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Industrial Engineering

PhD THESIS

– ABSTRACT –

Research on developing novel tree-like fractals for metal parts made by LPBF

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Introduction

Additive Manufacturing (AM), also widely known as 3D printing, has evolved into a versatile manufacturing technology capable of producing complex geometries, lightweight structures, and customized parts. Among AM technologies, Selective Laser Melting (SLM), part of the Laser Powder Bed Fusion (LPBF) is one of the most widely used methods for manufacturing high-density, complex metal parts with internal structures. The most known and studied internal structures are the lattice structures, which have a unit cell, that repeats itself to fill up space. Similar to lattice, fractals have the property of space filling, but here the geometry is not only repeated, but is also infinitely scalable maintaining all the geometric characteristics. The paradigm of nature inspired elements in engineering is not novel. Indeed, most lattice structures are bioinspired (e.g., honeycomb), and the concept of biomimicry or biomimetic (where structures found in nature can be optimized and implemented in engineering applications) is well established even for SLM.

Fractals are structures found in nature, like fern leaves, snowflakes and blood vessels. Characteristics of fractals are the self-similar structures, the recurring geometry, the ability to scale the geometry infinity, and can be described by iterative functions. Most known fractals are Mandelbrot, Koch Snowflake, Hilbert Curve, Menger Sponge, Sierpinski Triangle and many others. Fractal structures have applications in computer graphics, imagine processing and analysis, medicine, art, telecommunications and many others.

The **Motivation and main objective** of this work is to **study the feasibility of tree-like fractals in SLM as internal structures**, by developing tools to study the tree-like fractals mechanical properties based on various parameters. This requires mathematical models and numerical algorithms that are used to create fractals and to populate CAD models with tree-like fractals. Furthermore, to determine the feasibility of tree-like fractals, experimental test are required to study their mechanical properties. CAD samples with fractals will be manufactured using SLM for the testing purposes. The material used will be tool steel. Laboratory experiments will be conducted on the manufactured samples to collect data that will be used to develop numerical models that can predict the relation between the fractal parameters (for which we have full control) and mechanical properties. This work represents a single building block in the study of tree-like fractals as internal structures in SLM, and a brief guideline will be developed for using tree-like fractals in SLM. With further work more properties of the tree-like fractals can be discovered, and the guideline may be expanded, which can become the basis of new techniques in generative design.

The following specific objectives are proposed to achieve the main objective:

O1: Research on the state-of-the-art of SLM and nature inspired elements.

O2: Development of a computational model for generating tree-like fractals and integrating the fractal structures into CAD models.

O3: Design and manufacture SLM samples, with different geometrical parameters. Preliminary tests of the new fractals structures behavior with the SLM parts.

O4: Determination of tree-like fractals mechanical properties using Finite Element Analysis and laboratory experiments.

O5: Validation of the tree-like fractals in SLM manufacturing and proposing feasible applications.

State of the art on the internal structures within the SLM parts

Additive Manufacturing (AM) has evolved significantly, offering new possibilities for rapid prototyping and industrial production. One of the most mature metal AM techniques is Selective Laser Melting (SLM) — a powder bed fusion process that uses a high-power laser to melt and fuse metal powders layer by layer. This method allows for the creation of parts with complex internal geometries and near-full density comparable to cast parts [1, 4].

The process starts with a 3D CAD model that is sliced into layers and translated into a .STL file. The printer spreads metal powder on a build platform; the laser selectively melts powder according to each layer's design. After each layer, the build platform lowers, and a new powder layer is spread. Inert gases like argon create a safe, oxidation-free atmosphere. Once printing is complete, the part undergoes post-processing steps, including removal of support structures, heat treatment, and surface finishing [1, 9]. Process parameters, such as laser power, scanning speed, layer thickness, and hatching strategy, are important to the final part's quality. Improper parameters can result in defects like porosity or residual stresses [4, 9]. SLM can process a wide range of materials: titanium alloys (e.g., Ti6Al4V), steels (e.g., 1.2709 tool steel, stainless steel 316L), aluminium alloys, nickel alloys, and even ceramics [22, 24]. Multi-material printing is also possible but remains complex [4].
Applications include aerospace (lightweight structures like turbine blades), automotive, medicine (implants, scaffolds), heat exchangers, cutting tools, and molds with conformal cooling channels [3, 15, 16].

