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Article

Characterizing the Impact of Selective Laser Melting on Complex Lattice Geometries using Finite Element Analysis

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Abstract: Additive manufacturing (AM) has made significant strides in industries over the past century. Manufacturing techniques employing metallic dies have found applications across various engineering fields, particularly where there is a need for components that are both lightweight and durable. In the pursuit of optimizing both shape and performance, researchers have delved into the examination of lattice structures, often referred to as fill geometries. Among these geometries, certain examples exhibit intriguing properties such as a negative Poisson's ratio, as seen in auxetic structures, or an optimized mass/volume ratio, exemplified by the Gyroid structure. The primary aim of this endeavor is to delve into the analysis and characterization of metallic additive manufacturing through the employment of the Selective Laser Melting (SLM) technique. The focus extends to comprehending how this technique impacts intricate geometries, particularly those involving lattice structures. The methodology involves leveraging computer simulations using the ANSYS® software to execute studies utilizing finite element analysis. These studies serve the purpose of thoroughly delineating the effects of the additive manufacturing process in AM.

Keywords: Selective Laser Melting, Addictive Manufacture, Gyroid, Lattice Structures, Tripple periodic minimal surface.

1. Introduction

The search for lighter and stronger materials and geometries has been a goal for several industries, such as aerospace, automotive, and biomedical (Michael Ashby et al., 2019). In this sense, additive manufacturing (AM), popularly known as 3D printing, has gained prominence for its versatility and ability to produce complex geometries.

The AM process consists of manufacturing a geometry layer by layer using a material, with each layer representing a cross-sectional representation of the geometry. In 1979, Ross F. Housholder presented the initial description of a laser sintering AM system using powder. The material was deposited in thin, flat layers and sintered by a laser beam, solidifying the material through heat (Bourell et al., n.d.). The process described by Housholder later became known as Selective Laser Sintering (SLS).

From a derivation of this process, the Selective Laser Melting (SLM) process was created in the mid -1990s by the Fraunhofer Institute for Laser Technology (ILT) in Aachen, Germany, which uses metal alloy powders for the construction of its geometries. One of the main advantages of the SLM process is the ability to use metal alloys, such as titanium, which have high corrosion resistance, high toughness, and creep resistance. Another positive point is the cost reduction compared to conventional material subtraction processes, such as machining.

Despite all the benefits of the AM process using the SLM method, it still lacks the ability to produce large parts, being limited to small parts manufactured in generally inert chambers (Milewski, 2017).

For the composition and construction of the internal geometry of AM parts, it is necessary to use infill, which can be formed by an interconnected network of structural solids, such as plates made up of edges and faces of a cell.

Within this class, a structure called cellular solids stands out, which has a wide application in engineering due to its mass/volume ratio known as a gyroid (Khaderi et al., 2014).

In studying its structure, we one can observe a similarity with objects and structures found in nature, possessing a high level of interconnectivity and porosity. Due to these characteristics, the structure discovered by Alan Schonen in 1970 is naturally optimized, possessing greater rigidity and dimensional stability. The gyroid is part of the so -called triply periodic minimal surfaces (TPMS), structures that can be found in butterfly wings and beetle shells (Winter et al., 2015).

From a manufacturing point of view, structures belonging to the TPMS group present several challenges due to their high degree of interconnectivity and complexity. However, with the advent of AM, complex structures like the gyroid can be manufactured more easily compared to conventional methodologies. Additionally, AM allows the production of customized and small quantity parts, making it an attractive option to produce bespoke parts and low-volume prototypes.

Simulation study allows for a more in-depth analysis of the structure's properties, such as tensile, compression, bending, and fatigue resistance. This information is crucial for the development of new applications and materials, as well as for the validation of the use of these structures in specific applications.

The use of structures such as the gyroid in aerospace and automotive applications has shown promise, as these structures have a high strength-to-weight ratio. Still, it is essential to consider the challenges associated with the manufacturing of these structures, as well as mechanical properties and durability over time.

In this context, finite element simulation is a valuable tool for the study and analysis of complex structures manufactured by AM, allowing for the identification of possible failures and the development of more efficient solutions. Studies of this nature hold the potential to significantly bolster the progress of AM and its associated technologies, while also fostering widespread adoption of intricate structures across diverse industry sectors. The main goal of this work relies on apply a AM methodology to fabricate complex geometries and investigate the warping effects resulting from the laser material interaction process. The focus is on understanding the occurrence of failures and defects that may arise during the manufacturing process.

