Progress and Prospects of Additive Manufacturing in Lightweight Design

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Abstract. This study delves into the significant role and prospects of additive manufacturing in lightweight design for the aerospace and automotive industries. As these two industries continuously demand lightweight and high-performance materials, traditional manufacturing methods have become inadequate to meet increasingly complex design requirements. Additive manufacturing, an advanced technology that constructs objects by layering materials, has gradually emerged as a key solution to this challenge. By integrating advanced techniques such as topology optimization and porous grid/lattice design, additive manufacturing not only enables the production of complex and intricate components but also significantly reduces material usage and product weight while maintaining or enhancing structural performance. This is particularly crucial in the aerospace and automotive industries, where lightweight design can directly improve energy efficiency and operational performance. Research indicates that additive manufacturing has successfully produced lightweight components that meet or exceed industry performance standards. This not only confirms the vast potential of additive manufacturing in modern manufacturing but also foreshadows its increasingly important role in future material utilization and structural design. Overall, this study highlights the current advancements of additive manufacturing in lightweight design and anticipates its broad application prospects, especially in promoting more efficient and environmentally friendly production methods in the aerospace and automotive industries.

Keywords: Additive, Lightweight, Aerospace, High-performance.

1. Introduction

With the advancement of technology and human society, the demand for lightweight and high-performance materials is increasing, especially in industries such as aerospace.

In the aerospace industry, there is an increasing demand for lightweight aircraft. Lightweight not only improves flight efficiency but also reduces energy consumption. Additive manufacturing technology precisely controls the stacking of materials [1]. It can achieve precise manufacturing of complex structures, thereby meeting the demand for lightweight and high-performance components in the aerospace industry

In the automotive industry, with the rise of electric vehicles, the demand for lightweight materials is also increasing. Additive manufacturing technology provides the possibility for the automotive industry to manufacture lightweight components by optimizing the structure and reducing the quality of the components [1]. To improve the energy efficiency and range of the car

The design brought by additive manufacturing technology can enable the realization of complex structures. Traditional manufacturing processes face many limitations in manufacturing complex structures, while additive manufacturing technology can easily achieve the manufacturing of complex structures by stacking materials layer by layer [2]. This technology provides designers with greater design freedom, allowing them to optimize structures more flexibly and improve product performance

It can also promote innovative design: additive manufacturing technology encourages designers to break traditional design ideas and try more innovative structural designs [3]. Through additive manufacturing, designers can devote more energy to form and innovation, thereby promoting the development of innovative product design

Additive manufacturing technology precisely controls the number of materials used [4]. Additive manufacturing can reduce material waste in the manufacturing process. Compared with traditional

subtractive manufacturing, additive manufacturing can more efficiently utilize materials and reduce manufacturing costs

Additive manufacturing technology can also quickly produce complex component prototypes [4]. To shorten the product development cycle, designers can continuously optimize the product structure, improve product performance and quality through rapid iterative design

2. Commonly used Lightweight Methods

Additive manufacturing provides multiple effective methods for lightweight design. Here are some common lightweight methods:

2.1. Topology Optimization

Topology optimization is a mathematical method for optimizing material distribution within a given area based on given operating conditions, constraints, and response objectives. This method optimizes parts through finite element analysis (FEM), removes materials from areas, and reduces weight while maintaining part performance [5]. The state of the I-beam section and leaf spring bracket section is shown in Figs. 1 and 2.

