Topology Optimization of High-Power Electronics Enclosures using Generative Design & Additive Manufacturing

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I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

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Abstract

The development of electronic devices towards high performance and miniaturization has led to an increase in the heat dissipation problem. Traditional air-cooling methods are no longer sufficient to meet the high-density heat dissipation requirements. The thermal design optimization of heat sinks is necessary to minimize size and weight and improve heat removal, which can increase the speed of electronic devices. The use of sophisticated technology and proper design of heat sinks is crucial to avoid overheating and damage to electronic components. Porous metal has been shown to enhance forced convection heat transfer for better heat removal. However, the high-pressure drop associated with porous medium also needs to be considered in the design. The effective thermal management of heat sinks is a priority concern for researchers as overheating can threaten chip reliability and lifespan. The average heat flux of chips has increased from 50 W/cm2 in 2010 to 250 W/cm2 in 2012, which highlights the importance of effective thermal management. In addition, the use of micro-channel compact heat exchangers and flow boiling in mini- and micro channels have been suggested as effective cooling methods for high power density devices such as Micro Electromechanical Systems (MEMS), microprocessors, laser diode arrays and Light Emitting Diodes (LEDs). In this study, we will be investigating the effect of non-traditional geometries of heat-sinks for high power electronics used in aerospace applications.

Key Words: *High Performance Heat-sink, Topology Optimization, Non-linear Geometries*

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Chapter 1: Introduction

The contents of this dissertation are structured into six chapters. The introductory chapter provides an overview of the subject matter, along with background information and a review of relevant literature. Chapter two delves into the research methodology. In chapter three, we explore the topic of Topology Optimization of Heat Sinks, while chapter four examines the practical applications and uses of Triply Periodic Minimal Surfaces (TPMS). Chapter five is dedicated to the discussion of thermal analysis, and, lastly, chapter six is devoted to presenting the research findings and drawing conclusions.

1.1 Background, Scope and Motivation

In the realm of electronics, efficient thermal management is a pivotal consideration to ensure optimal performance, reliability, and longevity of components. Heat sinks play a vital role in dissipating excess heat generated by electronic devices, preventing potential thermal-induced failures. While forced convection methods, often involving fans or pumps, have been widely employed for this purpose, natural convection offers an alternative approach with unique advantages.

The scope of this study delves into the utilization of heat sinks for cooling electronics through natural convection. Natural convection relies on the innate movement of fluids due to temperature gradients, eliminating the need for external air circulation devices. The primary focus is on investigating the effectiveness of heat sink designs in enhancing heat dissipation solely through the principles of buoyancy-driven flow.

Motivating this research is the increasing demand for energy-efficient and reliable cooling solutions in scenarios where forced convection methods are impractical. In hermetically sealed equipment, such as medical devices, aerospace components, or sensitive electronics, external airflow becomes challenging due to sealed enclosures. Traditional cooling techniques like forced convection become ineffective or even counterproductive in such environments, as they can compromise the integrity of the enclosure or introduce contaminants.

As a result, exploring natural convection-based heat sinks becomes imperative. Understanding how different heat sink geometries, materials, and configurations impact heat dissipation in these constrained environments is crucial. This study aims to uncover optimized designs that ensure effective cooling while adhering to the limitations of hermetically sealed enclosures. By addressing this gap in cooling technology, we not only enhance the efficiency of electronic devices but also contribute to the broader goals of sustainability, reliability, and innovation in various industries.

1.2 Topology Optimization, Additive Manufacturing, and TPMS: A Multifaceted Approach

1.2.1Topology Optimization

Topology optimization is a computational method used to determine the optimal material distribution within a given design space while satisfying specific performance criteria and minimizing material usage. In the context of high-power electronics enclosures, topology optimization can enhance structural integrity, thermal management, and overall efficiency.

1.2.2 Additive Manufacturing

Additive manufacturing encompasses a variety of technologies that construct objects layer by layer from 3D computer-aided design (CAD) models. It offers unprecedented design freedom, allowing the realization of complex geometries that were previously unattainable with traditional manufacturing methods.

1.2.3 Triply Periodic Minimal Surfaces

Triply Periodic Minimal Surfaces (TPMS) are mathematical surfaces that divide space into equal-sized cells with minimal surface area. TPMS structures exhibit excellent mechanical properties, including high stiffness and strength, making them suitable candidates for lightweight and structurally efficient designs [2].

1.3 Application of TPMS in High Power Electronics Enclosures

Triply Periodic Minimal Surfaces (TPMS) are mathematical surfaces that have unique properties [3] and are often used in various engineering and scientific applications. While they are not commonly associated with high-power electronics enclosures, there are some innovative ways they could be applied:

- **Heat Sink Design:**

High-power electronics generate a significant amount of heat that needs to be dissipated efficiently. TPMS structures can be used as the basis for designing intricate heat sinks with a large surface area. The complex, porous nature of TPMS can enhance heat transfer and cooling efficiency compared to traditional heat sink designs [4].

- **Electromagnetic Shielding**

TPMS structures can be used as a template for designing electromagnetic interference (EMI) shielding materials. The repeating, periodic nature of TPMS can help create materials with unique EMI shielding properties, making them suitable for use in high-power electronics enclosures to protect sensitive components from external electromagnetic interference.

- **Acoustic Insulation**

TPMS structures can also serve as a model for designing acoustic insulation materials. High-power electronics enclosures often produce noise and vibrations that need to be minimized. TPMS-based materials can be engineered to reduce noise transmission and vibration propagation, improving the overall acoustic performance of the enclosure.

- **Structural Reinforcement**

TPMS structures can be used to reinforce the structural integrity of high-power electronics enclosures. The repeating geometric patterns of TPMS can be integrated into the enclosure's design to add strength and rigidity, ensuring it can withstand mechanical stresses and environmental conditions.

- **Optical Enhancements**

In some specialized applications, high-power electronics enclosures may require optical elements, such as diffusers or lenses. TPMS surfaces can be adapted for optical purposes, creating unique light-diffusing or focusing structures that enhance the performance of optical components within the enclosure.

- **Fluid Dynamics Optimization**

High-power electronics enclosures often require efficient cooling systems to dissipate heat. TPMS structures can be used to design internal flow channels or fins that optimize fluid dynamics for cooling purposes. The geometric properties of TPMS can enhance heat transfer and reduce pressure drop in cooling systems.

- **Aesthetic Design**

While not directly related to functionality, TPMS patterns can be incorporated into the exterior design of high-power electronics enclosures for aesthetic purposes. The visually striking and unique patterns of TPMS can give the enclosure a distinctive and appealing appearance.

It's important to note that these applications may involve complex engineering and manufacturing processes to adapt TPMS structures to specific high-power electronics enclosure requirements. Additionally, the choice to incorporate TPMS elements should consider cost-effectiveness, performance, and any potential challenges related to fabrication and material selection.

Incorporating TPMS structures into high-power electronics enclosures can lead to innovative solutions that enhance their thermal, structural, acoustic, electromagnetic, and even aesthetic properties. However, it's essential to conduct thorough research and engineering analysis to ensure that these applications meet the desired performance criteria and constraints of the specific electronics enclosure.

1.4 Literature Review

Several studies have been conducted to improve the thermal performance of heat sinks for electronic devices by optimizing various parameters such as the number and thickness of fins, the length and height of fins, and the orientation of fins [5]. Additionally, the use of Nano-fluids and porous media has also been studied to enhance the heat transfer rate. The results of these studies have shown that by properly designing and optimizing the heat sinks, it is possible to improve the thermal performance while also reducing the size and weight of the heat sinks. Tari and Mehrtash [6] derived a set of correlations of Nu number (Nu) for both upward and downward natural convection from PFHS by using large sets of experimental data from the literature. Hassan [7] studied the natural convection heat transfer inside a horizontal and vertical enclosure HS having rectangular fins and filled with Cu–water Nano fluid. Aminossadati and Ghasemi [8] recorded an increase in the heat transfer rate of natural convection in a 2D square cavity filled with water–CuO Nano fluid by increasing Ra number and volume fraction. Shen et al. [9] found that intensive fin arrays were effectively affected by the orientation. Jang et al. [10] investigated the effect of the orientation on the natural convection and radiation for a cylindrical HS used to cool an LED light bulb.

Costa and Lopes [11] improved the thermal performance of the HS for a light emitting diodes (LED) lamp operating under natural convection conditions. They reported that the objective core temperature of 65 C was registered by increasing the number of fins and their height and reducing the fin thickness. Kim and Kim et al. [12] optimized the fin thickness of a vertical FPFHS under natural convection when the varying was in the direction normal to the fluid flow. Türkakar and Özyurt [13] optimized the thermal design of silicon MCHS of Intel Core i7-900 Desktop Processor having a heat dissipating of 130 W. Hung and Yan [14] varied the channel height- or width-tapered of MCHS numerically to improve the thermal performance. Reyes et al. [15] optimized the hydrothermal performance of MCHS using water by the implementation of tip clearance between the tip of fins and the upper cover of HS including different heights.

In summary, there has been a lot of research on the thermal design optimization of heat sinks to minimize size and weight and improve heat removal. Porous metal has been shown to enhance forced convection heat transfer for better heat removal, but the high-pressure drop associated with porous medium also needs to be considered in the design. The thermal design optimization of heat sinks with different configurations, the use of sophisticated technology and porous metal, and proper design of heat sinks are essential to minimize size, weight, and improve heat removal. It is also important to consider the high-pressure drop associated with porous medium in the design. The amalgamation of topology optimization, AM, and TPMS holds the promise of revolutionizing the design and manufacturing of high-power electronics enclosures [16]. By optimizing structural integrity, thermal management, and weight, engineers can create highly efficient and customized enclosures to meet the ever-evolving demands of modern industries. Continued research and development in this multidisciplinary field is poised to deliver increasingly innovative and practical solutions, propelling high-power electronics enclosure design into a new era of efficiency and performance.

Chapter 2: Methodology

Contrary to forced convection, the parameters and their optimization in natural convection is limited to the shape and the geometry of the heatsink. This study aims to investigate the effects of Topology Optimization of heatsink geometry, and to further increase the thermal performance of the heatsink; the effect of mapping TPMS (Triply Periodic Minimal Surface) on the optimized heatsink.

2.1 Methodology

The objective of this study is to enhance the heat conduction properties of a given structure. To achieve this goal, the Solid Isotropic Material with Penalization (SIMP) method is employed, enabling the discovery of an optimal design while considering material constraints.

The initial phase of this investigation relies on MATLAB, a powerful computational tool, to generate a detailed design for the project. Subsequently, this design is converted into a STEP file format, specifically tailored for representing complex 3D geometries.

The next step involves the utilization of NTop, a software platform that facilitates digital refinement and sculpting of the design, akin to an artist molding clay.

Additionally, a mathematical technique known as Triply Periodic Minimal Surfaces (TPMS) is implemented to introduce a complex pattern into the design. This pattern has the potential to significantly enhance the structure's heat-conduction characteristics.

Following these preparatory stages, computational mathematics are employed to conduct a thorough assessment of the structure's heat management performance. Parameters such as temperature distribution across the structure are meticulously examined. The results of these mathematical analyses are visually presented in Figure 1.