2. Structure modeling

The structure employed the principles of the Gauss-Bonnet theorem to construct the triple periodic minimal surface (TPMS) in the parametric creation of the Gyroid geometry (Hyde et al., 1997). The nodal equation (Eq. 1) was incorporated into a Python script to generate the geometry, enabling the customization of multiple dimensional parameters. Within these TPMS structures, two different types of architecture exist. Bicontinuous TPMS are smooth infinite surfaces that partition space into two intertwined labyrinthine domains and exhibit three distinct lattice period ic (Kapfer et al., 2011).

For the construct of the Gyroid geometry a Python programming routine was developed for the implementation of this structure. The Cartesian variables x, y, and z were employed to represent the coordinates, enabling the definition of the structure's positioning and dimensions. The selected cellular structure had overall dimensions of 40mm x 40mm x 40mm, with a relative fill density of 25% of the total volume of the geometry. The wall thickness of the structure was set at 2 mm.

$$F(x,y,z) = \sin(2\pi x/a)\ \cos(2\pi y/a) + \sin(2\pi y/a)\ \cos(2\pi z/a) + \sin(2\pi z/a)\cos(2\pi x/a) \quad (1)$$

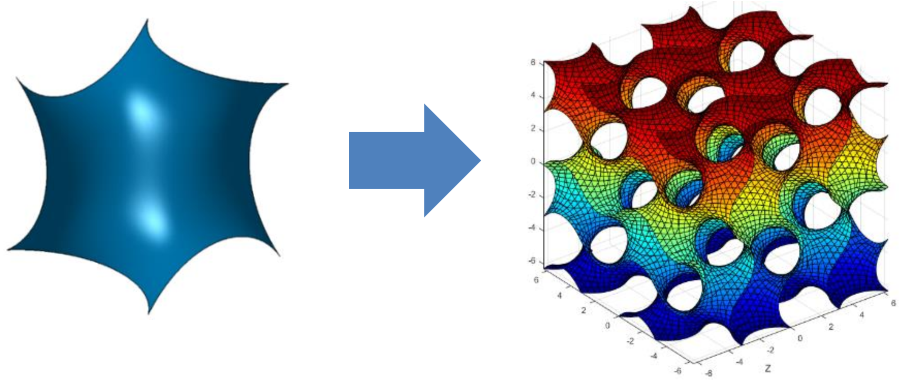


Figure 1. Gyroid lattice Structure

2.1 Numerical simulation

To model and evaluate simulation data in AM, a thermal-transient analysis was conducted. This involved applying thermal loads generated during the laser-based fabrication process along the cross-section of the geometry (Xiao & Zhang, 2007). The results of this analysis were used as input parameters for a static structural analysis, aimed at assessing the impact of the thermal loading on the structure.

The thermal analysis, in conjunction with the AM module, simulated the layer-by-layer construction of the geometry. Metallic powder material was sintered using a laser beam, similar to SLM (Selective Laser Melting) process. This interaction created a temperature gradient. As the material cooled and layers were built, geometric contractions could occur due to thermal variations, resulting in residual stresses and potential deformations in the process.

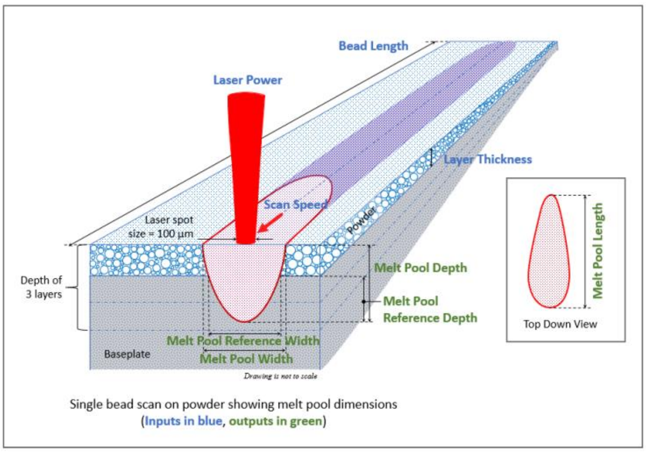
The SLM printing process is an iterative one, requiring the division of geometry production into layers and stages. It involves two distinct stages: construction, where the sintering of layers corresponding to the cross-section of the geometry takes place, and cooling of the geometry after each iteration process.

