METAL ADDITIVE MANUFACTURING WITH TOPOLOGY OPTIMIZATION METHODOLOGY FOR INNOVATIVE STRUCTURAL DESIGN

Elisaveta Doncheva [1], Martin Petreski [1], Filip Zdraveski [1]
[1] Ss.Cyril and Methodius University in Skopje, Faculty of Mechanical Engineering – Skopje

Abstract: *Metal additive manufacturing (MAM) is an exciting manufacturing process that has recently received a lot of scientific attention due to its ability to develop stress-optimized structural elements and products in a material-efficient, cost-effective manner. Indeed, MAM also known as rapid prototyping or three-dimensional printing of metal products, is one of the most promising aspects of manufacturing highly complex geometries. It is now regarded as a source of opportunities for achieving true design-optimized manufacturing through topology optimization methodology. This methodology can improve material distribution by generating complex geometries that are easily built layer by layer using data from a three-dimensional (3D) model. The article is intended to explore the current state of process development and investigates the future potential of topology-optimized design approaches for MAM in developing lightweight and effective products. It discusses the most recent research efforts and topology optimization applications on various products and how current techniques can produce structural elements with significant weight reduction. The study demonstrates the need for additional research in industrial structure optimization and design, and it emphasizes the importance of integrating appropriate material, process, structure efficiency, and performance characterization when using topology optimization to pursue flexible and high-performance products.*

Key words: additive manufacturing, computer-aided engineering (CAE), 3D printing, topology optimization

1. INTRODUCTION

Modern manufacturing aims to create sophisticated products that are functional, precise, light in weight, and, ideally, low in cost and production time. Additive manufacturing (AM) is a promising manufacturing technique that has met these expectations and promises many more. Originally designed for rapid prototyping with polymers (Pellens et al., 2020), this manufacturing process drew a lot of attention and sparked the development of other manufacturing techniques with similar methodologies for the development of products with complex geometries. The properties of the functional parts produced by AM are similar to those produced by traditional manufacturing techniques, but without material subtracting, allowing for the development of new product designs and solutions that are more appealing to the industry. Product design optimization and material advancement are regarded as the most important factors for innovative design solutions for products that can be manufactured using AM (Gebisa & Lemu, 2020). AM technologies enable the creation of products from a diverse range of materials, such as metals, polymers, ceramics, and composites (Uralde et al., 2022; Armstrong et al., 2022), and as a result, it is widely used in almost every industry, including aerospace, automotive, biomedical, energy, tooling, and construction (Uralde et al., 2022).

In recent years, most of the research has been focused on developing perfect algorithms for topology optimization (TO) of products that can be accurately manufactured with AM. Topology optimization is a sophisticated numerical iterative tool for creating parts with optimized material distribution within the constraints of a specific design while meeting specified load conditions, effectiveness, and boundaries (Pellens et al., 2020; Gebisa & Lemu, 2020; Zhu et al., 2021). This tool can be used to advance AM technology if successful algorithms are developed (Gebisa & Lemu, 2020). Metal additive manufacturing (MAM) undoubtedly made the greatest impact across a variety of industries (Armstrong et al., 2022). In addition to producing products with complex geometries that would be challenging to produce using any other conventional manufacturing process, it is expected to result in significant energy and material savings, lowering costs, and reducing environmental impact (Uralde et al., 2022). Lattice and topologically optimized structures are two examples of geometrically complex structures, primarily used to provide specified mechanical properties such as stiffness and impact absorption (Abdi et al., 2018). Indeed, topology optimization of structures and the use of lattice infill are two dominant strategies for designing next-generation lightweight structures (Wu et al., 2021). The combination, i.e., topology optimization of multi-scale structures, thus holds the promise of overall superior performance (Wu et al., 2021).