The main advantage of SLM is the ability to manufacture parts with internal lattice structures, which reduce weight while maintaining strength. They enable better energy absorption, thermal management, and mechanical performance [3, 5, 41]. Researchers optimize lattice topologies through topology optimization and study the impact of unit cell type, strut thickness, and geometry [25, 27].

Nature-inspired designs are widely studied in AM. Examples include beetle shell-inspired hyperboloid lattices, bamboo biomorphic structures for energy absorption, and diatom or glass sponge structures for high surface-area applications [27, 28, 49]. These bio-inspired solutions combine strength with lightweight efficiency, vital for aerospace and medical uses [15]. Fractals are complex, self-similar patterns found in nature and are also explored in AM. Fractal geometries like Hilbert curves, Koch curves, and Menger sponges have been used as infill structures or scan strategies to reduce residual stress and porosity [35, 36]. Tree-like fractals are mainly used as support structures rather than internal structures; they can minimize material usage and post-processing efforts [31, 32, 62].

Current algorithms for generating tree-like fractals often rely on L-systems, Iterative Function Systems, or genetic algorithms to optimize geometry for overhang support. Yet, applying these fractal concepts as internal structures in metal AM remains an underexplored area, offering potential for future research [60, 63].

Tree-like fractals as internal structures in metal AM represent a novel frontier that requires the development of new mathematical models and algorithms to fully realize their benefits. Continued research on mechanical properties, structural performance, and practical applications is needed to expand the use of fractals beyond supports and into fully integrated functional designs.

Computational Model for Tree-Like Fractal Structures in Additive Manufacturing

The presented section introduces a novel computational model designed for generating and integrating tree-like fractal structures as internal infill within mechanical parts produced by additive manufacturing, with a particular focus on Selective Laser Melting (SLM). Unlike conventional lattice structures commonly used in metal additive manufacturing, fractals offer an innovative design strategy inspired by natural forms such as trees, vascular systems, or root networks. This bio-inspired approach enables complex space-filling geometries that can simultaneously reduce weight and maintain or even enhance mechanical performance.

The computational model described in this section is rooted in mathematical foundations. Homogeneous transformation matrices, which are standard in rigid body kinematics and robotics, form the base of the fractal generation process. Each node and branch within a fractal structure is precisely defined using transformations that combine rotations and translations. The model outlines a clear parent–child relationship between nodes, ensuring that every branch direction, length, and orientation is computed in a consistent, repeatable manner. This mathematical rigor allows the fractal structures to be scalable, flexible, and highly customizable.

The data of each fractal is represented in clear tabular form. Each node's position, the corresponding angles, and lengths are stored in a structured format, making it straightforward to implement the entire algorithm in programming environments that support vectorized operations, such as Matlab or Python. The process begins by defining the input parameters, including the origin of the fractal, the branch angles, lengths, and the desired depth of recursion. Once the table is constructed, the nodes' coordinates are computed recursively. This systematic approach allows the designer to control whether the resulting fractal is symmetric or asymmetric, providing additional design freedom for tailoring the internal geometry to specific application needs.

Another feature of the computational model is its method for integrating fractal structures within existing CAD shells. Since fractals are inherently expansive, they must be trimmed to avoid extending beyond the boundaries of the part(figure 1). To achieve this, the model employs a surface–fractal intersection algorithm based on a widely used ray/triangle intersection method. This ensures that branches intersecting the shell surface are accurately identified and cut at the intersection points. The trimmed branches are then removed from further calculations to avoid artifacts or unwanted protrusions. This step guarantees that the resulting internal structure conforms precisely to the part's shape.

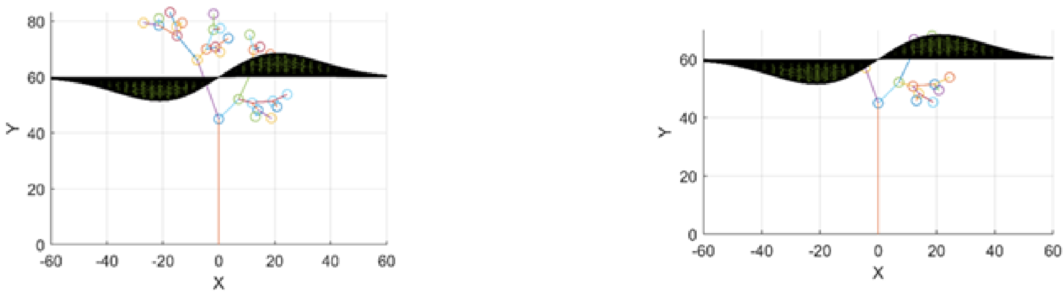
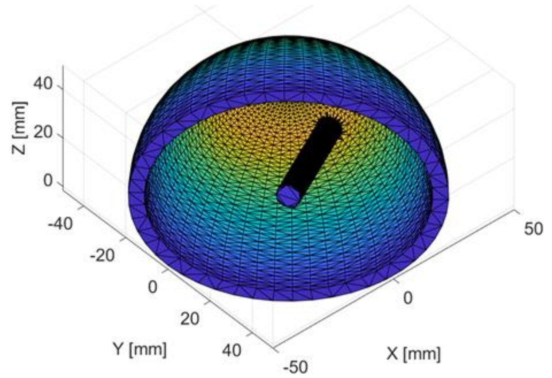


