ACADEMIC INTERNSHIP REPORT ON

Modelling and Analysis of TPMS Scaffolds for Biomedical Implants and Heat Exchangers

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Submited by

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Modelling and Analysis of TPMS Scaffolds for Biomedical Implants and Compact Heat Exchangers

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Abstract:

This research explores triply periodic minimal surface (TPMS) structures for biomedical implants and heat exchangers. Using Autodesk Fusion 360, researchers modeled gyroid, neovius, diamond, and primitive geometries with 316L stainless steel, revealing exceptional performance through tunable porosity and interconnected architecture.

Mechanical simulations demonstrated strong stress distribution and structural integrity, particularly promising for bone tissue engineering. The study acknowledges potential challenges like stress shielding while highlighting TPMS structures' versatility in biomedical and thermal applications, establishing a foundation for future multidisciplinary research.

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List of Symbols, Abbreviations, and Nomenclature:

- TPMS: Triply Periodic Minimal Surface
- CAD: Computer-Aided Design
- FEA: Finite Element Analysis
- mm: Millimeter
- AM: Additive Manufacturing

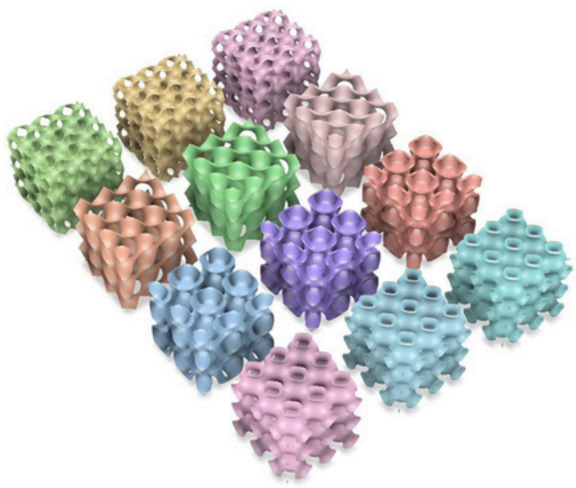
Chapter 1: Introduction

1.1 Overview of TPMS

Triply periodic minimal surface (TPMS) structures are a class of mathematically defined porous geometries characterized by minimal surfaces with zero mean curvature. These surfaces are continuous, self-repeating in three dimensions, and divide space into two distinct yet interconnected regions. The unique geometry of TPMS provides several advantages, such as minimizing stress concentrations and offering exceptional mechanical and permeability properties.

In biomedical applications, TPMS scaffolds mimic the intricate internal architecture of natural tissues like cancellous bone, offering a high degree of porosity while maintaining structural integrity. This property is essential for applications such as bone tissue engineering, where the scaffold must support cellular activity while withstanding physiological loads.

For energy-efficient systems, TPMS structures have proven to be highly effective in compact heat exchangers due to their high surface-area-to-volume ratio and interconnected channels that promote enhanced fluid flow and thermal transfer. The versatility of TPMS designs allows engineers to tailor the properties to specific applications by adjusting pore size, relative density, and material selection.



1.2 Motivation

The motivation for this study lies in addressing two significant engineering and biomedical challenges:

1. Improved Biomimicry in Tissue Engineering: The growing demand for advanced implants and scaffolds necessitates the development of designs that closely mimic the natural architecture of human tissues. Conventional lattice structures often fail to provide the desired combination of mechanical strength, biocompatibility, and interconnected porosity. TPMS structures overcome these limitations by replicating natural porous systems, facilitating better integration with biological tissues.
2. Energy Efficiency in Thermal Management: As industries move towards more compact and efficient systems, the need for advanced heat exchanger designs has increased. TPMS geometries, with their interconnected networks and tunable surface properties,
   - provide a promising solution for compact heat exchanger cores that require efficient fluid flow and heat dissipation.

This study aims to contribute to these domains by evaluating the mechanical performance of TPMS structures modeled in Autodesk Fusion 360 and providing a framework for their application in multifunctional engineering systems.