The lattice structure is a porous material that emphasizes the potential coexistence of efficiency and weight reduction (Abdi et al., 2018). It is created by repeatedly using lightweight unit cells that have excellent properties and require little material (Abdi et al., 2018; Alkebsi et al., 2021). These cells can be categorized as 2D or 3D and have the potential to have different aesthetics and characteristics (Gao et al., 2019). Furthermore, it has a high degree of stiffness and energy absorption (Abdi et al., 2018). To problems with multiple objectives or uncertain loading conditions, lattice structures have the intriguing property of being more resilient than topology-optimized solutions (Abdi et al., 2018; Gao et al., 2019). Topology optimization is a newer structural optimization technique that is based on design variables. Depending on the domain and design properties, structural optimization can be used in both continuum and discrete structures. The optimal solution for the perfect design is obtained systematically over several iterations. Figure 1 depicts the process of topology optimization (Zhu et al., 2021).

When designing topology-optimized structures, AM allows engineers to overcome the limitations of traditional manufacturing techniques, allowing them to focus on designing lightweight and high-performance structures (Zhu et al., 2021). The combination of topology optimization and additive manufacturing is an important step toward combining structural design and manufacturing. Aside from the vast manufacturing potential, AM introduces new engineering constraints and challenges, such as precision, structural connectivity, additional support structure, surface roughness, material properties, and so on (Zhu et al., 2021).

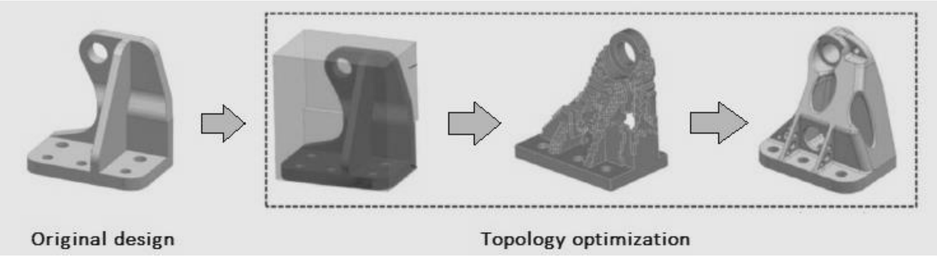

Figure 1: Topology optimization of an aerospace bracket design results in a weight reduction of 18% (Zhu et al., 2021)

This article covers several topics, including the basics of the TO process with discussions on its constraints, the benefits of its application, and the combination of AM and TO when producing metal parts in the second section. The third section provides a general description of metal additive manufacturing techniques and classifications, as well as the discovered relationship between design and redesign in additive manufacturing processes and discusses the process's sustainability and challenges. The last section concludes with a summary of the challenges and possible next steps.

2. TOPOLOGY OPTIMIZATION OF STRUCTURES FOR ADDITIVE MANUFACTURING

Topology optimization of structures provides a design solution with optimal size, shape, and material distribution while meeting product performance expectations. Depending on the manufacturing process, this technique combines Computer-Aided Design (CAD), Finite Element Analysis (FEA), and various algorithms (Gebisa & Lemu, 2020). CAD is used to create the initial model that will be used in FEA software to analyze stress and displacements when the part is subjected to specific loading conditions. This data is critical for TO, which involves removing sections of the part that do not carry any loads or have significant deformations. There are numerous topology optimization techniques, as shown in Table 1 (Ibhadode et al., 2023). The structure's design is modified within the constraints of known essential requirements. There may be goals like maximizing stiffness, as well as constraints like maximum deformation, stress, mass, or other variables that are critical to the part's performance (Gebisa & Lemu, 2020). The process continues with remodeling and correction of the obtained topologically optimized structure in CAD. The new design is validated in FEA software before it is used in manufacturing. With FEA the optimization is simplified to the analysis of properties of finite elements (Abdi et al., 2018).

Structural TO techniques provide numerous advantages in design, including time, processing energy, and material savings (Gebisa & Lemu, 2020). The best TO solution for a specific design can only be obtained by following the proper steps throughout the process. The first step is to establish clear criteria, which is followed by data collection and proper variable identification and definition (Gebisa & Lemu, 2020). The following step is to define evaluation criteria and to specify when the optimization process should be stopped (Gebisa & Lemu, 2020). The last step is to identify constraints (Gebisa & Lemu, 2020).

