Topology Optimization for Performance Enhancement of Automotive Components: Integration with Additive Manufacturing

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Abstract. Due to the continuous transformation of the automotive industry towards new energy and the urgent need for energy conservation and emission reduction caused by the non-renewability of fossil fuels, automotive lightweighting is becoming an important strategy to address these changes. Reducing the weight of vehicles can directly enhance energy economy, extend the driving range of electric vehicles, decrease the emission of harmful substances, and alleviate range anxiety at the same time. Topological optimization, as an important structural design tool, can generate lightweight configurations by optimizing the distribution of materials within a given design space, thereby reducing the weight of automobiles. However, the performance of traditional topology-optimized automotive parts is often limited by traditional manufacturing and processes. At this time, the emergence of additive manufacturing provides extremely high design freedom and can produce complex structures that cannot be achieved by traditional methods, making it an ideal manufacturing method for topological optimization. The focus of this study is to reduce the weight of automobiles through topology optimization while enhancing the performance of automotive components, emphasizing the integration of topology optimization and additive manufacturing processes. This research encompasses topological optimization calculations, addressing process constraints in additive manufacturing, exploring the complementarity among structural optimization design, print path planning, and mechanical properties.

Keywords: Topology optimization, additive manufacturing, lightweighting.

1 Introduction

The rise of new energy vehicles is constantly driving the automotive industry towards energy conservation and high efficiency. Against this backdrop, lightweight design has become a key strategy for achieving energy conservation and emission reduction. For every 10% reduction in vehicle weight, the fuel efficiency of traditional fuel vehicles can be significantly improved by 6-8%, or the range of electric vehicles can be significantly increased by 10-15%. Empirical studies confirm that mass reduction directly correlates with enhanced energy efficiency, validating lightweighting as a core strategy for sustainable transportation [1]. For vehicle shell

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brackets, chassis components and other parts that take up a large amount of vehicle weight and do not pursue aesthetics, lightweighting can achieve a balance between energy consumption and strength.

Topological optimization, as an advanced structural design method, through mathematical algorithms, finds the optimal material layout under the given design space and constraints, thereby generating bionic, efficient, and lightweight structures, achieving the dual goals of weight reduction and performance improvement. Bendsøe and Kikuchi proposed the homogenization method, which laid the foundation for topology optimization [2]. Zhu et al. reviewed the application of topology optimization in additive manufacturing and pointed out that the SIMP method is widely used in the design of lightweight structures due to its good convergence and ease of implementation [3].

However, the complex configurations generated by traditional topology optimization often face the predicament of performance degradation due to the difficulty in manufacturing with traditional processes. The emergence of additive manufacturing technology can effectively break through the limitations of the process. Manufacturing parts by accumulating materials layer by layer not only grants great freedom to design and can perfectly achieve complex results of topological optimization, but also its "additive" feature is highly consistent with the core concept of lightweighting. At the same time, additive manufacturing also introduces new challenges, such as the "step effect" in 2.5-axis printing, the demand for support structures, and the anisotropy of materials, all of which may affect the performance of the final components. Zhong et al. developed an as-continuous-as-possible extrusion-based fabrication method for surface models, which effectively suppresses the step effect and improves surface quality [4].

Therefore, the deep integration of topology optimization and additive manufacturing, while taking manufacturing constraints into account in the optimization design, is of vital significance for breaking through the traditional design and manufacturing bottlenecks and developing lighter, stronger and more reliable automotive parts. This study focuses on the integration of topology optimization and process, aiming to enhance the performance of automotive components while achieving effective lightweighting through the collaborative integration of the two.

2 Theoretical Basis of Topology Optimization

2.1 Basic Principles of Topology Optimization

Topological optimization is a structural optimization method whose aim is to find the optimal material distribution within a predefined design domain. Under a set of constraints, it uses mathematical algorithms to minimize or maximize the objective function. The objective function can be structural stiffness, strength, service life or other performance indicators. Constraint conditions can include material volume fraction, stress limit and manufacturing limit.

The design domain is divided into a finite number of elements by using finite element analysis. Each element is assigned a relative density variable, ranging from no material to having material. Topological optimization algorithms find the optimal material distribution by adjusting the relative density of each element. At the same time, the optimal solution is obtained by threshold processing of the relative density values, where elements with a relative density higher than a certain threshold are retained, and elements with a relative density lower than the threshold are removed.