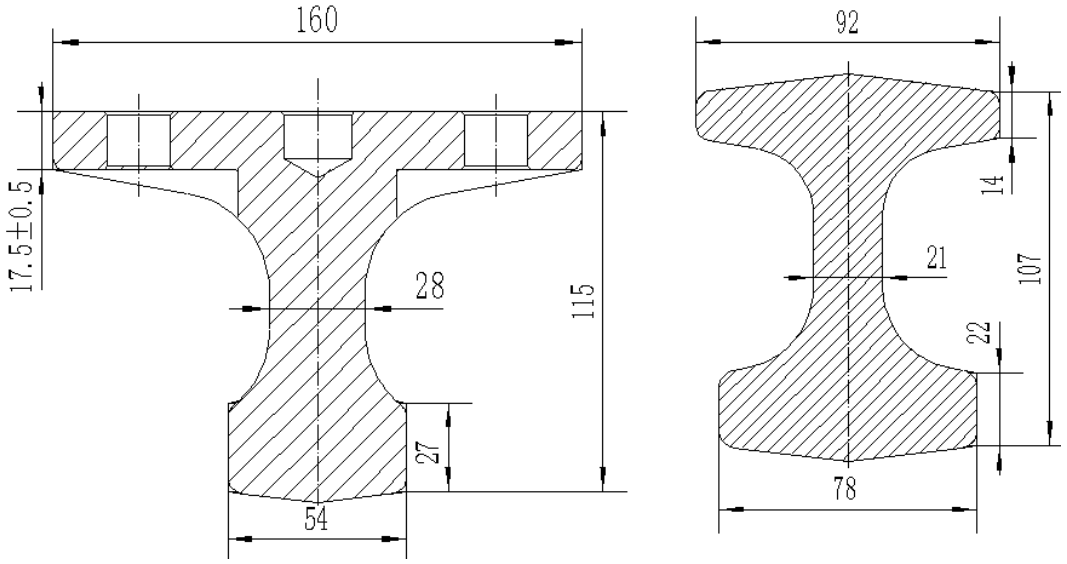


Fig. 1 State of the I-beam section and leaf spring bracket section before optimization [5]

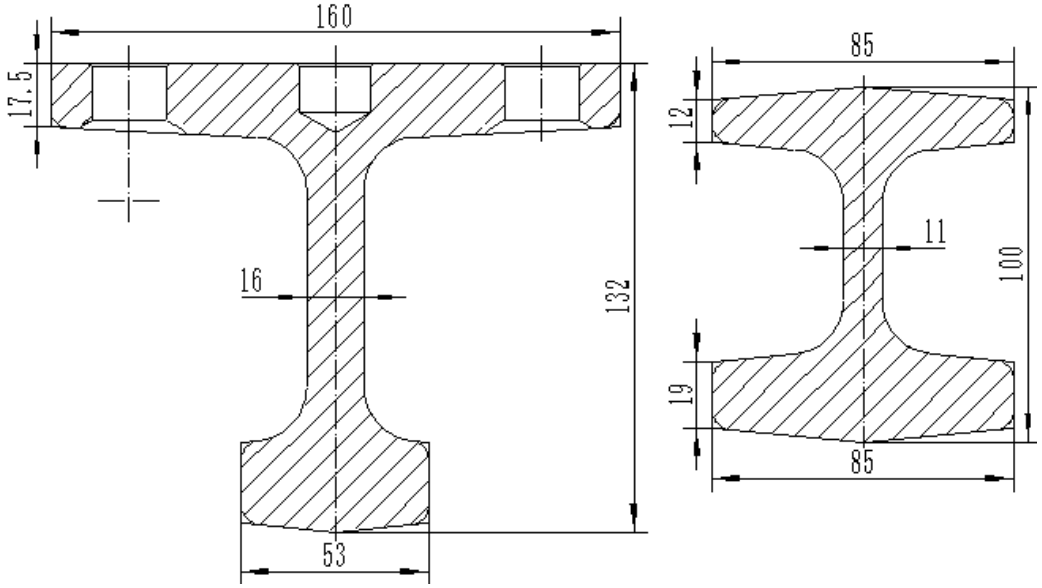


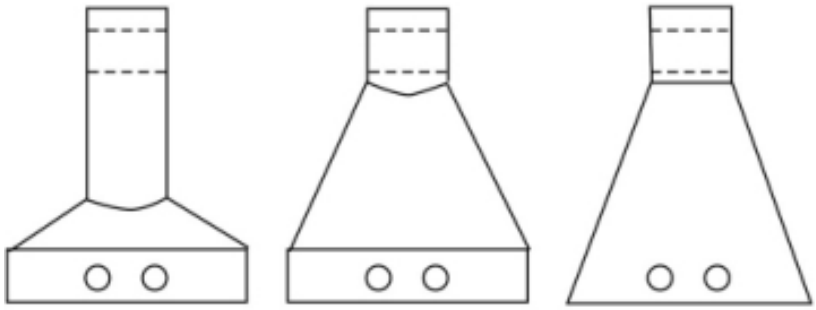
Fig. 2 State of the I-beam section and leaf spring bracket section after optimization [5]

2.2. Porous Grid/lattice Structures

By designing porous grids or lattice structures, the use of materials can be reduced at the microscopic level, thereby achieving. This structure not only reduces weight but may also improve the stiffness and energy absorption capacity of the parts

2.3. Integrated Structures

Integrating multiple components into a single unit reduces the use of connectors and fasteners, thereby reducing the total weight [6]. This method is particularly common in aerospace and automotive manufacturing. The aircraft component shape optimization scheme is shown in Fig. 3.



