

**DESIGN AND FABRICATION OF NOVEL MULTI-
MATERIAL MECHANICAL METAMATERIALS
USING ADDITIVE MANUFACTURING**

BY

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A Thesis Presented to the
COLLEGE OF GRADUATE AND INTERDISCIPLINARY STUDIES
KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

MECHANICAL ENGINEERING

MAY 2025

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

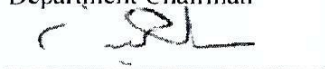
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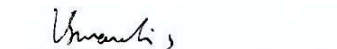
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I dedicate this thesis wholeheartedly to my mom, dad, brother, sisters and all family members and friends who supported me throughout my studies and every part of my life.

Acknowledgments

First and foremost, I begin by expressing my deepest gratitude to Allah Almighty for His infinite wisdom, guidance, and blessings upon me and all humanity. I am thankful to the Deanship of Graduate Studies and Department of Mechanical Engineering at King Fahd University of Petroleum and Minerals (KFUPM) for providing an excellent academic and research environment.

I would like to express my sincere gratitude to my supervisor, Dr. Aamer Nazir, for his continuous support, encouragement, and invaluable guidance which played a pivotal role in shaping the direction of my thesis and in helping me grow both academically and professionally. Special thanks to my committee members, Dr. Usman Ali and Dr. Suhail Vattathurvalappil for their unwavering support and constructive guidance. I would also like to thank Dr. Jafar Albinmoussa for letting us use the equipment in his lab for uniaxial compression testing. I would also like to extend my gratitude to Dr. Kashif Azher and Mr. Irfan Ahmed who supported me during the experimental and simulation phases of my work.

Heartfelt thanks to my parents, whose sacrifices, unconditional love, and belief in my dreams laid the foundation for all my achievements. To my siblings, fiancé, friends and loved ones, thank you for your encouragement, understanding, and patience throughout this journey. Lastly, I would like to thank the Pakistani community at KFUPM for their social support. Completing this thesis has been a challenging yet immensely rewarding journey. It would not have been possible without the support of all the individuals mentioned above.

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NOMENCLATURE

MM	Mechanical Metamaterial
AM	Additive Manufacturing
FDM	Fused Deposition Modelling
TPMS	Triply periodic minimal surface
PLA	Polylactic Acid
TPU	Thermoplastic Polyurethane
DOE	Design of Experiments
FEA	Finite Element Analysis
SEM	Scanning Electron Microscopy
ANN	Artificial Neural Network

ABSTRACT

Full Name : Muhammad Abbas

Thesis Title : Design and Fabrication of Novel Multi-Material Mechanical Metamaterials
Using Additive Manufacturing

Major Field : Mechanical Engineering

Date of Degree: 4th May, 2025

Current research on mechanical metamaterials has primarily focused on single-material structures, limiting the understanding of how combining multiple materials could enhance multifunctional mechanical performance. A significant knowledge gap remains in the design and fabrication of multi-material mechanical metamaterials and their potential to achieve superior strength, stiffness, and energy absorption compared to traditional homogeneous designs. Advances in additive manufacturing now enable the integration of different materials within complex metamaterial architectures. This study addresses the challenge of designing mechanical metamaterials with customizable properties arising from multi-material combinations to meet the growing demand for lightweight, high-strength, or energy-absorbing structures in advanced engineering applications. Three types of lattice structures i.e. plate-based, strut-based cubic, and triply periodic minimal surface (TPMS) diamond were fabricated using fused deposition modeling (FDM), with polylactic acid (PLA) for structural rigidity and thermoplastic polyurethane (TPU) for flexibility and energy absorption. A Design of Experiments (DOE), using the Taguchi method, was applied to optimize parameters such as unit cell configuration, core material thickness, and wall thickness for cubic lattices, while relative density and material ratio were key design factors for diamond lattices. An artificial neural network (ANN) model was also used to

predict design parameters for TPMS based on desired mechanical properties. Results showed that compression modulus, energy absorption, and peak load increased with higher relative density and PLA percentage. Energy loss in diamond structures slightly decreased with increasing relative density. Finite element analysis (FEA) demonstrated how material distribution and geometry influence mechanical performance, while scanning electron microscopy (SEM) revealed strong interfacial bonding between PLA and TPU layers. ANN-predicted TPMS structures also closely matched experimental outcomes. Across all three structures, varying material and geometric configurations enabled diverse mechanical properties, emphasizing the importance of customizability for targeted applications. This study highlights additive manufacturing as a transformative tool in developing next-generation multi-material metamaterials with significant potential for aerospace, biomedical, and other high-performance uses.

ملخص الرسالة

الاسم الكامل: محمد عباس

عنوان الرسالة: تصميم وتصنيع مادة مينا ميكانيكية جديدة متعددة المواد باستخدام التصنيع الإضافي

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: 4 مايو 2025

ركزت الأبحاث الحالية حول المواد الخارقة الميكانيكية بشكل أساسي على الهياكل أحادية المادة، مما حدّ من فهم كيفية تعزيز الأداء الميكانيكي متعدد الوظائف من خلال دمج مواد متعددة. ولا تزال هناك فجوة معرفية كبيرة فيما يتعلق بتصميم وتصنيع المواد الخارقة الميكانيكية متعددة المواد وقدرتها على تحقيق قوة وصلابة وامتصاص طاقة فائقين مقارنةً بالتصاميم المتجانسة التقليدية. وتتيح التطورات في التصنيع الإضافي تركيبات مواد مختلفة داخل المواد الخارقة الميكانيكية المعقدة. ومن ثم، تتناول هذه الدراسة تحدي تصميم مواد خارقة ميكانيكية ذات خصائص قابلة للتخصيص ناشئة عن مواد متعددة لتلبية الطلب المتزايد على الهياكل خفيفة الوزن وعالية القوة أو الماصة للطاقة في التطبيقات الهندسية المتقدمة. وقد صُنعت ثلاثة أنواع من الهياكل الشبكية، وهي هياكل القائمة على الصفائح والقائمة على (TPMS) شبكية متعددة المواد من الماس المكعب والثلاثي الدوري لتحقيق صلابة هيكلية، (PLA) مع حمض البولي لاكتيك (FDM) الدعامات، باستخدام نمذجة الترسيب المندمج لتحقيق المرونة وامتصاص الطاقة. تم تطبيق تصميم التجارب (TPU) والبولي يوريثان الحراري اللدن ، بالاستفادة من طريقة تاجوتشي، لتحسين معلمات مثل تكوين الخلية الوحوية، وسمك مادة اللب، (DOE) وسمك الجدار لهياكل الشبكة المكعبة متعددة المواد، بينما شكّلت الكثافة النسبية ونسبة المواد عاملي التصميم كما استُخدم نموذج التعلم الآلي للشبكات العصبية الاصطناعية. MM. الرئيسيين المختارين لهياكل الشبكة الماسية بناءً على الخصائص الميكانيكية المطلوبة. أظهرت النتائج أن TPMS للتنبؤ بمعلمات تصميم نظام (ANN) درست PLA. معامل الانضغاط، وامتصاص الطاقة، وحمل الذروة يتناسب طرديًا مع الكثافة النسبية ونسبة أيضًا خسارة الطاقة لهياكل الشبكة الماسية، والتي أظهرت انخفاضًا طفيفًا في نسبة خسارة الطاقة عند زيادة عن تأثير توزيع المواد وهندستها على الأداء الميكانيكي، (FEA) الكثافة النسبية. كشف تحليل العناصر المحدودة رؤى حول سلوك الواجهة، والذي أظهر (SEM) بينما قدّم تحليل الكسر باستخدام المجهر الإلكتروني الماسح

المتوقعة ذات الأهداف المختلفة، ANN كما تم اختبار هياكل الشبكة، PLA و TPU ترابطاً قوياً بين طبقات وأظهرت توافقاً ممتازاً بين القيم التجريبية والقيم المطلوبة. في جميع الهياكل الثلاثة، سمح التغيير في تكوينات المواد والهياكل للهياكل بسلوك مختلف وإعطاء مجموعة متنوعة من الخصائص الميكانيكية المتغيرة، والتي تُعد بالغة الأهمية لتخصيص الهياكل وفقاً للتطبيق المطلوب. وبالتالي، تُسلط هذه الدراسة الضوء على أهمية التصنيع الإضافي كأدوات تحويلية في تطوير الجيل القادم من المواد الفائقة متعددة المواد، مما يوفر إمكانيات كبيرة لتطبيقات الفضاء والطب الحيوي وغيرها من التطبيقات عالية الأداء

CHAPTER 1

INTRODUCTION

1.1 Background

Nature has always served as the primary architect, creating materials and structures that demonstrate exceptional strength, adaptability, and longevity. An intriguing feature of natural design is the strategic use of both flexible and rigid materials in a singular structure to attain an ideal equilibrium of characteristics. The combined effect of different components, ranging from bones to shells, plants to animal tissues, plays a crucial role in nature's capacity to generate robust, adaptable, and efficient systems. An exemplary illustration of the synergistic relationship may be observed in the exoskeletons of arthropods, including insects and crustaceans. The exoskeleton is composed of chitin, a rigid substance that offers both defense and structural reinforcement, while still possessing sufficient flexibility to enable mobility. The exoskeleton of the animal is composed of segments that are joined together by flexible and stretchable membranes, allowing the animal to move while yet having a durable exterior shell. The utilization of both rigid and flexible materials enables arthropods to possess both agility and resilience, which is a crucial element in their survival.

Metamaterials are artificially engineered structures designed to exhibit extraordinary properties not typically found in conventional materials. Initially conceptualized in the context of electromagnetic materials, the concept has evolved and expanded across various fields, including acoustics, optics, and mechanics. Their unique behaviors primarily result from carefully designed periodic architectures rather than solely from their intrinsic material composition, enabling designers to manipulate waves, vibrations, and mechanical

properties at unprecedented levels.

Mechanical metamaterials (MMs) represent a specialized class of these engineered structures, specifically tailored to exhibit remarkable mechanical properties through their geometrical design. Such properties include negative Poisson's ratios (auxetic behavior), tunable stiffness, exceptional energy absorption, and lightweight yet high-strength characteristics. These structures are often realized in the form of lattice architectures periodic cellular frameworks such as strut-based, plate-based, or triply periodic minimal surface (TPMS) lattices. Due to their customizable mechanical responses, MMs have become highly relevant in fields requiring superior mechanical performance, energy dissipation capabilities, and controlled deformation under load, such as aerospace, automotive, biomedical implants, and protective systems.

Simultaneously, multi-material systems where two or more distinct materials are integrated within a single structure have gained increasing interest in engineering applications. By combining materials with complementary properties, engineers can exploit unique mechanical synergies, achieving performance unattainable with single-material systems alone. Such combinations often include rigid and flexible components, stiff and compliant layers, or structural and energy-absorbing materials, significantly enhancing the overall performance, resilience, and functionality of components. However, conventional multi-material combinations present several technical challenges, notably interfacial incompatibility, thermal mismatch, and difficulties in controlling precise material distribution, thus limiting their broader adoption.

The concept of multi-material MMs merges the strengths of both fields by strategically combining materials within carefully engineered lattice geometries. This integration leverages the geometric advantages of MMs while simultaneously benefiting from tailored material combinations, significantly enhancing properties such as strength, stiffness, ductility, and energy absorption. Multi-material MMs are uniquely capable of achieving performance that far exceeds the capabilities of homogeneous materials or conventional composites. Their design flexibility allows precise control over deformation behavior, energy dissipation patterns, and structural resilience, enabling engineers to tailor structures specifically to complex and demanding applications.

Additive manufacturing (AM), commonly known as 3D printing, has emerged as an essential enabling technology in the fabrication of multi-material MMs. The inherent layer-by-layer building approach of AM facilitates precise placement and distribution of multiple materials, allowing complex, multi-material lattice structures to be fabricated with high precision. AM techniques, especially fused deposition modeling (FDM), enable cost-effective and rapid prototyping, significantly reducing design iteration time and enhancing the feasibility of fabricating intricate geometries and multi-material interfaces previously challenging or impossible using conventional manufacturing methods.

Among multi-material MMs, lattice structures such as strut-based, plate-based, and TPMS configurations have demonstrated distinct mechanical advantages. Strut-based lattices, composed of interconnected rods or beams, provide high strength-to-weight ratios and tunable stiffness, making them suitable for structural applications demanding lightweight

and structural efficiency. Plate-based lattice structures, characterized by interconnected thin plates, often exhibit superior stiffness, stability, and enhanced energy absorption properties, particularly advantageous in load-bearing and impact-resisting components. TPMS-based lattices, including diamond and gyroid geometries, offer smooth and continuous surfaces, leading to isotropic mechanical properties and efficient stress distribution. Their unique geometry enhances resilience and significantly increases energy absorption capacity.

Systematic optimization of design parameters is critical to fully realizing the potential of multi-material mechanical metamaterials. Techniques such as the Taguchi Design of Experiments (DOE) methodology offer a structured and efficient approach for determining optimal configurations. This method systematically evaluates the impact of critical parameters including lattice geometry, relative density, material ratios, and structural dimensions on mechanical properties like strength, stiffness, and energy absorption. Such systematic optimization ensures that multi-material mechanical metamaterials are precisely tailored to desired application-specific performance criteria while significantly reducing experimental and computational costs.