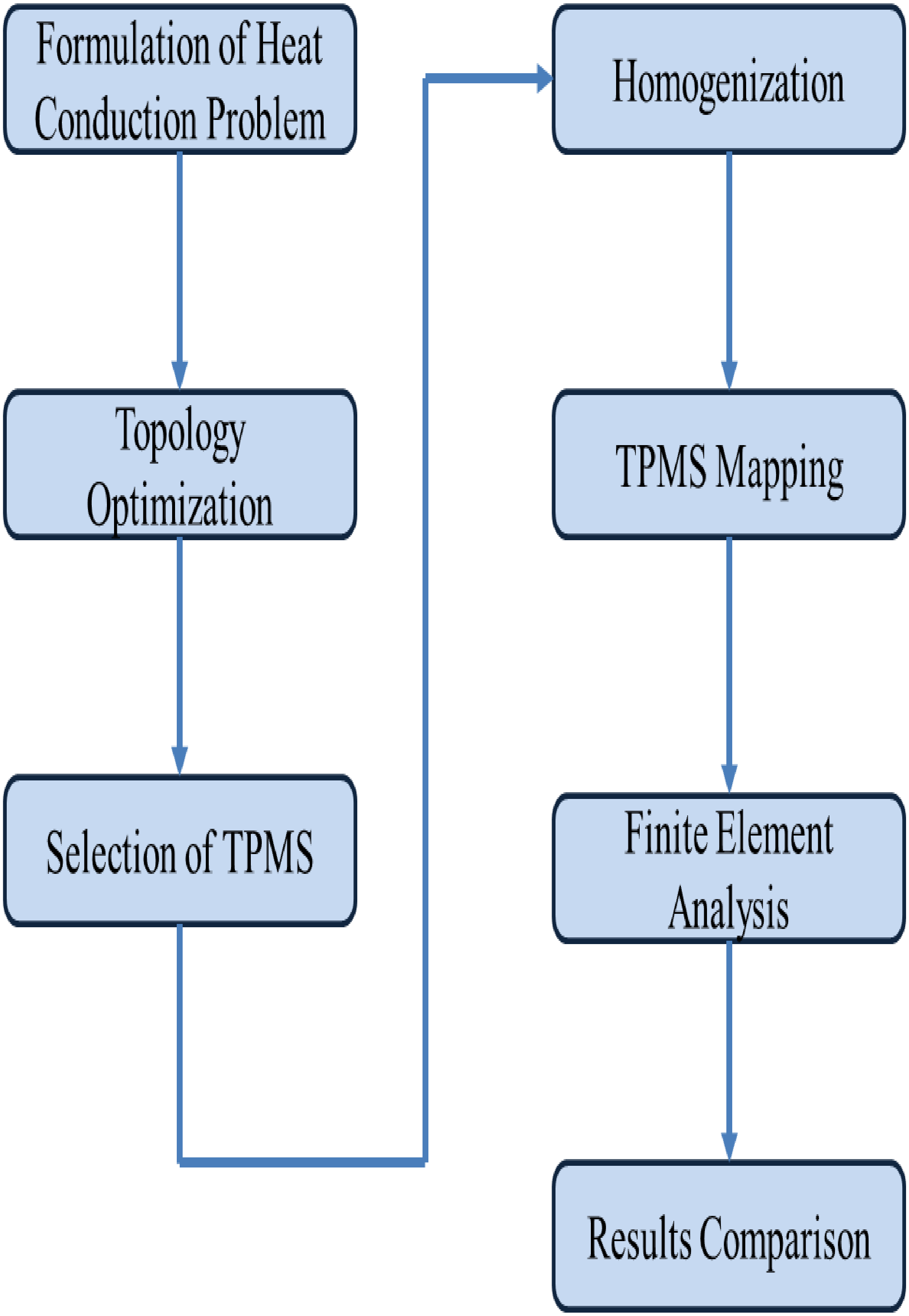

Figure 1 Methodology Flowchart

Chapter 3: Topology Optimization of Heat Sink

3.1 Topology Optimization

Topology optimization has emerged as a transformative tool in enhancing heatsink design [17]. By employing advanced computational algorithms, this technique refines the material distribution within heatsinks to achieve optimal heat dissipation. Topology optimization unveils intricate geometries that efficiently manage heat while ensuring structural integrity, leading to high-performance heatsinks that adapt to complex thermal challenges [18]. This approach has the potential to reshape the thermal management landscape across industries, addressing the growing demand for efficient and reliable cooling solutions in various electronic applications.

3.1.1 SIMP (Solid Isotropic Material with Penalization)

SIMP (Solid Isotropic Material with Penalization) is a widely used method in topology optimization for finding the optimal distribution of material within a given design domain [19]. The goal of SIMP topology optimization is to determine the most efficient layout of material to achieve a desired structural performance while minimizing the use of material.

3.1.1.1 Basic Principle

1. **Design Domain:**

   The process starts with defining a design domain, which is the region in which material can be distributed. This is often represented as a grid or mesh.

2. **Density Field:**

   SIMP uses a density field, represented by a scalar variable (often denoted as "rho"), to specify the material distribution in the design domain. A value of 0 indicates no material (void), while a value of 1 indicates solid material.

3. **Objective Function**:

   The objective in SIMP topology optimization is to find the optimal distribution of material that minimizes the compliance (often related to stiffness) while satisfying certain constraints. Mathematically, it can be stated as:

   Minimize:

   Min Objective Function = $\sum$ density × element stiffness

   This equation represents the trade-off between minimizing material (density) and minimizing deformation (stiffness).

4. **Constraints:**
   Constraints can be added to ensure that the optimized design meets specific requirements. These constraints could relate to stress limits, displacement limits, or volume fractions (the total volume of solid material in the design).

3.1.1.2 Penalization Technique

The "penalization" in SIMP refers to the way the optimization process penalizes intermediate density values.

1. **Element Stiffness:**
   The stiffness of each finite element in the mesh is calculated based on the density of the material within that element. This means that the stiffness of an element is directly proportional to the density.

2. **Exponent (p):**
   SIMP introduces an exponent (usually between 1 and 3) to control the penalization. This exponent (often denoted as "p") determines how strongly intermediate density values are penalized. Higher values of "p" lead to more binary (0 or 1) material distributions.

3. **Intermediate Densities:**
   During the optimization process, intermediate densities (between 0 and 1) are allowed. However, these intermediate densities are penalized in the objective function. The penalization factor is typically expressed as:

   Penalty = density ^{p}

   So, higher density values (closer to 1) are favored while lower density values (closer to 0) are discouraged.

4. **Density Update:**
   In each iteration of the optimization process, the density field is updated. Elements with low penalized densities tend to move toward 0 (void), while elements with high penalized densities tend to move toward 1 (solid).

3.1.2 Iterative Optimization

SIMP topology optimization is an iterative process. It starts with an initial density distribution and then iteratively updates the density field to minimize the objective function while respecting the constraints. Each iteration involves recalculating the stiffness, penalizing intermediate densities, and updating the density field [20]. Optimization continues until convergence is reached, where the final density field represents the optimized material distribution. The resulting design typically consists of a binary distribution of material (0 or 1), where the solid regions represent the optimal locations for material to achieve the desired structural performance [21].

In summary, SIMP topology optimization is a powerful technique for finding efficient material layouts within a design domain. It balances stiffness and material volume by penalizing intermediate densities, resulting in designs that are often characterized by a sparse distribution of material, making them lightweight and structurally efficient [22].

3.2 Formulation of Heat Conduction Problem

A homogenous design domain Ω is considered as shown in Fig. 2, with a fixed temperature $T = To$ applied at ΓTo. A surface heat flux $q.n = q^*$ is applied on the boundary $\Gamma q1$ with a unit normal vector n. The remaining boundaries $\Gamma q2$ are thermally insulated. It is noted that $\Gamma = \Gamma T0 \cup \Gamma q1 \cup \Gamma q2 \subset d\Omega$ and $\Gamma T0 \cap \Gamma q1 \cap \Gamma q2 = \emptyset$. Only steady state analysis is considered, and all materials are thermally isotropic. For steady-state heat conduction, the energy equation is simplified to:

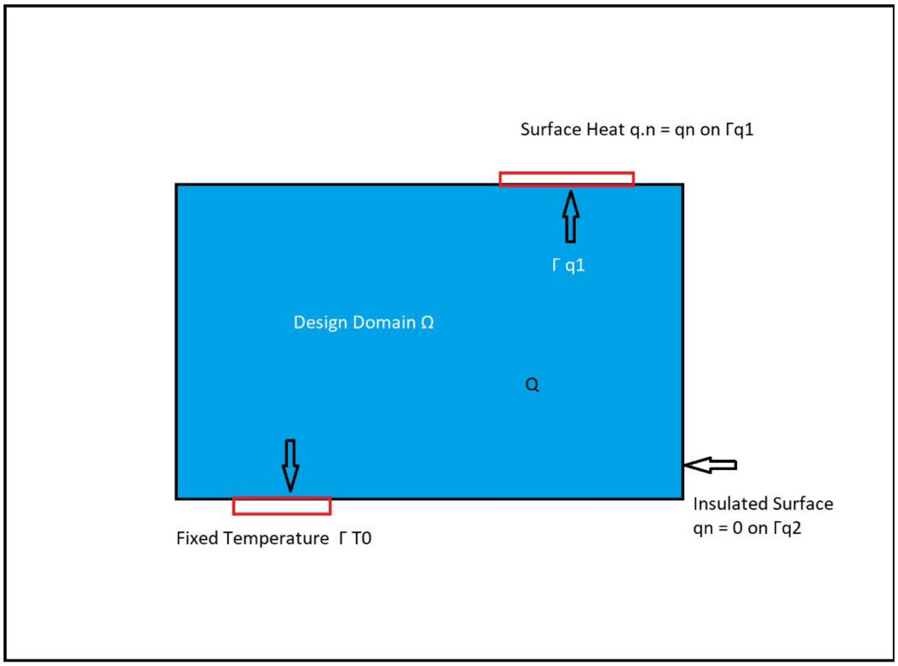

Figure 2 Formulation of Heat Conduction Problem

$$k\nabla^2 T+Q=0 \qquad (1a)$$

$$T = To \text{ on } \Gamma\ To \qquad (1b)$$

$$q.n = qn \text{ on } \Gamma q1 \qquad (1c)$$

$$qn = 0 \text{ on } \Gamma q2 \qquad (1d)$$

where, q is the heat flux that can be represented by Fourier's law of heat conduction. Where, T, Q, and k denote the temperature field (state variable), internal heat generation and thermal conductivity. Equation (1a) is referred to as Poisson's equation.

3.3 Optimization

The optimization of the heatsink in accordance with the Heat Conduction Problem, an opensource MATLAB code named Top3D [23] is used.

- **User Defined Parameters:**
    - **nelx, nely, nelz:** These parameters define the number of elements in the x, y, and z directions, respectively, to discretize the 3D design space. They determine the resolution of the optimization.
    - **volfrac:** This parameter represents the desired volume fraction of material in the design. It defines the amount of material that should occupy the design domain.
    - **penal:** The penal parameter is used in the SIMP (Solid Isotropic Material with Penalization) method, which controls the penalization of intermediate densities. It influences the distribution of material.
    - **rmin:** The rmin parameter sets the radius of the filter. It's used for sensitivity filtering and affects how design changes propagate through the structure.
- **User Defined Material Properties:**
    - **k0:** Represents the thermal conductivity of the material with good thermal properties.
    - **kmin:** Represents the thermal conductivity of the material with poor thermal properties.
- **User Defined Support Fixed DOFs:**
    - **il, jl, kl:** These arrays define the indices of elements that are fixed in the x, y, and z directions, respectively. In other words, these are regions where no material movement is allowed.
    - **fixedxy:** Calculates the fixed degrees of freedom (DOFs) in the x and y directions based on the provided indices.

  - **fixednid:** This variable calculates the fixed DOFs for the entire 3D design domain. It's a list of the DOFs that are fixed.

- **Finite Element Analysis:**

  The code prepares for finite element analysis (FEA) by defining key parameters.

  - **nele:** Represents the total number of elements in the 3D design space.
  - **ndof:** Represents the total number of degrees of freedom (DOFs) in the system.
  - **F:** Initializes a force vector, with a value of -0.01 at the first degree of freedom. This represents an applied load.
  - **U:** Initializes a displacement vector, which will be computed during FEA.
  - **freedofs:** Contains a list of DOFs that are not fixed, i.e., those that can move.

- **Filtering:**
  - The code prepares a filter for sensitivity filtering. Sensitivity filtering helps to smooth out the design changes during optimization.
  - **iH, jH,** and **sH** are arrays used to store filtering information.
  - A series of nested loops compute the filter values for each element and its neighbors based on the rmin parameter.