Chapter 2: Literature Review

2.1 Advances in TPMS for Biomedical Applications

The adoption of TPMS designs in biomedical engineering has been driven by their ability to mimic natural systems and provide tailored properties for specific applications. Key advancements include:

1. **Biomimicry:**
   - TPMS designs draw inspiration from natural structures such as bones, corals, and marine sponges. These natural systems demonstrate exceptional mechanical performance and biological functionality, which are replicated in TPMS geometries to create scaffolds that promote cellular activity and tissue regeneration.
2. **Biomedical Relevance:**
   - Cell Adhesion and Proliferation: The high porosity and interconnected architecture of TPMS scaffolds provide a conducive environment for cells to attach, proliferate, and differentiate.
   - Vascularization: The interconnected channels facilitate the flow of nutrients and oxygen, essential for tissue integration and long-term implant success.
   - Stress Mitigation: The isotropic nature of TPMS structures ensures uniform stress distribution, reducing the likelihood of implant failure.

- **Material Compatibility:**
   - The use of biocompatible materials like 316L stainless steel enhances the functionality of TPMS scaffolds. This material offers excellent corrosion resistance, durability, and strength, making it suitable for both temporary and permanent implants.

2.2 Manufacturing Challenges and Solutions

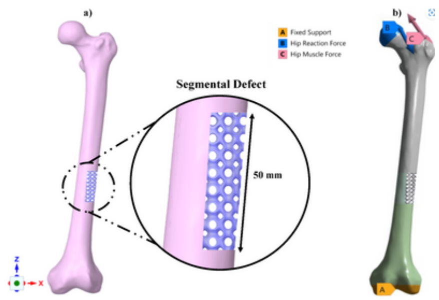
- The fabrication of TPMS structures presents unique challenges due to their intricate geometries, but advancements in manufacturing technologies have addressed many of these issues:
- Challenges with Traditional Manufacturing:
- Conventional techniques such as casting or machining often fail to accurately produce the complex geometries of TPMS designs, leading to defects and limitations in scalability.
   - Additive Manufacturing (AM) Solutions:
   - Precision and Control: AM technologies, such as selective laser melting (SLM) and electron beam melting (EBM), provide precise control over pore size, relative density, and structural topology, making it

possible to fabricate complex TPMS designs.

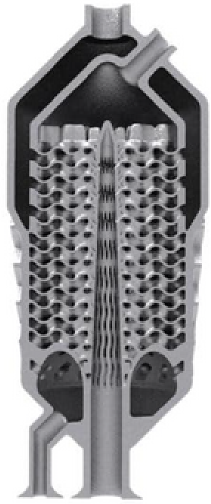
- Customization: AM enables the creation of patient-specific implants by customizing the geometry to match individual anatomical requirements.
- Scalability: The layer-by-layer fabrication approach of AM ensures scalability without compromising the accuracy of the final structure.
- Surface Modifications:
- Post-processing techniques, such as surface polishing and bioactive coatings (e.g., hydroxyapatite), enhance the biointegration and mechanical properties of AM-fabricated TPMS scaffolds.

2.3 Future Directions in TPMS Research

Emerging research in TPMS applications focuses on multi-material scaffolds, dynamic loading simulations, and hybrid structures for combined biomedical and engineering purposes. These advancements aim to further refine the functionality and adaptability of TPMS structures in diverse fields.



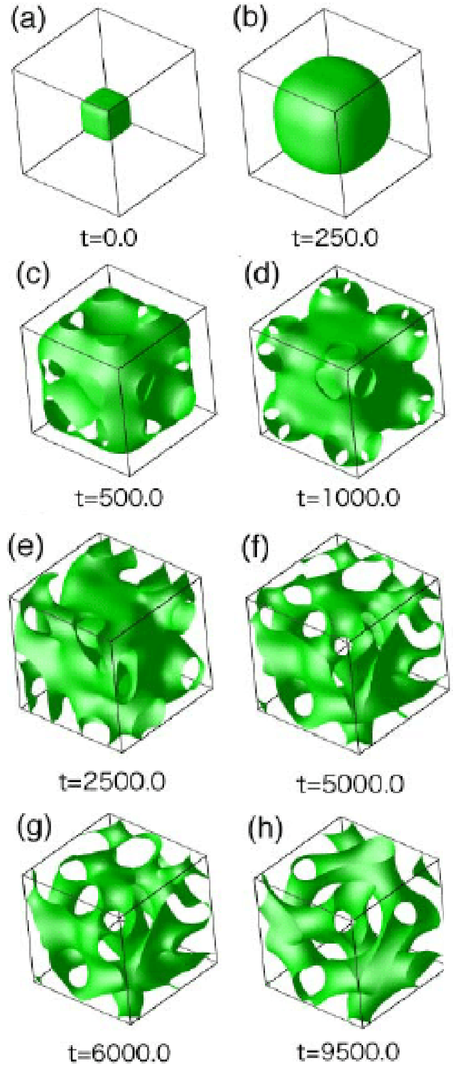
(a) Femur critical size defect replaced with anatomically matched scaffold (b) Loading and boundary conditions on the construct.