Furthermore, the complexity and vast design space of multi-material mechanical metamaterials necessitate advanced computational methods. Machine learning (ML), specifically artificial neural networks (ANN), provides a powerful approach to predict and optimize mechanical properties of these metamaterials rapidly. ANN models can establish accurate predictive relationships between design parameters and desired mechanical

outcomes, enabling efficient inverse design. By training ANN models on experimental data, designers can swiftly determine optimal material distributions and lattice geometries, significantly enhancing the accuracy, speed, and effectiveness of the design and optimization processes.

Considering these aspects, this thesis addresses critical gaps in understanding and optimizing multi-material mechanical metamaterials, specifically focusing on cubic (strut-based and plate-based) and TPMS diamond lattice configurations composed of Polylactic Acid (PLA) and Thermoplastic Polyurethane (TPU). These polymer-polymer combinations were selected for their complementary mechanical attributes: PLA providing structural rigidity, stiffness, and dimensional stability, while TPU offers flexibility, high elongation at break, and superior energy absorption capabilities. Through a comprehensive combination of experimental characterization, numerical analysis, systematic optimization, and ML-driven inverse design methodologies, this research seeks to elucidate the intricate interactions between materials, geometry, and mechanical performance in multi-material mechanical metamaterials.

Ultimately, the insights and findings derived from this study are expected to significantly impact fields such as aerospace, automotive, biomedical, and protective equipment, where precise control over mechanical properties, lightweight structures, and tailored deformation behaviors are essential. This research emphasizes the transformative potential of multi-material mechanical metamaterials, positioning them as critical solutions for developing next-generation materials and structures that can meet increasingly

sophisticated engineering requirements.

1.2 Applications

The potential applications of the multi-material mechanical metamaterials studied in this thesis extend across various industrial and consumer sectors, emphasizing their versatility and practicality. The automotive seats shown in Figure 1.1a illustrate a direct implementation of lattice-based metamaterials, similar to the cubic and TPMS diamond lattice structures explored in this research. Combining rigid polymers such as PLA for structural stability and flexible elastomeric materials like TPU for comfort and energy absorption, these seats significantly enhance passenger comfort and safety, while reducing overall vehicle weight and improving fuel efficiency. This optimized multi-material approach is particularly relevant for Saudi Arabia's developing automotive manufacturing industry.



Figure 1.1. Practical applications of multi-material mechanical metamaterials explored in this thesis, demonstrating enhanced mechanical performance, energy absorption, and tailored comfort in a) automotive seating, b) customized footwear [1], and c) protective helmets [2].

Similarly, the footwear application demonstrated in Figure 1.1b employs lattice-structured metamaterials to create customized shoes and insoles. By integrating stiff and flexible polymer combinations, specifically PLA and TPU, the resulting footwear can effectively absorb impact forces, reduce user fatigue, and provide personalized comfort and ergonomic support. Such customizable lattice-based footwear aligns with the growing consumer preference for personalized products and supports opportunities for local manufacturing, thus positively contributing to Saudi Arabia's athlete's consumer and industrial markets. The protective helmet illustrated in Figure 1.1c further exemplifies the benefits of multi-material metamaterials in enhancing safety and comfort in protective gear. The internal lattice cushioning structures, typically made from flexible TPU, paired with a rigid outer shell, effectively dissipate impact energy, providing superior protection and comfort to users. This type of multi-material configuration makes these helmets ideal for sports, military, and industrial safety applications. Given the increased emphasis on safety standards in Saudi Arabia, the adoption of multi-material lattice-based helmets represents a valuable innovation for improving occupational safety and recreational protection. Collectively, these examples illustrate the broad industrial relevance and significant practical benefits offered by the multi-material mechanical metamaterials explored in this thesis, underscoring their potential impact within Saudi Arabia and beyond.

1.3 Motivation and Justification

Currently, there is a growing study focusing on multi-material mechanical metamaterial structures to improve mechanical properties as compared to traditional material structures. Based on a critical review of existing literature, research into mechanical metamaterials has predominantly focused on single-material configurations, with multi-material

capabilities still at an early exploration stage. Most studies to date have concentrated on honeycomb or gyroid-based lattice structures, extensively analyzing their mechanical behavior, performance limitations, and functional adaptability. In contrast, cubic and diamond lattice structures have received significantly less attention, particularly regarding their multi-material potential. This gap in research represents a critical oversight, given that these lattice geometries possess unique characteristics which may offer distinct mechanical advantages. Recent comparative analyses indicate that diamond lattice structures exhibit superior energy absorption and loading capabilities compared to other widely studied structures such as body-centered cubic (BCC), honeycomb, and gyroid lattices.

Furthermore, from the literature review, it is evident that both geometry and material composition significantly influence the mechanical properties of mechanical metamaterials. Optimization of these parameters plays a crucial role in realizing optimal mechanical performance. While existing research on machine learning-assisted lattice structure design primarily focuses on single-material configurations for determining geometrical parameters, studies addressing the inverse design of multi-material structures remain limited.

Therefore, this study specifically investigates single and multi-material cubic and diamond lattice structures fabricated via Fused Deposition Modeling (FDM) additive manufacturing. Through experimental compression testing, critical mechanical properties, including peak load, compression modulus, and energy absorption, were evaluated. Additionally, the energy loss% during unloading was also quantified. To systematically explore and optimize these structures, the experimental data was employed to train an

artificial neural network (ANN) model aimed at facilitating inverse design. This approach enables the targeted selection of lattice structure parameters to achieve desired mechanical outcomes. Several design iterations were conducted based on varying mechanical properties predicted by the ANN model, and the fabricated multi-material lattice structures demonstrated strong agreement with experimental results. This research thus addresses critical gaps in current literature by thoroughly examining the relationship between geometry, material composition, and mechanical performance, establishing a foundation for optimized multi-material cubic and diamond metamaterial designs [3], [4], [5], [6].

1.4 Objectives

The following objectives will be covered through the course of this thesis:

1. Design of multi-material samples and analysis of the samples using Finite Element Analysis.
2. Additive manufacturing of the designed samples using fused deposition modelling technique and mechanical characterization of the designed multi-material specimen using universal compression testing machine.
3. Fracture analysis of the tested specimens using Scanning Electron Microscope (SEM).
4. Performing machine learning optimization to design a multi-material specimen with better mechanical properties.

1.5 Organization of the Thesis

The thesis is divided into five chapters, each presenting a different aspect of the research. Chapter 1 introduces the research by highlighting the evolution and significance of metamaterials, mechanical metamaterials, and multi-material configurations and its applications. It outlines the motivation and justification for the research, Furthermore, it

defines specific objectives, highlighting the scope and significance of the study, and presents the overall structure of the thesis. Chapter 2 provides an in-depth literature review, critically examining existing research related to multi-material mechanical metamaterials. It critically examines traditional multi-material manufacturing methods, highlighting their limitations and contrasting them with recent advancements in multi-material additive manufacturing technologies. The chapter also explores various multi-material lattice structure designs, emphasizing their mechanical performance characteristics. Chapter 3 presents a comprehensive description of the research methodology, detailing the systematic design process of multi-material mechanical metamaterials structures, finite element analysis (FEA) procedures, fabrication methodologies, and fracture analysis methods. It also elaborates on the development and training of artificial neural networks (ANNs) for predicting optimal design parameters based on desired mechanical properties. Chapter 4 presents and analyzes the research findings comprehensively, discussing experimental results from mechanical characterization tests, comparing the performance of strut-based and plate-based cubic lattice structures alongside TPMS diamond lattice structures. It explores the relationships between design parameters, material ratios, and mechanical performance indicators, and compares numerical simulations (FEA) and experimental results along with proposing a novel MM lattice structure. Chapter 5 synthesizes the conclusions drawn from the comprehensive analysis, highlighting key contributions to advancing knowledge on multi-material mechanical metamaterials and proposing recommendations for future research directions.

CHAPTER 2

LITERATURE REVIEW

Recent advancements in additive manufacturing have resulted in an increased emphasis on multi-material systems, particularly those engineered for customized mechanical properties and multifunctionality. However, only 270 research papers have been published for multi-material additive manufacturing from 2020 onwards. A keyword co-occurrence network derived from relevant academic literature (Figure 2.1) demonstrates the interconnected nature of this study domain. The primary terms "multi materials" and "additive manufacturing" highlight the key emphasis areas, while neighboring clusters indicate specialized fields such as lattice structure design, metamaterials, powder bed fusion, and mechanical testing. Fused deposition modelling (FDM) is an essential procedure in multi-material research because to its accessibility and compatibility with thermoplastic materials. This thesis aims to expand upon the established intersections of mechanical metamaterials, multi-material extrusion, and design for additive manufacturing by investigating multi-material lattice structures made from PLA and TPU. These structures are engineered to provide widely diverse mechanical behaviors, aiding in the further investigation of performance-optimized multi-material structures.

referred to as "artificial atoms". Based on their characteristics, the recently produced metamaterials can be broadly categorized into four groups: electromagnetic metamaterials (EMMs), acoustic metamaterials (AMMs), thermal metamaterials (TMMs), and mechanical metamaterials (MMMs). An illustration of different types of meta materials is shown in Figure 2.2.

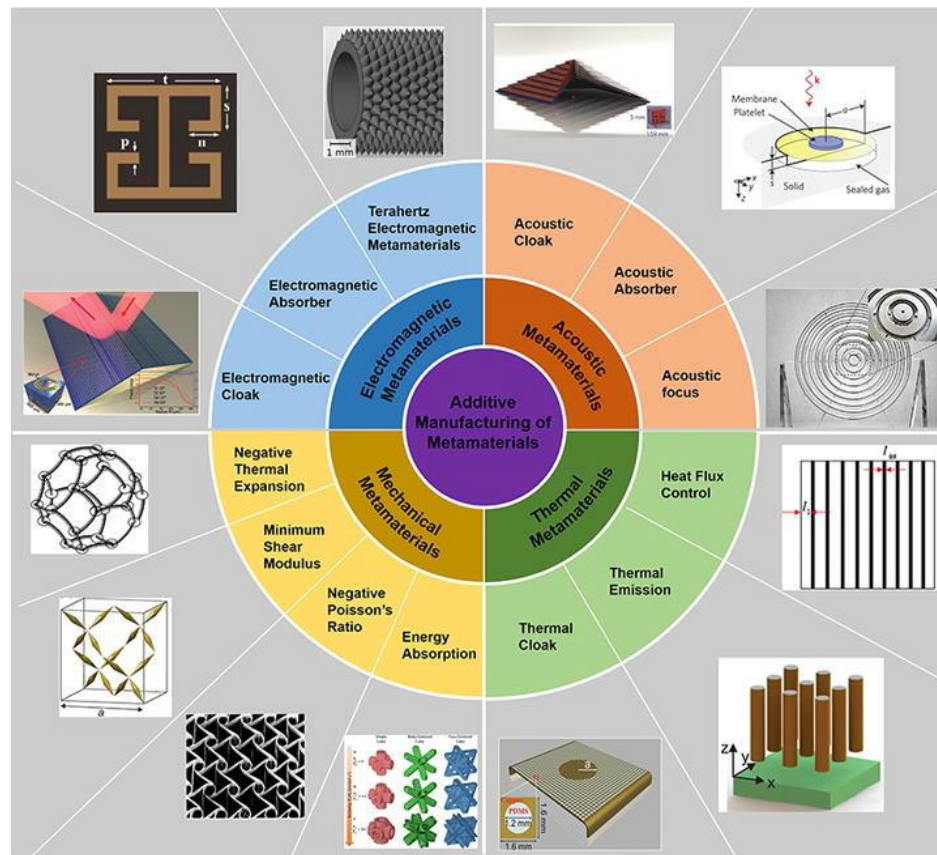


Figure 2.2. Different types of metamaterials based on their applications [10].

By analytically designing their microstructures, MMs can acquire unique and unusual mechanical characteristics [11], [12]. MMs may be made to exhibit desirable behavior by changing the interaction between material and structure. This allows for the incorporation of desirable functionality beyond their mechanical characteristics into their texture. Nevertheless, the realm of science may be vast, and scholars have only

just begun to explore its possibilities. Figure 2.3a depicts the "MM tree of knowledge" which classifies mechanical metamaterials based on their multifunctionality and autonomy, both within and beyond the mechanical domain. The tree is based on many studies that examine the future trajectory of the complete meta-materials family, encompassing well-established optical and electromagnetic metamaterials. Figure 2.3b depicts the current degree of development of MMs, both within and beyond the mechanical field. It also provides an overview of the future direction, which involves incorporating artificial cognition into the fabric of MMs.