2.2 Print parameters

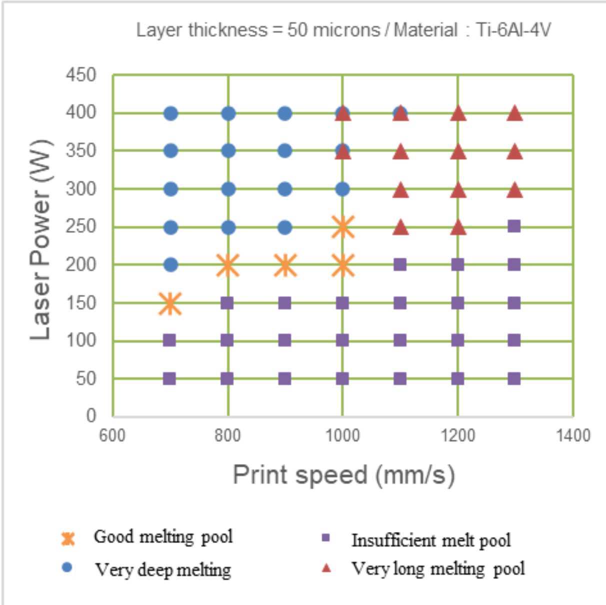
The selected material for this research is the Ti-6Al-V4 alloy, a metallic composition composed of 6% aluminum and 4% vanadium in a titanium matrix. This alloy was chosen due to its physical, mechanical, and chemical properties, which make it highly relevant and widely applied in the industry (Yang Guangand Xie, 2022). Recognized for its strength, lightness, and corrosion resistance, the Ti-6Al-V4 alloy is frequently employed in prominent sectors such as aerospace, automotive, and biomedical (AMFG. 2019). Its unique combination of characteristics makes it an ideal choice for applications that require high performance and durability.

A comprehensive study was conducted to determine the optimal power and speed values for fabricating the geometry using Ti-6Al-V4 material. Parametric single-bead simulation was employed to gather crucial insights into the melt pool characteristics during the AM process. This simulation provided valuable data on the melt pool's geometry, including width, length, and depth (see Figure 2).

By obtaining these preliminary data, it becomes possible to calibrate the machine settings according to the specific material being used. This calibration process allows for the identification of the most suitable configurations based on the observed behavior of the melt pool. With the objective of prioritizing faster printing speed, a value of 1000mm/s and a power of 250W were adopted in order to minimize voids between layers caused by inadequate material fusion.



a) Melt pool parameters. Ansys. (2021)



a) Melt pool simulation results

Figure 2. Print parameter calibration

2.3 Thermal and static analyses

Simulation of the manufacturing process requires the analysis to follow the actual build process, solidifying the part layer by layer. Since the thermal and structural aspects have a weak interaction, it is possible to initially simulate the thermal phenomena layer by layer and then use these temperature results in a subsequent structural simulation.

In an AM process simulation, the model evolves over time, meaning that elements are progressively added. Initially, the entire part is meshed with a layered mesh, and then the element birth and death technique is used to activate the element layers and simulate the build progression. Additionally, the relevant boundary conditions, such as thermal convection surfaces, also evolve.

The build process is considered complete when all the element layers have been added. The analysis times and time steps are determined by the process parameters and are not known in advance.

The model does not consider the beam scan pattern due to its complexity and computational cost. Actual metal powder deposit layers are aggregated into "super layers" of finite elements for simulation purposes. This grouping approach is appropriate since the temperature histories of adjacent layers are similar (Ansys. 2021).

For the AM process, the build platform is used as a reference for applying the preheating temperature gradient, which varies depending on the type of material being used. This parameter is essential for minimizing temperature variations during the printing process and also for improving adhesion of the print to the build platform in the initial layers. Figure 3 illustrates three stages in the printing process, showing the temperature variation during the layer processing.

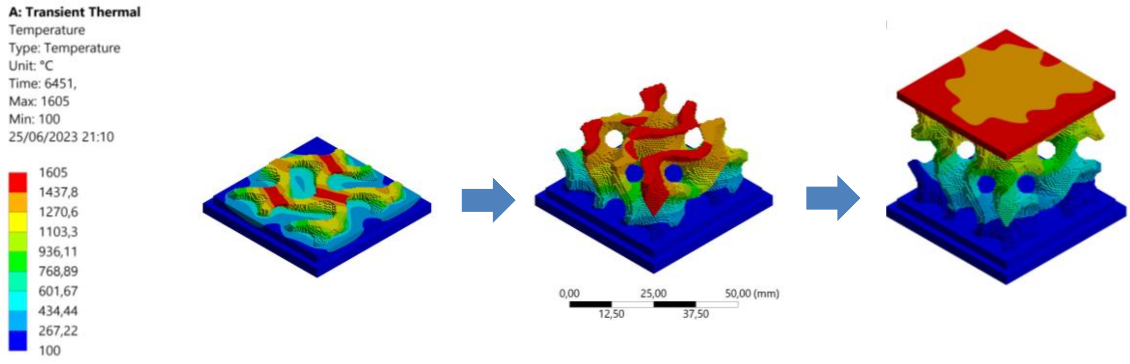


Figure 3. Evolution of print process

In the structural analysis stage, the thermal loads from the AM process, coupled with compressive loading, are applied as boundary conditions (Figure 4). Upon solving the static structural step, deformations, failures, and residual stress in the geometry can be evaluated in relation to the printing process. This evaluation process is conducted iteratively, examining the stress field history as a function of the layer printing time for the geometry.

