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The Application of Additive Manufacturing Technology in Automotive Component Design Optimization

Yuntao Zhu

Changzhou Institute of Technology, Changzhou, China
1075702895@qq.com

Abstract. With the shift toward electrification, lightweight architectures, and intelligent systems in the automotive sector, demand for high-performance, tailor-made components is rising, while traditional manufacturing methods struggle to cope with complex geometries and accelerated design cycles. Therefore, this study investigates the application of additive manufacturing technology in the design optimization of automotive components to achieve lightweight structures, functional integration, as well as customized solutions. By reviewing the literature on additive manufacturing processes and material properties, and examining specific component cases, this study investigated strategies for improving part performance via parameter tuning, data refinement, and topology design. The results reveal that additive manufacturing can notably reduce part weight and enhance overall system performance, yet it still faces challenges such as process defects, an incomplete standardization system, and industrial application bottlenecks. Future efforts should prioritize multi-material integrated printing and the intelligent closed-loop management of process-performance, which are key to wider adoption of additive manufacturing in the automotive sector.

Keywords: Additive Manufacturing, Design Optimization, Topology Optimization, Automotive Components, Lightweighting

1. Introduction

The Fourth Industrial Revolution has greatly reshaped the global manufacturing landscape [1]. Thus, the automotive industry is undergoing a transformation towards electrification, lightweighting, and smart technologies, leading to a growing demand for high-performance, customized, and complex structural components. However, traditional manufacturing processes can no longer meet the high demands of current production. As designs become more sophisticated and component geometries more complex, challenges such as rising costs, extended lead times, and limited design flexibility emerge. In this context, Additive Manufacturing (AM), or 3D printing, with its “layer-by-layer” fabrication approach, provides a transformative solution for the innovative design and production of automotive components [2]. Unlike traditional manufacturing processes, AM has the advantages of short manufacturing cycles, customization, lightweight, and integration, saving a significant amount of time and cost compared to traditional methods. In recent years, significant progress has been made in the field of additive manufacturing. For example, in powder bed fusion (PBF) technology, the weight of engine connection brackets was reduced by 43.8%, whereas the first-order resonance

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frequency increased by 23%, achieved through topology optimization and Selective Laser Melting (SLM) techniques [3]. But challenges in practical implementation arise, such as limited integration of AM in the design of critical automotive load-bearing components and the lack of optimization methods tailored for SLM. Thus, this paper explores AM strategies for optimizing the design of key automotive load-bearing components such as engine brackets and chassis suspension parts, focusing on the SLM process in PBF. It also introduces a topology optimization-based design framework that aligns with SLM constraints, hence enabling optimization from design to performance validation. This method enhances part lightweighting and performance, while ensuring SLM process stability, thereby supporting the intelligent and electrified progression of the automotive industry.

2. Fundamentals of additive manufacturing technology and material properties

2.1. Additive manufacturing processes and principles

In contrast to traditional subtractive manufacturing methods, AM is a technology that builds objects by adding material layer by layer. And its core principle is to transform a three-dimensional digital model into a physical object via a process of layer-by-layer accumulation [4]. Initially, the additive manufacturing process begins with creating a digital model using computer-aided design (CAD) software, which is then converted into a printable format, such as an STL file. After the model data is sliced and transformed into G-code, the printer can build the object layer by layer based on the instructions. The technological principles of additive manufacturing vary depending on the method used. For instance, Fused Deposition Modeling (FDM) uses the thermal melting of heated materials, Stereolithography (SLA) employs ultraviolet lasers to solidify liquid resin, while SLM adopts lasers to fuse metal powders. These technologies all depend on precise material deposition processes, with different additive manufacturing methods tailored to different application scenarios. The advantages of additive manufacturing include the ability to create complex structures, reduce material waste, and boost production efficiency. With ongoing advancements, it has found widespread applications in fields such as aerospace, automotive, and healthcare.