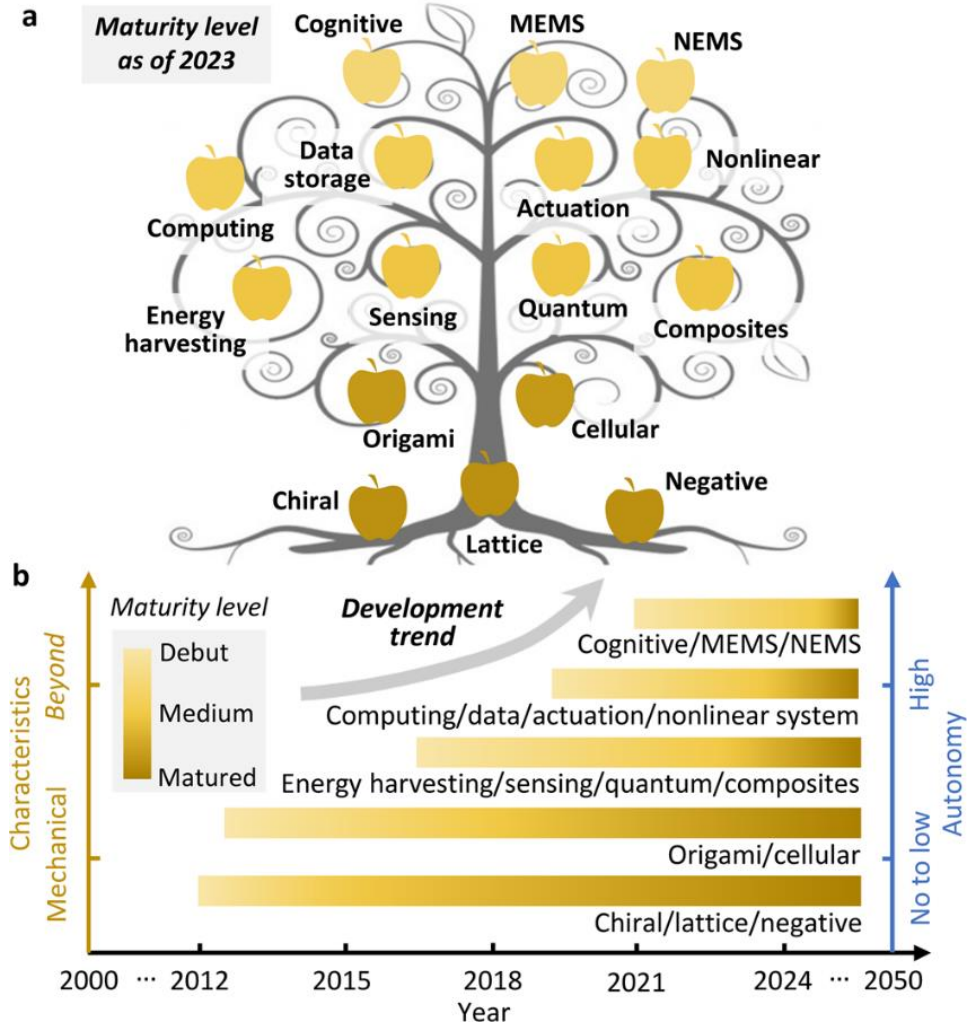


Figure 2.3. Knowledge tree of Mechanical Metamaterial. a) Mechanical metamaterials' future involves increasing mechanical functionalities and achieving cognition and autonomy. b) Mechanical metamaterials are maturing towards cognitive integrated systems [13].

Lattice structures (LSs) are strong, lightweight, low-density, and energy-absorbing [14], [15]. Cars, ships, airplanes, marine engineering, and other applications have used them extensively [16], [17]. Their complex microstructure provides unusual mechanical properties such a negative-Poisson-ratio (NPR), compressibility, and stiffness. Due to their capacity to tolerate fractures, indentation, sound absorption, and impacts, negative

Poisson's ratio (NPR) lattice materials have been widely used in engineering. Some examples of LSs are given in the Figure 2.4.

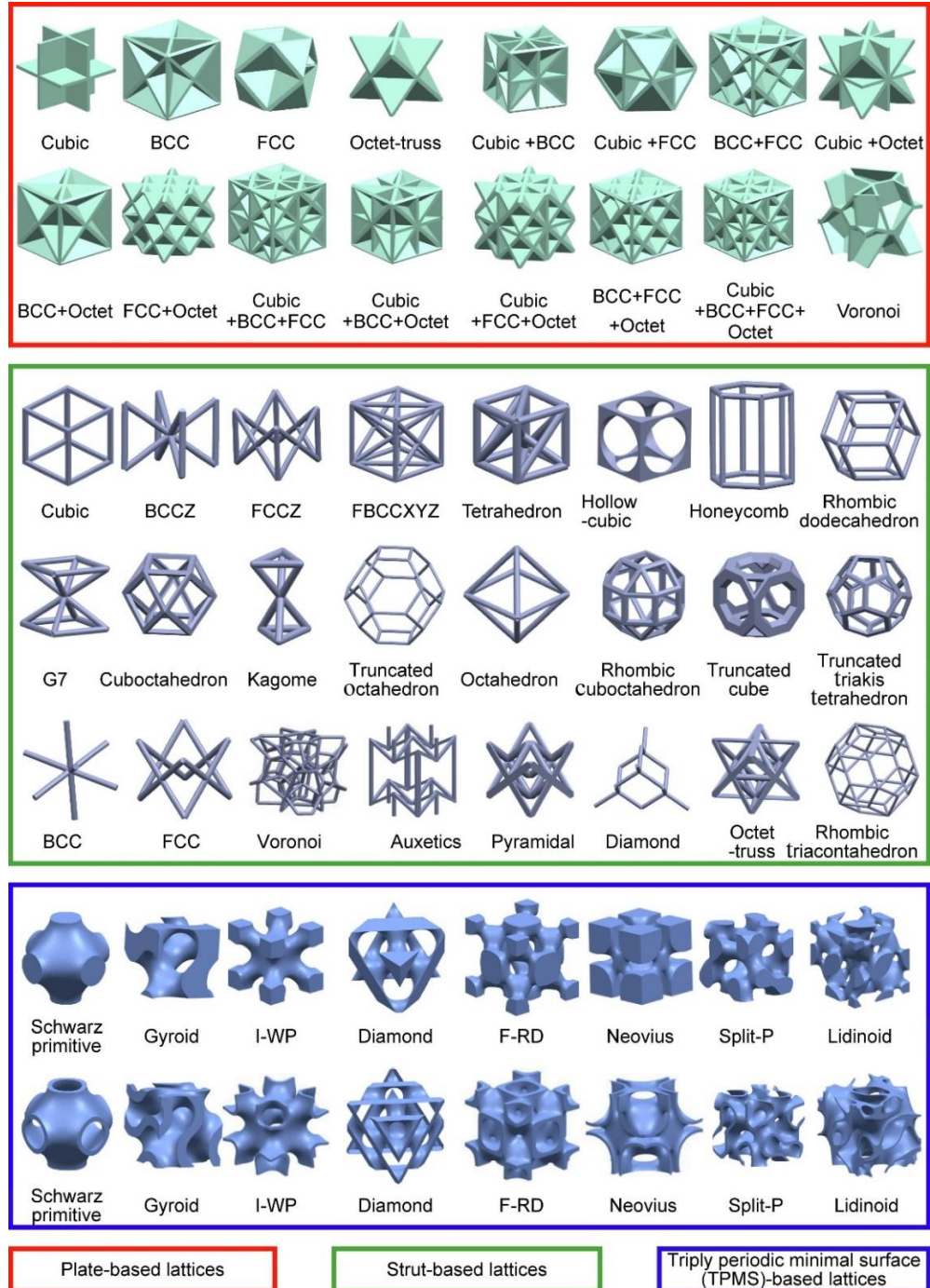


Figure 2.4. Example of unit-cell patterns used in additive manufacturing since 2005 [18].

Due to the unique characteristics that additive manufacturing technology provides, it is an excellent choice for the production of components that have lattice structures. For the purpose of fabricating MMs, a number of additive manufacturing technologies have been utilized, and the manufacturability of these structures has been explored. Several design approaches for MMs have been presented, and a number of specialized software programs have been developed in order to bring conceptual technology into the realm of industrial practice. When choosing the material, design, and porosity of Mechanical metamaterials, it is necessary to take into mind the mechanical behavior of the structures. Figure 2.5 represents frequently used techniques in additive manufacturing (AM).

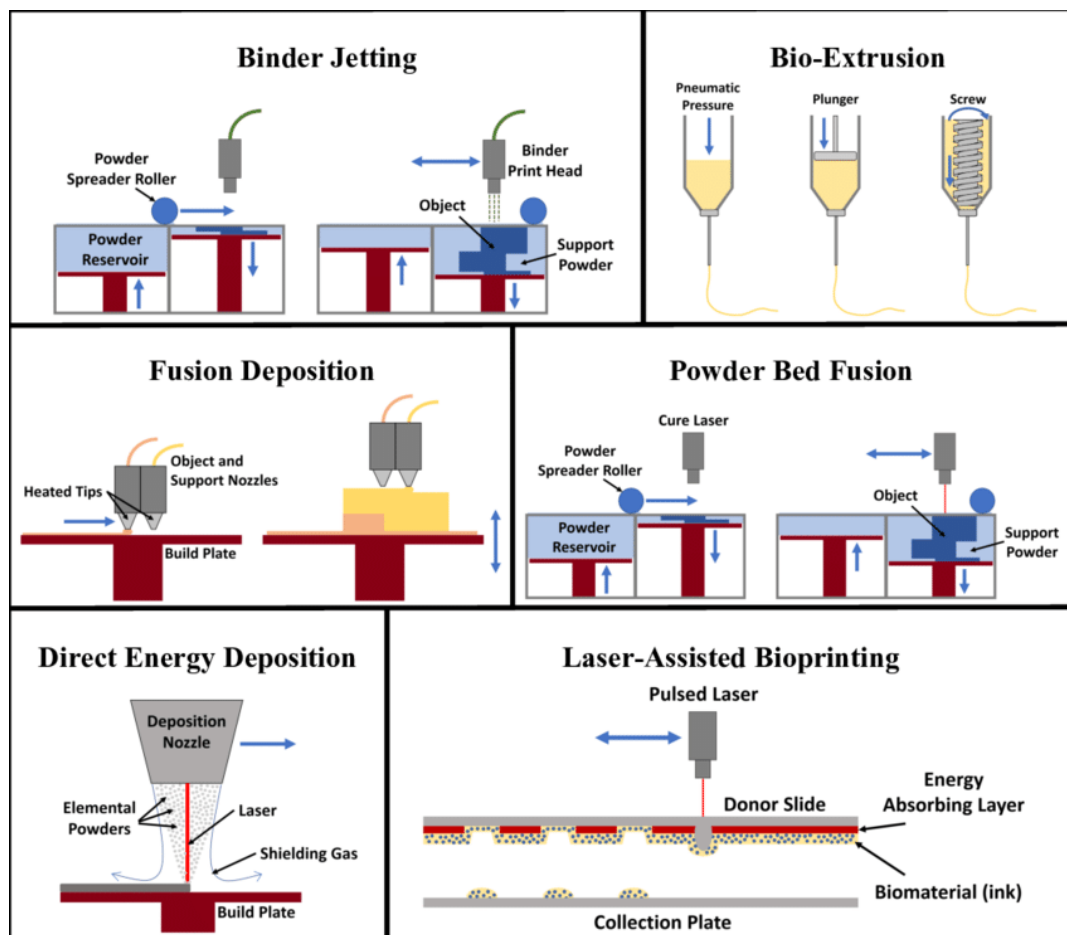


Figure 2.5. Frequently used techniques in additive manufacturing (AM) [19].

2.2 Conventional methods

In the past, various conventional methods were used to join at least two materials together. These methods include casting, welding, forging, machining and molding processes. A schematic diagram for these techniques is given in Figure 2.6.