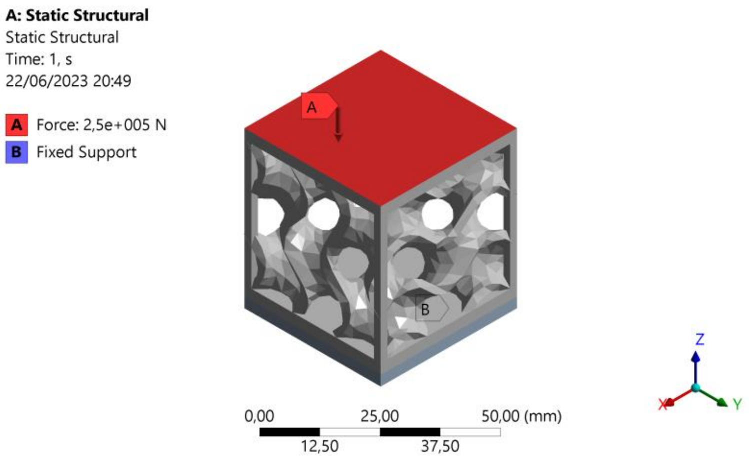


Figure 4. Boundary conditions for static analysis

3. Results and discussions

Due to inherent processing flaws and inadequate cooling uniformity, dimensional distortions may arise in the fabricated geometry. These distortions primarily stem from variations in the contraction rate of the material at different temperatures, leading to permanent deformations in the geometry.

Deformations occurring during the AM process can significantly impact the geometrical precision and pose a risk to the successful completion of the process. The deposition of material onto the printing surface relies on a movable cylinder or blade, and any warping or distortion in the geometry can result in mechanical collisions with the intended part, thereby impeding the completion of the printing process (Yadroitsev et al., 2007).

Throughout the AM process, the metallic powder undergoes cyclic heating and cooling for each layer, as illustrated in Figure 5. These thermal cycles are a recurring feature throughout the entire fabrication process.

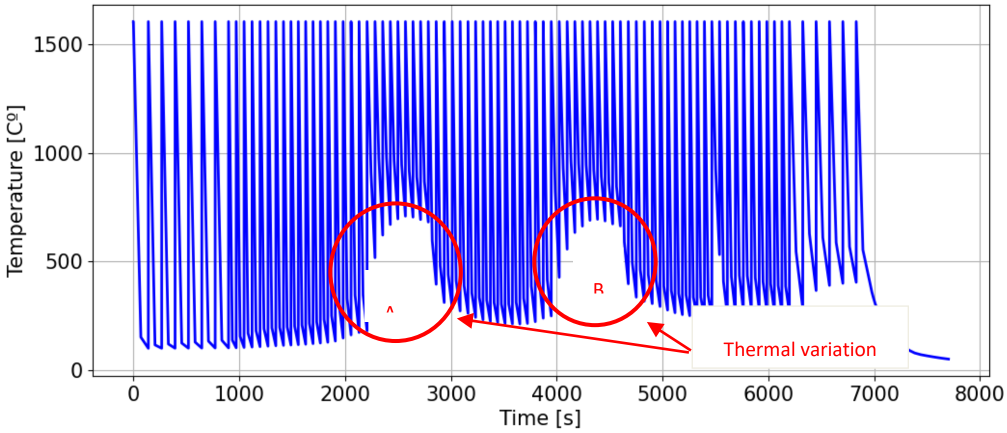
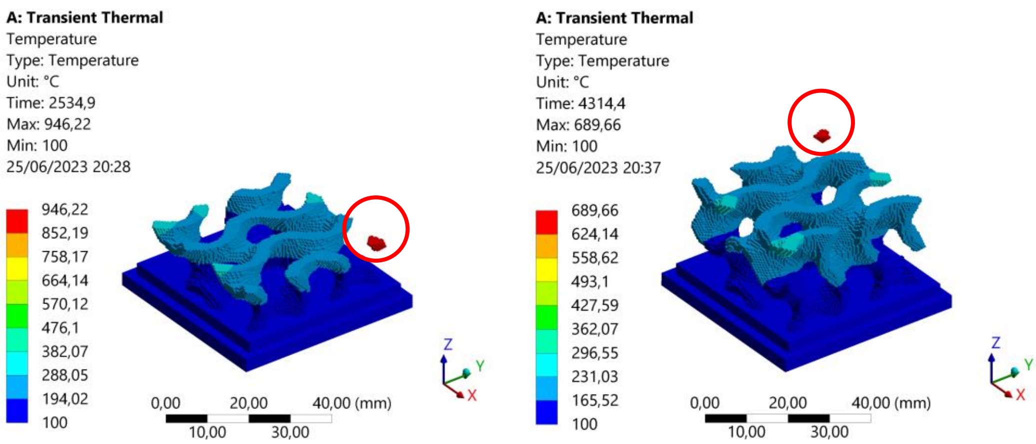