2.2 Mathematical Model of Topology Optimization

The mathematical model of topology optimization can be expressed.

$$f(\rho) = \frac{1}{2}U^T KU \quad (1)$$

ρ is the vector of relative densities of elements, U is the displacement vector, and K is the global stiffness matrix. (1)

$$V(\rho) = \sum_{i=1}^{n} \rho_i V_i \leq V_o f \quad (2)$$

V_i is the volume of element i, V_o the volume of the design domain, and f is the volume fraction. (2)

$$\sigma_i(\rho) \leq \sigma_{allow} \ for\, all\, i \quad (3)$$

σ_i is the stress of element i, and σ_{allow} is the allowable stress. (3)
To ensure that the optimized structure can be manufactured using additive manufacturing, additional constraints have been added. For example, support structure constraints, minimum feature size constraints, and overhang Angle constraints.

2.3 Topology Optimization Algorithms

2.3.1 SIMP Method

The SIMP method is currently the most widely used topology optimization algorithm. It assumes that the Young's modulus of an element is a function of its relative density [5].

$$E_i(\rho_i) = E_0 \rho_i^p \ (4)$$

E_0 is the Young's modulus of the solid material, and p is the penalization factor from 3 to 5, The SIMP method uses an optimization algorithm such as the Method of Moving Asymptotes (MMA). Efficient implementations of SIMP, leveraging high-performance computing, enable its application to large-scale industrial problems [6]. The process is repeated until the convergence criterion is met.

2.3.2 ESO Method

The ESO method is an evolutionary optimization algorithm that starts with a solid design domain and gradually removes elements that are less effective in carrying loads [7]. The basic idea is to calculate the performance metric of each unit, such as strain energy density, and remove the units whose performance metric is lower than a certain threshold. Repeat this process to limit the target volume.
This method is simple and easy to implement, but it is prone to causing the whole to be incomplete. To enhance the performance of ESO methods, various improvement approaches

have been proposed, such as the bidirectional ESO (BESO) method, which allows an element to be added back to the design domain if it is found to be valid in subsequent calculations.

2.3.3 LSM Method

The LSM method can generate smooth boundaries and is suitable for handling shape variations and topological variations. However, it is more complex to implement than the SIMP method and requires more computing resources.

2.4 Topological Optimization Calculations for Automotive Components

This study employs the SIMP method to conduct topological optimization calculations for automotive components. Optimize by using the topology optimization module. Topological optimization computation involves many steps.

Define the design domain and non-design domain, Application load and boundary conditions, set optimization parameters include volume fraction, penalty factor, convergence criterion, manufacturing constraints, Topology Optimization using the SIMP method. Iteratively update the relative densities of each element until the convergence criterion is met. At last, post-process the optimization results

3 Topology Optimization Considering Additive Manufacturing Constraints

3.1 Process Constraints of Additive Manufacturing

Specific constraints need to be considered in the topology optimization of additive manufacturing processes. A systematic classification of AM constraints provides a foundation for integrating manufacturability into early design stages [8]. These limitations include support structure, minimum feature size, overhang Angle, and step effect.
Most additive manufacturing processes require support structures to maintain the overhanging parts of components during the printing process. The support structure increases manufacturing time and cost and may damage the surface of the components during disassembly. Therefore, it is necessary to minimize the demand for support structures in topological optimization design as much as possible.
Additive manufacturing processes have the smallest feature dimensions that can be manufactured. Features smaller than the minimum feature size may not be printed accurately or may crash during the printing process. Therefore, topological optimization design should ensure that all features are larger than the minimum feature size.
The cantilever Angle refers to the Angle between the cantilever surface and the horizontal plane. In 2.5-axis printing, overhang angles exceeding 45 degrees require support structures.
Therefore, topological optimization design should limit the overhang Angle to avoid manufacturing structures that require support as much as possible.
The "step effect" like figure 1 is a common defect in 2.5-axis printing, which is caused by the layer-by-layer deposition of materials. The step effect leads to surface roughness and stress concentration, affecting the mechanical properties of components. Quantitative analysis reveals that the stair-step effect significantly compromises the fatigue life of components fabricated by

material extrusion [9]. Therefore, topological optimization design should take the step effect into account and minimize its influence.