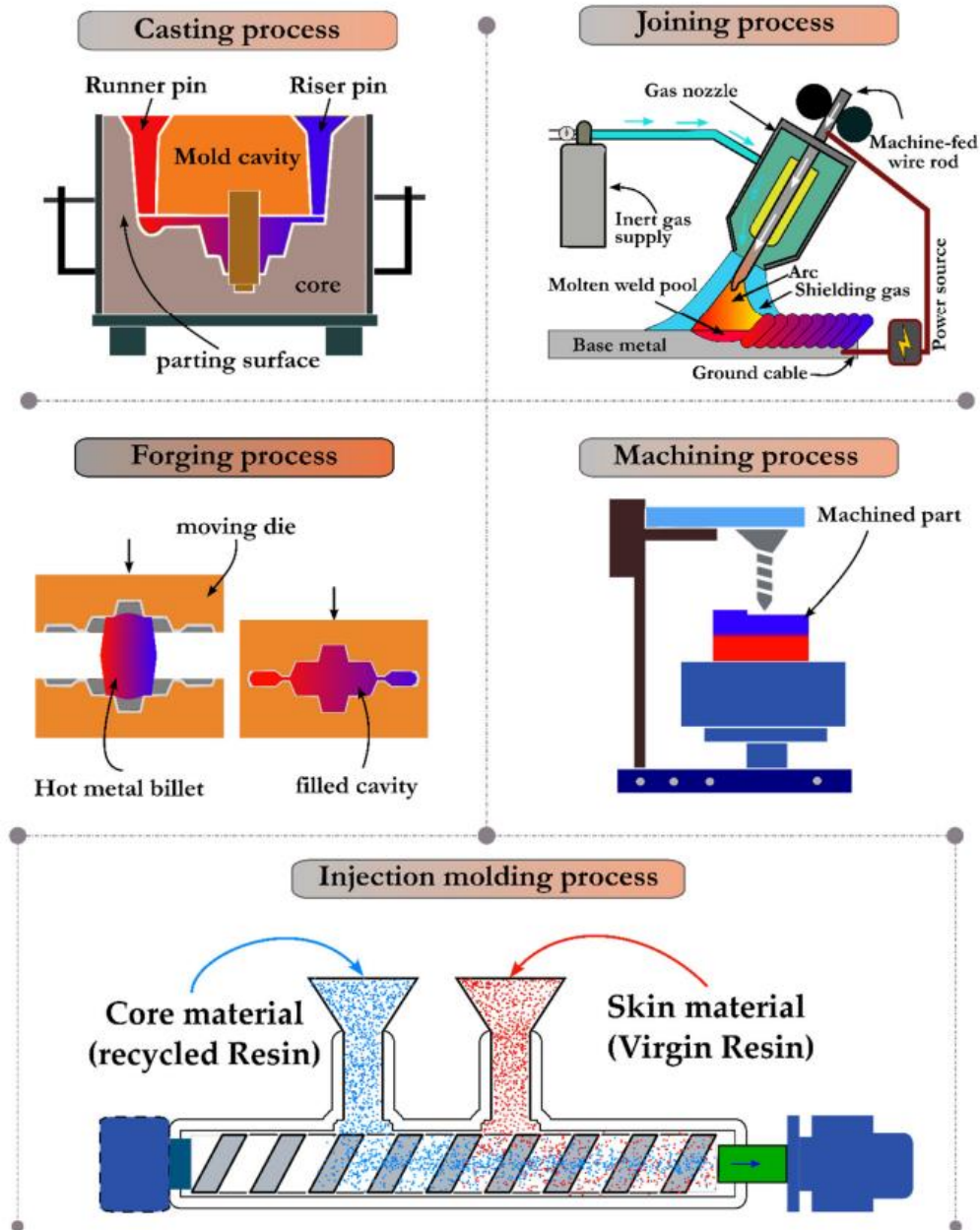


Figure 2.6. Schematic diagram for conventional manufacturing techniques used for creating single and multi-material structures [20].

Meschut et al. presented two innovative joining technologies based on traditional joining processes, REW (Rotational Extrusion Welding) and FEW (Friction Extrusion Welding), for a steel/aluminum material combination. They characterized these processes based on their technological properties and found that REW and FEW offer advantages over purely thermal or mechanical processes, with low process forces and high potential for profile-intensive constructions. The results showed that FEW has a process time of 1.7 seconds, slightly longer than REW and SPR, but offers flexibility in material and sheet thickness [21].

Wohletz et al. studied the effects of cold and warm forging on the bond strength and formation between steel and aluminum billets in multi-material designs. Warm forging was found to improve bond strength by equalizing flow stress, despite increased oxidation at elevated temperatures. The results showed that sound bonding was achieved, with bond strength increasing at specific temperature levels, though with some variability [22].

Marcel et al. investigated increasing interlayer bonding strength of plastic and addressed challenges in free-form surface structuring and chip extraction. It focuses on combining metal and plastic components in a single process, addressing the challenges of bonding and machining dissimilar materials. The robot-based manufacturing cell enables precise, cost-effective production of multi-material parts, enhancing flexibility and reducing tool costs [23].

Priyadarshi et al. developed a methodology for designing in-mold assemblies with articulated joints, focusing on mold design and joint clearance variation to meet performance goals. They presented proven templates for creating revolute, prismatic, and spherical joints and provided a mold design process for multi-material products with

articulated joints. By eliminating the need for post-molding assembly, the methodology reduces the complexity and number of parts in multi-material designs, improving efficiency and product quality. The approach benefits multi-material manufacturing by enabling the creation of complex, functional parts in a single molding process, reducing the need for multiple materials and assembly steps, thus streamlining production and enhancing design flexibility [24].

Despite these innovations in conventional manufacturing techniques, there were some downsides to them as well. One of the main issues for using conventional methods was the increase in processing time as a long setup time for working with the big machines was needed. This would ultimately increase the overall production cost of the prepared parts as well. The need for post processing after the manufacturing of parts using conventional methods also increased the production time and cost of the manufactured part. Conventional methods such as casting needs a big investment, high energy and consumables for ensuring quality of the manufactured parts [25].

2.3 Multi-Material Additive Manufacturing processes

MMAM is one of the most popular technologies in industries now a days. It utilizes the principle of adding material layer by layer to form a solid component. Multi-Material Additive Manufacturing (MMAM) has become a revolutionary method in 3D printing, allowing the incorporation of several materials or compositions into a single component. MMAM methods can improve the performance of AM printed components by adding various materials or different compositions of the same material to increase functionality and complexity inside a single component. MMAM provides multiple possibilities for

creating challenging, efficient, highly customized, and valuable parts with enhanced characteristics. The use of materials at multiple stages can customize the characteristics of the parts, including electrical, thermal, mechanical, optical, and multifunctional capabilities.

Design of single material lattice structures restricts the design flexibility as the material dictates the response of the lattice. For example, ceramic materials can increase the strength of lattice structures. However, this may result in a brittle response [18]. Similarly, using polymeric materials may increase the ductility of the lattice structure, though this may come at the expense of overall strength [19]. Therefore, material customizability is required to overcome these challenges and achieve the desired mechanical properties. Multi-material lattice structures provide a possible solution to this problem as the combination of different materials enables the ability to customize the mechanical properties [20], [21], [22], [23]. However, more work is required to identify structures with high energy absorption and with a balanced combination of stiffness and ductility. Previous studies have demonstrated the potential of multi-material structures in various configurations, such as honeycomb, gyroid, and sandwich designs [24]. These studies highlighted enhanced energy absorption, flexibility, and tailored mechanical behavior under diverse loading conditions. Researchers have also developed strategies inspired by nature's sophisticated micro-architected multi-material architectures, such as bone [25] and nacre [26], to achieve superior and tunable mechanical properties. For instance, a "brick-mortar" geometry with alternating hard and soft constituents mimics biological materials to achieve a superior balance of strength and toughness [27]. There are a number of different techniques which can be used in MMAM with their own advantages and

disadvantages a wide range of material selection. These techniques include Material extrusion, vat photopolymerization, material jetting, direct energy deposition, binder jetting etc. The different types of additive manufacturing are given in Figure 2.7.

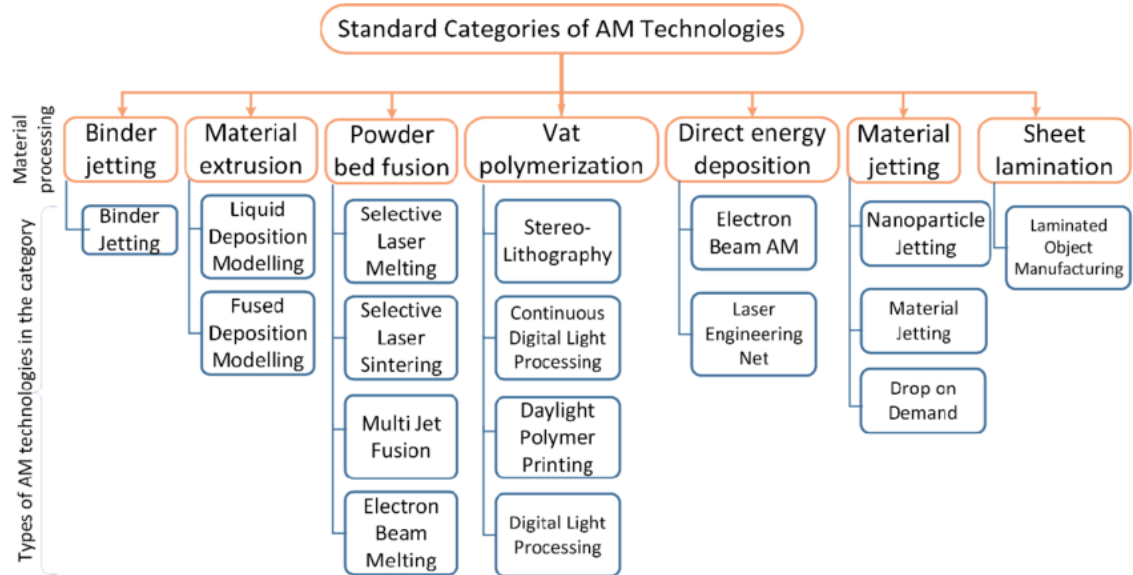


Figure 2.7. Categories and sub-categories of different additive manufacturing techniques [26].

Choosing an appropriate MMAM technique for producing multi components requires an extensive knowledge of the upsides and drawbacks of each AM process which also includes the selection of suitable material with suitable technique. A wide range of materials has been used in MMAM. The materials pairings under analysis were either within the same category, such as polymer-polymer, or include two other categories, such as polymer-metal. As depicted in Figure 2.8, Polymers and metals are the two most extensively researched material groups, with 76 and 66 articles dedicated to their study, respectively. Within the realm of polymers, the most often studied materials are Polylactic

Acid, Acrylonitrile Butadiene Styrene, Poly-ether-ether-ketone, and Polyethylene Terephthalate. These materials are examined in order to enhance properties such as strength, stability, functionality, etc.

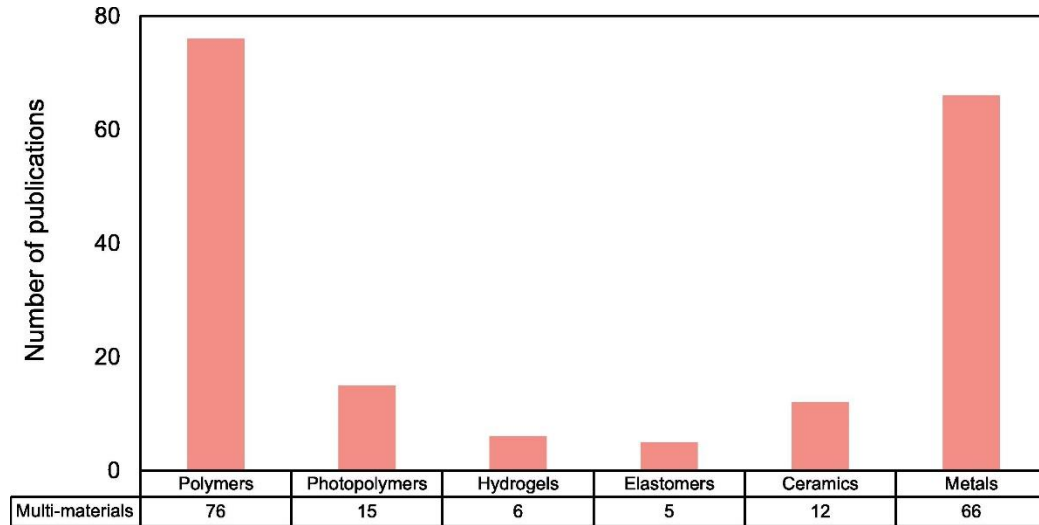


Figure 2.8. The use of material combinations in the additive manufacturing of multi-materials discussed in the literature [27].

2.3.1 Polymer-polymer:

Thermoplastic polymer is a key component in the MMAM process, used to fabricate multi-material, monolithic components. The thermoplastic polymer chains present challenges in mobilization via chemical reaction, unlike thermoset plastics. The combination of thermoset and thermoplastic polymer is seldom used in the MMAM system. The dominant use of thermoplastic polymers in hot-melt extrusion-based systems promotes the growth of the MMAM system across various research areas, including studying the affinity of dissimilar materials and their mechanical properties in fabricated monolithic structures.

Yin et al. [28] investigated the interfacial bonding strength in multi-material FDM of TPU and ABS by examining the effects of nozzle temperature, build stage temperature, and

printing speed. They found that increasing the build stage temperature from 30°C to 68°C enhanced bonding strength by 93%. A heat transfer-based polymer inter-molecular diffusion model was developed to understand and predict bonding behavior. Experimental results closely matched numerical simulations, validating the model's accuracy. This study offers valuable insights into optimizing processing parameters to improve mechanical performance in multi-material FDM parts.

Baca et al. [29], studied the effect of tensile properties of multi-material samples prepared by Fused Deposition modeling. Different combinations of samples prepared by PLA, HIPS and ABS were used in this study. According to him, even though the tensile stress of sample prepared from PLA only was highest, the tensile elongation at break was higher for multi-material samples, especially the combination of ABS, HIPS and PLA together. It showed that the multi-material sample is more suitable for applications where high stress and elongation is priority.

In another study [30], multi-material structures were fabricated using two-photon polymerization (2PP) with monomers including Pentaerythritol triacrylate (PETA), Bisphenol A ethoxylate diacrylate (BPEDA), Trimethylolpropane ethoxylate triacrylate (TMPETA), and Poly(ethylene glycol) diacrylate (PEGDA). Initiators used were DETC, DETX, Irgacure 369, Irgacure 819, and EDB. The authors established empirical relationships between printing parameters and material properties to achieve precise deposition of different materials with uniform composition and optimized mechanical properties. Multi-material architectures with high spatial resolution and stability were successfully demonstrated. This work advanced 2PP for high-resolution additive manufacturing of complex functional multi-material systems.