2.2. Material properties and process influence

The properties of the material itself determine its suitable manufacturing process and the theoretical upper limit of performance, while the material and process jointly determine the final performance of the part. Typically, additive manufacturing materials exist in the form of powder, liquid resin, and filament. For example, titanium alloy (Ti-6Al-4V) and aluminum alloy (AlSi10Mg) are commonly used metal materials, and they are suitable for SLM technology when in powder form. These two materials have relatively high melting points and require high-power lasers for processing, but the final parts exhibit high strength, corrosion resistance, lightweight properties, and excellent overall performance [5]. For filament-based manufacturing processes, special attention must be paid to the consistency of the diameter, as it affects the stability of filament feeding, coating size accuracy, and surface cleanliness, since surface grease or oxides may lead to porosity defects.

In metal additive manufacturing, thermal cycling and cooling rates are key process factors that influence the performance of the parts. Specifically, rapid cooling regulates the microstructure by suppressing grain growth, resulting in fine grains, which, based on the Hall-Petch effect, improve the mechanical properties of the part [6]. However, localized intense heating and cooling can lead to uneven thermal expansion and contraction, generating significant internal stresses. If no annealing treatment is performed, these internal stresses may cause the part to deform or crack. Almost all

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additive manufacturing parts require post-processing to meet the final usage requirements, which mainly include support structure removal, heat treatment, and surface treatment. Surface treatments like sandblasting, polishing, and machining can boost surface roughness and dimensional accuracy, while heat treatment eliminates residual stresses, closes internal pores such as through Hot Isostatic Pressing, and HIP, and optimizes mechanical properties such as solution treatment and aging, which is particularly critical for precipitation-hardening alloys like Ti-6Al-4V and Inconel 718 [11,12].

3. Practical approaches and strategies for additive manufacturing of high-performance automotive components

3.1. The design objectives for high-performance components

For the design of high-performance automotive components, the focus is on achieving maximum lightweighting, customizing performance, and ensuring the seamless integration of features.

Specifically, lightweight design forms the foundation for improving performance and efficiency. AM uses topology optimization to precisely allocate materials, remove unnecessary parts, while ensuring the stiffness and strength of the components. This approach significantly reduces weight while enabling the lightweight design of complex structures that meet high-strength requirements. Besides, functional integration is key to enhancing system performance and reliability. Traditional designs often require multiple parts to work together, while AM allows for the creation of complex geometries or multifunctional components in a single molding process. And this integrates multiple functions into a single part, further reducing assembly steps and improving the overall stability and reliability of the system. AM makes it possible to integrate more complex functions, minimizing connection points and potential failure points between components. Moreover, rapid iteration is at the core of accelerating innovation and production. AM, through digital design and rapid printing technologies, breaks down the time barriers inherent in traditional manufacturing methods. Design changes and optimizations can be implemented in a short time, allowing products to quickly move into validation and production phases. This flexibility and efficiency greatly shorten the product cycle, enabling rapid response to market demands and technological advancements. Through these design objectives, AM enables breakthroughs in high-performance automotive component design.

3.2. The application of laser powder bed fusion technology in the automotive industry

In automotive components, laser powder bed fusion (L-PBF/LB-PBF), commonly known as SLM, is currently the most widely used mainstream technology. Powder Bed Fusion (PBF) accounts for 54% of the metal additive manufacturing market [6]. This success stems from its precision forming capabilities and the ability to create complex structures, making it vital for meeting the automotive industry's demands for customization and lightweighting. The layer-by-layer laser melting process of SLM allows for precise control of the melt pool, ensuring good metallurgical bonding between layers and thereby maintaining the structural integrity of load-bearing or high-precision automotive parts. For instance, the Fraunhofer Institute in Germany, in partnership with U.S. engineering metal parts supplier MacLean-Fogg, successfully developed large die-casting mold inserts for the transmission housings of Toyota hybrid models such as the Yaris Hybrid, utilizing L-PBF/LB-PBF technology and the new tool steel material L-40 [5]. And this collaboration highlights the powerful advantages of SLM in manufacturing complex parts. In addition, the brake calipers of the Bugatti Chiron are with titanium SLM (Ti-6Al-4V) and tested under real conditions, showing excellent heat resistance during braking [7]. Moreover, research by Lien et al. showed the advantages of AM and

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its optimization of component topology. For example, their optimization reduced the brake caliper's weight to 2.9 kg, a 43% reduction compared to traditional calipers, highlighting SLM's potential in enhancing performance and reducing weight [8].

3.3. The optimization strategies for component performance

The optimization of component performance encompasses the refinement of design, manufacturing, materials, and post-processing to attain an optimal balance between performance and cost. And this requires a multi-faceted approach to effectively balance performance with cost-efficiency [9].