- **Initializing & Loop:**
  - The code initializes the design variable x with the desired volume fraction. This variable represents the distribution of material within the design space.
  - It enters an optimization loop with a specified maximum number of iterations (**maxloop**) and a termination criterion (**tolx**) to check for convergence.

Inside the loop:

- Finite element analysis (**FEA**) is performed to compute displacements (**U**) and the compliance of the structure (**ce**).

- Sensitivity analysis is performed to calculate gradients (dc and dv) that help in determining how design changes affect the compliance and volume.

- Sensitivities are filtered to reduce noise and improve optimization stability.

- The optimization algorithm (optimality criteria) updates the design variable x to achieve the desired volume fraction while minimizing compliance.

- Convergence is checked based on the change in design variables (change).

- Iteration information is printed, including iteration number, objective function value, volume fraction, and change in design.

- If specified (displayflag), a 3D visualization of the current material distribution is displayed.

- **Display Function:**
    - The code includes a display_3D function that generates a 3D visualization of the optimized material distribution.

    - It loops through the design domain and visualizes regions with material density greater than 0.5 as solid material.
    - The visualization provides an isometric view of the optimized design.

In the pursuit of optimizing complex structures using the provided MATLAB code for 3D topology optimization, a systematic approach was employed, necessitating the execution of multiple iterations and the careful selection of input parameters to attain the most favorable design outcomes.

The iterative process began with an initial exploration of the problem space. A baseline configuration was established by setting the parameters **nelx, nely, nelz, volfrac, penal,** and **rmin** based on engineering intuition and domain expertise. This initial guess served as a starting point for the optimization process.

A series of iterations were then systematically executed, with each iteration refining the material distribution to minimize compliance while adhering to predefined constraints. A crucial aspect of these iterations was the assessment of the convergence of the optimization process. Convergence criteria, typically based on the change in design variables or the attainment of a specific objective function value, were meticulously defined to gauge the progress of each iteration.

The optimization parameters themselves were not static throughout the process. They were subjected to thoughtful adjustments between iterations. The penal parameter, governing the penalization of intermediate densities, was fine-tuned to balance the stiffness of the resulting structures. The rmin parameter, determining the radius of the sensitivity filter, was adjusted to control the smoothness of design changes and mitigate potential noise in the optimization process.

Each iteration provided valuable insights into the evolving design. The results, including the optimized material distribution (**xPhys**), objective function values (**c**), and compliance values, were meticulously recorded. These results were then subject to rigorous analysis, assessing both the performance of the optimized structures and the convergence of the optimization process.

Through this iterative journey, the most effective input parameters gradually emerged. The selection of these parameters was driven by a delicate balance between computational efficiency and design optimality. The optimized parameters were those that consistently yielded structures of superior performance while respecting engineering constraints.

In essence, the iterative approach to running the code allowed for a dynamic exploration of the design space, enabling the gradual refinement of the input parameters. This systematic and iterative process ultimately led to the selection of the most suitable parameters, optimizing the structural design to meet the desired objectives effectively.

The input parameters obtained after multitude of iterations are:

1. Elements in x, y & z: 100, 100 & 5
2. Volume Fraction: 0.2
3. Penalization Factor: 4
4. Minimum Radius: 1.5

The optimized geometry is shown in figure 3.

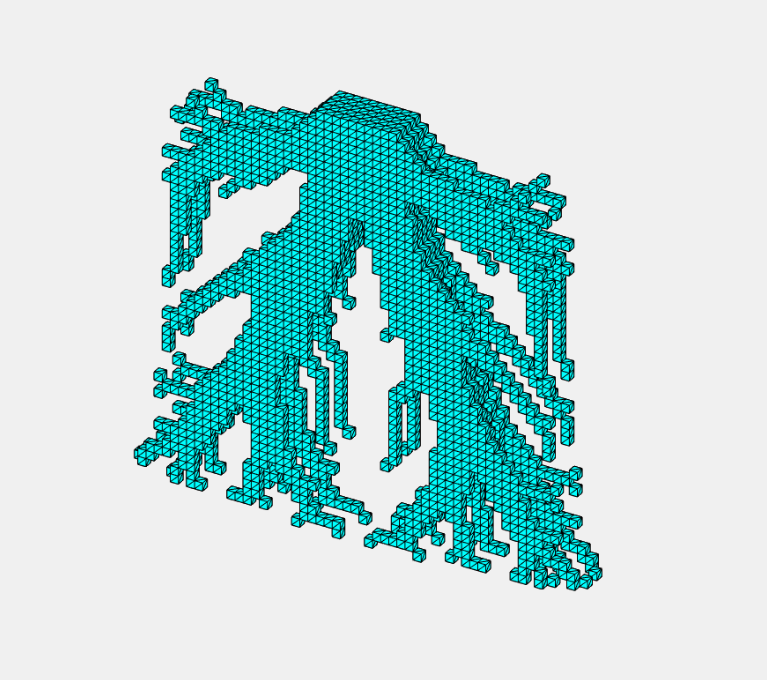

Figure 3 Optimized Heat Sink

Chapter 4: Triply Periodic Minimal Surfaces

4.1 TPMS

Triply Periodic Minimal Surfaces (TPMS) are a class of mathematical surfaces that possess several unique properties, primarily characterized by their ability to divide three-dimensional space into two interpenetrating labyrinths without any overlap. These surfaces are minimal surfaces, which means they have the smallest possible surface area for their given boundaries. TPMS exhibits fascinating geometric properties and have wide-ranging applications in various fields [24].

1. Geometric Properties:

Periodicity: TPMS are periodic, meaning they repeat themselves in three orthogonal directions (x, y, and z) to fill all three-dimensional space. This periodicity makes them ideal for applications requiring structured, repeating patterns.

Minimal Surfaces: TPMS have the smallest surface area possible for a given volume, making them mathematically elegant and geometrically efficient. This property contributes to their stability and structural strength.

Interpenetrating Networks: TPMS divide space into two intertwined networks or labyrinths without overlapping. These networks can have different geometries, such as gyroids, diamonds, or others, depending on the specific TPMS.

High Symmetry: Many TPMS exhibit high degrees of symmetry, which adds to their aesthetic appeal and mathematical elegance. For example, the gyroid TPMS has cubic symmetry [25].

2. Mathematical Formulation:

TPMS can be mathematically described using partial differential equations (PDEs) that involve trigonometric or hyperbolic functions. The specific equations vary depending on the TPMS type. For example, the gyroid TPMS is described by trigonometric functions.

The equations for TPMS capture the balance between the mean curvature (the average of the principal curvatures) and the Gauss curvature (the product of the principal curvatures), resulting in a surface with zero mean curvature [26].

4.1.1 Gyroid

- **Mathematical Formula:** The Gyroid can be represented by the equation:

$$\sin(x) * \cos(y) + \sin(y) * \cos(z) + \sin(z) * \cos(x) = 0$$

- **Characteristics:** Gyroid is known for its labyrinthine structure with a high degree of symmetry. It has chiral forms: Gyroid I-WP (Ia3d) and Gyroid P-WP (Pa3d).

- **Applications:** Gyroid structures have been found in various biological systems, including cell membranes and butterfly wings. The TPMS structures are used to design metamaterials with exceptional properties, such as negative refractive indices and acoustic properties. These metamaterials have applications in creating lenses, cloaking devices, and sound absorbers. The intricate and lightweight nature of Gyroid TPMS makes them suitable for designing lightweight but strong materials. This is particularly valuable in aerospace and automotive industries for constructing lightweight yet durable components.

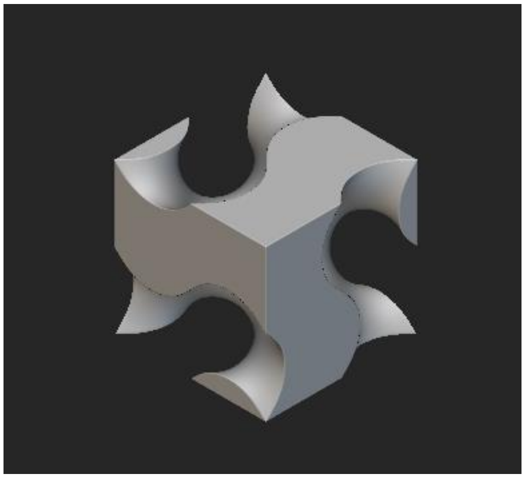

Figure 4 Gyroid Unit Cell

4.1.2 Diamond

- **Mathematical Formula**: The Diamond surface can be represented as:

$$\sin(x)*\sin(y)*\sin(z)+\sin(x)*\cos(y)*\cos(z)+\cos(x)*\sin(y)*\cos(z)+\cos(x)*\cos(y)*\sin(z)= 0$$

- **Characteristics:** Diamond TPMS exhibit a diamond-like lattice structure. They come in two forms: Diamond D-WP (Fd3m) and Diamond P-WP (Pn3m).

- **Applications**: Diamond structures are valued for their exceptional mechanical properties, making them suitable for designing lightweight and strong materials. These structures have been used to design metamaterials with specific properties, such as negative refractive indices. These metamaterials can find applications in optics, microwaves, and acoustics for creating lenses, cloaking devices, and unique waveguides. Diamond TPMS structures have inspired the design of metal foams used in lightweight structural components, thermal insulation, and impact absorption applications.

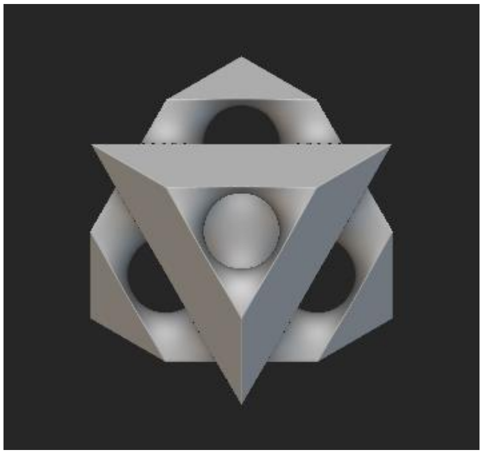

Figure 5 Diamond Unit Cell

4.1.3 Schwarz Primitive

- **Mathematical Formula**: Schwarz Primitive surfaces are represented as:

$$\cos(x)+\cos(y)+\cos(z)= 0$$

- **Characteristics**: These surfaces exhibit simple cubic symmetry and are classified as Schwarz P-WP (Pm3m), Schwarz D-WP (Im3m), and more.

- **Applications**: Schwarz Triply Periodic Minimal Surfaces (Schwarz TPMS) are a class of minimal surfaces with unique geometric properties. They are named after the German mathematician Hermann Schwarz, who extensively studied these surfaces. Schwarz TPMS have found applications in various fields due to their intricate and visually appealing patterns, as well as their mathematical elegance. Schwarz TPMS patterns are used as templates to create porous materials with controlled pore size and distribution. These materials find applications in filtration, separation processes, and catalysis. Schwarz TPMS structures are employed to design acoustic metamaterials with specific acoustic properties, such as sound insulation and wave manipulation. These materials have applications in noise control and acoustic engineering.

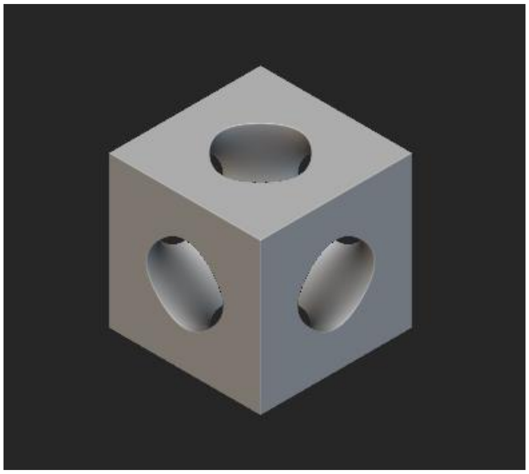

Figure 6 Schwarz Unit Cell

4.1.4 Lidinoid

- **Mathematical Formula**: Lidinoid TPMS can be represented as:

  sin(2*x) * cos(y) * sin(z) + sin(2*y) * cos(z) * sin(x) + sin(2*z) * cos(x) * sin(y) - cos(2*x) * cos(2*y) - cos(2*y) * cos(2*z) - cos(2*z) * cos(2*x) + .3 = 0

- **Characteristics**: Lidinoid surfaces have a complex and curved structure. They include Lidinoid L-WP (Fd3m) and Lidinoid C-WP (Fd3c).