Topology optimization is an excellent design tool for creating specific designs that can be manufactured by AM, a new process that produces parts layer upon layer, allowing for easy and quick production of products distinguished by shape, materials, and functional complexity (Gebisa & Lemu, 2020). It can be used for new designs and redesigns of existing lightweight products with solid or cellular structures within. Figure 2 depicts the product development process using TO. The initial design of the structure in CAD software is topology optimised to a new design over several iterations in which variables and constraints are calculated (Pellens et al., 2020). After obtaining the final design, the following step is using AM to produce the structure. Although additive manufacturing has the potential to produce parts with complex geometries and shapes with high accuracy, the new design can introduce new constraints, defects, a lack of connectivity between layers, additional support structures, surface roughness, and other issues (Zhu et al., 2021). For maximum product performance, deep integration of product design and manufacturing with considerations of AM constraints and material properties is required (Zhu et al., 2021).

Additive manufacturing with TO in mechanical design and manufacturing is an intriguing topic for many researchers, with applications in a wide range of industries. However, due to the requirements of multiscale and multi-functional structures, topology optimization and its numerical design schemes still have a lot of content to develop (Pellens et al., 2020; Zhu et al., 2021). To realize the integration of material, structure, process, and performance, AM itself must be improved by predicting and controlling its material mechanics behaviors, and fabricating more complex functional structures (Zhu et al., 2021).

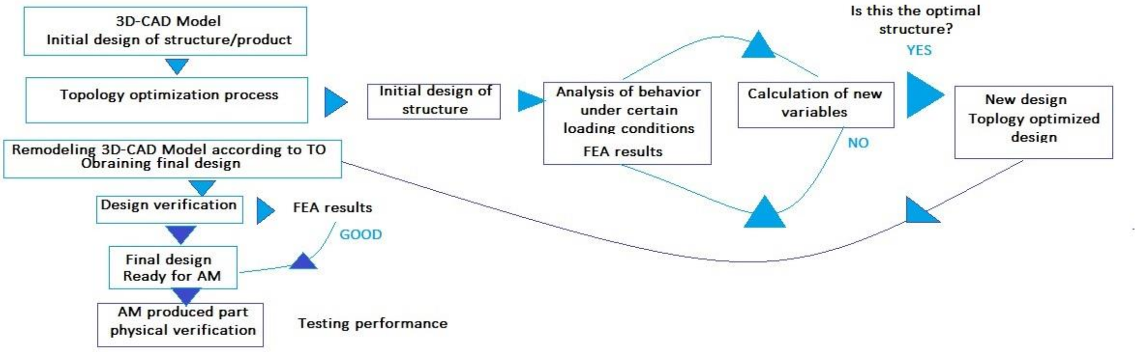

Figure 2: Topology optimization in the process of product development

Table 1: Topology optimization classification (Ibhadode et al., 2023).

Topology optimization	Density-based	Solid isotropic material with penalization
		Rational approximation of material properties
		Coined from the hyperbolic trig. function SINH
	Hard-kill	Evolutionary structural optimization
		Bi – evolutionary structural optimization
	Boundary variation	Level set
		Phase field
	Non-gradient methods	Genetic algorithm
		Particle swarm optimization
		Simulated annealing
		Artificial inteligance

The advantages of combining TO and AM in machine design and manufacturing have resulted in a wide range of applications in industries such as aerospace, automobiles, aviation, medicine, and so on (Pan et al., 2020). The design of parts with high stiffness while being small and light results in lower fuel consumption, increased quality, and carrying capacity (Alkebsi et al., 2021). Cellular and lattice structures are primarily used in the design of engineering elements and parts and are regarded as an excellent solution for lowering manufacturing costs while increasing carrying capacity. Lattice structures' excellent properties make them ideal for the development of structures with improved manufacturing performance (Pan et al., 2020). Furthermore, lattice structures are biocompatible and strong, with the ability to be designed to mimic the shape of human tissue and bone to replace diseased organs (Pan et al., 2020). Figure 3 shows two examples of products fabricated with TO and AM (Wu et al., 2021).