Figure 5. Thermal cycle of print process

Using the graph to analyze the heating and cooling cycles, it is possible to observe areas with non-uniform cooling behavior compared to the other layers. This type of temperature variation occurs in fractions of the geometry that lack connections to supports or other parts of the object, resulting in areas with less material and compromising the cooling time between layers.

Based on the analysis of Figure 5, it was possible to determine the area affected by the variation in thermal cycles, as depicted in Figure 6. These temperature variations result in residual stresses and dimensional distortions, as observed in Figure 7. The absence of supports for the marked area led to permanent deformation in the geometry, compromising dimensional accuracy. This effect was observed in other areas of the component as well.

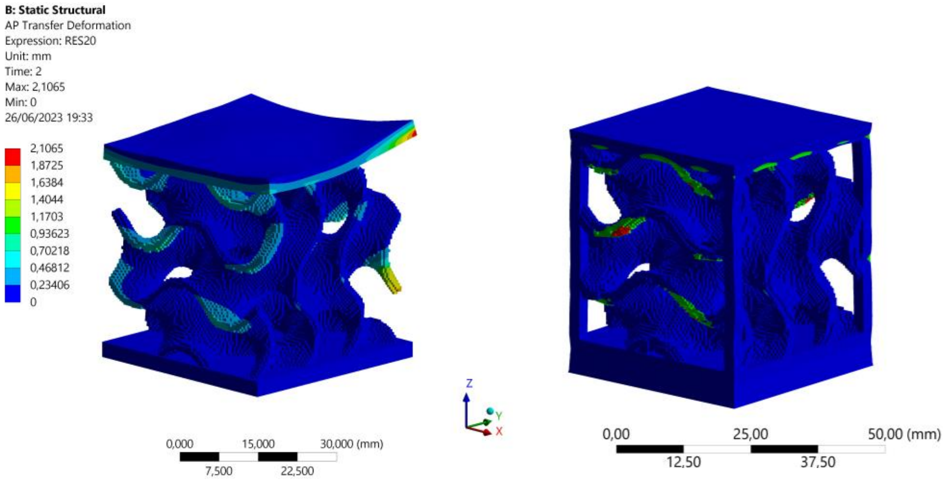


a) “A” point b) “B” point

Figure 6. Thermal evaluation of heat source

To address the discussed processing flaws, it was necessary to use complementary geometries known as supports. The purpose of these structures is to eliminate the deformation area highlighted in Figure 6, minimizing excessive displacements of the geometry during the manufacturing process.

By comparing the two geometries shown in Figure 7 and the graph in Figure 8, a significant reduction in total deformation can be observed. As a result, there is an improvement in the convergence of numerical results due to the reduction of abrupt displacements.