Figure 1. Trimmed fractal example

Beyond the fractal generation and trimming, the work details two robust strategies for converting the abstract branch and node data into manufacturable 3D volumes. The first approach, the geometric computational method (figure 2), operates directly on surface meshes. It constructs each branch as a cylinder, stitches intersecting branches together at nodes, and merges the entire fractal structure with the shell mesh. The second approach, referred to as the CAD method, uses CAD software tools to generate each branch as a cylinder, rotate and translate it into the correct position, and then merge it with the shell model. Trimming can be done using the negative of the CAD shell as a cutting tool.



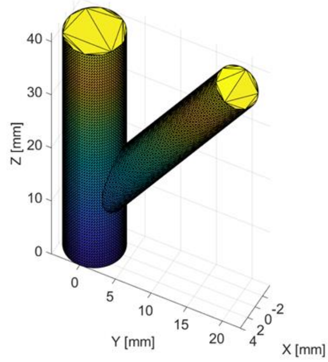


Figure 2. Geometric computational model

The practicality of the proposed computational model was demonstrated through several case studies (figure 3). One example involved a planar plate combined with a curved surface shell, which was filled with four distinct fractal structures. Each fractal was defined by unique input parameters, such as varying branch lengths, angles, and depth levels, highlighting the system's ability to handle complex, multi-origin geometries. Another illustrative case study featured a double hemispherical shell populated with twenty-four tree-like fractals. This example underscored the computational model's scalability and its capacity to adapt to organically shaped cavities, typical of biomedical applications or lightweight aerospace components. Furthermore, simple test samples designed for mechanical experiments are presented. This included compression and bending specimens where planar parts were connected by multiple fractal structures.

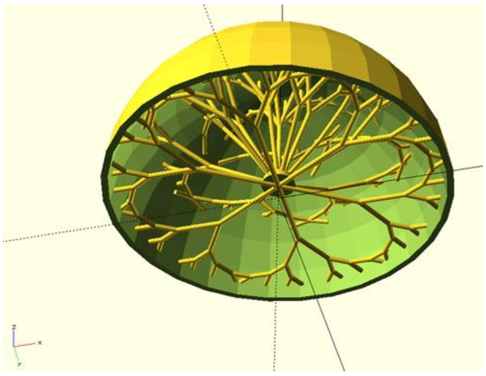
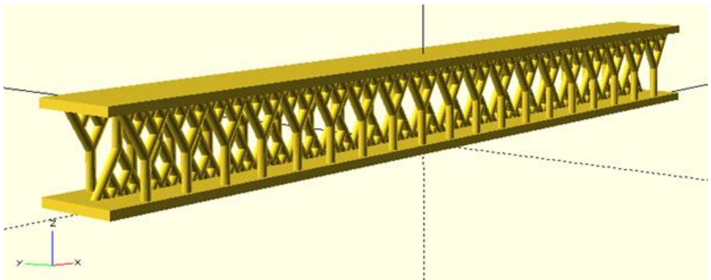



Figure 3. Case studies

In conclusion, the computational model for tree-like fractal structures represents an important step forward in the design of internal structures for metal additive manufacturing.

It combines mathematical precision with practical implementation strategies, ensuring that the resulting infills are manufacturable, structurally coherent, and tailored to the designer's specifications. The recursive nature of fractals makes them particularly well-suited for multi-scale designs, which can be exploited to improve stiffness-to-weight ratios, energy absorption, and even thermal management in metal parts.

Experimental Research on Testing and Producing SLM Parts with Embedded Fractal Structures

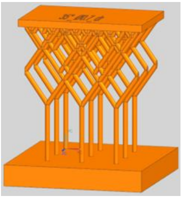
In this section all details about the experimental testing of tree-like fractals, including manufacturing and simulations are presented. Beside this, a prediction model is provided and also a comparation to the well known lattice structures is made.