Topology optimization generates lattice structures with enormous potential for AM lightweight designs, but there can be issues such as overhang constraints, and each part must be additionally supported to prevent warping and collapsing (Gao et al., 2019). Removing the support materials after AM can be a waste of time, energy, and materials, as well as cause part damage. Topology-optimized self-supporting structures may be a solution to this problem.

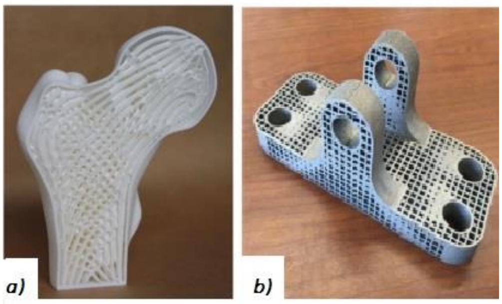

Figure 3: 3D multiscale structures designed with topology optimization and produced with AM, a) bone-inspired infill structures, b) variable density lattice structure (Wu et al., 2021)

The combined use of lattice structure and additive manufacturing technology is a game changer in industrial design. AM technology allows for design flexibility, a wide range of sizes, the use of different materials, the creation of a program for automatic processing, and the saving of energy and money [8Pan et al., 2020). Support materials must be added when designing lattice structures with suspended geometry, which results in material waste and increases post-processing time (Pan et al., 2020).

3. METAL ADDITIVE MANUFACTURING

Metal additive manufacturing (MAM) began in the early 1990s with the creation of a binder jetting printer (by Ely Sachs and co-workers), which used inkjet printer heads to spray layers of metal powders with adhesives that held them in place, resulting in a 3D part (Pragana et al., 2021). The next steps in evolution led to the use of high-energy lasers for metal powder processing and the development of direct metal laser sintering (DMLS), which was based on the technology proposed for additive manufacturing of polymers (Pragana et al., 2021). The use of an electron beams thermal energy source in MAM began in the late 1990s, with the development of the so-called "3D welding" technique, which combined traditional welding techniques with robotics (Pragana et al., 2021). This process opened new possibilities for using an electric arc and computer-aided manufacturing (CAM) software to control the movement of the tool as it built the 3D metal part layer by layer. This is known as wire-arc additive manufacturing (WAAM), and the feedstock is welding wire. MAM techniques have been continuously developed and improved over the years.

Different classifications of processes were made in various literature as AM techniques evolved. The most fundamental classification is based on the following criteria: base material (polymer, ceramics, metals); bonding method (direct and indirect process); and raw material input state (liquid, molten, powder, solid layer)(Frazier, 2014; Yakouta et al., 2018). Another classification of AM systems exists to differentiate technologies: powder bed, powder feed, and wire feed systems (Armstrong et al., 2022; Frazier, 2014). These systems can use a variety of energy sources: electron beams, lasers, arcs, and so on. According to the EN ISO/ASTM 52921 (2015) standard, additive manufacturing processes are classified into seven types based on adhesion and bonding method: VAT photopolymerization, material jetting, material extrusion, powder bed fusion, binder jetting, direct energy deposition, and sheet lamination (Pragana et al., 2021; Yakouta et al., 2018). Binder jetting (BJ), powder bed fusion (PBF), sheet lamination (SL), and direct energy deposition (DED) are four of these categories that are now used to manufacture metal parts. When it comes to metals, the other three categories, vat photopolymerization (VP), material jetting (MJ), and material extrusion (ME), are mostly used as indirect additive manufacturing (Pragana et al., 2021; Yakouta et al., 2018; Zhang et al., 2018). These metal-testing processes are in the early stages of development; commercial systems do not exist (Zhang et al., 2018).