Tee et al. [31] study explored the geometric accuracy and mechanical performance of multi-material composites fabricated using material jetting (PolyJet) technology. The researchers used Agilus30™ (a soft, rubber-like material) and VeroMagentaV™ (a rigid material) to create structures with varied compositions and particle arrangements. It was found that geometric accuracy is acceptable above 500 μm , and that the orientation and geometry of reinforced particles significantly affect composite stiffness under compression. Tensile tests revealed that 45°-oriented samples exhibited lower strength than parallel ones, while particle composition influenced fracture behavior. SEM analysis confirmed strong bonding between hard and soft materials, critical for reliable multi-material structures.

Even though a lot of work is done for polymer-polymer base MMAM, some drawbacks have also been stated in different literatures. Thermoplastics used in the extrusion process face challenges due to their chemical structures and formulation. Dissimilar polymer materials often have mature chains, unlike thermosets that crosslink open monomers. This can cause mismatches in thermal expansion coefficients, leading to distortion and low dimensional stability. Additionally, mechanical integrity at interfaces can be reduced due to chemical incompatibility or low affinity [32].

2.3.2 Other Combinations

Despite the existence of various AM methods for metal printing, they are primarily limited to single-metal compositions due to machine-specific restrictions such as a single powder-feeding unit. A new powder-feeding design with multiple materials feeding sources could address this limitation. Premixed powders can also be used for multifunctional components [33]. The main challenge is bonding dissimilar materials, making compatibility crucial for

MMAM. Wei et al. [34] used selective laser melting (SLM) to fabricate multi-material components from dissimilar titanium alloys, Ti-5Al-2.5Sn and Ti-6Al-4V. A defect-free metallurgical bond with a $\sim 70\ \mu\text{m}$ diffusion zone was achieved in both as-deposited and annealed conditions. Microstructural analysis revealed martensitic α' in the as-deposited state, and equiaxed α and lamellar $\alpha+\beta$ after annealing. Interfacial bonding strength exceeded the strength of the Ti-5Al-2.5Sn alloy in both conditions. Post-annealing, the mechanical properties of the dual-alloy structure matched those of forged monolithic counterparts, confirming effective integration [35], [36].

A vast variety of thermoplastics have been combined together in MMAM. They have different applications in aerospace, biomedical and automotive industry due to being light weight and are easily processed as compared to metals. The most widely used polymer in MMAM is PLA as it is biocompatible, biodegradable and recyclable material. ABS is also another widely used filament for polymer based additive manufacturing but it releases toxic gases when it is utilized during additive manufacturing. Metal-polymer MMAM, a blend of PLA and metals, has been utilized in bio-inspired soft robot fabrication. However, low process temperatures hinder strong bonding between metals and polymers. Metals are used as fillers to enhance polymer properties, but research on mechanical properties is limited. As metal ratio increases, shrinkage and pore formation become main limitations. Chueh et al. [37] developed a hybrid additive manufacturing system combining FFF and laser-based PBF to fabricate metal/polymer multi-material components which included several 3D components made of hybrid stainless steel (SS 316L), copper (Cu10Sn) and polymer (PLA, PET). Interlocking geometries and laser heating enabled strong metal/polymer joints without adhesives. SEM and EDS revealed defect-free interfaces with good polymer

infiltration. Tensile and shear tests confirmed reliable joint strength, though challenges remained in laser-depositing copper on polymer substrates. The method enabled functional prototypes including implants, mobile phone cases, and architectural models, demonstrating its versatility.

Combining metal and ceramic together in MMAM is in its development stage. However, forming a strong bond between metals and ceramics is challenging due to high melting point mismatch and thermal expansion, resulting in thermal stresses. High temperatures can cause metals to evaporate, affecting the desired multi-material composition and limiting the structural application of metal-ceramic MMAM components. Pfeiffer et al. [38] the fabrication of $\text{Al}_2\text{O}_3/\text{Cu-O}$ composites through pressure-less infiltration of Cu-3.2 wt% O alloy into paper-derived alumina preforms. The composites exhibited excellent mechanical and electrical properties, such as fracture toughness up to $6 \text{ MPa}\cdot\text{m}^{0.5}$, bending strength up to 342 MPa, and electrical conductivity up to 2 MS/m, depending on the copper volume fraction. The addition of copper improved fracture toughness and strength, while decreasing Young's modulus and hardness. XRD, SEM, and EDS analyses confirmed the formation of CuAlO_2 in the alumina matrix. The use of Laminated Object Manufacturing (LOM) enabled the production of complex geometries suitable for electronic and electromechanical applications [39], [40].

Other material combinations including Polymer – ceramic [41], Polymer-wood [42] and Polymer – glass [43] was also studied. However, the difference in temperature is the main cause of non-compatibility between these materials which is why it is difficult to combine these different types of material together in a structure. Therefore, this study focuses on Polymer–Polymer multi-material combinations, as polymers generally exhibit similar

processing conditions, improved interface compatibility, and enhanced structural integrity, making them ideal candidates for multi-material additive manufacturing applications.

2.4 Multi-material Metamaterials additive manufacturing

Johnston et al. [44] studied the effect of multi-material auxetic structures under compression. They combined PLA with Nylon and TPU in honeycombed-entrant and anti-tetrachiral structure and did quasi static compression testing on these samples. They concluded that multi-material structures are capable of withstanding repeated loads. The combination of a low stiffness, high failure strain elastomer in a dual material cellular structure can result in elastic buckling when subjected to compression. All three structures exhibited different mechanical properties. The anti-tetrachiral structure composed of PLA-TPU material maintained its maximum energy capacity even after undergoing many loading cycles.

Flexural properties of a multi-material honeycomb structure were studied by Yavas.et al [45]. They prepared honeycomb structures by incorporating TPU as core and PLA as the shell of the structure and investigated the change in flexural properties of the structure by changing the length and thickness of the multi-material honeycomb structure. According to them, as the ratio of core to strut thickness increases, the flexural modulus and strength of the multi-material struts consisting of a TPU core, and a PLA shell eventually decrease. However, the multi-material lattices exhibited a much higher energy absorption capacity than the individual constituents, with the difference being around two to three times greater. A semi-brittle failure was seen in the complete PLA lattice, but all of the multi-material lattices demonstrated a gradual failure with various stress peaks during the deformation process. This resulted in an increase in the energy absorption capacity of the material.

In another study, Lopez et. al [46], studied the tensile mechanical behavior of multi-material sandwich structure. They used FDM to manufacture the samples and used PLA, HIPS and ABS in a sandwich structure and studied the effect of altering the build orientation. They revealed that compared to a homogeneous material, the multi-material structure exhibited superior elongation at break. Different sandwich samples have distinct mechanical characteristics when compared to one other. The alteration in the arrangement of the material mostly determines the tensile strength, elongation at break, and stiffness within the range of thirty to fifty percent.

The effect of relative density in multi-material gyroid structure was studied by Teawdeswan et al [47]. They made a TPMS Gyroid structure with PLA and TPU with FDM and observed the change in the mechanical properties of the structure while changing the relative density of the materials under compression test. Their testing has shown that the multi-material gyroid structure can achieve a mechanical property that is in between that of pure PLA structures and pure TPU structures. This enables a higher level of design flexibility to be employed in the development of gyroid structures.

From the literature, the results clearly demonstrate the significant advantages of fabricating multi-material metamaterials. Such combinations enable precise control over structural properties, enhanced energy absorption, tailored mechanical performance, and improved durability under various loading conditions. The capability to strategically combine materials with complementary properties within complex geometries not only expands design possibilities but also allows the development of multifunctional components optimized for specific engineering applications. Thus, exploring multi-material metamaterials is essential to advancing material performance and broadening their

applicability across diverse engineering fields.

2.5 Machine learning and additive manufacturing

Additive manufacturing (AM), particularly fused deposition modeling (FDM), has revolutionized the fabrication of lattice and multi-material structures by enabling the production of complex geometries that are challenging to achieve through traditional manufacturing techniques [48], [49]. FDM stands out due to its accessibility and simplicity, allowing for the seamless printing of different thermoplastic materials such as PLA [50], TPU [51], Nylon [52], ABS [53] and HIPS [54]. Process parameters in FDM significantly influence the mechanical properties of fabricated structures, and optimizing these parameters is critical for achieving desired performance. Utilizing these parameters efficiently requires the understanding of the data driven or statistical models which can help in enhancing the predictive accuracy [55].

Theoretical and numerical approaches are the most commonly used techniques used to find the properties of a lattice structures. Theoretical approaches focus on deducing the average compressive force under different loading conditions. McFarland [56], Wierzbicki [57], and later Mahmoudabadi et al. [58] and Yin et al. [59], used energy conservation principles to improve the out-of-plane predictions of quasi-static compression forces. Similarly, Gibson and Ashby [18] developed quasi-static force predictions, while Hu and Yu [60] and Reid Peng [61] extended this to low- and high-velocity impacts using cell collapse mechanisms and shock wave theory for in-plane deformation. Numerical simulations, such as finite element analysis, have also been employed to model the axial and lateral compression [62]. These simulations offer higher accuracy than theoretical models, reduce

costs, and enable the analysis of physical quantities that are difficult to measure experimentally [63].

Advanced data driven models that incorporate machine learning techniques offer accurate solutions and require lower computational resources [64]. These machine learning models are utilized in many applications e.g. prediction of texture-based stress-strain response [65], notch fracture load [66], cyclic response [67], etc. Machine learning (ML) is increasingly integrated into design for additive manufacturing (DfAM) to unlock high-performance metamaterials and optimize topological designs. In AM processes, ML algorithms assist in fine-tuning process parameters, monitoring in-process defects, and analyzing powder spreading, leading to improved reliability and precision [68].

Currently, there is a growing study focusing on multi-material mechanical metamaterial structures to improve mechanical properties as compared to traditional material structures. Based on the existing literature on MMs, it is evident that researchers are now in the first phase of studying the multi-material capabilities of these structures. The majority of the work is done on honeycomb structures or gyroid. Very little work is done in Cubic and TPMS lattice structures. From the literature review, it was evident that the mechanical properties of a Mechanical metamaterial are influenced by both its geometry as well as the composition of the material. Furthermore, the optimization of the parameters significantly influences the achievement of optimal outcomes from these structures. This study aims to examine the impact of geometry and material composition on the mechanical characteristics of cubic and diamond MM lattice structures. The investigation will involve the use of Fused Deposition Modelling (FDM) and quasi-static compression testing, as well

as Finite Element Analysis (FEA) using ANSYS.SEM will be used to analyze the interfacial behavior between PLA and TPU layers. Furthermore, multi-material diamond lattice structure will be optimized through the implementation of machine learning techniques in order to get the structure that possesses the desired characteristic.

CHAPTER 3

METHODOLOGY

3.1 Design conceptualization for the multi-material lattice structures

Conventionally, all the materials have one specific property, and they are utilized based on the property they possess. However, there are various applications where different materials give better properties, especially in terms of strength-to-weight ratio. The examples for such a class of material are composites, as they are revolutionary in terms of the strength-to-weight ratio [69]. Similarly, MMs are also revolutionizing lightweight structures with superior properties [70]. Considering the combination of the multimaterial approach from composite and MMs with the revolutionary fabrication technique that is AM, the researchers can bring a fold of new structures to different application areas. Hence, the concept of combining different materials in MMs needs careful understanding of the mechanics of such structures and how they will behave. The importance of adding different materials in a specific location may enhance the properties, but it may also not be very effective for the increase in the strength of the MM if added in different locations. In this regard, for multimaterial MMs, we can design the structures based upon the effective stiffness (EI), subjected to combined compression loading and bending or buckling in the struts [71], [72]. The approach presented in Figure 3.1 encompasses the interaction between multimaterials and also the location dependence in the MMs. In this way, the optimization or selection of the material can be idealized for design experiments (DOE), simulations, or optimization. The mathematical formulation is derived from the buckling and bending phenomenon that occurs in columns and beams or struts, respectively. Such models have been used in the studies either by using analytical approach or finite element modelling

(FEM) [73] of the structures which has different material and different configurations for the composite [74], [75]. This approach can be applied to the multimaterial MMs with the exception related to interlayer adhesion strength, as this is out of the scope of this study for now. However, the interlayer adhesion between multimaterials will be visualized using optical microscopy in the later section. It is evident from the many studies that the orientation and type of material in multimaterial structures have different effects on the structures in terms of the strength and other properties. In this study, we have added TPU between PLA within the cubic MMs in both plate- and strut-based configurations in the horizontal and vertical struts. From the previous studies [76], [77], [78], it is quite evident that the vertical struts bear more buckling load while the horizontal members are under the influence of the bending and, to some extent, axial elongation. Hence, the increase in strength-to-weight ratio can be expected with the methodology defined in Figure 3.1. Schematic representation of possible use of multi-materials in MMs and how it can affect the mechanical properties. Hence, the initial DOE is evaluated due to the above-mentioned reasons, and in a later section, we utilize the FEA to validate our results with the experimental results.