The first step was the CAD design of test specimens, using Siemens NX software, and parametric fractal geometries are developed, that can be easily modified by adjusting parameters like: the branch length, branching angles (denoted α), and branch diameter. This parametric flexibility ensured that multiple configurations could be tested without rebuilding models from scratch.

To determine printability and structural robustness, samples were initially created with varying branch diameters: Ø0.5 mm, Ø0.7 mm, and Ø1 mm. Observations during preliminary tests demonstrated that branches thinner than 0.7 mm tended to deform due to thermal stresses during printing, while thicker branches provided better stability but added unnecessary weight. The diameter of Ø0.7 mm was chosen as the optimal compromise for the following samples.

Different samples were designed to explore how fractals perform under compression (figure 4), bending (figure 5), and tensile loads(Figure 6). Two configurations, denoted S and SJ (with angle α=35°), were studied — with SJ differing by having alternating rows of fractals inverted upside down to study orientation effects on buckling behavior. Bending samples were more elaborate, containing up to 57 fractals arranged in three rows within a slender plate structure. By varying the angle α (from 25° to 45°), the research systematically investigated how geometry affects flexural performance. For tensile tests, the samples contain two rows of fractals were designed: one configuration had all fractals aligned identically, while the other inverted every other fractal in the row.

For comparation for flexural tests, specimens containing conventional lattice structures were designed with similar strut diameters and unit cell sizes, ensuring fair comparison with the fractal infill.



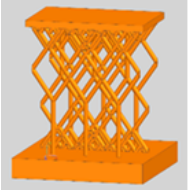
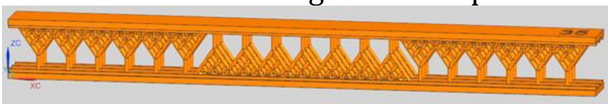


Figure 4. Compression sample S and SJ, CAD models



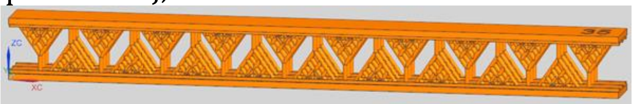


Figure 5. Bending sample S and SJ, CAD models

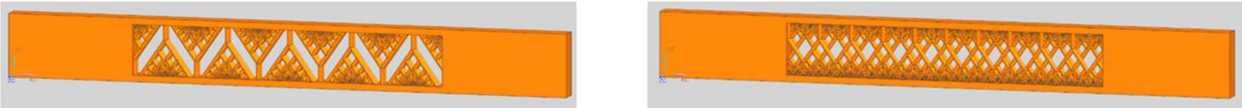


Figure 6. Traction sample SJ and SJ-1, CAD models

All samples were produced on a Renishaw AM400 SLM system, using maraging tool steel 1.2709 (M300). This high-strength steel is well-suited for tooling inserts and structural parts requiring excellent tensile and yield properties. The process parameters included a laser power of 200 W, a scan speed up to 2 m/s, and a layer thickness of 40 µm. Special attention was given to the build orientation and support structures, particularly since overhanging branches in fractals pose challenges for heat dissipation and dimensional stability. After printing, supports were removed either manually or using Electrical Discharge Machining (EDM), followed by light surface polishing. Notably, no heat treatments were applied, which means the results reflect the as-built material condition.

Finite Element Analysis (FEA) was conducted in ANSYS to simulate the mechanical response of the samples with tree-like fractal infill. Simulations used elastic material properties adjusted for potential print defects, which can locally reduce the effective Young's Modulus of the fractal regions compared to bulk material. Boundary conditions were tailored to mimic real test setups: for compression, a force was applied to the top plate; for bending, a three-point bending fixture was replicated; and for tensile tests, clamped ends pulled the sample until failure. Calibration runs ensured that simulation results matched experimental data within a relative error margin below 10%, providing confidence in the numerical predictions.

The experimental tests were carried out on Instron universal testing machines. For compression, the SJ configuration generally resisted higher compressive loads than the uniformly oriented S samples, demonstrating how orientation affects load paths and buckling (figure 7).

In bending, results revealed that the angle parameter α plays a crucial role: as α increased, the force–displacement curves changed systematically, confirming a causal relationship between fractal geometry and flexural behavior (figure 8). While the S configuration resisted to higher peak loads, it was more prone to local fractures at weak points, which were visible as spikes in stress–strain curves. By contrast, the SJ configuration deformed more uniformly, indicating a more distributed load transfer.