MAM processes can be direct or indirect, depending on the stage of final product development, whether they are produced according to design and requirements, or if additional traditional manufacturing processes are required to obtain the final product (Pragana et al., 2021). Indirect MAM is used in conjunction with processes such as investment casting, sand casting, die casting, and injection molding, and it is primarily used for 3D printing of nonmetallic materials such as polymers, photopolymers, ceramics, waxes, resins, and composites (Pragana et al., 2021). The MAM process consists of several stages that vary depending on the type of product created. Before printing larger quantities, it is sometimes necessary to print a prototype to determine sustainability. Furthermore, certain parts necessitate the use of postprocessing treatments and quality inspections. Figure 4 depicts a schematic representation of the MAM's basic workflow.

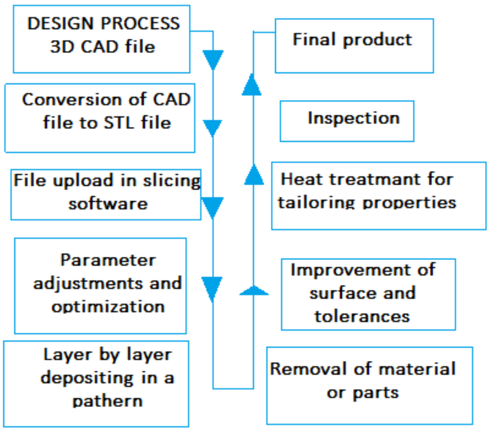

Figure 4: Basic workflow of MAM process

Additive manufacturing processes are thought to be less efficient than traditional manufacturing methods. There are up to 85% differences in energy consumption when using wire feedstock versus powder feedstock (Bambach et al., 2017). Power consumption has a significant impact on process costs, but little research has been conducted on this topic. Hybrid process combinations can accelerate process integration on an industrial scale by increasing build-up rates (Bambach et al., 2017).

4. CONCLUSIONS

This paper aims to summarise fundamental knowledge of topology optimization and additive manufacturing techniques for metal product fabrication. It discusses the benefits of using TO tools in design and manufacturing, as well as how TO and AM work together to create high-performance, multifunctional, and lightweight structures. In conclusion, this article discusses the stages of structural optimization for AM, as well as how to apply these methodologies. It emphasizes the importance of structural design optimization based on novel configurations such as lattice structures within design constraints and functional requirements.

The field of MAM is exciting and advancing at a rapid pace (Armstrong et al., 2022; Yakouta et al., 2018). Innovative methods and applications continue to emerge, and more R&D is required to address challenges in:

- process control and modeling to ensure quality, consistency, and reproducibility across AM machines,
- optimization and design of practical industrial structures,
- characterization of the performance of scale-related lattice structures,
- understanding relationships between topologically optimized structures and material properties,
- effect of the AM process on material anisotropy and fatigue performance,
- design and manufacturing of complex multi-material functional systems,
- influence of AM processing parameters on microstructures, surface features, and mechanical properties by experiments or modeling
- hybrid and multi-material additive manufacturing.

This knowledge can be used to predict and optimize the desired physical and mechanical properties, as well as to create strategies for AM materials design or inverse design. Metal additive manufacturing has expanded its applicability in recent years; therefore, further research incorporating `numerical tools such as topology optimization methods, parameter optimization in additive manufacturing, and incorporating designs using graded cellular structures under mechanical and thermal loads is required. Many limitations and challenges exist in recently developed metal additive manufacturing processes, such as process repeatability, complex thermal stresses, and material microstructural implications (Yakouta et al., 2018). These factors influence the density of additive parts, and thus all mechanical properties and material properties.