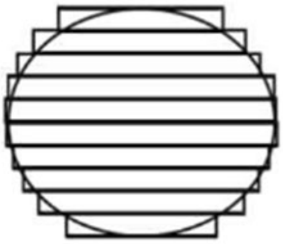

Fig. 1. Step effect

3.2 Step effect constraint integration

The step effect is considered in the finite element model by modifying the material properties or the geometric model. For example, the Young's modulus of the material can be reduced in the direction perpendicular to the printing direction to account for the anisotropic properties caused by the step effect. Alternatively, the geometric model can be modified to include the step effect, and the stress concentration caused by the step effect can be analyzed.

3.3 Topology Optimization Considering Additive Manufacturing Constraints

To fully leverage the advantages of both topological optimization and additive manufacturing, it is imperative to avoid post - hoc design adjustments and instead directly incorporate manufacturing constraints into the optimization algorithm itself. This approach ensures that the generated geometric structures not only exhibit superior performance but are also inherently easy to manufacture with minimal defects. The primary additive manufacturing constraints under consideration include reducing support structures, controlling the minimum feature size, limiting the overhang angle, and mitigating the stepping effect. A significant advancement in this domain is presented in the recent work by Xu et al, Self-support structure topology optimization for multi-axis additive manufacturing incorporated with curved layer slicing [10]. Comparative studies of curved-layer slicing strategies demonstrate superior surface quality and mechanical integrity over traditional planar methods [11].

This study directly addresses a major limitation of the traditional 2.5-axis additive manufacturing, namely the need for supporting structures for the overhanging structures. It proposes a pioneering method that integrates the concept of self-supporting structures into the topology optimization framework. This framework focuses on multi-axis additive manufacturing systems that can deposit materials along curved layers. Xu et al. emphasized a key innovation point, which is to incorporate the slicing of curved layers into the optimization process [10]. The traditional topology optimization method first optimizes and then slices them into planar layers, which often results in the need to optimize the overhanging parts. In contrast, their method optimizes the structure while simultaneously considering the continuous curved paths. This is achieved by defining a hanging constraint relative to the continuously changing building direction. Therefore, the optimization algorithm aims to find a material layout with self-supporting ability in this curved layer manufacturing mode. Their research shows that the practical significance of this method lies in significantly reducing or even eliminating the need for sacrificial supporting structures. The benefits this brings include reducing material waste, shortening printing time, and avoiding damage to the surface of components when removing supports. In addition, by matching the structural geometry with the additive manufacturing curved deposition path, the continuity of the material along the principal stress path is enhanced, and its mechanical properties can also be improved. The research by Xu et al. provides a powerful mathematical framework for the collaborative optimization of structural performance and manufacturability in advanced additive manufacturing processes, offering a more precise solution compared to traditional constraint processing methods. In our application of automotive components, a similar principle has been adopted. For instance, when optimizing the suspension control arm, a standard 2.5-axis system typically imposes a 45-degree suspension Angle constraint relative to the build platform. However, by adopting multi-axis thinking, the optimization process can design and manufacture self-supporting geometers by dynamically changing the tool path, thereby achieving more efficient and targeted part design and manufacturing.

4 Correlation Between Additive Manufacturing Path Planning and Mechanical Properties

4.1 Influence of Printing Path on Mechanical Properties

The printing path in additive manufacturing has a significant impact on the mechanical properties of the printed parts [12]. The main factors affecting mechanical properties include printing direction, layer thickness, path mode and overlap rate.

The mechanical properties of additively manufactured parts are anisotropic. Experimental characterization confirms pronounced anisotropy, with tensile strength in the deposition direction exceeding transverse strength by up to 50% in polymer-based AM [13]. The tensile strength and stiffness in the printing direction are higher than those in the transverse direction. This is because the layers are bonded together in the printing direction, and the bonding strength between the layers is lower than the strength of the material itself.

The layer thickness affects the surface quality and mechanical properties of the printed part. The smaller the layer thickness, the smoother the surface and the better the mechanical properties, but it will also increase the manufacturing time.

Path patterns include linear, zigzag and circular patterns. Different path patterns affect the distribution of internal stress and the combination between layers. For instance, compared with the linear path pattern, the zigzag path pattern has a better bonding effect between layers.

The overlap rate between adjacent paths affects the density and mechanical properties of the printed parts. A higher overlap rate will lead to higher density and better mechanical properties, but it will also increase the manufacturing time.

4.2 Dynamic Adaptive Tool Path Planning Algorithm

To improve the mechanical properties of additively manufactured automotive parts, a dynamic adaptive tool path planning algorithm is proposed. This algorithm is based on the topological optimization results and the principal stress direction of the components.