- **Applications**: Lidinoid Triply Periodic Minimal Surfaces (Lidinoid TPMS) are a class of minimal surfaces with distinctive geometric properties. While not as well-known as some other TPMS types like the Gyroid or Schwarz surfaces, Lidinoid TPMS offer unique geometric patterns and mathematical elegance. While their applications may not be as extensive as other TPMS types, they still find use in several areas. Lidinoid TPMS continue to be subjects of mathematical research, particularly in the fields of topology and geometry, where their intricate structures are explored for their unique properties. Lidinoid TPMS can inspire the design of nanostructures with specific patterns and properties. These nanostructures have potential applications in nanoelectronics, sensors, and surface coatings.

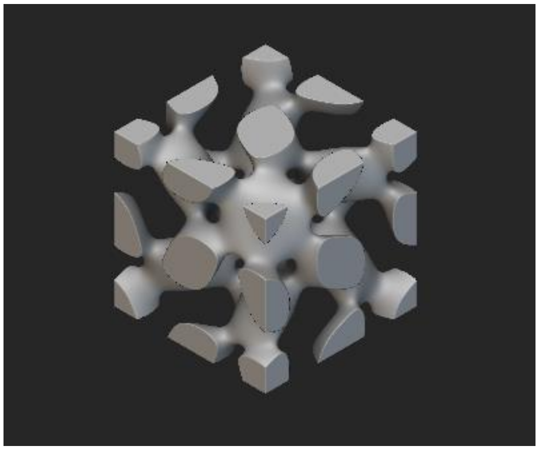

Figure 7 Lidinoid Unit Cell

4.1.5 SplitP

- **Mathematical Formula:** The SplitP TPMS can be described using the following equation:

$$1.1*(\sin(2*x)*\sin(z)*\cos(y)+\sin(2*y)*\sin(x)*\cos(z)+\sin(2*z)*\sin(y)*\cos(x))-0.2*(\cos(2*x)*\cos(2*y)+\cos(2*y)*\cos(2*z)+\cos(2*z)*\cos(2*x))-0.4*(\cos(2*x)+\cos(2*y)+\cos(2*z)) = 0$$

- **Characteristics**: SplitP surfaces feature a unique segmented structure, where regions with different curvatures meet. This distinctive structure can be attributed to its mathematical formulation.

- **Applications**: SplitP TPMS have been of interest in materials science and engineering for their potential to create materials with controlled mechanical properties. Their segmented structure offers opportunities for creating materials with varying properties in different regions. In biomedical applications, SplitP TPMS patterns can be used to design biocompatible materials with controlled porosity for tissue engineering and drug delivery systems.

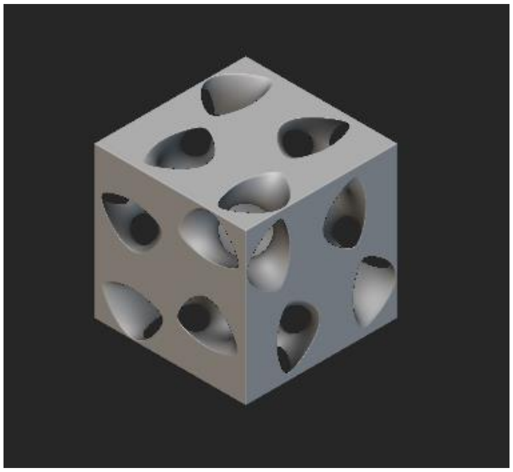

Figure 8 SplitP Unit Cell

4.1.6 Neovius

- **Mathematical Formula**: The Neovius TPMS can be expressed through the equation:

$$3*(\cos(x)+\cos(y)+\cos(z)) +4*\cos(x)*\cos(y)*\cos(z)=0$$

- **Characteristics**: Neovius surfaces have a gyroid-like appearance but differ in terms of their symmetries and minimal surface properties.

- **Applications**: Neovius TPMS are being explored for their potential in creating metamaterials with unique optical and mechanical properties. Their intricate structure makes them valuable for designing advanced materials with controlled properties. While Neovius TPMS may not be as commonly applied as some other minimal surfaces, their unique geometric properties make them valuable in various scientific, artistic, and engineering contexts. As research and technology advance, new and innovative applications for these surfaces may continue to emerge.

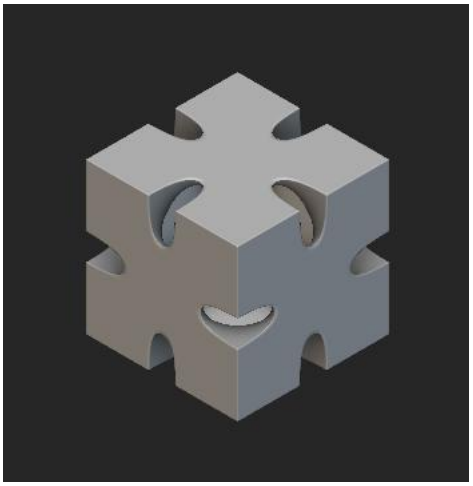

Figure 9 Neovius Unit Cell

4.2 Fin Geometry

The MATLAB code was modified to export STL (Stereolithography) files from the powerful topology optimization algorithm, Top3D. This integration allowed for the efficient transfer of optimized geometry into a more versatile 3D modeling environment. Once the STL file was generated by Top3D, it was transported into AutoDesk Inventor, a robust CAD (Computer-Aided Design) software.

Within AutoDesk Inventor, the imported STL geometry underwent a meticulous cleaning process. This involved refining the model to ensure uniformity in its edges and surfaces, resulting in a smoother and more aesthetically pleasing 3D representation. This step was crucial for achieving precision and ensuring that the final design met the desired specifications.

Following the cleaning process, AutoDesk Inventor played a pivotal role in facilitating the conversion of the STL file into a STEP (Standard for the Exchange of Product Data) file format. STEP files are universally recognized and compatible with various CAD and CAE (Computer-Aided Engineering) software packages. This format ensured the interoperability of the geometry across different platforms and software applications.

The finalized STEP file served as the bridge for importing the optimized geometry into Ntopology, a cutting-edge software tool known for its advanced capabilities in generative design and topology optimization.

In this intricate process, the seamless flow of data from Top3D to AutoDesk Inventor and finally into Ntopology was pivotal. It not only expedited the transition between various stages of design and optimization but also ensured that the final geometry was primed for realization, whether through additive manufacturing or traditional manufacturing methods.

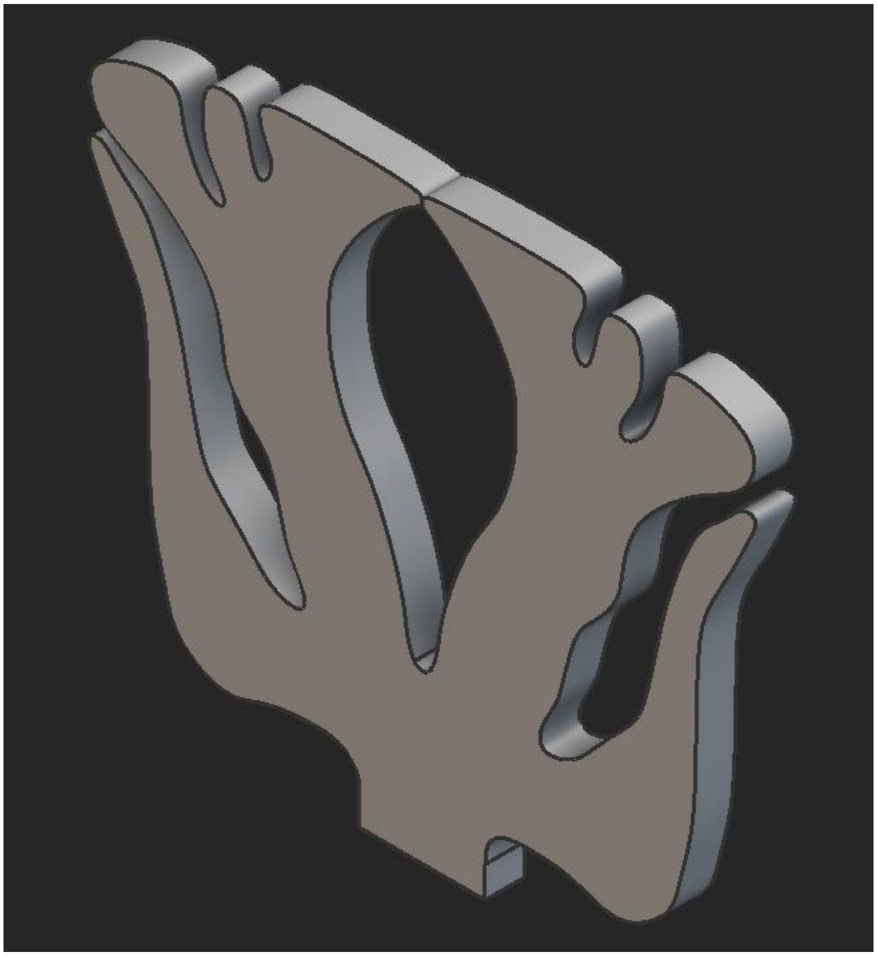

Figure 10 Cleaned Fin Geometry

4.3 Topologically Optimized Heat Sink

After the meticulous cleaning and optimization of the fin geometry, the next phase of the design process involved transforming this refined structure into an efficient heatsink with specific parameters. In this case, the objective was to create a heatsink with a 5mm-thick base and an array of precisely 9 fins.

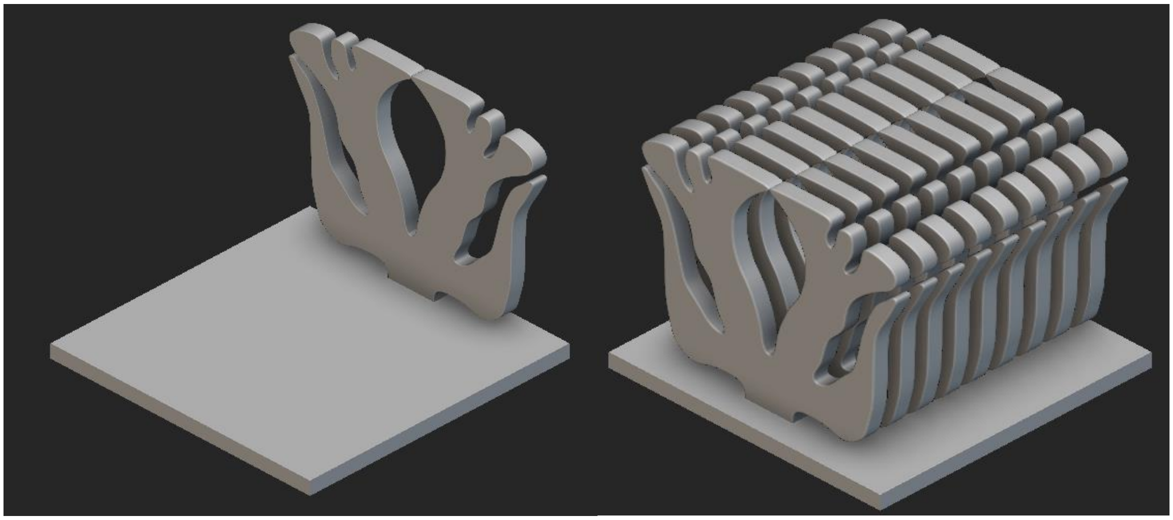

Figure 11 Topologically Optimized Heat-Sink

4.4 TPMS Mapping

A multi-objective topology optimization approach was implemented by modifying the top3d code. The objective was to minimize thermal compliances by optimizing the material distribution. Density mapping methods were employed to create a variable density TPMS-based structure based on the multi-objective optimization output. Gyroid was selected for mapping due to its superior stability characteristics [27]. TPMS-based structures are advantageous as passive heat sinks because of their lightweight and high mechanical strength. Additionally, the high surface area to volume ratio offered by TPMS could enhance the heat removal process in convective heat transfer applications.

