

Topology Optimization for Metal Additive Manufacturing: Constraints, Challenges, and Emerging Solutions

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ABSTRACT

Engineering components used in the fields of aerospace, automotive, and biomedical engineering need to exhibit lightness and strength. Balancing lightness and mechanical strength is necessary to improve performance while reducing total system weight and energy consumption. Additive Manufacturing (AM), along with Topology Optimization (TO), may present solutions for achieving these requirements through creating high-performance, low-weight geometries which cannot be produced via conventional manufacturing techniques. This review paper, which reviews academic literature published between the years of 2015 and 2025, examines the limitations and associated solutions for designing mechanical components optimized for AM, including overhang limitations or constraints and minimizing support structures, anisotropy and orientations when building, self-weight, and performance versus fatigue. Overall, TO for Metal AM produces designs with less weight and greater structural integrity while producing structures that do not require additional supports. While there have been many positive results from TO for Metal AM, it has limited use due to high costs and complexity of implementation, suggesting the need for further development in this space to make it more applicable.

INTRODUCTION

Components that need to meet multiple needs such as being both mechanically robust and light-weight are needed for several fields of engineering including biomedical, automotive, and aerospace. It is critical to make these components light enough to both improve their performance as well as reduce their energy consumption and total system mass. In the automotive industry, lightweight yet durable components increase overall energy efficiency; in the biomedical field, lowering the weight of implants improves comfort and allows precise customization to an individual's anatomy; and in aerospace manufacturing, every kilogram saved can result in fuel savings over an aircraft's lifetime. New technologies such as Topology Optimization (TO) and Additive Manufacturing (AM), provide great opportunities to overcome some of the limitations mentioned previously, by providing designers and engineers with the ability to create complex, high performance geometries that cannot be fabricated using conventional manufacturing

processes. This paper will discuss the limitations of optimizing mechanical designs for additive manufacturing

Topology Optimization (TO)

Topology optimization (TO), an advanced structural design method, can provide the best possible structure arrangement by distributing material to meet predetermined stress conditions, performance requirements, and limitations (Zhu et al., 2021). For many applications, lightweight design is essential for not only optimal product performance but also for reducing material and manufacturing costs (Daynes, 2022). However, generated layouts often include complex geometries that cannot be produced utilizing traditional subtractive manufacturing techniques. Therefore, novel manufacturing techniques capable of generating highly complex geometries are necessary.

Additive and Metal Additive Manufacturing (AM/MAM)

Due to its ability to create needed complex shapes with ease, additive manufacturing, commonly known as 3D printing, is well-suited for creating such complex geometries. AM constructs the component by joining materials through sequential layers (Zhu et al., 2021). A prominent subset of AM is metal additive manufacturing (MAM), which uses metal powders or wires to produce high-strength, functional components. There are several types of MAM processes, including powder bed fusion (PBF), directed energy deposition (DED), and binder jetting, each of which offers unique advantages in terms of precision, material compatibility, and production speed (Ibhadode et al., 2023). MAM has opened the door to new design freedoms that align with the goals of TO.

The Synergy Between TO and MAM

Combining topology optimization with Metal Additive Manufacturing enables the development of a robust workflow that eliminates the inherent limitations associated with traditional manufacturing methods. By combining performance-driven design with fabrication technologies capable of producing complicated structures, parts will be both stronger, lighter and more functionally integrated than their traditionally designed counterparts.

However, turning optimal digital models into physical parts requires consideration of process-specific restrictions such as stress formation, anisotropic properties, and the need for supports. Early consideration of these issues will ensure realization of all potential benefits offered by TO and MAM.

METHODS

The focus of this literature review is on academic papers examining the potential for combining Topology Optimization (TO), Metal Additive Manufacturing (MAM), and mechanical component design. These references were produced from 2015 through 2025. AM-specific issues such as fatigue, self-weight,

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Vol 12, No 1.

anisotropy, support minimization, and overhang restrictions were highlighted, along with applications in the biomedical, automotive, and aerospace sectors. Literature was identified through searching databases such as Materials Today, Applied Sciences, Structural & Multidisciplinary Optimization, and the Chinese Journal of Aeronautics. Additional literature was also located by utilizing Google Scholar and ScienceDirect. Relevant search terms used include “Topology Optimization,” “Additive Manufacturing,” “Metal 3D Printing,” “Support Structure Design,” “Overhang Constraints,” “Anisotropy,” “Fatigue,” and “Multi-Axis AM.” Articles that presented case study examples illustrating the integration of TO and AM, or proposed methods to address MAM restrictions were selected. The subject matter of these articles includes anisotropy and build orientation; self weight; fatigue and performance; constraints and support structure minimization. Based upon applicability to engineering practice as well as experimentation, simulation, or new methodologies utilized to solve problems, eight out of the thirteen reviewed articles were selected for inclusion in this review.