Heat exchanger made using ntopology

Chapter 3: Methodology

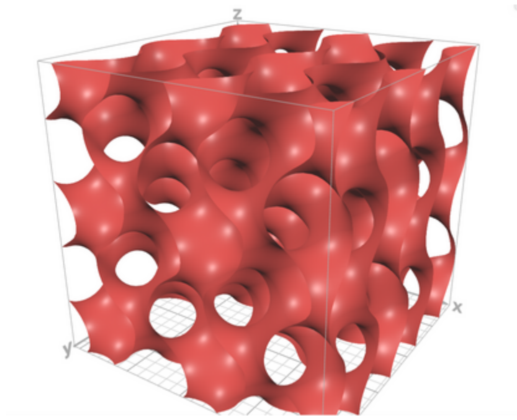
3.1 Design of TPMS Structures



The design of TPMS structures was conducted using Autodesk Fusion 360, a powerful CAD/CAM/CAE tool. Four distinct types of TPMS geometries—Gyroid, Neovius, Diamond, and Primitive—were selected for this study due to their unique structural and mechanical characteristics. Each structure was designed with varying thicknesses of 1 mm, 2 mm, and 3 mm to analyze how the material distribution affects the mechanical properties such as stress distribution, deformation, and load-bearing capacity.

Design Process

- **Mathematical Generation:** The TPMS structures were generated using implicit equations representing minimal surfaces. Desmos 3d graphing calculator was used.

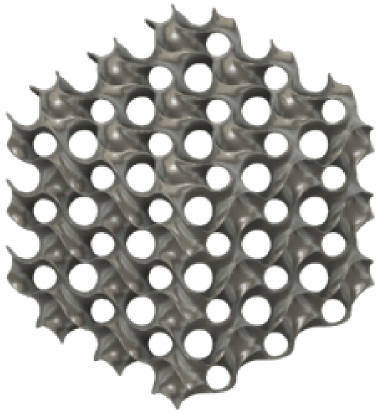


$$\left(\frac{2\pi}{a}x\right)\cos\left(\frac{2\pi}{a}y\right)+\sin\left(\frac{2\pi}{a}y\right)\cos\left(\frac{2\pi}{a}z\right)+\sin\left(\frac{2\pi}{a}z\right)\cos\left(\frac{2\pi}{a}x\right)=t$$

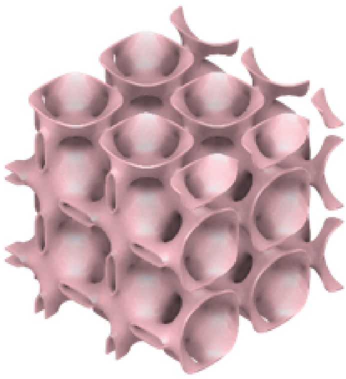
a: it is the lattice constant

t: it is the porosity of the structure

1. Parametric Modeling: Parameters such as cell size and wall thickness were varied systematically to create multiple design iterations.
2. Final CAD Models: The completed models were exported in the STL format for further simulation.



Gyroid 1 mm



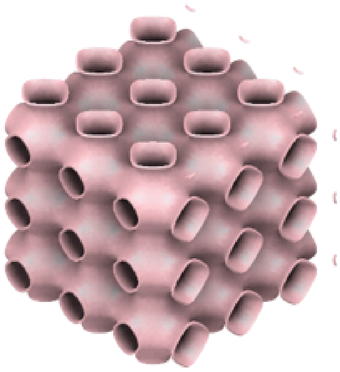
Neovius 1 mm

1. Parametric Modeling: Parameters such as cell size and wall thickness were varied systematically to create multiple design iterations. Final CAD Models: The completed models were exported in the STL format for further simulation.