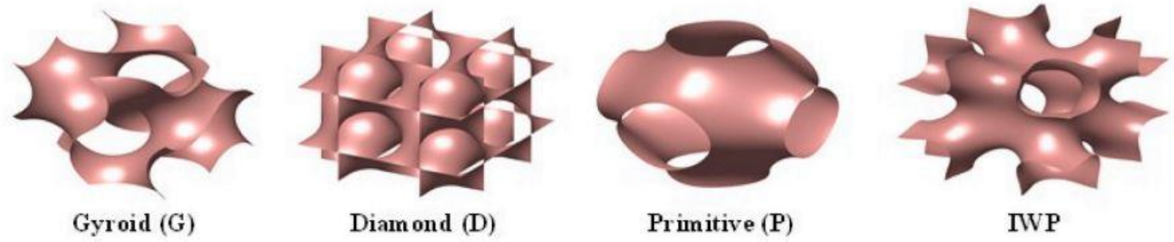

Figure 12 Isosurfaces for Gyroid (G), Diamond (D), Primitive (P) and IWP

The TPMS surfaces were generated using the level set approximation equation:

Ø(x, y, z) = c^2

where c is the level set constant that controls the thickness of the TPMS-based sheet-networks. The equation for Ø(x, y, z) of a TPMS-sheet is given by:

$$\Phi_G(x,y,z) = \left[sin\frac{2\Pi x}{L_x} cos\frac{2\Pi y}{L_y} + sin\frac{2\Pi y}{L_y} cos\frac{2\Pi z}{L_z} + sin\frac{2\Pi z}{L_z} cos\frac{2\Pi x}{L_x} \right]^2$$

where LX, Ly, and Lz are unit cell lengths in the x, y, z directions, respectively. The level set constant c can be a constant or a function of (x, y, z) to get a graded TPMS-based structure in that direction.

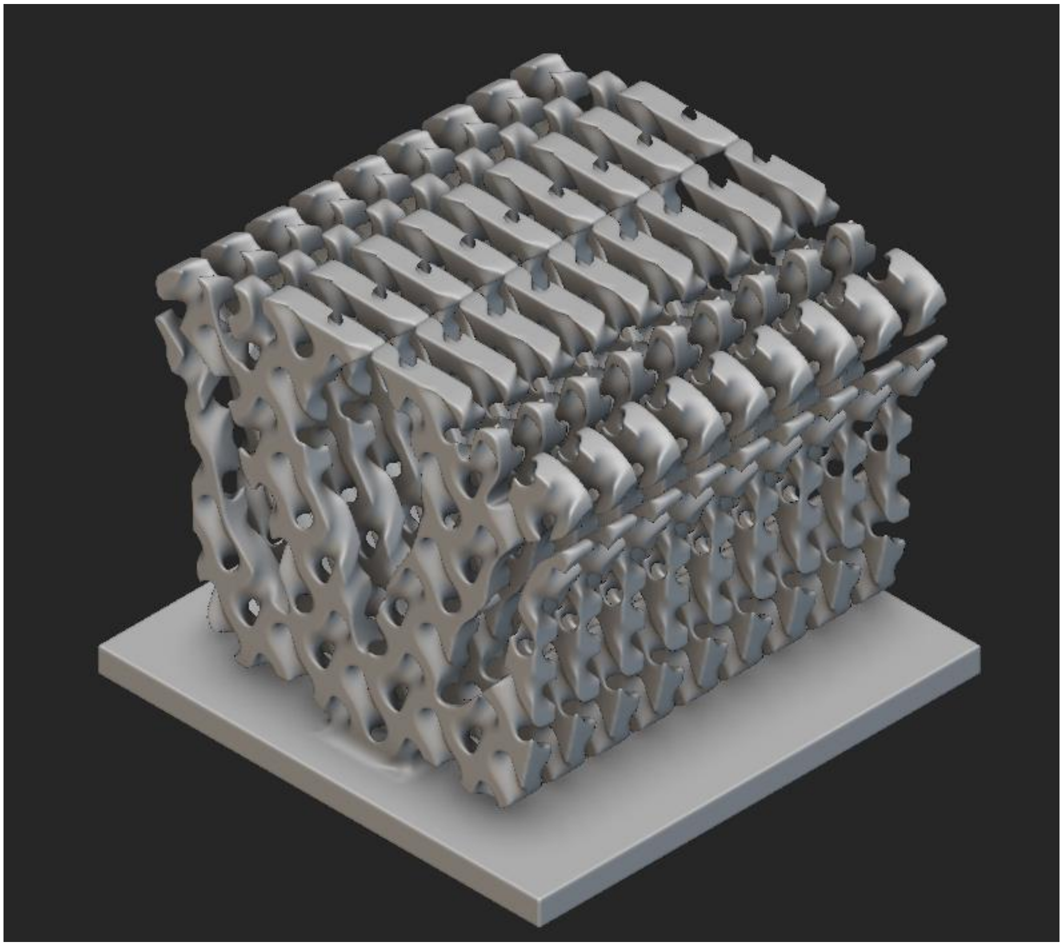

Figure 13 Optimized Heat Sink with TPMS Mapping

Chapter 5: Thermal Analysis

5.1 Heat Transfer Modes

Heat transfer is a fundamental process in electronics cooling, where managing heat generated by electronic components is crucial to ensure optimal performance and prevent overheating. There are three primary modes of heat transfer: conduction, convection, and radiation.

- **Conduction:**

Conduction is the transfer of heat through a solid material without the actual movement of the material itself. It occurs due to the transfer of kinetic energy from one particle to another within the solid.

Example in Electronics Cooling: When a computer processor (CPU) generates heat, it conducts this heat through its solid structure to a heat sink, which is designed to dissipate the heat into the surrounding air.

- **Convection:**

Convection is the transfer of heat through the movement of a fluid (liquid or gas). It can be natural (natural convection) or forced (forced convection). In natural convection, heat transfer occurs due to density differences in the fluid caused by temperature variations.

Example in Electronics Cooling: In a laptop, warm air rises naturally around the heat-generating components (e.g., CPU and GPU). As the air rises, it carries heat away from the components, contributing to cooling.

- **Radiation:**

Radiation is the transfer of heat in the form of electromagnetic waves, such as infrared radiation. Unlike conduction and convection, radiation does not require a medium (solid, liquid, or gas) for heat transfer and can occur through a vacuum.

Example in Electronics Cooling: While radiation is a mode of heat transfer, it is not a primary mechanism in electronics cooling. It becomes more significant in extremely high-temperature environments, such as spacecraft electronics.

- **Natural convection**

Natural convection is commonly observed in electronic systems, such as laptops, desktop computers, and electronic enclosures. Understanding and optimizing natural convection can significantly impact the cooling efficiency of these devices.

Natural convection is considered an energy-efficient cooling method as it does not require additional energy input, such as fans or pumps. This can lead to reduced power consumption and longer device lifespans. In consumer electronics like laptops and desktops, natural convection allows for quieter operation since there are no noisy fans involved. This is essential for enhancing user comfort.

Natural convection is particularly valuable in small and compact electronic devices where space is limited. It enables efficient cooling without the need for bulky cooling solutions.

By focusing on natural convection in electronics cooling, we aim to explore the principles and mechanisms that govern heat transfer in these systems. This knowledge can contribute to the development of more efficient and reliable cooling solutions for electronic components and devices, ultimately improving their performance and lifespan.

5.2 Analysis

In this thermal analysis study, three different heat sinks were evaluated for their performance in dissipating heat generated by a 90W power amplifier with a 30 x 30 mm footprint. The study aimed to determine which heat sink design provided the most effective cooling, with the base temperature of the heat sinks serving as the key performance metric.

Heat Sink Types:

- **Straight Fin Heat Sink:**

Featuring a traditional straight fin design the bounding volume, number of fins, and base dimensions were kept identical to the other two heat sinks.

It was used as the benchmark for comparing the performance of the other designs.

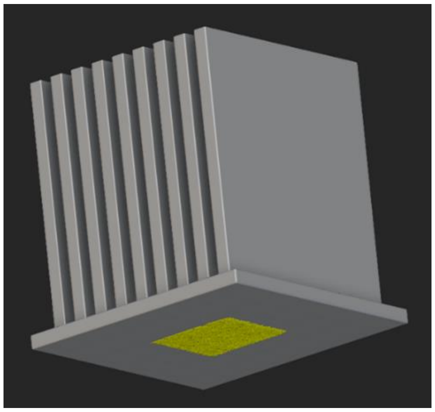

Figure 14 Straight Fin HS with heat load

- **Topologically Optimized Heat Sink:**

This heat sink design was optimized using topology optimization techniques.

The goal was to find the most efficient material distribution within the given design space while keeping the base dimensions and bounding volume consistent.

The optimization aimed to minimize the base temperature by enhancing thermal performance.

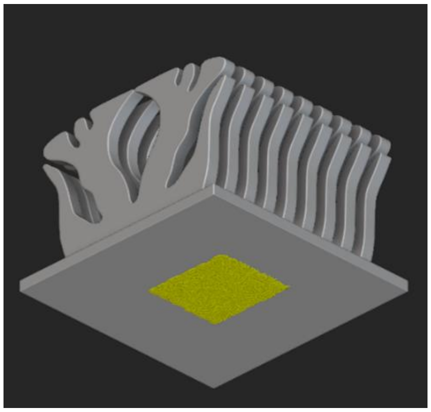

Figure 15 Topologically Optimized HS with heat load

- **Topologically Optimized Heat Sink with TPMS Mapping:**

Building upon the topologically optimized design, this heat sink incorporated Triply Periodic Minimal Surfaces (TPMS) mapping.

Gyroid TPMS mapping introduced complex surface geometries, to further improve heat transfer properties.

Like the previous design, the base dimensions and bounding volume remained the same.

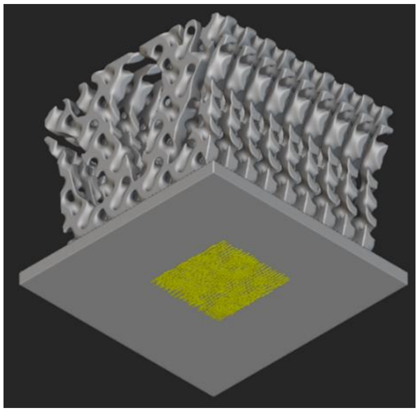

Figure 16 TPMS Mapped HS with heat load.

Common Parameters:

Base Dimensions: 100 x 100 x 5 mm

Bounding Volume: Consistent for all three heat sinks

Number of Fins: Consistent for all three heat sinks

Heat Load:

A 90W power amplifier with a 30 x 30 mm footprint was used as the heat source.

Performance Metric:

The primary performance metric was the base temperature of the heat sinks.

Lower base temperatures indicate more efficient heat dissipation and better thermal management.

By comparing the base temperatures of the three heat sink designs under the same heat load conditions, the study aimed to determine which design provided the most effective cooling solution for the 90W power amplifier. This analysis would provide valuable insights into the thermal performance of these heat sinks and their suitability for cooling electronic components with similar power dissipation requirements.

Comparison of the performance of the Heat Sinks were performed using the same boundary conditions and parameters. The simulation was performed using the software NTopology, and the same software was used to generate the geometries.

Contrary to other modeling and Simulation tools, Ntopology works with implicit body as its native geometry scheme, rather than explicit body. Which means better surface mesh of complex geometries and low failure rate as the complexity increases.

The meshing has been done using a 3-stage approach, where firstly a volume mesh is created by utilizing “Mesh from Implicit Body”, which works by generating a 3D grid of voxels throughout the bounding box of the object. The voxels that interest the input body are maintained, and a mesh is generated from the voxel edges. The second stage is the “Re-mesh Surface”, which cleans up the defects in the mesh, consolidates meshes into fewer elements, and/or spatially varies the mesh density. It gives more control over size, shape, and uniformity if the original mesh. Thirdly the FE boundary is selected by flood-fill, which selects surface entities on a FE mesh. The entities available to be selected are nodes, faces or edges.