RESULTS

The design of metal additive manufacturing (MAM) and additive manufacturing (AM) necessitates a comprehensive examination of process constraints while concurrently capitalizing on the capabilities of AM (Garaigordobil et al., 2022).

Overhang Constraints and Support Structure Minimization

In particular, there is a large amount of interest in imposing overhang limitations during the topology optimization process. Design options created through traditional TO may have high manufacturing costs as a direct result of the substantial number of supports needed to keep the design from collapsing (Zhu et al., 2021). Overhang constraints can ensure that generated designs can be fabricated without collapsing during the printing process, reducing the need for supports. By adding these types of limitations to the design phase, engineers can create structures that are capable of being manufactured without supports. In turn, this enhances manufacturability. There are two ways to enforce limitations on overhanging to decrease the number of supports used; one is by means of projection-based optimization procedures and the other is through global constraint methods like the SUSAN algorithm.

An algorithmic approach to minimizing or eliminating support structures in AM is a possible resolution to the problem. Gaynor and Guest (2016) developed a projection-based optimization procedure that directly minimizes the imposition of overhang constraints along with minimum length scale constraints. Instead of having to rely on sacrificial supports to hold the geometry together, Gaynor’s procedure ensures that all parts of the final model lie in the build direction at angles greater than a predetermined minimum self-supporting angle established by the manufacturer. This is achieved by performing multiple projections, first establishing the minimum length scales and secondly establishing support criteria, without requiring any additional constraints.

Regarding the alternate method of enforcing limitations on overhanging, Garaigordobil and colleagues (2018) utilize a global overhang constraint method that incorporates a unique application of the SUSAN (Smallest Univalued Segment Assimilating Nucleus) edge detection algorithm. The method uses a 3x3 element mask to examine each element as well as its eight adjacent neighboring elements, thus determining the local edge direction and identifying the orientation of material boundaries. Utilizing a specified maximum overhang angle provided by the engineer, the software identifies any non-printable contours and establishes a self-supporting contour ratio. The self-supporting contour ratio is then implemented as an inequality constraint with respect to volumetric constraints. As opposed to needing additional support structures when fabricating parts, this penalty against unsupported geometries minimizes reliance upon such additional support structures. Both algorithms were shown on benchmark problems such as MBB (Messerschmitt-Bölkow-Blohm) and cantilever beams, with optimized structures meeting overhang and length scale restrictions. Despite their success, however, both methods currently experience limited adoption in industry due to issues such as an increase in computational complexity, sensitivities to process specific parameters, and difficulty in incorporating them into commercially available design processes.

Anisotropy and Build Orientation

Another important problem related to metal additive manufacturing (AM), is material anisotropy. Material anisotropy refers to the directional dependency of material properties resulting from the layer by layer deposition of materials in metal AM (Shin et al. 2025). Frequently, parts produced using metal AM will have lower values of strength and stiffness in the build direction than in the in-plane directions, making these parts less reliable in load bearing applications. Therefore as designs become more complicated with TO, it is necessary to account for anisotropic behavior to ensure that the optimal design does not only exist but is also stable.

Shin et al. (2025) propose a novel space time topology optimization strategy that combines optimizations for material layout and build order for multiple axis metal AM. This methodology uses a pseudo-time field to manage the orientation of each stage of the build, enabling handling of anisotropic material behavior through modeling orientation dependent stiffness. When applied in conjunction with restrictions placed on the maximum allowable angle of overhanging sections and limits imposed on the continuity of depositions, this framework demonstrates the potential of optimizing designs to meet complex manufacturing requirements while maintaining acceptable structural performance. In addition to demonstrating the ability to create compliant designs through adjusting build orientation, number of stages in the build, and manner of depositing material, the authors demonstrate through numerical examples, including isotropic and anisotropic L-shapes and cutaway cantilevers, that virtually unlimited levels of compliance can be achieved (Shin et al. 2025).

Although the approach is highly flexible and effective, it has seen limited adoption within industry due to the high computational costs associated with this approach, the difficulty in developing multi-axes process plans, and the need for accurate material models which may be difficult to develop in practice.

Self-Weight

Another major challenge in Metal Additive Manufacturing (AM) is the effect of self-weight on the manufactured component throughout the manufacturing process. Self-weight can cause distortion, sagging and/or collapse of printed parts due to lack of support for each feature being printed one layer at a time. Large or heavy prints have an added problem when self-weight combines with geometric characteristics such as overhanging edges, as overcoming this issue becomes difficult (Zhu et al., 2021). Disregarding self-weight from designs created using TO results in structurally valid geometries that cannot physically exist because these geometries cannot survive the printing process.