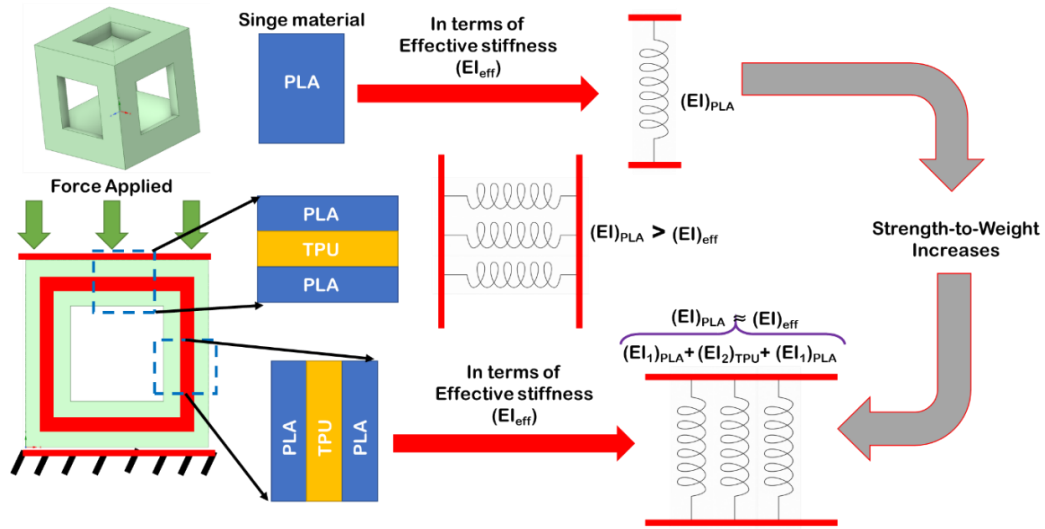


Figure 3.1. Schematic representation of possible use of multi-materials in MMs and how it can affect the mechanical properties

3.1.1 Strut-based and plate-based multimaterial cubic lattice structures

The Figure 3.2 depicts the methodology used in this study. The strut-based and plate-based multi-material cubic structures were designed in SolidWorks and fabricated using FDM. The mechanical properties, i.e. compression modulus, energy absorption and peak load were calculated using the results from quasi-static compression of the structures. The experimental results were validated with the simulated results using Finite Element Analysis. SEM were used for the fracture analysis of the multi-material meta material cubic samples.

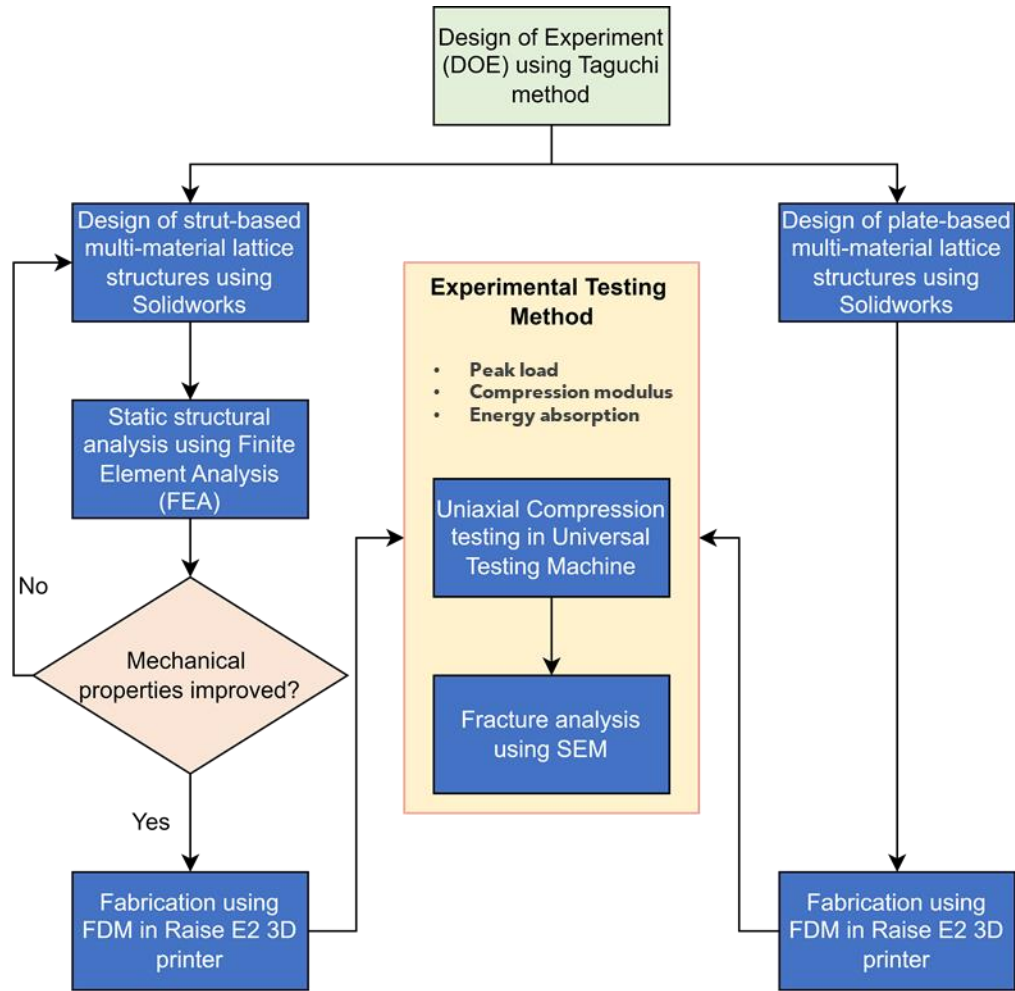


Figure 3.2. Methodology for designing and fabrication of cubic multi-material mechanical metamaterials using FEA and additive manufacturing.

Figure 3.3 depicts the methodology used for the second part i.e. multi-material TPMS diamond lattice structure namely model 3. The first step was the design of the TPMS diamond structure using nTop, followed by fabrication through Fused Deposition Modeling (FDM) on an E2 3D printer. Once the samples were printed, they underwent compression testing using a Universal Testing Machine to assess their mechanical properties. Key parameters such as peak force, energy absorption, and compression modulus were determined from these tests. The data obtained was then fed into a feed-

forward machine learning model, which was trained to identify optimal design parameters. Based on the trained model, new samples were printed with desired structural characteristics. Finally, the printed samples underwent another round of mechanical testing, and the results were analyzed to validate the effectiveness of the optimized design. This iterative approach helped refine the TPMS structure by leveraging data-driven insights to enhance its mechanical performance.

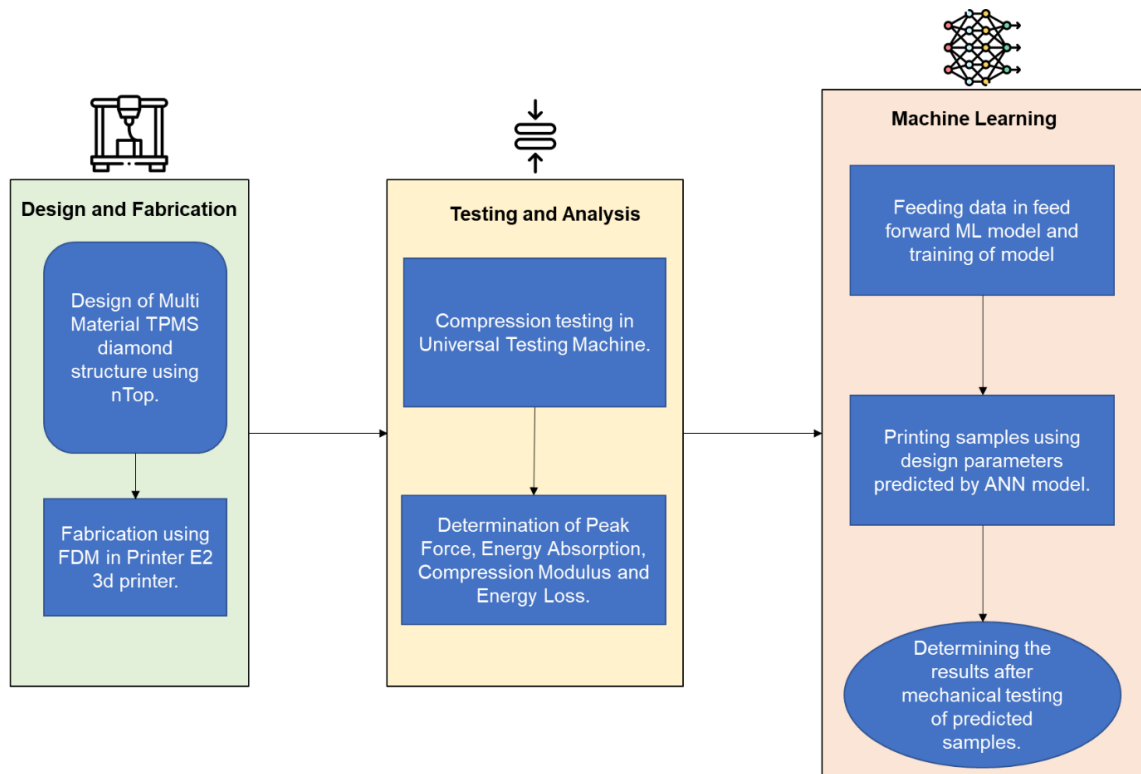


Figure 3.3. Methodology for designing, fabricating, testing and optimizing single and multi-material diamond lattice structures using additive manufacturing, UTM and machine learning

For the design, different types of MMs were used. At first, strut-based lattice structure namely Model 1 and plate-based structure namely Model 2 were designed. Both structures are simple cubic structures. The bounding box used for both structures was 60x60x60 mm. A DOE was designed with parameters i.e. model number, Unit cell configuration, core material (TPU) thickness and total wall thickness, as shown in Table 3.1. Taguchi method was applied on all the parameters using Minitab Statistical Software to reduce the number of experiments needed to understand the influence of selected parameters, making it more efficient in terms of time and resources. For Taguchi method, the L18 orthogonal array was selected to provide a balanced structure of parameters for this study. The DOE for Model 1 and Model 2 along with the parameters are shown in the Figure 3.4 and Table 3.1.

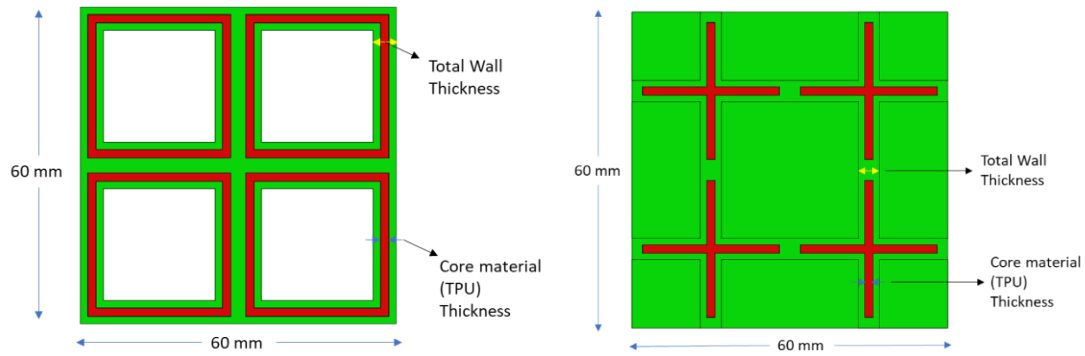


Figure 3.4. Geometric representation of the plate-based (left) and strut-based (right) lattice structures, highlighting total wall thickness and core material (TPU) thickness for a unit cell.

All CAD models were made on Solidworks 2022. The material selected for the outside structure was PLA while TPU 95-A was selected for the material inside the model in the same shape as the outside, shown in green and red respectively, for model 1 and model 2 in Figure 3.5. The TPU structures were extracted as separate bodies in the CAD models so they can be printed using different material as compared to the PLA part of the cubic

structures.

Table 3.1. Design matrix of all parameters for the experimental study for Model 1 and Model 2.

Model no	Unit cell Configuration	Core material (TPU) thickness	Total Wall Thickness
1	2x2x2	0.8	3.6
1	2x2x2	1.2	4
1	2x2x2	1.6	4.4
1	3x3x3	0.8	3.6
1	3x3x3	1.2	4
1	3x3x3	1.6	4.4
1	4x4x4	0.8	4
1	4x4x4	1.2	4.4
1	4x4x4	1.6	3.6
2	2x2x2	0.8	4.4
2	2x2x2	1.2	3.6
2	2x2x2	1.6	4
2	3x3x3	0.8	4
2	3x3x3	1.2	4.4
2	3x3x3	1.6	3.6
2	4x4x4	0.8	4.4
2	4x4x4	1.2	3.6
2	4x4x4	1.6	4

PLA and TPU were used for this study because both materials are printed at similar temperatures. Also, as TPU is hyperelastic and has high elongation with excellent wear and chemical resistance properties while PLA is stiff, the combination of both materials can give a large range of different mechanical properties. All samples were fabricated 3 times

to ensure good results in mechanical testing.