The parameters for Meshing are as follows:

- Tolerance: 0.8 mm
- Edge Length: 1.5 mm
- Shape: Triangle
- Span Angle: 30 deg
- Growth Rate: 2

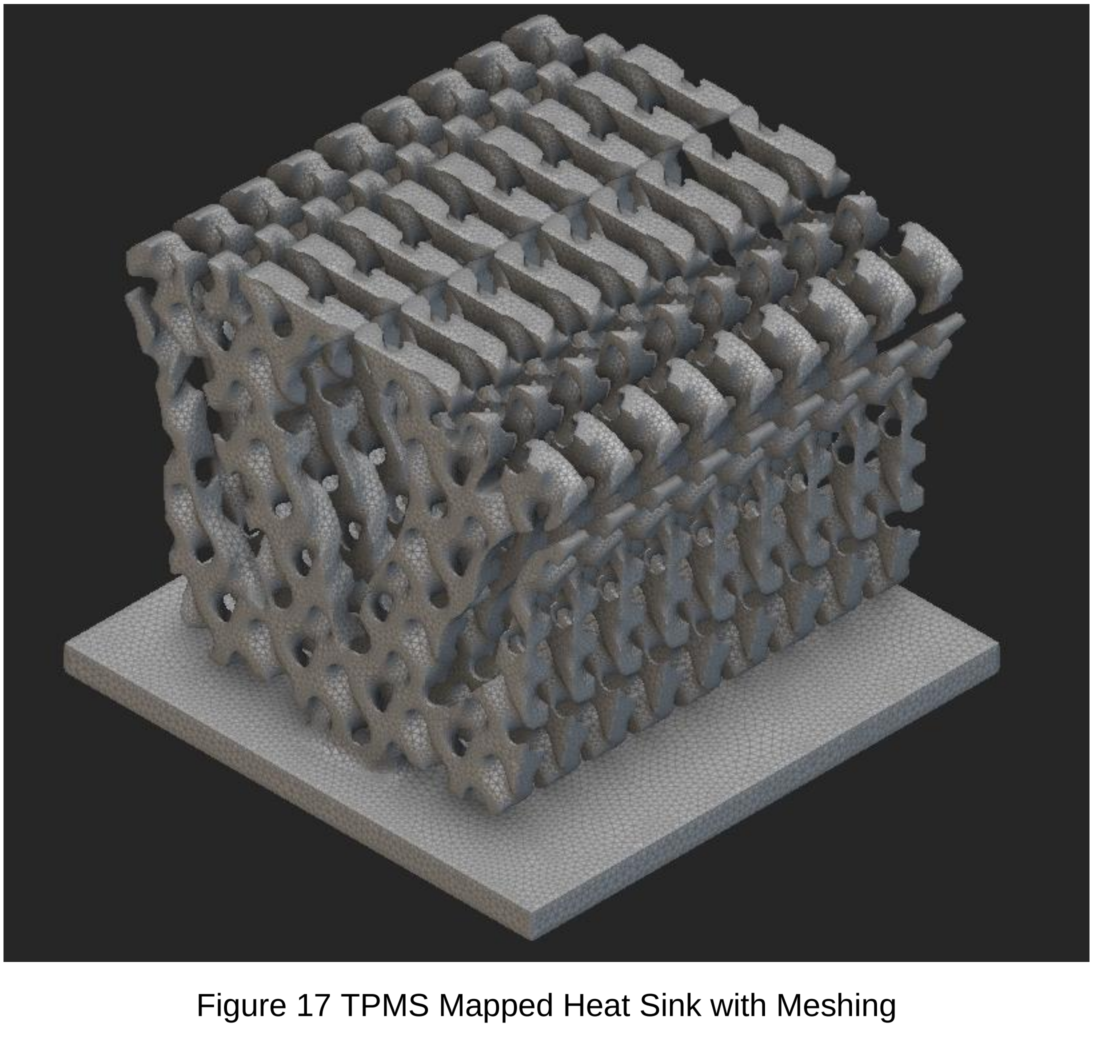

Figure 17 TPMS Mapped Heat Sink with Meshing

5.3 Material

The material used for the geometries for analysis is Aluminum 6061 – T6. The properties are used as per the library of the software.

5.4 Setup

The simulation setup is set to cool a 30 x 30 mm heat dissipating device, with a heat generation value of 90 Watts. A convective boundary is created along the fins of the heat-sink with an ambient temperature of 300K. The simulation parameters are set to steady state natural convection.

steady state natural convection.

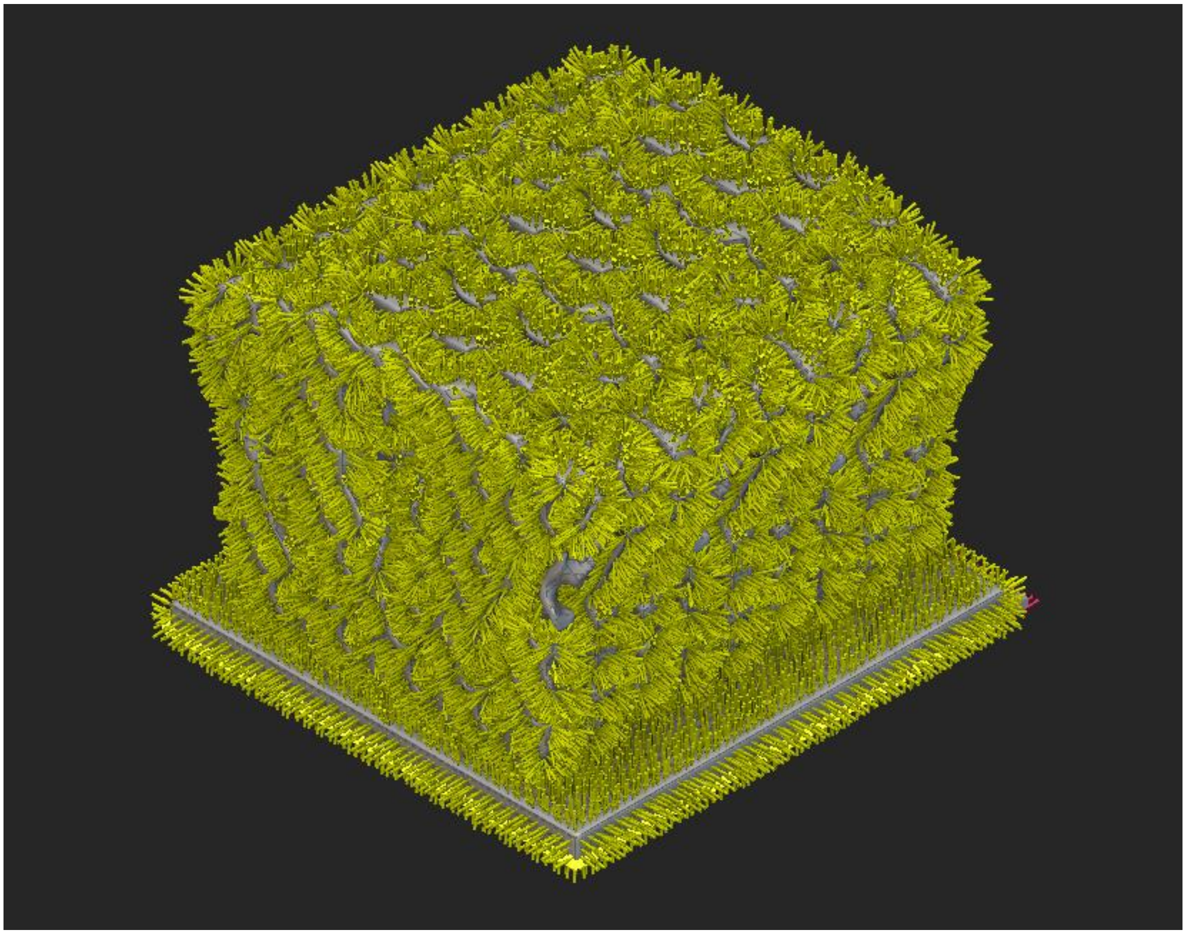

Figure 18 Convection Boundary

The boundary conditions are limited to the conduction from the base and the convection through the surfaces.

Chapter 6: Results & Conclusions

6.1 Results

The results of the simulation show significant improvement in the heat extraction properties of the mapped and optimized heat sink, with more than 60% reduction in mass and a temperature drop of more than 7 K at the base. It is imperative to note that the performance of the optimized heatsink greatly depends upon the geometry and the orientation of the TPMS field.

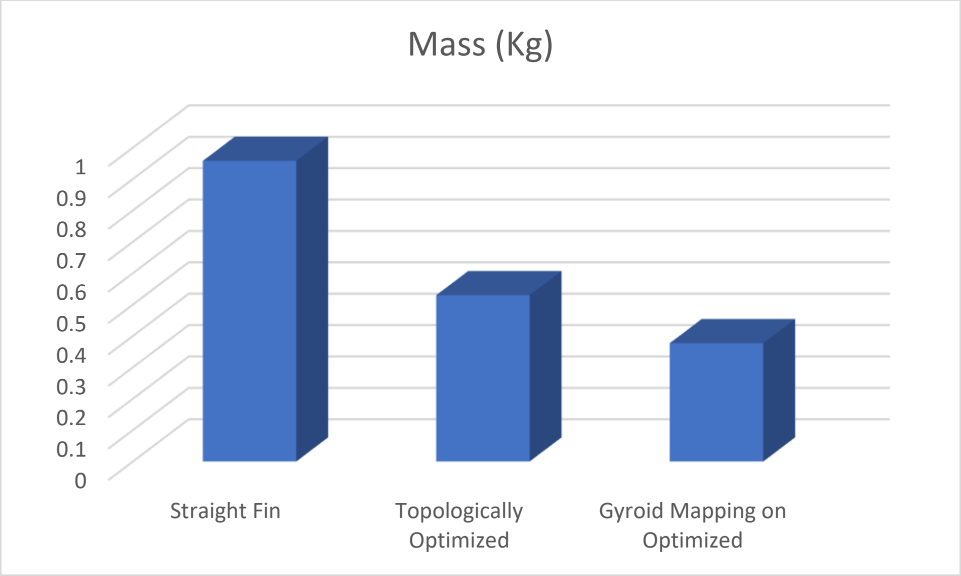

Figure 19 Mass properties of Heat Sinks

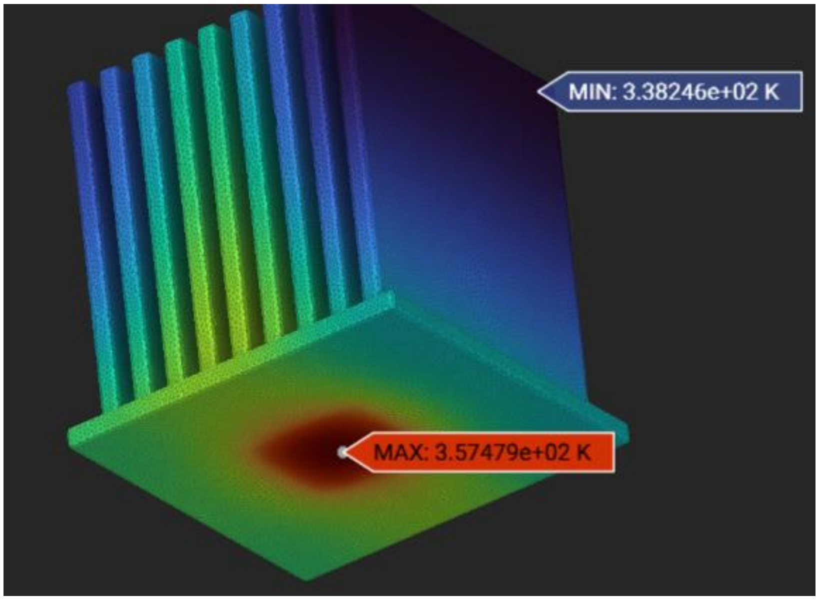

Figure 20 Base & Fin temperature of Straight Fin Heat Sink

Contrary to initial belief, the increase in the surface area of the optimized heat sink is not enough to be more than the conventional heat sink, as the reduction in volume occurred during the topology optimization is much significant.