1. Material Properties of 316L Stainless Steel

Material	Stainless Steel 316L
Density	7.990E-06 kg / mm^3
Young's Modulus	193.00 GPa
Poisson's Ratio	0.25
Yield Strength	170.00 MPa
Ultimate Tensile Strength	485.00 MPa
Thermal Conductivity	0.016 W / (mm C)
Thermal Expansion Coefficient	1.590E-05 / C
Specific Heat	500.00 J / (kg C)

Diamond 1 mm



Primitive 1 mm

1. 316L stainless steel offers:
2. High Biocompatibility: Suitable for direct contact with biological tissues without causing adverse reactions.
3. Resistance to Corrosion: Performs well in saline and bodily fluid environments.
4. Mechanical Robustness: Capable of withstanding significant loading without failure.

3.3 Simulation Setup

Mechanical simulations were conducted in Fusion 360 to evaluate the performance of TPMS scaffolds under realistic loading conditions. The simulation process included the following steps:

a. **Meshing:** High-quality finite element meshes were generated to capture stress and deformation details accurately.

b. **Boundary Conditions:** 10N Compression forces were applied uniformly across the top surface of the scaffold, with the bottom surface fixed to replicate load-bearing scenarios.

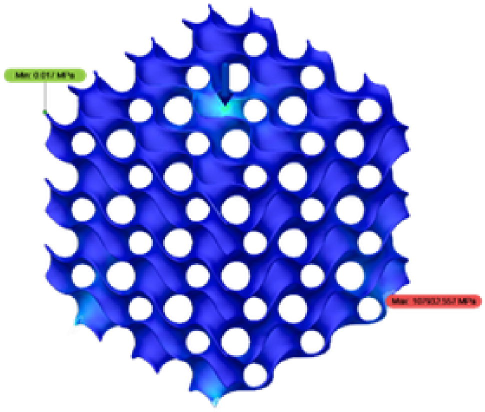
c. **Parameters Evaluated:**

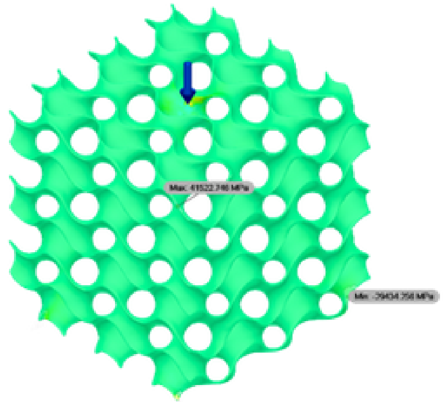
   i. **Von Mises Stress**: To identify areas prone to failure.

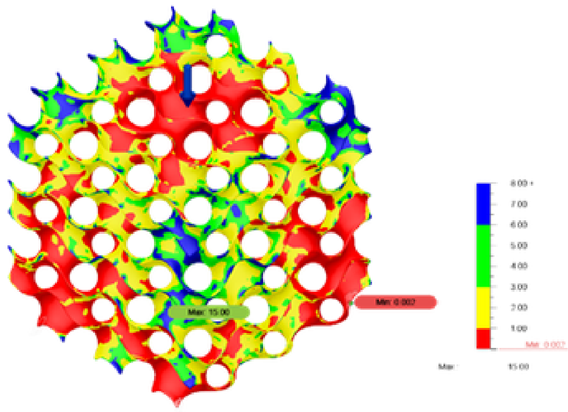
   ii. **Maximum Principal Stress:** To understand tensile stress distributions.

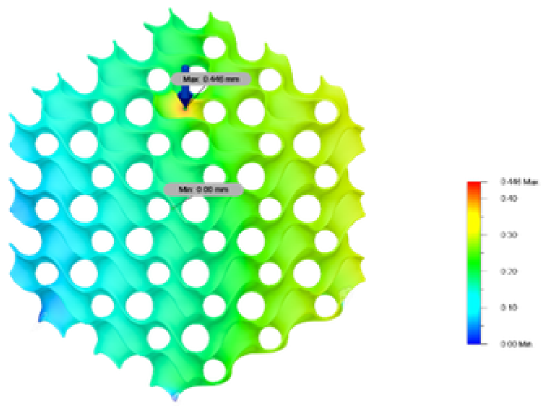
   iii. **Factor of Safety (FoS):** To assess overall structural reliability.

   iv. **Deformation:** To measure the scaffold's displacement under load.