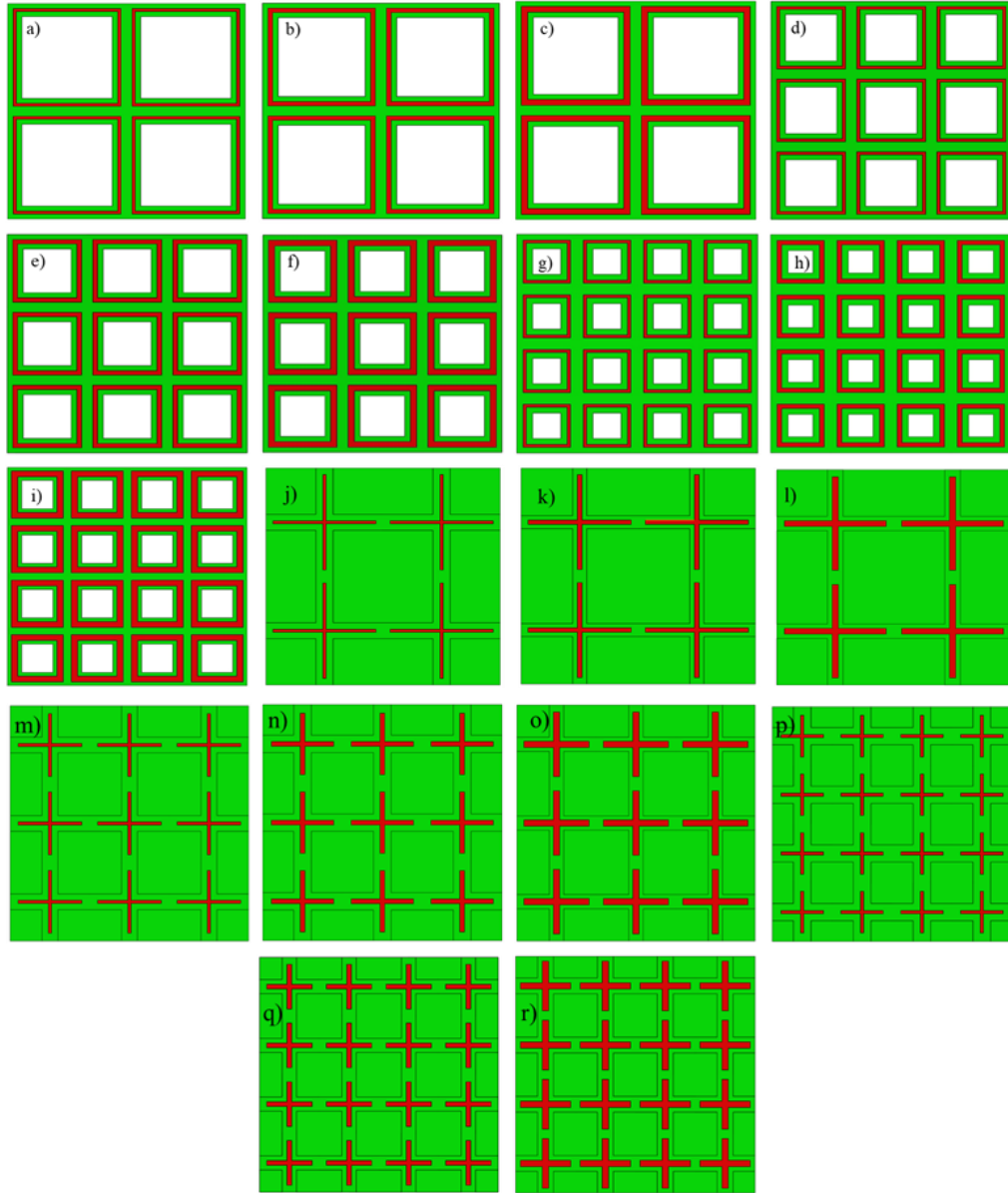


Figure 3.5. Schematic diagrams of the nine variations in Model 1 (a-i) and Model 2 (j-r) to assess the effect of geometric design on multi-material metamaterial properties.

3.1.2 TPMS diamond multimaterial lattice structures

Triply Periodic minimal surface (TPMS) diamond lattice structure namely model 3 was also chosen for this study. For design, the cell size was kept at $15 \times 15 \times 15$ mm with a bounding box of $30 \times 30 \times 30$ mm instead of $60 \times 60 \times 60$ mm like Model 1 and 2 to overcome the issue that could be encountered during mechanical characterization, where the load cell can be insufficient to effectively compress highly dense and stiff structures. For the CAD models, the commercial software nTop was used for designing. Two different implicit bodies were made, one for PLA and one for TPU. A cube of with a bounding box of $30 \times 30 \times 30$ mm with the required total thickness was made with the structure type diamond. Then another implicit body was made with the thickness for TPU body was made and then subtracted from the first body to get PLA implicit body using Boolean subtract. Both bodies were then saved in 3mf format. The thickness of both bodies was kept as shown in Table 3.2 for samples with varying relative density and percentage of PLA and TPU. A minimum feature size of 0.6 mm was used for both the TPU and PLA lattice structures. As discussed previously, PLA was selected for the boundaries as it provided a rigid outer layer provided structural support to the overall multi-material lattice structure. On the other hand, TPU was selected for the inner regions to add the elasticity and impact resistance to the lattice.

Table 3.2. Design matrix of all parameters for the experimental study for single and multi-material diamond structures

RATIO	RELATIVE DENSITY	TOTAL THICKNESS	THICKNESS OF TPU	TOTAL VOLUME
	(%)	(mm)	(mm)	(mm³)
100% TPU	40	2.58	2.58	10812
1PLA: 3 TPU	40	2.58	1.94	10812
2 PLA: 2 TPU	40	2.58	1.29	10812
3 PLA: 1 TPU	40	2.58	0.65	10812
100% PLA	40	2.58	0	10812
100% TPU	50	3.21	3.21	13509
3 PLA: 1 TPU	50	3.21	0.81	13509
2 PLA: 2 TPU	50	3.21	1.62	13509
1PLA: 3 TPU	50	3.21	2.42	13509
100% PLA	50	3.21	0	13509
100% TPU	60	3.84	3.84	16215
3 PLA: 1 TPU	60	3.84	0.97	16215
2 PLA: 2 TPU	60	3.84	1.94	16215
1PLA: 3 TPU	60	3.84	2.9	16215
100% PLA	60	3.84	0	16215

The details of the various multi-material models with varying percentage of PLA and TPU (25% PLA, 50% PLA, 75% PLA) are shown in Figure 3.6. Full dense TPU and PLA structures were also manufactured (0% PLA, 100% PLA). Multi-material samples with varying TPU-PLA percentage with varying relative densities (40%, 50%, 60%) were also manufactured to study the effect of varying densities on the performance of multi-material parts. Relative densities were used to describe the volume of the printed lattice structures with respect to a solid cube by changing the thickness of the PLA-TPU in the overall lattice structure. All multi-material lattice structure samples were printed with 100% infill.

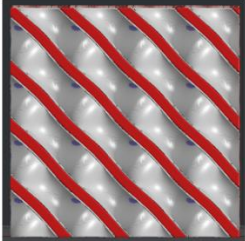
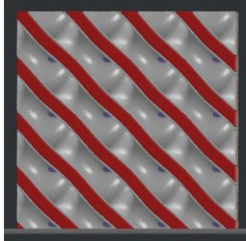
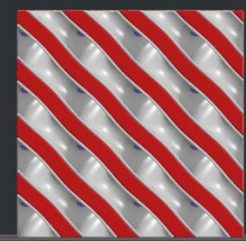
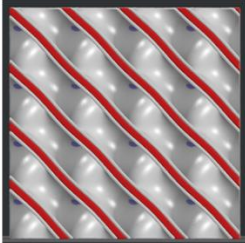
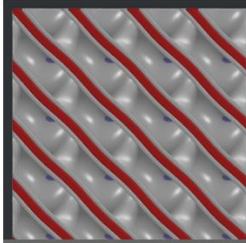
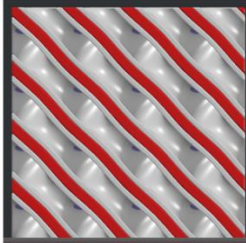
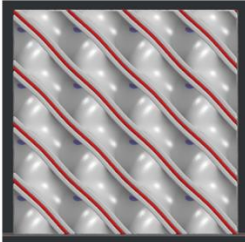
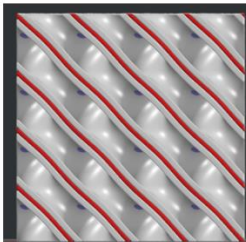
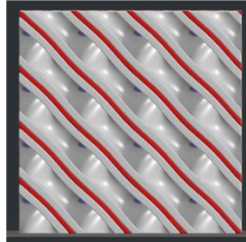
1 PLA : 3 TPU			
2 PLA : 2 TPU			
3 PLA : 1 TPU			
Relative Density	40%	50%	60%

Figure 3.6. Schematic diagrams of the nine variations in diamond structures to study the effect of geometric design on multi-material metamaterial properties.

3.2 FEA analysis of multi-material cubic structure

For the finite element analysis of multi-material specimens, ANSYS static structural was used for compression simulation for mechanical properties. The effects of changing parameters on the mechanical properties of the specimen were studied in Ansys Software. A mesh size of 5 mm was used for all structures. A boundary condition of fixed support was given to the bottom plate, and a deformation with 1200 steps for a 30mm deformation was used for these simulations (Figure 3.7a). The material properties used in the simulations were calculated using tensile experimentation as well to get the best possible results, where a 5-parameter Mooney-Rivlin was used to get the hyperelastic properties of TPU under large deformations, shown in Table 3.3.

Table 3.3. Mechanical properties of TPU, derived from tensile experiments and characterized using the 5-parameter Mooney-Rivlin model.

Property	Value
Material Constant C10	$-2.9573 \times 10^7 \text{ Pa}$
Material Constant C01	$3.9671 \times 10^7 \text{ Pa}$
Material Constant C20	$1.5092 \times 10^7 \text{ Pa}$
Material Constant C11	$-5.0124 \times 10^7 \text{ Pa}$
Material Constant C02	$5.5562 \times 10^7 \text{ Pa}$
Incompressibility Parameter	0.00 Pa^{-1}

A mesh size of 5 mm was used for TPU structures, and a mesh size of 3mm was used for PLA structures. The PLA structure was selected as the contact body while the TPU structures were as target bodies as seen in Figure 3.7b and c. Frictionless support was

applied in both x and z directions, as Frictionless support ensures the symmetry plane allows tangential movement while preventing normal displacement, accurately replicating the behavior of the full structure. The loading conditions are also replicated, similar to experimental conditions, such as displacement at the top of the LS while the fixed support is at the bottom of the structure.

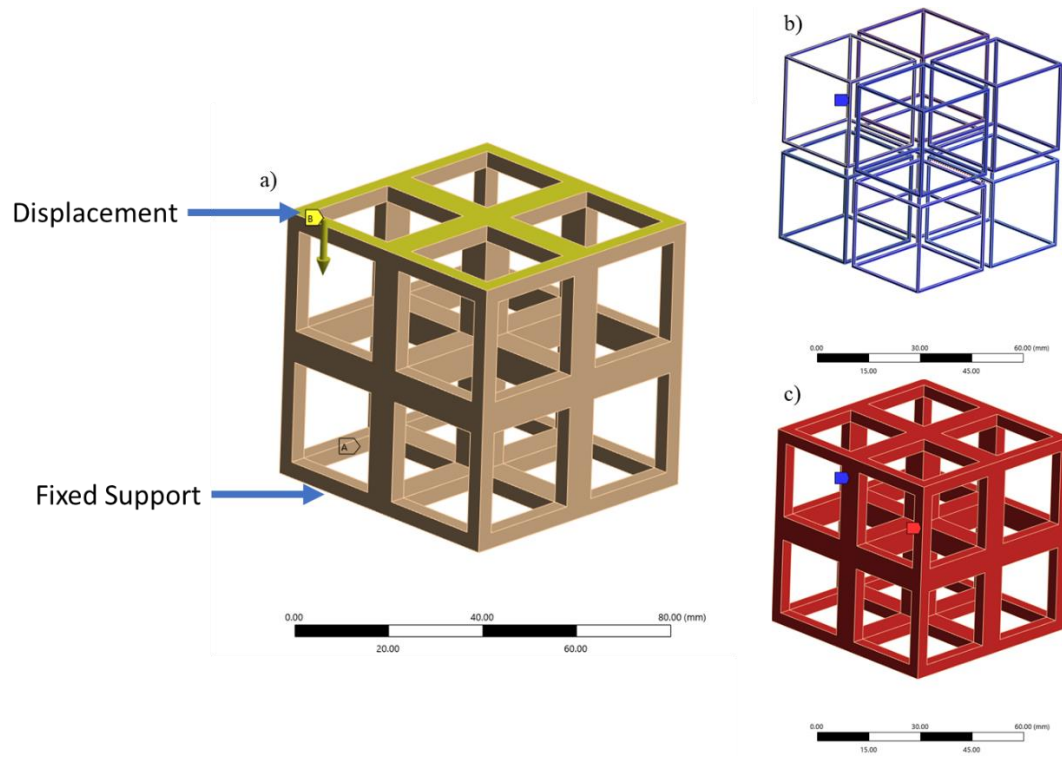


Figure 3.7. Multi-material structures showing a) Boundary conditions, b) TPU (blue) as the target body and c) PLA as the contact body for Model 1.