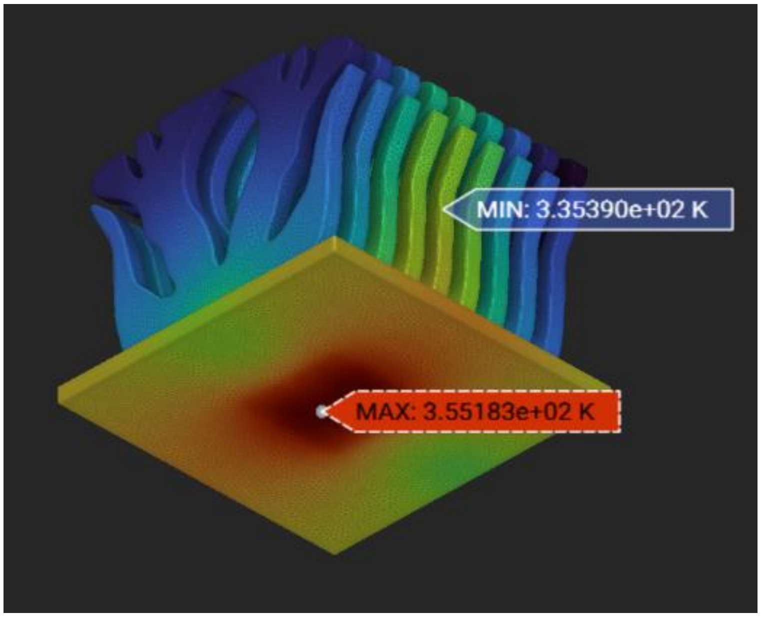

Figure 21 Base & Fin temperature of Topologically Optimized Heat Sink

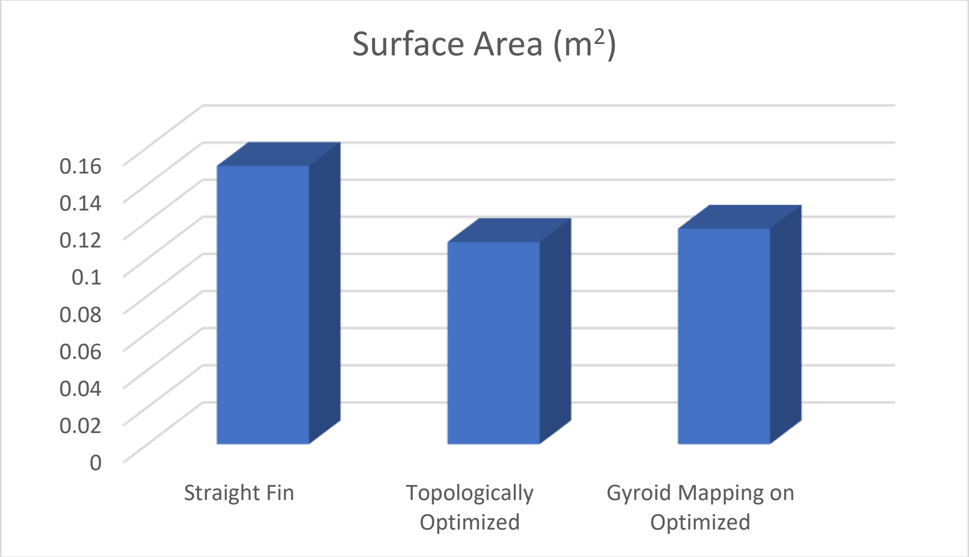

Figure 22 Surface Area Comparison of Heat Sinks

The mapped heat-sink shows significant reduction in base temperature, along with reduction in mass.

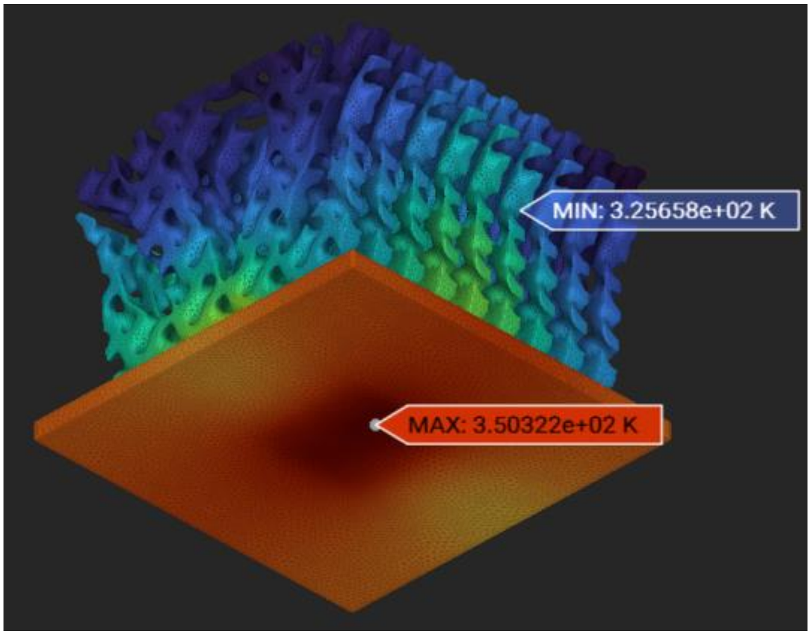

Figure 23 Base & Fin temperature of TPMS Mapped Heat Sink

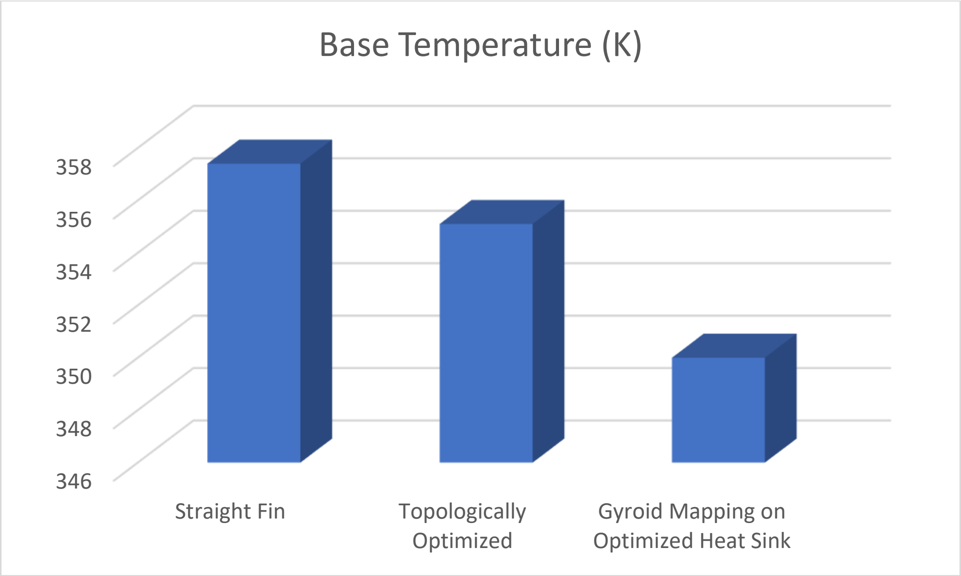

Figure 24 Base Temperature Comparison of Heat Sinks

6.2 Prototype Manufacturing

Due to unavailability of Aluminum/Copper for additive manufacturing, the prototype was printed using PLA filament, so that the manufacturability of the design can be confirmed. The decision to print the prototype of the heat sink using PLA filament was primarily driven by practical reasons. Here are the key factors behind this decision:

- **Material Availability:** PLA filament is widely available and commonly used in 3D printing. It can be easily sourced, making it a readily accessible material for prototyping.

- **Cost-Efficiency:** PLA filament is relatively affordable compared to metals like Aluminum or Copper. This cost-effectiveness is especially important for early-stage prototypes and concept validation.

- **Rapid Prototyping:** PLA allows for quick turnaround times in 3D printing. This rapid prototyping capability enables the creation of multiple iterations of the design in a shorter time frame.

- **Low Barrier to Entry:** PLA filament is user-friendly and suitable for a wide range of 3D printers. It has a low barrier to entry, making it accessible to a broader audience, including researchers and hobbyists.

- **Confirmation of Manufacturability:** Printing the prototype in PLA serves the primary purpose of confirming the manufacturability of the heat sink design. It allows researchers to assess whether the design can be successfully produced using additive manufacturing techniques.

- **Iterative Design:** PLA facilitates an iterative design process, where multiple design variations can be tested and refined without the constraints and costs associated with metal fabrication.

- **Environmental Considerations:** PLA is biodegradable and has a lower environmental impact compared to some other plastics. This aligns with considerations for sustainable and responsible material choices.

In summary, the decision to use PLA filament for the prototype was primarily driven by the need to overcome material unavailability, achieve cost-efficiency, and quickly validate the manufacturability of the heat sink design. PLA serves as a practical and accessible alternative for the initial stages of design development and testing.

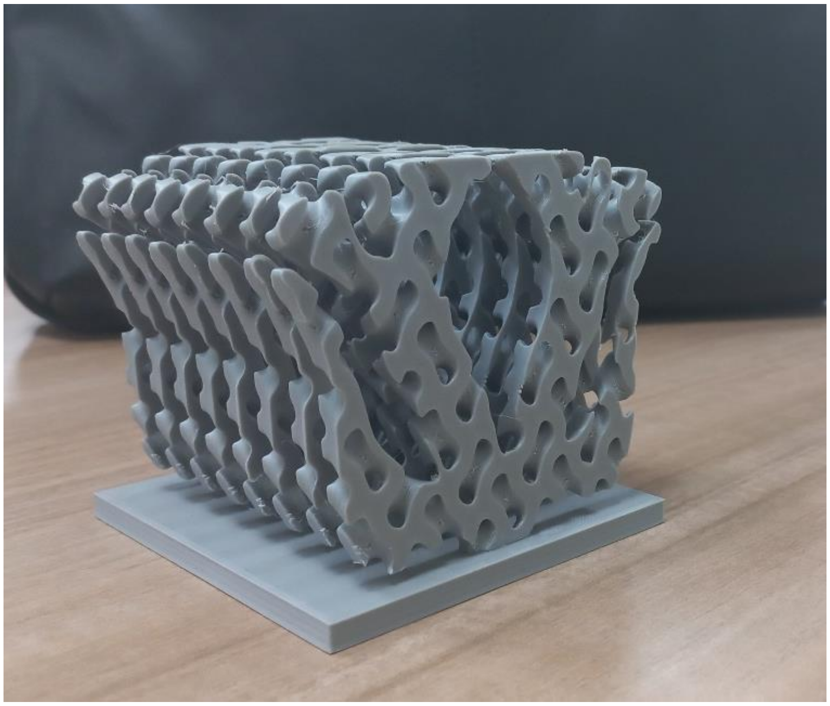

Figure 25 3D Printed Protype of TPMS Mapped Heat Sink

6.3 Conclusion

The study's results indicated that scaling the heat transfer area had a significant impact on the topology of the heat sink, which is essential for dissipating thermal energy. The optimized topologies tended to extend towards domain boundaries, resulting in complex structures with deep pockets that may not be suitable for commercial applications. To address this issue, the proposed methodologies were utilized to convert the intricate optimized structure into a TPMS structure with smoothly connected surfaces, such as gyroid solid and sheet. The study demonstrated that the mapping approaches could generate thermally comparable structures based on TPMS cellular structures.