For tensile tests, the orientation also influenced the results. Samples with alternating fractal orientation achieved higher ultimate loads and delayed fracture initiation, suggesting that fractal arrangement can tune ductility (figure 9).

Figure 7. Samples S and SJ after compression

Figure 8. Sample SJ and S, after bending

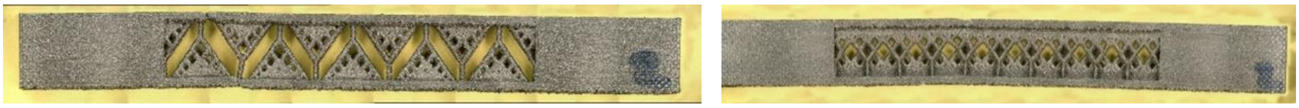


Figure 9. Sample SJ and SJ-1, after traction

A comparation between tree-like fractals and lattice structures was made based on bending tests. While lattice structures showed higher overall strength, they exhibited local deformations concentrated near the point of force application. But, the tree-like fractal structures deformed more globally, maintaining the parallelism of the enclosing plates and distributing energy more evenly. Figure 10 highlight this difference.

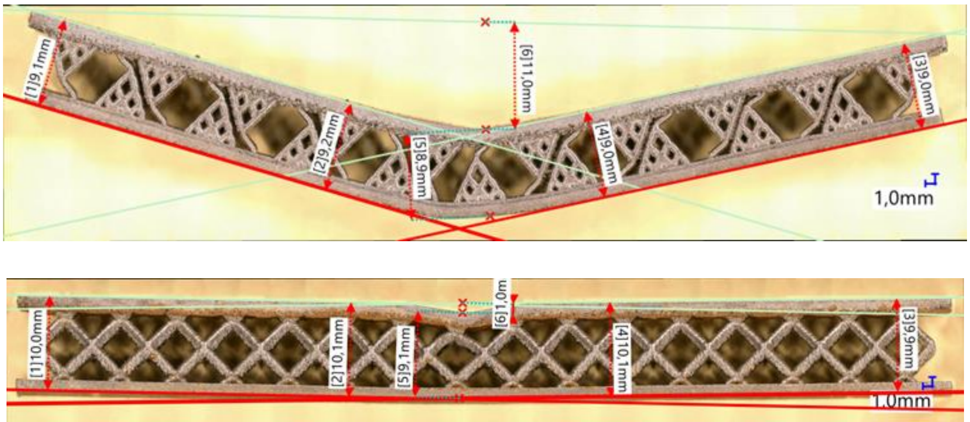


Figure 10. Difference between tree-like fractal structure and lattice structure after bending

Although the absolute strength of lattice structures remained superior, the more uniform deformation of fractals suggests promising applications for energy absorption, such as protective gear or crash-impact zones.

Building on the consistent relationship observed between the branch angle α and mechanical response, a numerical regression model to predict stress–strain curves for bending tests is proposed. This model is based on polynomial fitting, achieved high statistical accuracy (R^2 values close to 1). Validation with additional samples confirmed its reliability, with prediction errors falling within the natural experimental variability (figure 11).

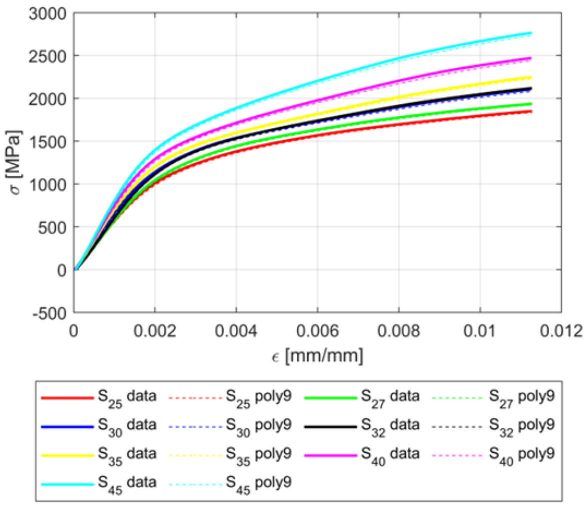


Figure 11. Comparation between the computed model and the experimental data, for S samples

Such a predictive tool allows engineers to tailor internal fractal geometries for specific flexural performance requirements without relying solely on costly trial-and-error testing.