(a) (b) (c)

Fig. 3 Aircraft component shape optimization scheme. (a)Raw component view; (b)Optimize View 1; (c)Optimize View 2 [6]

2.4. Material Selection

Choosing materials with low density and high specific strength is an important way to achieve lightweight. For example, light metal materials such as titanium alloys, aluminum alloys, and magnesium alloys have been widely used in aerospace and automotive manufacturing [7].

2.5. Structural Innovative Design

Through innovative designs such as hollow sandwich/thin-walled reinforced structures, hollow lattice structures, etc., lightweight can be achieved without sacrificing performance. These designs are often combined with topology optimization techniques to further optimize material distribution [8].

Additive manufacturing provides various effective methods in lightweight design, including topology optimization, porous mesh structure, integrated structure, material selection, and structural innovation design. These methods often need to be combined in practical applications to achieve optimal lightweight results.

3. Research Status of Lightweighting in Additive Manufacturing

3.1. Design Categories using Topology Optimization Techniques

3.1.1. Manufacturing of complex lightweight structures

Structures designed through topology optimization often have complex geometric shapes and highly lightweight characteristics. Additive manufacturing technology can accurately manufacture these structures, achieving weight reduction while maintaining or improving structural performance.

3.1.2. Multi-material and multifunctional structure

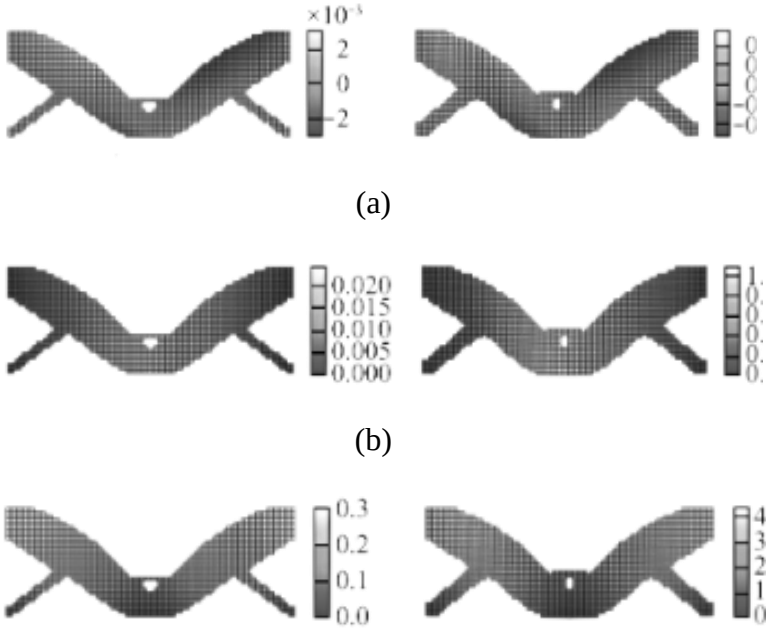
Topology optimization combined with additive manufacturing makes it possible to manufacture multi-material and multifunctional structures. The reasonable distribution of different materials in the structure can further enhance the overall performance of the structure.

3.1.3. Integrated design and manufacturing

The combination of topology optimization and additive manufacturing technology has achieved an integrated process from design to manufacturing. Topology optimization provides the optimal material distribution scheme in the conceptual design stage, while additive manufacturing technology can directly realize these complex structures without the need for molds and multiple processes in traditional manufacturing [9].

3.1.4. Process optimization and support structure design for expansion and supplementation

In response to potential issues such as thermal deformation and collapse of overhanging parts in additive manufacturing processes, researchers have optimized manufacturing processes through methods such as thermal coupling topology optimization and self-supporting structure design, reducing the use of supporting structures and improving manufacturing accuracy and efficiency [10]. A comparison of workpieces after topological optimization techniques is shown in Fig. 4.