Extract the principal stress direction of the component from the finite element analysis results. Algorithmic generation of toolpaths aligned with principal stress trajectories has been shown to enhance stiffness and failure resistance under operational loads [14]. The principal stress direction is the direction of the maximum stress in the component and generates the initial tool path. The initial tool path is generated based on the topological optimization results. The tool path design follows the material distribution of the optimized structure and adjusts the tool path to align with the direction of the principal stress. Ensure that the material is deposited along the direction of maximum stress to enhance the tensile strength and rigidity of the component. Finally, based on the surface quality and mechanical property requirements, optimize the layer thickness and overlap rate. Smaller layer thickness and higher overlap rate are adopted in key areas, while larger layer thickness and lower overlap rate are used in non-key areas.

4.3 Topology Optimization Considering Toolpath-Dependent Mechanical Properties

Deeper integration involves associating optimization results with subsequent additive manufacturing process parameters, particularly with the tool path planning, to further enhance the manufacturability of the components and their final mechanical properties. The printing path is not merely a manufacturing instruction; it fundamentally affects the structure and defects of the manufactured components. Traditional topology optimization assumes that materials have isotropic properties. Incorporating anisotropic material models derived from process parameters allows for performance gains unattainable with isotropic assumptions [15]. However, AM components have anisotropic characteristics, and the strength and stiffness of the components are significantly better in the deposition direction than in the transverse direction. A truly AM-oriented integrated design approach must take anisotropy into account during the optimization stage. This can be achieved by developing an anisotropic material model, where the elastic modulus is a function of the local printing direction. Then, the topology optimization algorithm not only distributes the material based on the stress field but also distributes it based on the arrangement direction of the printing beads or layers. This can effectively design anisotropic characteristics conducive to the structure. Based on the dynamic adaptive tool path planning algorithm introduced, a collaborative cycle can be established with topology optimization.

The research by Xu et al. on multi-axis AM with curved layers, while focused on self-support, implicitly opens the door for this advanced integration [10]. Their method of aligning the deposition path with favorable geometric orientations can be extended to align with principal stress directions.

To integrate topological optimization for tool path optimization, we can conduct initial topological optimization, assuming a quasi-isotropic property, to obtain the initial optimal material layout and the corresponding principal stress field and analyze the principal stress directions at various locations within the optimized design area. Generate a tool path based on the stress field, ensuring that the deposition direction is as consistent as possible with the local maximum principal stress direction. This ensures that the direction of the strongest material is maintained, and based on this new optimized tool path direction, update the anisotropic material model used for topological optimization. Finally, use this updated, path-related material model to re-perform topological optimization. This algorithm now will generate a new geometric structure, which is the optimal one for the specific anisotropic characteristics caused by the planned processing path.

In conclusion, the integration of topology optimization and additive manufacturing is evolving from simply ensuring manufacturability to jointly completing the design structure and manufacturing process and jointly enhancing the performance of designed components. The work of Xu et al. on self-supporting optimization of multi-axis AM provides an important foundation for this advanced integration, demonstrating that by combining design algorithms with advanced manufacturing capabilities [10], people can achieve unprecedented levels of performance and efficiency in automotive parts.

5 Conclusions

This paper presents an integrated approach to enhancing the performance of automotive components through the synergistic combination of topology optimization and additive manufacturing.

The core contribution of this work is the development of a topological optimization method that actively integrates key additive manufacturing process constraints. By directly incorporating the support structure, minimum feature size, overhang Angle and "step effect" into the optimization algorithm, the generated design not only has high performance, but also has minimal defects and manufacturability. This improves the traditional post-optimization adjustment and ensures the integrity of the design from the very beginning.

In addition, the proposed dynamic adaptive tool path planning algorithm aligns the deposition path with the principal stress direction within the optimized structure, which is an important step in the collaborative design of the structure and its manufacturing process.

In conclusion, the research results confirm that the deep integration of topology optimization and additive manufacturing is a powerful strategy for automotive lightweighting, providing a way to develop lighter, stronger and more reliable components. Future work will focus on extending this approach to dynamic and multi-physics optimization problems and exploring its application in a wider range of advanced additive manufacturing materials and multi-axis systems. Emerging methods in multi-physics optimization address coupled thermal-structural and fluid-structure interactions, expanding the scope of AM-enabled designs.

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