a) Supportless Gyroid b) Gyroid with supports

Figure 7. Implementation of support structures

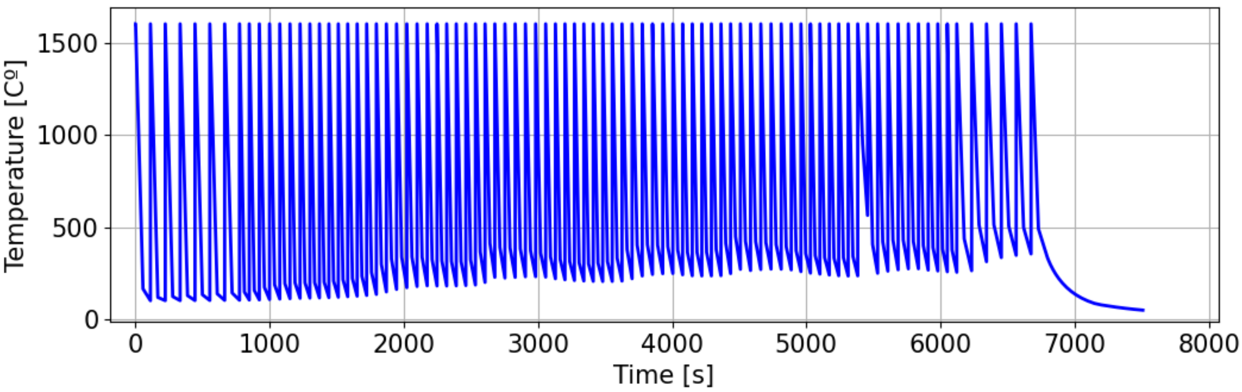
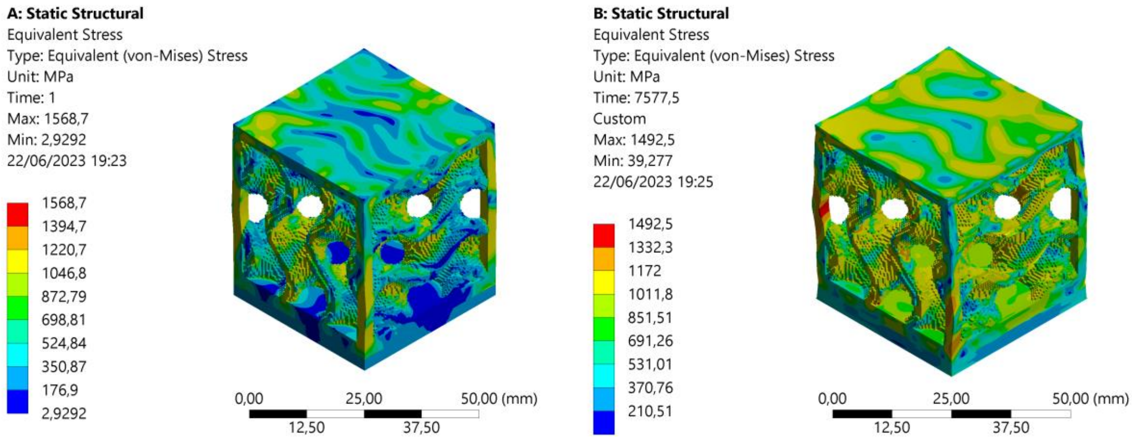


Figure 8. Improved temperature variation response in the processing cycle

3.1 Compression analyses

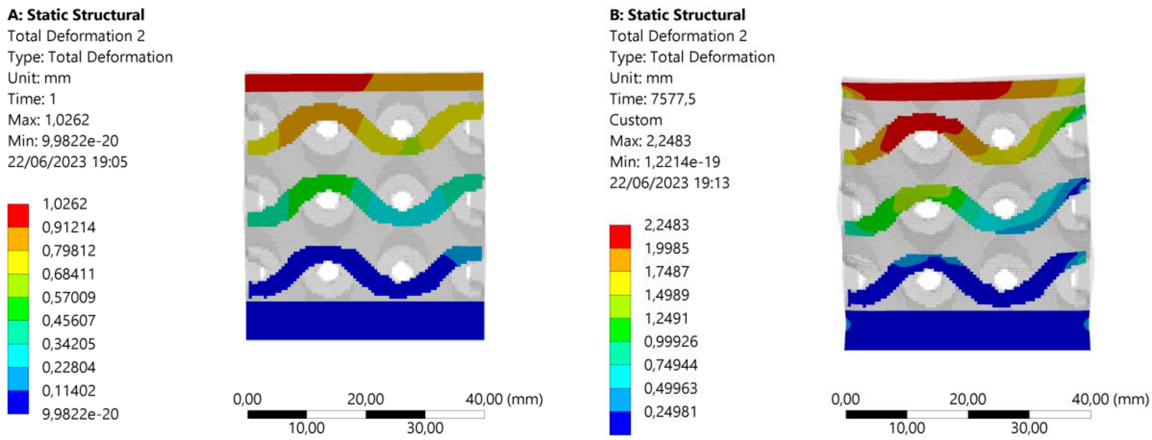
The objective of the comparative simulation between the two geometries is to evaluate the influence of the SLM manufacturing process on the geometry. The simulation applies the boundary conditions as previous discussed, with a specific focus on the application of a 250kN load.