In particular, design optimization is key to improving performance, with topology optimization being crucial. The "design freedom" inherent in AM allows topology optimization to significantly reduce component weight while ensuring strength. By precisely adjusting material distribution and removing unnecessary parts, the structure can be made both lightweight and sufficiently strong. In process control, optimizing energy input and scanning strategies is crucial. The matching of laser power and scanning speed directly impacts the quality of the build. Proper selection and adjustment of these process parameters can reduce defects, enhance part density and strength, and improve overall performance. The synergistic optimization of materials and processes is equally important. By precisely selecting materials and tailoring the appropriate process, the best combination can be achieved to further enhance part performance. Materials influence both the mechanical properties of components and the process itself, and optimizing both can maximize product performance. Besides, enhancing post-processing techniques can greatly boost component performance. The combination of surface treatment and heat treatment improves both surface quality and internal strength. Surface treatment enhances wear resistance and corrosion resistance, while heat treatment increases material strength and toughness. This integrated approach boosts overall part performance, ensuring stability and reliability in real-world applications.

4. Challenges and future development

4.1. Standardization and industrial bottlenecks

The standardization system in additive manufacturing is still underdeveloped, lacking a full-chain standard that covers design, production, and certification. According to the Additive Manufacturing Standardization Roadmap 3.0 jointly released by the American National Standards Institute (ANSI) and America Makes, there are currently 141 standardization gaps in the industry, of which 54 are high-priority [10]. These gaps involve critical aspects such as material performance testing, process parameter calibration, and non-destructive evaluation. These deficiencies limit the industrialization and reliability certification of additive manufacturing technologies to a certain extent.

In addition to standardization issues, industrial costs also pose a significant barrier to large-scale adoption. Beyond material costs, equipment investment and post-processing expenses account for a substantial portion of the total cost [11]. The price of an industrial-grade SLM device can reach several million RMB, while post-processing operations like heat treatment and surface polishing account for approximately 30%-50% of the total cost. For conventional automotive components with an annual output exceeding 100,000 units, the cost of additive manufacturing remains 3-5 times higher than that of traditional processes. Therefore, it is currently mainly suitable for high-end, customized, or small-batch production scenarios, such as components for high-performance sports cars.

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4.2. Future technological development trends

The future development of additive manufacturing technology will primarily focus on three areas: material utilization and cost control, process integration and efficiency improvement, and intelligent quality control. Regarding material efficiency and cost management, the “powder-in-a-beam” laser cladding approach can enhance powder utilization to 95%, cut processing costs per unit area by roughly 21%, and allow the reuse of retired lasers, thereby reducing equipment acquisition costs by around 30% [12,13]. In terms of process integration and efficiency improvement, the combination of additive manufacturing with traditional casting and forging processes is emerging as a new direction. For example, the “3D-printed inserts + die casting” composite process developed by the Fraunhofer Institute can shorten the manufacturing cycle of automotive transmission molds by more than 50% while also doubling the service life of the molds [14]. For intelligent quality management, artificial intelligence techniques have been integrated into all stages of the manufacturing process to achieve high-precision control. The deep reinforcement learning optimization framework developed by the ShanghaiTech University team uses a corrected Rosenthal equation combined with the Proximal Policy Optimization (PPO) algorithm to rapidly solve the temperature field, significantly improving the forming accuracy of IN718 alloy printed parts by 35% and reducing hardness variation by 31.8% [15].

5. Conclusion

This study reveals that additive manufacturing , based on the layer-by-layer accumulation principle, has emerged as a key technology in the automotive industry, offering lightweight design, complex geometries, customization, and rapid production. Moreover, mainstream processes like SLM/L-PBF have demonstrated tangible benefits, including reduced component weight and improved durability. However, large-scale adoption remains constrained by incomplete full-chain standardization and high costs of equipment and post-processing, which make conventional component production 3-5 times more expensive than traditional methods. Future strategies should prioritize multi-material printing, hybrid additive-traditional manufacturing, AI-driven process control, and boosted material recycling and cost efficiency. The implementation of targeted strategies help close standardization gaps, alleviate industrial bottlenecks, and promote broader adoption of additive manufacturing in automotive production.

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