5. REFERENCES

Armstrong, M., Mehrabi, H.A. & Naveed, N. (2022) An overview of modern metal additive manufacturing technology. *Journal of Manufacturing Processes*. 84, 1001-1029. https://doi.org/10.1016/j.jmapro.2022.10.060

Abdi, M., Ashcroft, I.A., & Wildman, R.D. (2018) Design optimization for an additively manufactured automotive component. *International Journal of Powertrains, 7*, 142. https://doi.org/10.1504/IJPT.2018.090371

Alkebsi E. A. A., Ameddah H., Outtas T. & Almutawakel A. (2021) Design of graded lattice structures in turbine blades using topology optimization, *International Journal of Computer Integrated Manufacturing*, 34 (4), 370-384. https://doi.org/10.1080/0951192X.2021.1872106

Bambach, M.D., Bambach, M., Sviridov, A., & Weiss, S. (2017) New process chains involving additive manufacturing and metal forming – a chance for saving energy?, *Procedia Engineering, 207*, 1176-1181. https://doi.org/10.1016/j.proeng.2017.10.1049

Frazier, W.E. (2014) Metal Additive Manufacturing: A Review. *J. of Materi Eng and Perform.* 23, 1917–1928. https://doi.org/10.1007/s11665-014-0958-z

Gebisa, A. W. and Lemu, H. G. (2017) A case study on topology optimized design for additive manufacturing. In: IOP Conference Series: Materials Science and Engineering, Volume 276, First Conference of Computational Methods in Offshore Technology, (COTech2017), 30 November - 1 December 2017, Stavanger, Norway.

Gao J., Luo Z., Li H., Gao L., (2019) Topology optimization for multiscale design of porous composites with multi-domain microstructures, *Computer Methods in Applied Mechanics and Engineering*, Vol. 344, pp. 451-476. https://doi.org/10.1016/j.cma.2018.10.017

Ibhadode, O., Zhang, Z., Sixt, J., Nsiempba, K. M., Orakwe, J., Martinez-Marchese, A., Ero, O., Shahabad, S.I., Bonakdar, A. & Toyserkani, E. (2023)Topology optimization for metal additive manufacturing: current trends, challenges, and future outlook, Virtual and Physical Prototyping, 18:1. https://doi.org/10.1080/17452759.2023.2181192

Pellens, J., Lombaert, G., Michiels, M., *et al.* (2020) Topology optimization of support structure layout in metal-based additive manufacturing accounting for thermal deformations. *Struct Multidisc Optim.* 61, 2291–2303. Available from: https://doi.org/10.1007/s00158-020-02512-8

Pan C., Han Y., Lu J. (2020) Design and Optimization of Lattice Structures: A Review. *Applied Sciences*. 10(18):6374. https://doi.org/10.3390/app10186374

Pragana, J.P., Sampaio, R., Bragança, I.M., Silva, C., & Martins, P. (2021) Hybrid metal additive manufacturing: A state–of–the–art review, Advances in Industrial and Manufacturing Engineering, 2, 100032. https://doi.org/10.1016/j.aime.2021.100032

Uralde, V., Veiga, F., Aldalur, E., Suarez, A., Ballesteros, T. (2022) Symmetry and Its Application in Metal Additive Manufacturing (MAM). *Symmetry*,14, 1810. https://doi.org/10.3390/sym14091810

Wu, J., Sigmund, O. & Groen, J.P. (2021) Topology optimization of multi-scale structures: a review. *Struct Multidisc Optim* 63, 1455–1480. https://doi.org/10.1007/s00158-021-02881-8

Yakouta, M., Elbestawib, M.A. & Veldhuis, S.C., (2018) Review of Metal Additive Manufacturing Technologies, *Solid state phenomena*, Vol. 278, pp 1-14. https://doi.org/10.4028/www.scientific.net/SSP.278.1

Zhu, J., Zhou, H., Wang, C., Zhou, L., Yuan, S., Zhang, W. (2021) A Review of Topology Optimization for Additive Manufacturing: Status and Challenges. *Chinese Journal of Aeronautics*. 34 (1), 91-110. Available from: https://doi.org/10.1016/j.cja.2020.09.020

Zhang, Y., Wu, L., Guo, X. et al. (2018) Additive Manufacturing of Metallic Materials: A Review. *J. of Materi Eng and Perform* 27, 1–13. https://doi.org/10.1007/s11665-017-2747-y