(a)

(b)

(c)

Fig. 4 Comparison of workpieces after topological optimization techniques. (a)Comparison of topology structure's displacement along the x direction; (b)Comparison of topology structure's displacement along the y direction; (c)Temperature distribution comparison of topology structure [10]

3.2. Examples of Topology Optimization Techniques

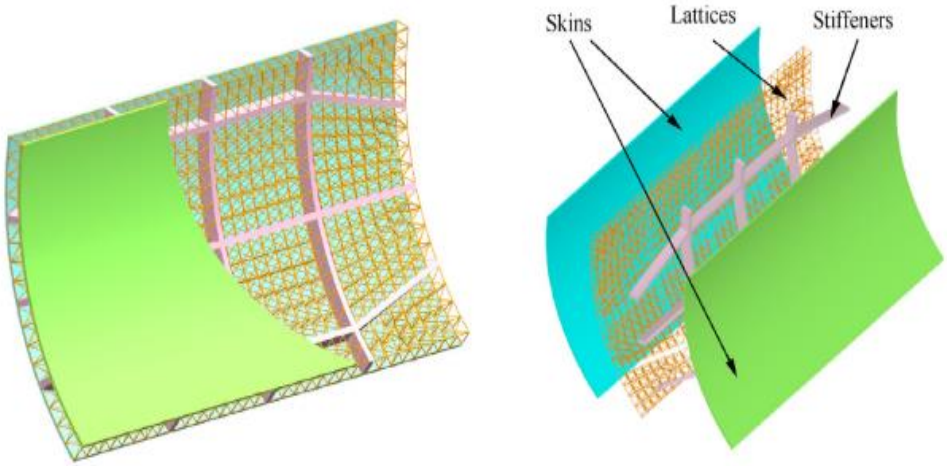
Traditional manufacturing methods often struggle to produce complex structures after topology optimization, while additive manufacturing technology (such as 3D printing) has become the key to achieving topology optimization design due to its ability to manufacture complex shapes. Additive manufacturing technology can accurately place materials in the required positions, thereby producing lightweight structures that conform to topology optimization design

Topology optimization technology is used for the lightweight research of traction machine casing, to minimize flexibility and the constraint of structural quality. Combined with additive manufacturing technology, finite element simulation analysis software, and computer-aided design software, the lightweight design of traction machine casing is achieved [11]. Verified the feasibility of using additive manufacturing technology to process complex structural components and demonstrated the potential application of topology optimization combined with additive manufacturing in lightweight design. **The** FDM molded traction casing model is shown in Fig. 5



Fig. 5 FDM molded traction casing model [11]

In addition, some studies combine reinforcement structures with lattice structures and optimize layout to achieve lightweight design in the aerospace field. Suitable lattice units are selected based on the 3D printing direction, process, mechanical properties, and functional requirements of materials, and then their macroscopic equivalent elasticity is calculated through energy-based homogenization methods. At the same time, reinforcement structures are modeled, and layout optimization design is carried out using finite element analysis methods [12]. By integrating topology optimization with additive manufacturing, the integration of materials, structures, processes, and performance has been achieved, significantly improving the efficiency and effectiveness of lightweight design in aerospace. An illustration of thin-walled structure with lattices and stiffeners is shown in Fig. 6.



(a) (b)

Fig. 6 Illustration of thin-walled structure with lattices and stiffeners. (a)Overall model; (b)Decomposition view [12]

Topology optimization technology combined with additive manufacturing technology provides an efficient, precise, and sustainable solution for structural lightweight design. By removing excess materials and optimizing material layout, topology optimization technology can significantly reduce weight without sacrificing structural performance, while additive manufacturing technology, with its unique manufacturing capabilities, enables these complex optimization designs to be realized. The application of this combination not only promotes the development of lightweight manufacturing but also brings revolutionary changes to multiple fields such as aerospace and mechanical engineering

3.3. Research Status of Porous Grid Structure Design

The main principle of achieving structural lightweight in additive manufacturing through the design of porous mesh structures is that by introducing porous structures, the amount of material used can be effectively reduced without significantly reducing the mechanical properties of the structure, thereby achieving the goal of weight reduction