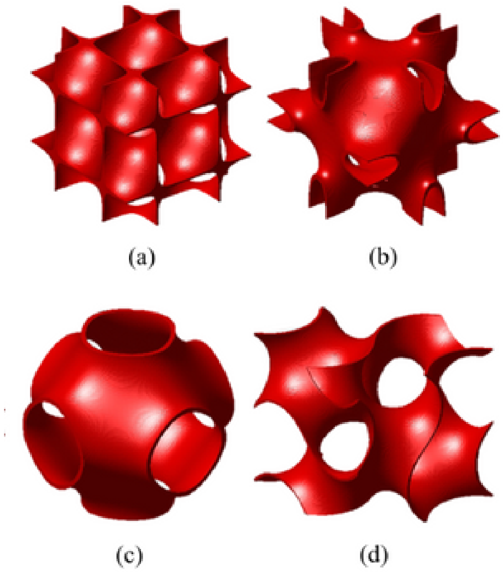


Chapter 4: Modeling of TPMS Structures

4.1 Overview of TPMS Geometry

Each TPMS geometry exhibits unique properties that make it suitable for specific applications:

1. **Diamond:**
   - Known for its high stiffness, making it ideal for axial load applications.
   - Offers superior mechanical stability under compression.
2. **Neovius:**
   - Balances structural rigidity and porosity, making it versatile for multiple uses.
3. **Primitive:**
   - Features stretching-dominated deformation, contributing to its high strength.
   - Effective for applications requiring enhanced load-bearing capacity.
4. **Gyroid:**
   a. Exhibits isotropic behavior, ensuring uniform load distribution.
   b. Provides a balance between mechanical strength and porosity.



Chapter 5: Simulation Analysis and Results

5.1 Mechanical Properties

Elastic Modulus

- Gyroid and Diamond: These structures exhibited a higher elastic modulus, demonstrating their suitability for load-bearing applications.
- Primitive: This design showed enhanced resilience due to its stretching-dominated deformation.

Stress Distribution

- Gyroid: Displayed uniform stress distribution, reducing the risk of failure.
- Primitive: Highlighted localized stress zones, but withstanding higher loads due to structural strength.

Placement of Results:

- Include color-mapped stress distribution plots for each TPMS geometry under compression.
- Add a bar chart comparing elastic modulus across different thicknesses.
-

5.2 Observations on Porosity

- High porosity in TPMS designs enables nutrient transport and vascularization, which are critical for tissue integration.
- Porosity was tunable by modifying the relative density, allowing flexibility to adapt to specific biomedical applications.

Placement of Data:

- Add a table summarizing porosity and relative density values for each geometry and thickness.
- Include a cross-sectional image of a TPMS scaffold showing interconnected porosity.

Note on Thermal Analysis

- *Thermal properties and heat transfer simulations for compact heat exchanger applications are reserved for future work. This will include evaluations of thermal conductivity and fluid flow efficiency in TPMS geometries.*

Chapter 6: Applications and Discussion

6.1 Biomedical Applications

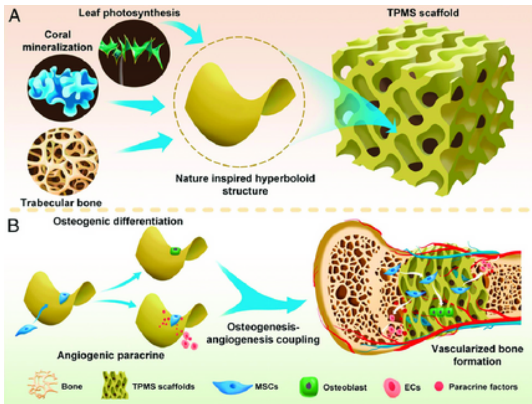
TPMS scaffolds have gained significant attention in the field of biomedical engineering due to their ability to mimic the architecture and functionality of natural tissues. Their unique properties make them ideal for a variety of biomedical applications:

1. **Bone Scaffolds**

- TPMS scaffolds closely resemble the internal structure of cancellous bone, offering a balance between mechanical strength and porosity. Key benefits include:
  - **Biocompatibility:** Materials like 316L stainless steel ensure the scaffold is safe for implantation, reducing the risk of adverse reactions.
  - **Load-bearing Capability:** The structural integrity of TPMS designs, combined with their ability to distribute stress uniformly, makes them suitable for load-bearing applications such as hip or knee replacements.
  - **Facilitating Bone Regeneration:** The porous architecture supports osteointegration by allowing bone tissue to grow into the scaffold, promoting natural healing.

