing technology in temporary buildings, absorbable medical devices, and other scenarios

5.5 Cross-field Technology Transfer and Civil-Military Integration

In the future, it is necessary to break down disciplinary barriers and promote lightweight algorithms, such as Wang et al. 's skin-framed structure [15], to migrate towards defense equipment manufacturing, developing multifunctional components with high strength, stealth, and low cost. For example, applying Li et al. electromagnetic wave absorption lattice design to the skin of unmanned reconnaissance aircraft can achieve dual breakthroughs in mechanical performance and stealth capabilities [6]

6 Conclusions

Research on 3D printing technology for military service environments has shifted from single-material development to material-structure-process collaborative innovation, demonstrating significant potential in fields such as aerospace and biomedicine. This paper systematically reviews performance breakthroughs in high-performance metals, smart polymers, and ceramic matrix composites, revealing the advantages of biomimetic topology optimization and lattice design in lightweighting and impact resistance. It also summarizes the current challenges of cost and standardization in practical applications.

Research findings indicate that 3D printing technology, through multi-material composites and computation-driven design, can meet the multifunctional integration requirements of components in extreme environments. However, its large-scale application is still constrained by issues such as insufficient interface bonding strength, poor process stability, and lagging detection technologies. Future efforts should focus on breakthroughs in gradient material interface design, intelligent manufacturing system development, and cross-disciplinary technology integration, while also paying attention to the innovation of environmentally friendly materials and their full lifecycle management.

As artificial intelligence and digital twins integrate more deeply, 3D printing is expected to evolve from a "manufacturing tool" into an "integrated platform for intelligent design, manufacturing, and operation." This will provide more efficient and sustainable solutions for advanced equipment manufacturing. This technological innovation will not only advance the process of Industry 4.0 but also inject new momentum into national strategic fields such as defense, security, and healthcare.

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