Case studies for the proposed methods

Two case studies were chosen as possible applications of parts containing tree-like fractal structures as internal structures. Afterwards, a short guideline is described on how to choose and apply the new developed tree-like fractals.

The first case study is the use of tree-like fractal structures within a shrink fit chuck, figure 12. The main goal of this design experiment is to demonstrate how fractal geometries can be used to reduce the weight of a solid metallic chuck while maintaining mechanical and dynamic performance requirements. A simplified CAD model of the chuck was designed with an internal cavity that will be filled with the fractal structures. This cavity has walls of 1 mm thickness to ensure structural integrity, and the cavity was included only in the region that supports the cutting tool.

The tree-like fractals were designed as paired structures, mirrored to their origin points. This mirrored arrangement helps maintain balance within the rotating chuck and ensures that the fractal crowns reach and intersect both the conical outer walls and the cylindrical surface. In total, ten main fractal layers were created, each progressively stepping from the base of the cone towards the top. Within each layer, the fractal depth was defined to be four levels deep, allowing the branches to spread and overlap in a controlled manner.

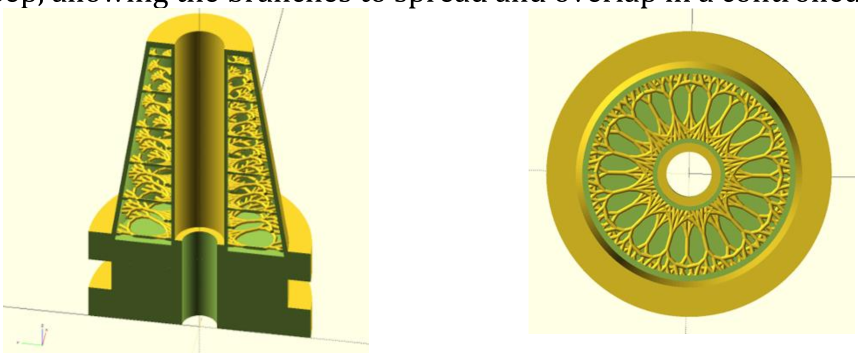


Figure 12. Section of the shrink fit chuck with tree-like fractal infill

In section views, the fractals can be seen intersecting the conical walls, the cylindrical mounting area, and each other within the same layer, creating a dense but well-distributed structure.

Despite its technical promise, this design remains conceptual and was not manufactured. It is important to know that producing a shrink fit chuck with internal fractals would require careful attention to additive manufacturing design rules and functional testing under real tool-holding conditions.

The second case study focuses on the design of a safety helmet that contains tree-like fractals for energy absorption (figure 13). The helmet must achieve a careful balance between strength and controlled crushability, ensuring it can absorb impact energy effectively while protecting the wearer's head.

For this application, the roots of each tree-like fractal are positioned along the inner hemisphere of the helmet shell, while the crowns grow outward, filling the cavity and intersecting the outer surface. Sixteen main layers were used, forming concentric "crowns" that extend from the base of the hemisphere to its pole. The fractal depth was set at four levels, and the branch angles were chosen to achieve a balanced spread. The helmet's fractals maintain the same branch lengths across layers to provide a more uniform distribution of material for impact absorption.

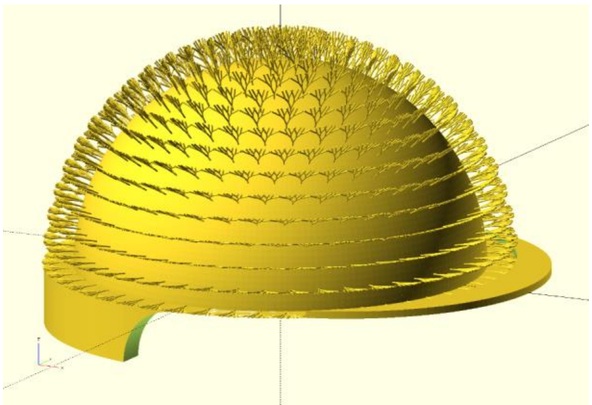


Figure 13. Helmet with tree-like fractals

The final CAD model shows the helmet without the outer shell to reveal the intricate network of fractals arranged in layered crowns. This configuration illustrates how tree-like fractals could provide a hierarchical structure for dissipating impact forces, spreading the energy across multiple levels rather than concentrating it at discrete points.