2. **Tissue Engineering:**

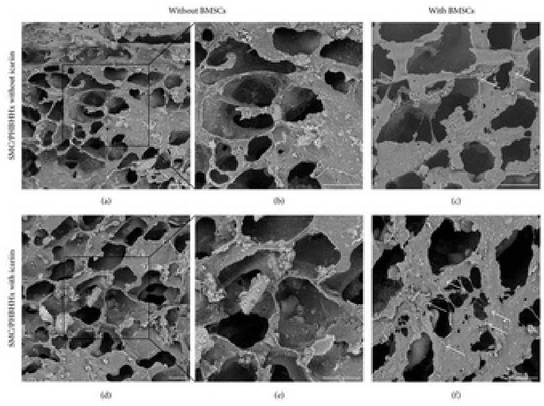
- TPMS geometries provide a supportive environment for tissue engineering by enabling:
  - **Enhanced Permeability:** The interconnected pores facilitate the flow of nutrients, oxygen, and waste, ensuring a conducive environment for cell proliferation and differentiation.
  - **Customizable Porosity:** By adjusting design parameters, the porosity can be tailored to meet specific requirements, such as higher permeability for vascular tissues or increased strength for cartilage regeneration.
  - **Vascularization Support:** The scaffold's design encourages the formation of blood vessels, which is crucial for long-term tissue survival.



microscopic images or cross-sections of TPMS scaffolds integrated with bone or tissue

6.2 Challenges in Implementation

While TPMS structures hold great promise, there are challenges to their widespread implementation:



1. **Manufacturing Defects**
    - **Issue:** Additive manufacturing (AM) processes such as selective laser melting (SLM) or electron beam melting (EBM) can introduce defects such as uneven pore distribution, residual stresses, or incomplete fusion of material layers.
    - **Impact:** These defects can compromise the mechanical integrity and reliability of the scaffold.
    - **Mitigation:** Post-processing techniques like heat treatment, surface polishing, or hot isostatic pressing (HIP) can reduce defects and improve performance.
2. **Design Trade-offs**
    - **Porosity vs. Strength:** High porosity enhances permeability but reduces mechanical strength. Achieving an optimal balance between these properties remains a critical design challenge.
    - **Customization Complexity:** Adapting TPMS structures for patient-specific requirements demands advanced computational modeling and manufacturing precision.

Chapter 7: Conclusion

This study demonstrates the immense potential of 316L stainless steel TPMS scaffolds for biomedical applications, particularly in bone tissue engineering and other implantable devices. The key findings include:

1. **Mechanical and Biomimetic Advantages:**
   - TPMS structures offer tunable properties such as porosity and strength, enabling them to mimic natural tissues.
   - Mechanical simulations showed that designs like Gyroid and Diamond distribute stress uniformly, reducing failure risks.
2. **Material Viability:**
   - The use of 316L stainless steel ensures durability and biocompatibility, making it suitable for long-term implantation.
3. **Future Scope:**
   - The study establishes a foundation for extending TPMS applications to compact heat exchangers and other multi-functional systems.
   - Future work will focus on thermal properties analysis, dynamic loading simulations, and hybrid material integration to enhance functionality further.

Appendices

Appendix 1: Modeling Parameters

Details of the parameters used for designing TPMS structures:

- Geometries: Gyroid, Neovius, Diamond, Primitive
- Thickness Variations: 1 mm, 2 mm, 3 mm
- Material: 316L stainless steel
- Software: Autodesk Fusion 360

Appendix 2: Simulation Results

Summarized results from the mechanical simulations:

- Stress-Strain Data: Highlighting elastic modulus, von Mises stress, and deformation for each TPMS geometry and thickness.
- Elastic Modulus Comparison:
  - Gyroid: ~140 GPa
  - Diamond: ~150 GPa
  - Primitive: ~130 GPa

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