Garaigordobil et al. (2022) developed a new approach that allows for both the incorporation of overhang constraint limitations as well as the effects of the component's own weight in the optimization process itself. Using an extended version of the SUSAN methodology, the system is capable of detecting unsupported angle conditions and determining whether specific characteristics can resist gravity forces throughout the manufacturing process. Additionally, the algorithm was successful in identifying and eliminating designs which would be subject to excessive sagging or collapse prior to completion through its ability to establish a direct relationship with the elastic properties of materials, thereby relating the maximum allowable overhang to the component's strength. Results from benchmark tests of MBB and cantilever beam were also positive in demonstrating that the printed parts had no need for additional support to remain structurally intact at the time of printing. Overall, this process has generated self-supporting structures capable of resisting gravitational loads as well as enabling the potential for developing larger or heavier additive manufactured parts.

An emerging approach for Powder Bed Fusion involves real time monitoring of a manufacturing process during operation using sensors that provide feedback to enable adjustments to be made to a manufacturing processes operating parameters in order to produce better parts. The correlation study of Mani et al. (2015) concerning the Powder Bed Fusion process illustrated strong correlations of many different operating parameter inputs with two primary quality metrics (residual stresses and part densities).

Fatigue and Performance

A major challenge in metal additive manufacturing is achieving satisfactory fatigue performance during cyclic loading, particularly for aerospace components that can be subject to severe operating conditions over long durations. Traditional Topology Optimization (TO) has emphasized static compliance; however, as stated previously, the slow accumulation of damage due to prolonged exposure to stress is typically overlooked in such analyses.

To address this issue, Chen et al. (2021), developed an alternative approach to the fatigue problem by developing a new framework for Multi-Load Topology Optimization. The authors analyzed a bracket configuration under 19 different extreme symmetric and asymmetric load cases which simulated uneven fixture loads and bolt loosening. As demonstrated in various examples, this methodology resulted in reduced strain energy levels; thereby reducing the likelihood of localized stress concentrations that may

lead to rapid fatigue failure. Using selective laser sintering and CAD-based reconstruction, the newly designed aerospace bracket exhibited a 37% reduction in weight relative to the original part and experimental testing showed compliance with required fatigue life criteria. These results clearly illustrate that the combination of fatigue based TO and AM provides both lightweight designs and longer service life, making them highly beneficial for reliability critical aircraft applications.

DISCUSSION

The findings of the current study indicate that there is increasing agreement in the field about the need to incorporate manufacturing-oriented algorithms as part of topology design processes to advance metal AM from theoretical viability to reliable production. Across the evaluated examples, the incorporation of overhang constraints, anisotropy modeling, self-weight considerations, and fatigue performance criteria produced designs that were not only structurally efficient but also demonstrably manufacturable.

Expansions and Future Advancements

The next generation of topology optimization for additive manufacturing will likely use artificial intelligence (AI), machine learning (ML), and deep learning (DL) to make designs more efficient. The analysis of vast amounts of data about previously made parts can be done with AI optimized methods which will show the patterns that were difficult to see with traditional methods. This type of data-driven method has big opportunities in high-performance industries like aerospace and automotive.

In addition, there is another technology that has shown much promise: adaptive, real-time optimization systems. In-process sensing and closed loop control have been researched for the Powder Bed Fusion Process. It was found that there is a relationship between the process parameters and the quality outcomes; specifically residual stress and part density (Mani et al., 2015).

Areas for Improvement

Although there have been significant developments with regards to TO, the results of the study demonstrate unresolved trade-offs. Self-supported designs typically require more materials than their unconstrained counterparts due to design constraints. Although the additional materials used provide greater manufacturability benefits, they highlight an opportunity to improve the constraint function used. Most current implementations also assume ideal printing conditions and therefore utilize simple material models. While these assumptions allow for comparison to benchmarks, they do not permit a direct application into industrial settings which contain factors such as defects and surface finish. The future challenges facing TO are computational intensity, cost and integration of process specific parameters. Therefore, further development is required to create effective methods that address all of the real world issues associated with manufacturing so that TO can be reliably implemented into practical manufacturing applications.

Limitations

There are limitations to this study. Firstly, much of the data used in this study is based on numeric benchmark problems which provide a useful basis for comparison but may not fully reflect the reality and complexities of components as they are manufactured in real world situations. Secondly, many foundational studies have been conducted using datasets that are now outdated and do not represent current advances in multi-axis printing. Experimental validation also varied across all literature reviewed. Some studies involved physical fabrication and testing while other studies rely solely on simulation results, with limited real-world reliability and validity. Additional studies need to be done to extend experimental validation, improve computational efficiency, and develop more accurate material models that better reflect industrial manufacturing conditions.

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