Figure 9 depicts the von-Mises stress distribution across the entire specimen. The analysis reveals a pronounced variability in the stress field for the SLM-fabricated gyroid structure. This phenomenon can be ascribed to the thermal loading imparted during the laser-based manufacturing process. The successive cooling cycles induce plastic deformations due to material contraction, thereby engendering residual stresses throughout the geometry. Such residual stresses significantly influence the structural performance under operational conditions.



a) Base Gyroid b) MA Gyroid

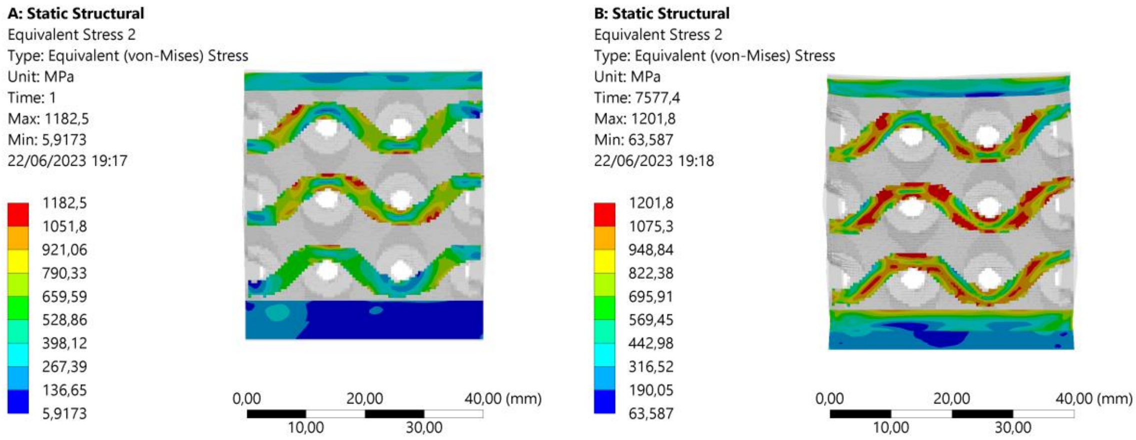
Figure 9. Equivalent (von-Mises) Stress comparative models



a) Base Gyroid b) MA Gyroid

Figure 10. Total deformation comparative model

As depicted in Figure 10, the geometry subjected to the AM process exhibited a deformation approximately twice as significant as a base geometry when subjected to the same magnitude of compressive loading.



a) Base Gyroid b) MA Gyroid

Figure 11. In plane Equivalent (von-Mises) stress comparative stress model

Upon comparing the two geometries illustrated in Figure 11, it becomes apparent that the geometry subjected to the AM process displays a significantly broader distribution of stress fields. This observation can be directly attributed to the occurrence of thermal cycles during the fabrication process, resulting in the generation of residual stresses within the geometry. Consequently, the affected regions are more susceptible to deformations and failures due to the presence of elevated stress levels. In order to further assess the performance of these two components, the maximum energy versus displacement relationship is evaluated and presented in Figure 12.

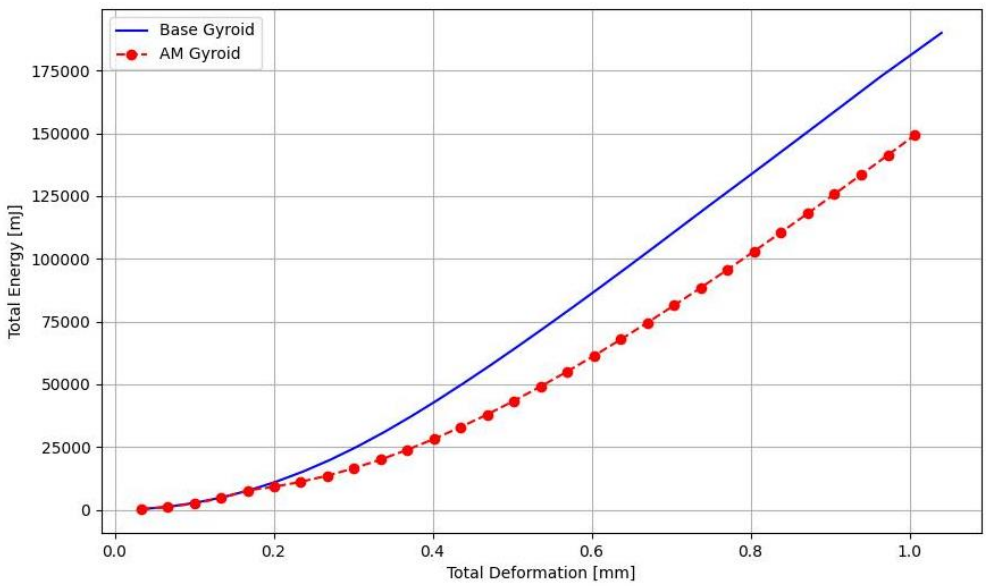


Figure 12. Comparative between base and AM Gyroid of maximum energy absorption

4. Conclusions

The present study aimed to characterize the processing of gyroid-type geometries when subjected to the SLM manufacturing process. The complex nature of these geometries, combined with the absence of external walls in their modeling, led to observed dimensional instabilities during the simulations.