The helmet concept was not physically manufactured for testing within this study. The authors acknowledge that, although the internal fractals help reduce weight and may improve impact performance, a metal AM helmet could still be heavier than conventional polymer-based helmets. Furthermore, extensive impact and shock absorption testing would be necessary to validate whether tree-like fractals truly offer performance advantages over other infill structures like foams or standard lattices.

Following, an initial guideline based on the preliminary characterization of fractal behavior presented in this research is proposed. Still, more research needs to be done to fully understand the tree-like fractals behaviour under different conditions.

The geometrical parameters of the fractal must be chosen carefully to align with the intended function and the desired mechanical performance of the final part. For example, the branch angle plays a significant role in how the fractal expands inside the part: a smaller branching angle allows the fractal to reach the shell surface more quickly but may cover less of the inner surface, while a larger angle can help fill the part more uniformly and create a denser, more supportive structure. Similarly, branch length must balance reach and compactness. Longer branches can intersect the shell faster but risk extending beyond the intended boundaries, whereas shorter branches require additional levels to fill the space effectively, and can result in a denser structure.

The thickness of the struts or branches is equally important. It must be within the capabilities of the SLM process to avoid print defects like unintended bending during fabrication. Based on this research, a minimum branch diameter of about 0.7 mm is recommended, as thinner branches were shown to deform or fail to print properly. This parameter must be adjusted to match the material and printer used, as well as the part's functional requirements.

The density and orientations of fractal internal structures play also an important role: Higher density can enhance strength and stiffness but may increase the overall weight. An optimal balance must be found based on the chosen application. The orientation and placement of each fractal tree within a part can be controlled by the computational model; each fractal can have its own unique origin and direction, which provides design freedom but requires careful planning to avoid manufacturing issues such as unsupported overhangs.

Finite Element Analysis (FEA) can help predict stress distribution and identify weak points, but it remains limited, especially when trying to simulate the complex interactions that occur during the SLM process. As shown in this research, simulation results align with experimental outcomes primarily within the linear elastic range but can diverge under more complex conditions. Therefore, experimental testing remains essential to accurately assess how fractal geometries behave under real mechanical loads. The bending tests conducted in this study demonstrated, for instance, that smaller branching angles tend to bend more easily, while wider angles can sustain higher loads before deforming.

In terms of materials and process parameters, the guideline remains flexible. In this study only tool steel 1.2709 was used, due to availability and its known performance in SLM. Post-processing methods, support removal, and building orientations should also be determined based on the specific material properties and the intended function of the final part. The initial tests and prediction model developed in this research provide a starting point for such adjustments.

Conclusions and contributions

The main objective of the thesis, to study the feasibility of introducing fractal structures as internal structures in parts manufactured by Selective Laser Melting for different applications, was achieved through the completion of the specific objectives. The following conclusions were found after doing the research for each objective:

O1: Research on the state-of-the-art of SLM and nature inspired elements.

- Fractals are natural elements that are often used in AM for their space filling properties. Tree-like fractals are used in SLM manufacturing, but only as support structures. The design of the tree-like fractals is limited by geometric parameters and their generations starts from the part overhang to the bottom.
- The research on the state of the art regarding the applicability of fractals in AM, with focus on SLM leads to the gap, that tree-like fractals are not used as internal structures for SLM parts and a new algorithm for their generation is necessary. Besides this, also studies on their mechanical behavior are necessary.

O2: Development of a computational model for generating tree-like fractals and integrating the fractal structures into CAD models.

- A computational model was developed to generate tree-like fractal structures (as internal structures for SLM parts).
- The computational method is easily scalable and offers flexibility on the geometric parameters: origin of the fractal, number of levels, length and diameters of the branches (on each level), and angles between the branches.
- Two ways to generate the tree-like fractals (in 3D) were defined, a geometric method (computes parts from intersection of surfaces) and a CAD method (computes parts using standard CAD tools).

O3: Design and manufacture SLM samples, with different geometrical parameters. Preliminary tests of the new fractal structures behavior with the SLM parts.

- Samples were designed for three mechanical tests: compression, bending, and traction. For each test two configurations (S and SJ) of the tree-like fractals arrangement were chosen, and for the bending tests each configuration had a variation of the geometric parameter angle between two branches.
- The samples were manufactured by the SLM printer Renishaw AM400, from tool steel 1.2709, in three specimens.The appropriate strut diameter for this study was found to be 0.7 mm (a strut diameter of 0.5 mm is already deformed from the printing process).
- The compression experiments showed that the tree-like fractal can reach a force between 1200 and 1600 N, depending on the configurations.The tensile testing was not concluding and showed that the design and fractal arrangement affected the results. For samples SJ a force of 7000 N was necessary, while for SJ-1 the force was almost doubled. The bending samples had a uniform behavior and could resist more than 1300 N. The bending samples were selected to be used for more detailed research.
- Form all the preliminary mechanical tests, it could be concluded that the fractal geometry, arrangement/configuration has an influence on the mechanical properties.