6.4 Future Work & Limitations

The experimental validation of the heat sink design was not possible due to the current unavailability of Aluminum/Copper for 3D printing. As a result, the optimized heat sink design could not be physically constructed and evaluated for its performance. However, once the material becomes available, experimental validation will be conducted to verify the optimized design's effectiveness. Despite this limitation, the study's results provide valuable insights into the potential of topology optimization and TPMS structures to enhance heat sink performance, which can help advance the development of more efficient thermal management systems. A proposed test setup will be implemented as soon as the material is available, which will involve monitoring the temperature distribution and heat dissipation rate of the heat sink when subjected to a constant heat source. The experimental results will be compared with the simulation results to assess the accuracy and reliability of the simulation approach. The proposed test setup will provide valuable information on the thermal performance of the optimized heat sink design, allowing for further refinement and optimization of the design for practical applications.

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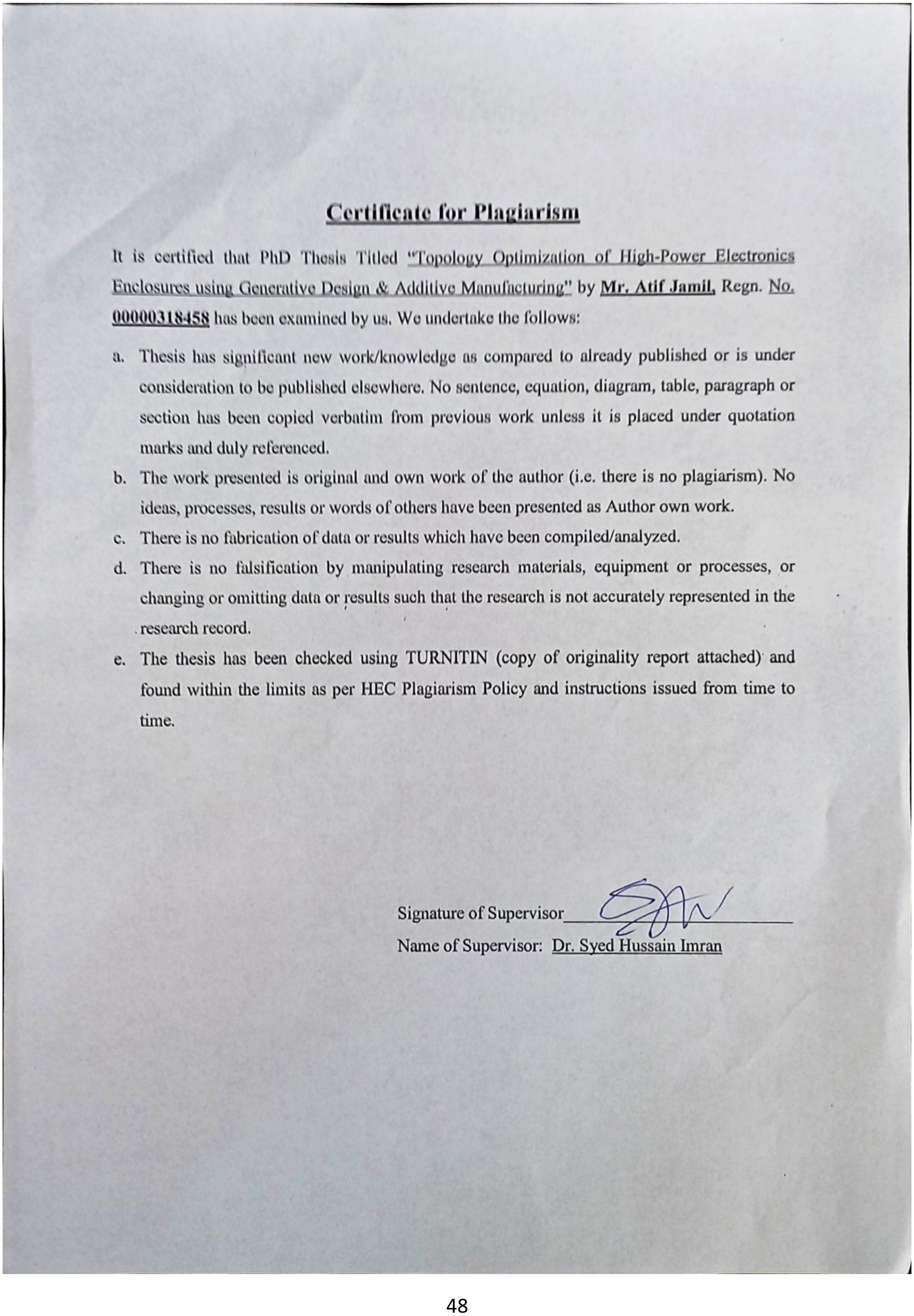

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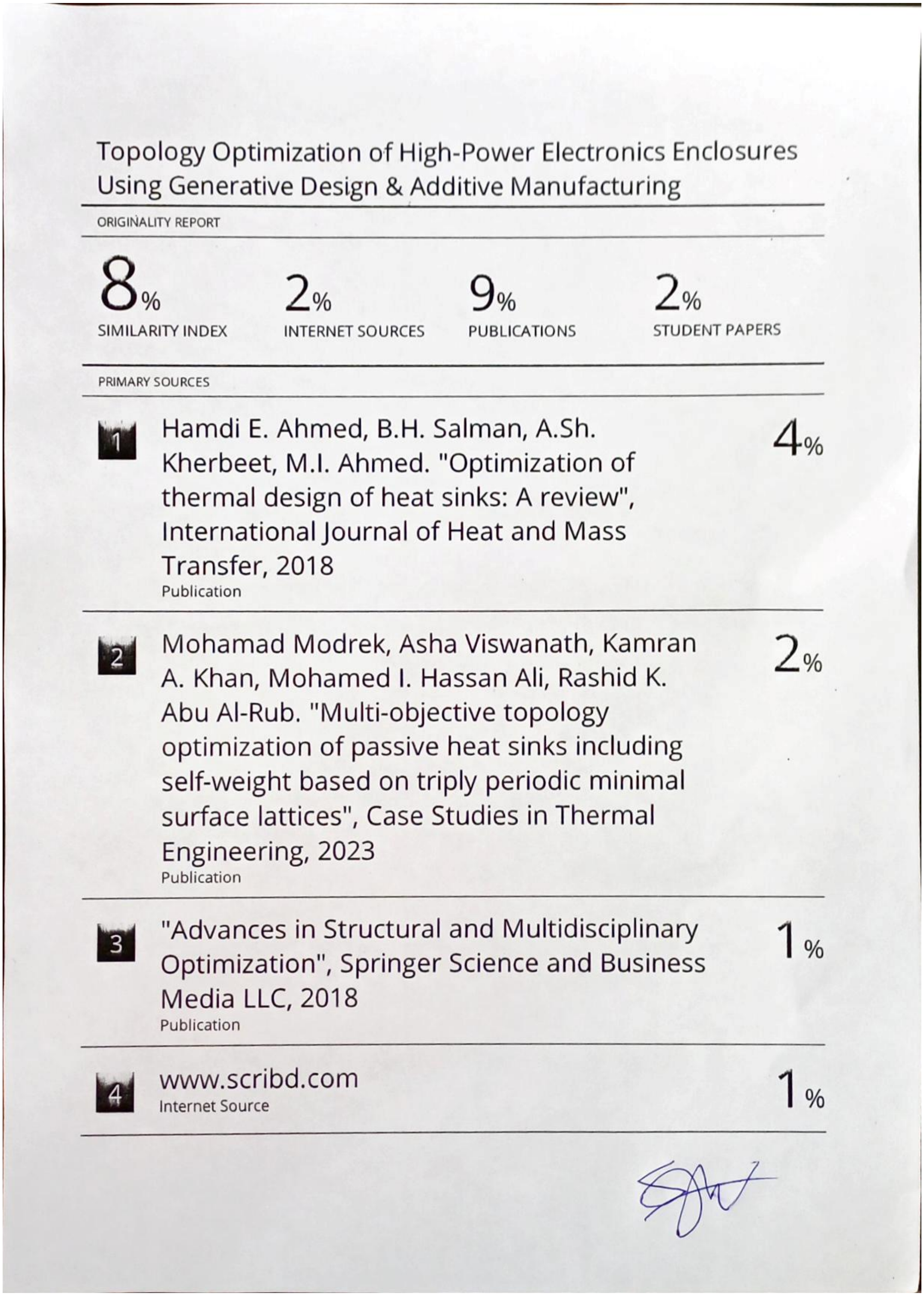

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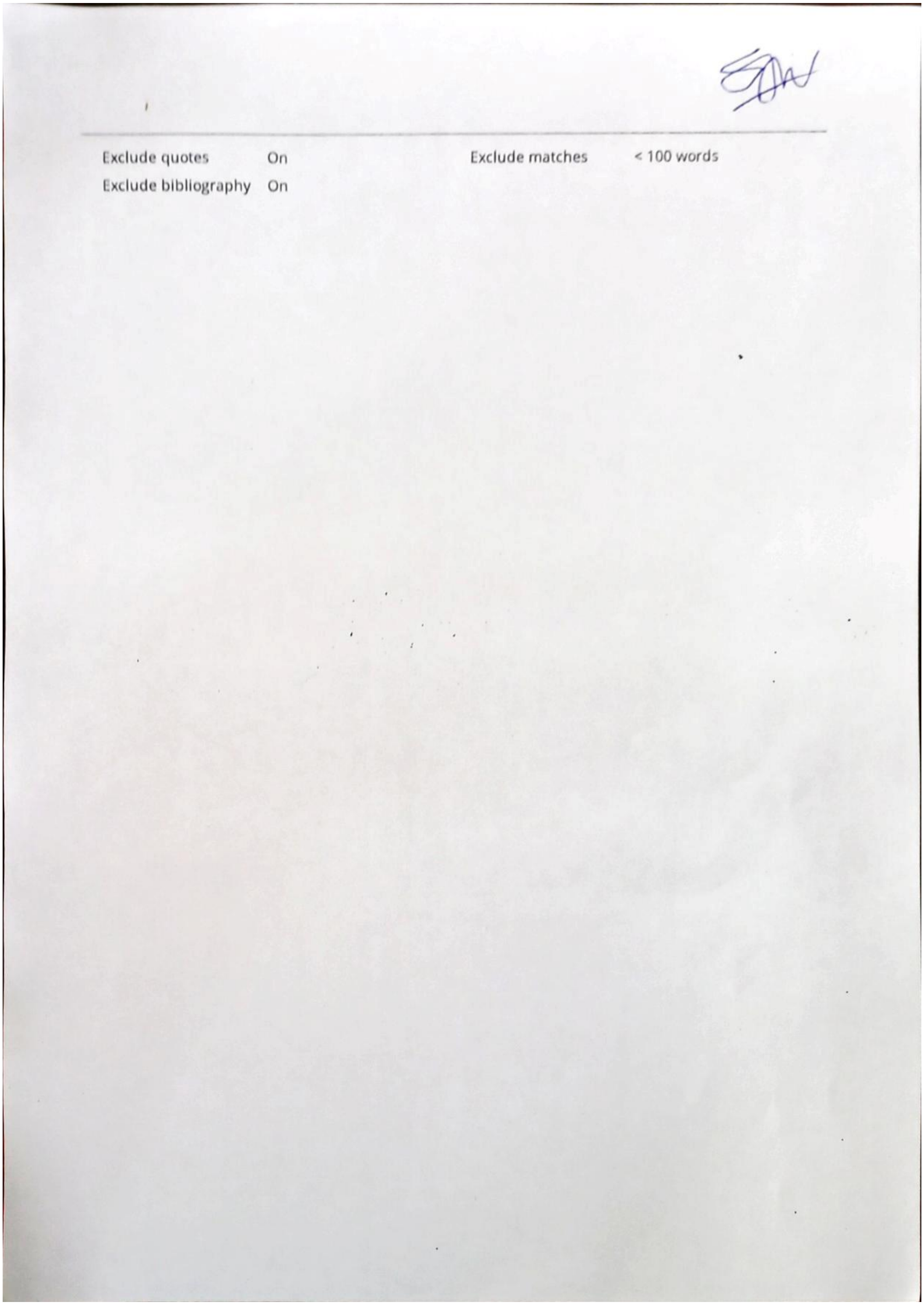

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