The investigation addressed several challenges, including geometry creation, processing considerations, and the application of appropriate boundary conditions for the AM process. The utilization of nonlinear materials and the SLM manufacturing process provided valuable insights and constituted a significant contribution to this research.

The exploration of printing parameters played a critical role in obtaining initial reference results for the processing of the selected material. Optimized power and speed settings were identified to enhance the strength and reliability of the AM process, minimizing failures and defects in the fabricated geometry.

Furthermore, the study focused on analyzing deformations resulting from the interaction between the laser and the material. This investigation provided valuable insights into dimensional distortions that can affect the performance and manufacturing of geometries using the AM process. Based on the collected data, support structures were strategically implemented at the model's edges to mitigate warping effects and improve the convergence of numerical results.

In conclusion, the proposed analysis methodology yielded satisfactory results by quantifying the impact of the AM process on the manufactured geometries. The study and analysis of the results enable the prediction of behavioral patterns and potential issues arising from the specific manufacturing method employed. These findings hold significant importance in the production of parts using the SLM process, considering the associated high manufacturing costs.

5. Acknowledgments

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6. References

AMFG. (2019). A Guide to 3D Printing With Titanium. Available at: https://amfg.ai/2019/06/18/titanium-3d-printing-guide/#.

Ansys. (2021). ANSYS engineering analysis system user's manual 2021.

Bourell, D. L., Beaman, J. J., Leub, M. C., & Rosenc, D. W. (n.d.). History of Additive Manufacturing and the 2009 Roadmap for Additive Manufacturing: Looking Back and Looking Ahead.

Procedia Manufacturing, 41, 193–199. doi: 10.1016/j.promfg.2019.07.046

Gibson, L. J., & Ashby, M. F. (1997). Cellular Solids: Structure and Properties. 2nd ed. Cambridge University Press. doi: 10.1017/CBO9781139878326

HYDE, S., NINHAM, B. W., ANDERSSON, S., LARSSON, K., LANDH, T., BLUM, Z., & LIDIN, S. (1997). The Mathematics of Curvature. The Language of Shape, 1–42. doi: 10.1016/B978-044481538-5/50002-2

Kapfer, S. C., Hyde, S. T., Mecke, K., Arns, C. H., & Schröder-Turk, G. E. (2011). Minimal surface scaffold designs for tissue engineering. Biomaterials, 32(29), 6875–6882. doi: 10.1016/j.biomaterials.2011.06.012

Khaderi, S. N., Deshpande, V. S., & Fleck, N. A. (2014). The stiffness and strength of the gyroid lattice. International Journal of Solids and Structures, 51(23–24), 3866–3877. doi: 10.1016/j.ijsolstr.2014.06.024

Milewski, J. O. (2017). Additive Manufacturing of Metals: From Fundamental Technology to Rocket Nozzles, Medical Implants, and Custom Jewelry. Additive Manufacturing of Metals.

Schoen, A. H. (1970). Infinite periodic minimal surfaces without self-intersections.

Winter, B., Butz, B., Dieker, C., Schröder-Turk, G. E., Mecke, K., & Spiecker, E. (2015). Coexistence of both gyroid chiralities in individual butterfly wing scales of Callophrys rubi. Proceedings of the National Academy of Sciences, 112(42), 12911–12916. doi: 10.1073/pnas.1511354112

Xiao, B., & Zhang, Y. (2007). Laser sintering of metal powders on top of sintered layers under multiple-line laser scanning. Journal of Physics D: Applied Physics, 40(21), 6725–6734. doi: 10.1088/0022-3727/40/21/036

Yadroitsev, I., Ludovic, T., Bertrand, P., & Smurov, I. (2007). Strategy of manufacturing components with designed internal structure by selective laser melting of metallic powder. Applied Surface Science, 254, 980–983. doi: 10.1016/j.apsusc.2007.08.046

Yang Guang and Xie, Y., Z. S., R. Y., & W. C. (2022). Methods and Mechanism of Powder Mixing for Selective Laser Melting. Manufacturing Technology Journal, 22(1), 102–110. doi: 10.21062/mft.2022.006