O4: Determination of tree-like fractals mechanical properties using Finite Element Analysis and laboratory experiments.

- The preliminary study was made only on the samples with the parameter angle of α = 35°, with two geometrical configurations. Compression, bending and traction tests were conducted in laboratory but also using FEA.
- The laboratory experiments and the FEA analysis suggested that the geometric parameters of the tree-like fractals influence the mechanical behavior of tested samples.
- The bending tests were expanded and samples with configuration S and SJ, the parameter angle α, 25°, 27°, 30°, 32°, 35°, 40° and 45° were manufactured and studied. The mechanical properties showed that the parameter angle has casual influence on mechanical strength; for both S and SJ configurations the increase of the angle α leads to the increase of the stress-strain ratio.

O5: Validation of the tree-like fractals in SLM manufacturing and proposing feasible applications.

- A numerical model was made using polynomial regression to describe the stress-strain curves from the experimental data. The numerical model accurately describes the data with errors between 2.5% and 5.7% (depending on the sample), which is lower than the natural variability between each set of three experiments (per sample).
- A comparation between tree-like fractal structures and lattice structures was made, using the mechanical properties from bending experiments. Fractals structures have better deformability and can have potential for impact absorption. The lattice structures though had better mechanical strength.
- The behavior of the tree-like fractals can be used for application in safety, but also to fill cavities. Two case studies were proposed, where the whole methodology for introducing the tree-like fractals into the pars was explained.

To achieve the main objectives of the thesis, following personal contributions were made:

- Consistent literature review on internal structures used in metal parts made by SLM. Extended research on the state of the art, regarding structures inspired by nature and fractal structures applied in additive manufacturing.
- Development of a computational model for generating tree-like fractals based on homogeneous transformation matrices with predefined input parameters for the fractal geometry.
- Development of algorithms to generate tree-like fractal structures for CAD components by considering volume, fractal shapes, and intersections.
- Design of various samples in CAD environments (NX and Matlab) with different geometrical parameters for the tree-like fractal structures, based on the computational models.
- The designed samples with internal tree-like fractals were simulated using Finite Element Analysis.
- The samples were manufactured, and laboratory experiments were conducted for compression, bending, and traction to determine the mechanical properties of the components.
- A numerical model to predict the mechanical behavior of parts containing tree-like fractals, was developed based on the stress-strain curves of the bending experiments.
- A comparation between lattice structures and the new tree-like fractal internal structures was made.

- The methodology to implement and customize the fractal structures into parts, summarized into a flowchart.
- Two case studies were proposed as applications for tree-like fractal internal structures.
- Guideline for choosing the appropriate tree-like fractals for applications, based on parameters and characteristics of tree-like fractals.

The following research results were disseminated (3 journal papers, 2 conference presentations, 2 poster presentations):

- Computational Model for Tree-like Fractals Used as Internal Structures for Additive Manufacturing Parts, published in Applied Scienced (ISI Q1);
- Analysis of the Mechanical Behavior of Tree-like Fractal Structures in SLM-Manufactured Components, published in Materials (ISI Q2);
- Mechanical properties evaluation of the samples made by SLM, with tree-like fractals internal structure published in Acta Technica Napocensis and presented at the MTeM conference in Cluj Napoca, 2023;
- Tree-Like Fractal Structures Modeling and Their Application in 3D Printed Bones, presented at MESROB conference in Craiova, 2023;
- Geometrie de tip fractal in piesele fabricate prin SLM, presented as a poster at the International Fair ICE-USV Suceava, 2022;
- Research on improving the internal structures for metal parts made by SLM, presented as a poster at the Research and Innovation conference UTCN, Cluj-Napoca, 2025.

This thesis marks only an initial step in exploring tree-like fractals as internal structures for SLM metal parts. More research is needed to fully understand their mechanical behavior for different geometries and shapes, and to improve numerical models and simulations. In the future, fractal generation could even be automated for generative design based on desired properties. Possible future applications include porous medical implants, impact absorption, and controlled deformability, with more uses likely to emerge as their mechanical performance becomes better understood.

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