In terms of design, solid modeling software was used to optimize the shape and size of common honeycomb and lattice structures, ultimately completing the design of porous structures with different pore types, sizes, porosities, and pore distributions [13]. Additive manufacturing technology enables the design of porous structures to be freer, molding to be more convenient, and performance to be more controllable, providing strong support for lightweight design

In the design of porous grid structures, a stress-based variable single parameter non-uniform grid parameter optimization design method is used to achieve the lightweight design of the structure by discretizing the design space and filling different lattice structures according to stress distribution. Case studies have shown that this method can significantly reduce weight while maintaining the mechanical properties of the structure [14]. The finite element analysis results of the optimized model are shown in Fig. 7

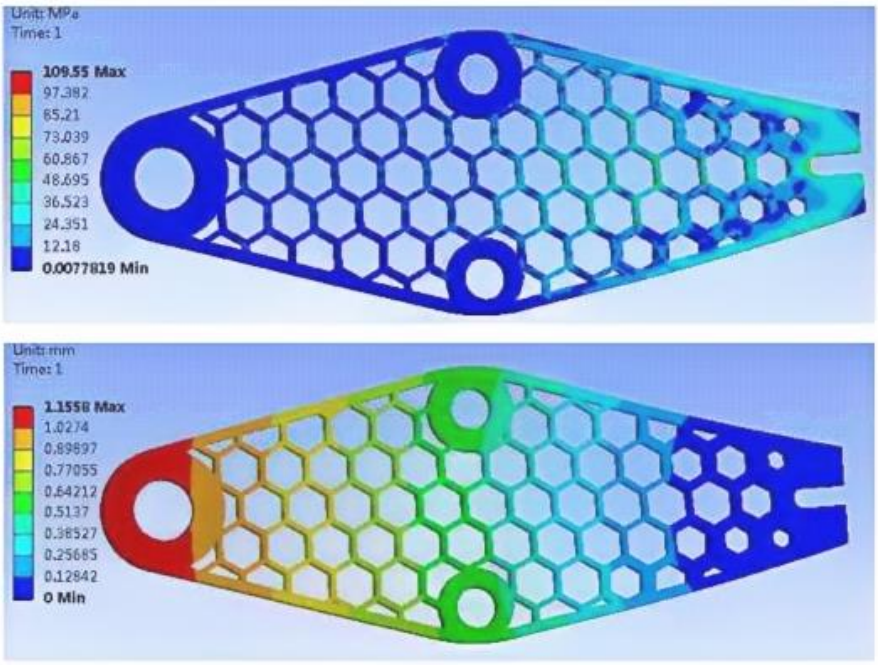


Fig. 7 Finite element analysis results of the optimized model. (a)Stress simulation of the optimized model; (b)Simulation of structural displacement after optimization [14]

4. Conclusion

This article summarizes the research progress and application status of additive manufacturing technology in the field of lightweight design. Starting from the design freedom of additive manufacturing technology, this study comprehensively explores its application background in key industrial fields such as aerospace and automotive. This research that this technology greatly improves the manufacturing capability of complex structures through precise control of discusses its unique advantages in complex structure manufacturing and innovative design. Additionally, it deeply analyzes various lightweight methods, including topology optimization, porous grid structure, integrated structure, material selection, and innovative structural design. These methods often need to be combined in practical applications to achieve the best results.

Research shows that by combining additive manufacturing technology with topology optimization techniques, precise manufacturing of complex lightweight structures is achieved, which not only

reduces weight but also improves structural performance. The successful fabrication of multi-material and multi-functional structures further demonstrates the huge potential of additive manufacturing in driving product innovation. The widespread application of porous grid structure design effectively reduces material usage and enhances the flexibility of lightweight design. This study also verifies the lightweight effects of additive manufacturing technology in practical projects such as traction machine shells and aerospace components through examples, fully demonstrating the feasibility and application value of this technology.

Although additive manufacturing technology has made significant progress in lightweight design, there are still some limitations, such as high manufacturing costs and relatively slow production speeds. Looking ahead, with the continuous advancement of technology, additive manufacturing technology is expected to be more widely used in large-scale industrial production. Future research should focus on improving production efficiency, reducing costs, developing new high-performance materials, and optimizing additive manufacturing processes. Meanwhile, interdisciplinary collaboration will also provide new opportunities for the future development of additive manufacturing technology.

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