3.3 Fabrication of multi-material designed structures

For the fabrication of multi-material specimens, the fused deposition modeling (FDM) was utilized using a Raise E2 3D printer (Figure 3.8). This printer can print a 3D specimen using two different materials. As both PLA and TPU are supported by this printer, this

printer was selected. One of the main drawbacks of using this printer is the extrusion width of the printed filament by the 3D printer. While printing the parts, if the width of the printed layer was less than 0.6 mm, it did not print any material, leaving empty spaces in between the structure. To overcome this problem, the DOE was adjusted so that the minimum width was at least 0.6 mm for the smooth fabrication of all multi-material structures. For slicing the CAD files, Ideamaker 5.0.6 was used as it has native support for printing multi-material specimens and is also recommended by the makers of the printer used for this study. A dehumidifier, Sunlu Filadryer S2, was also used to remove humidity from TPU filament, as it is highly hygroscopic and can cause issues like stringing and oozing if left moist. The TPU was kept at 55 degrees in the dehumidifier for 16 hours before printing and was left turned on while printing as well.



Figure 3.8. Raise 3D E2 printer (left) and Dehumidifier (right).

Before slicing the CAD files in Ideamaker, the CAD files must be converted to a 3MF file using the save as option, so that in Ideamaker we can select each part inside and outer and define them according to the material present in the left and right nozzles. The printing speed was kept at 60 mm/s, and the layer height was 0.2 mm/s. The nozzle temperature

for printing TPU was 210 degrees, and printing PLA was 205 degrees. The printing bed was kept at 55 degrees, and the infill rate was 100% for all samples. The printed samples for all unit cell configurations for Model 1 and Model 2 can be seen in Figure 3.9.

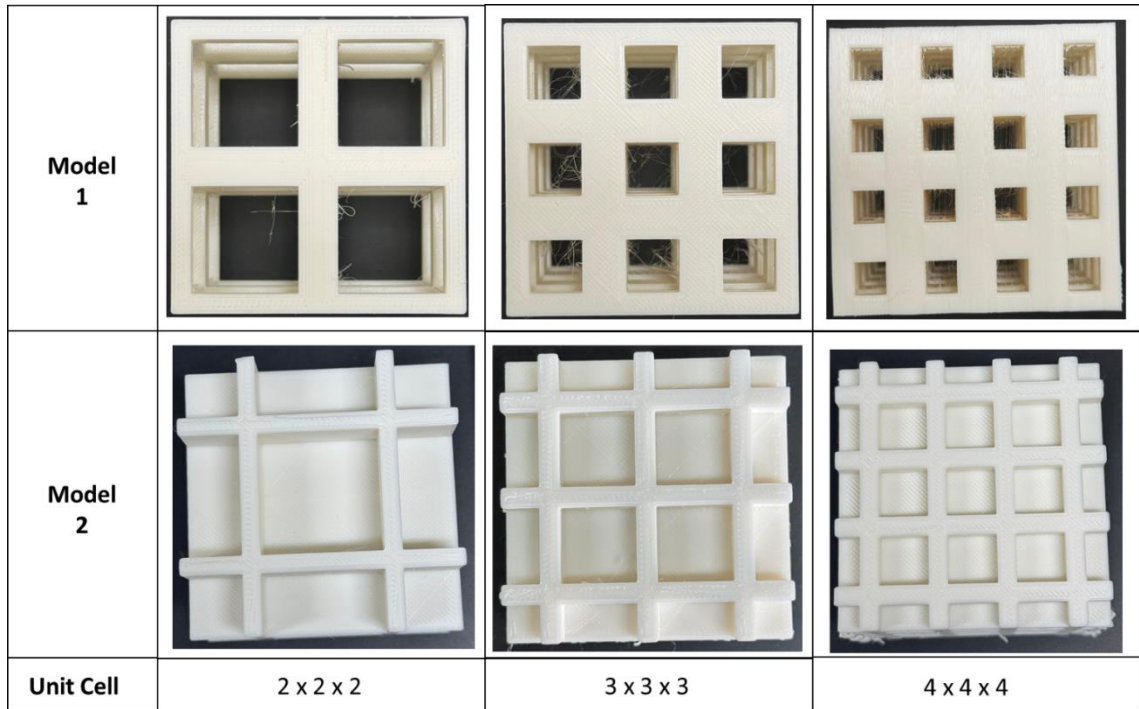


Figure 3.9. Fabricated multi-material samples of Model 1 (Strut based) and Model 2 (Plate based) with unit cell configurations of 2×2×2, 3×3×3, and 4×4×4.

Similarly, different combinations of Model 3 were also printed which can be seen in Figure 3.10.

Fabricated Sample			
Relative Density	40%	50%	60%

Figure 3.10. Fabricated 25% PLA diamond lattice structures with 40%, 50% and 60% relative density. In the printed samples, white sections were manufactured with TPU while the Black sections were manufactured with PLA.

Figure 3. 11a showcases one of the printed samples from Model 2. In this sample, two distinct materials are used to create a multi-material structure. The red section, made from PLA, forms the outer rigid layer, providing structural support and rigidity to the model. In contrast, the inner section, displayed in white, is printed with TPU that adds elasticity and impact resistance to the design. While FDM is a versatile and widely used 3D printing technique, some limitations became evident during the printing of samples from Model 2. In this particular model, the design includes long bridging areas, sections where the printer must span gaps without underlying support, and large overhangs that extend outward from the base structure. These features presented specific challenges during the printing process. In the middle section of the sample, bridging sag was noticeable. This defect occurs when the extruded filament struggles to maintain a straight line over unsupported areas, sagging downward under its own weight due to insufficient cooling or support. Bridging sag can lead to a less precise structure and a compromise in dimensional accuracy, as the filament drops and fails to form a clean, taut bridge between two supported points. Additionally,

overhang curling was observed at the corners of the samples. Overhang curling happens when the edges of overhanging sections begin to lift or curl upward. This can result from uneven cooling or material shrinkage at the edges, leading to a warping effect. Overhang curling is particularly problematic for FDM, as it can cause layers above the curled sections to misalign or print inconsistently, impacting the surface finish and dimensional accuracy. To solve these issues, support structures were added to the model during slicing in the Ideamaker. After printing the materials, the support structures were removed from the samples, and an improvement in the layers was observed, as can be seen in Figure 3. 11d.

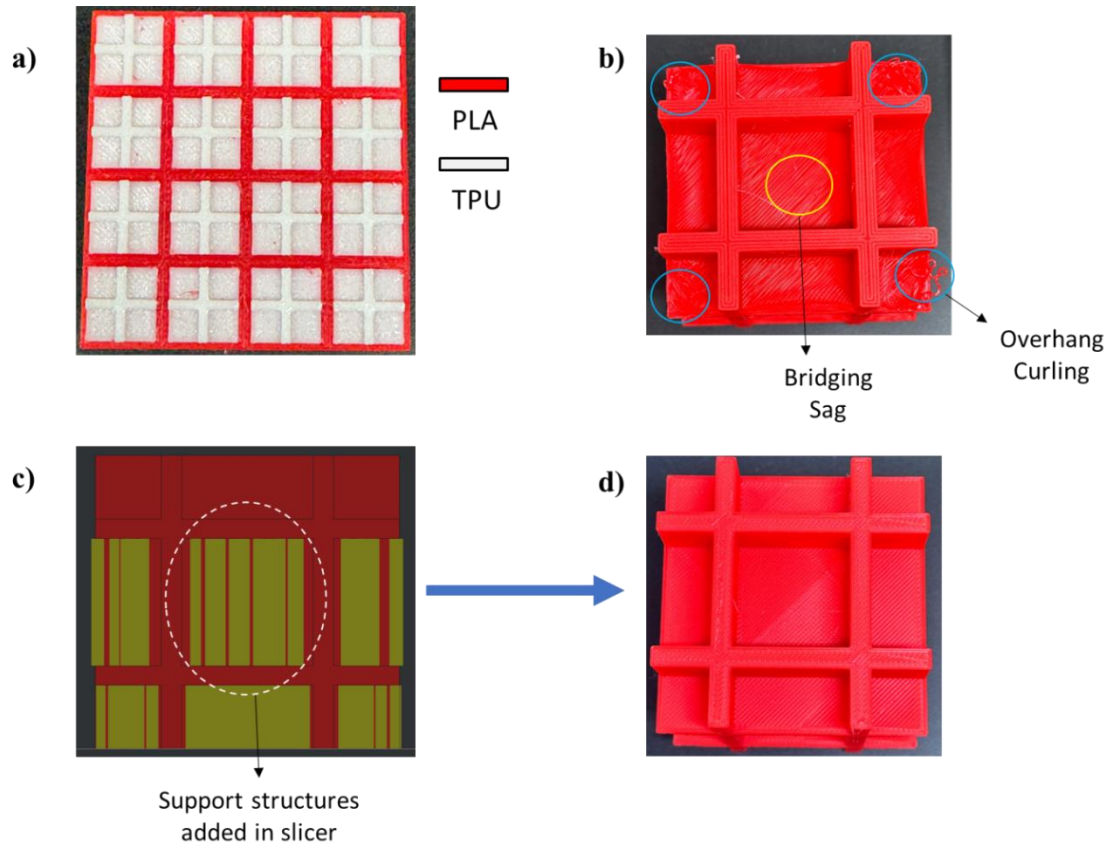


Figure 3. 11.a) Distribution of PLA (red) and TPU (white) in Model 2, (b) fabrication defects observed in the initial print, (c) added support structures using slicing software to address defects, and (d) final printed model showcasing improved quality after incorporating supports.

3.4 Mechanical Characterization of multi-material lattice structures

Universal testing machine (Instron 3367) with a load cell capacity up to 50 kN was used to test samples with lower density under quasi-static uniaxial compression with a velocity of 2 mm/min (Figure 3.12). For test samples with higher density, another universal testing machine with a load cell of 1000 kN was used. The corresponding force-displacement curves were extracted, and the results were used to determine the peak load and compression modulus. Peak load was calculated as the highest point with a stable load for

most samples. However, the peak load was taken at 15 mm deformation for samples that did not exhibit this behavior, especially in Model 3. Energy absorption was also determined as shown below:

$$E = \sum_{i=1}^n 0.5 \times (F_i + F_{i-1}) \times (d_i - d_{i-1}) \quad (1)$$

where E is the absorbed energy, F_i and F_{i-1} are the force values at consecutive displacement points, and d_i and d_{i-1} represents the incremental displacement between two successive measurements [79].

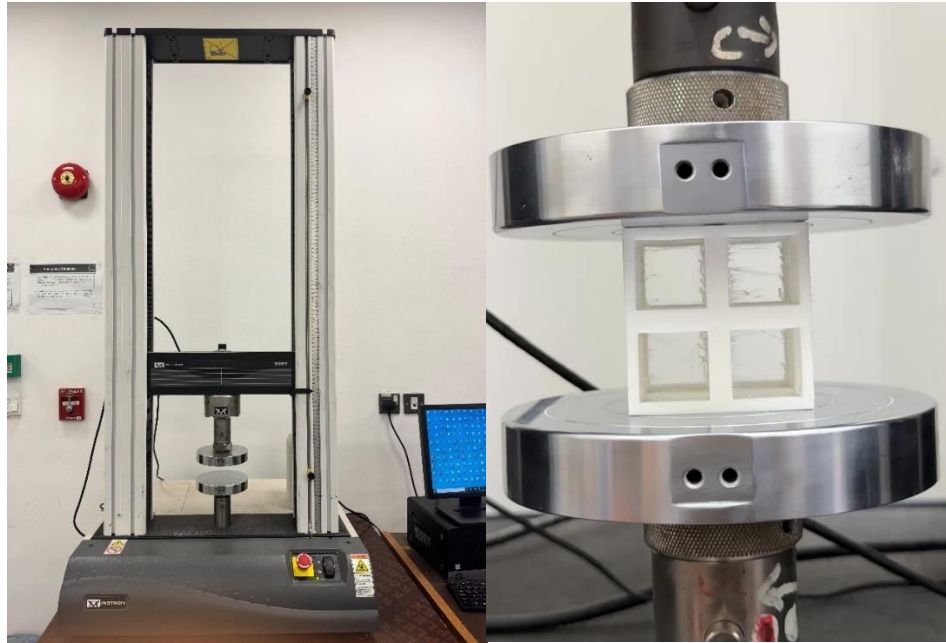


Figure 3.12. Universal compression testing machine (left) and a specimen placed in plates of machine (right).

3.4.1 Fracture analysis of tested multi-material cubic samples

After mechanical testing of the specimens, the fracture analysis was done on tested samples of Model 1 and 2. Fractured samples were examined under a Scanning Electron Microscope (JEOL SEM model JSM-6460) to capture high-resolution images of the multi-material 3D printed surfaces, facilitating a detailed analysis of the fracture behavior and interfacial characteristics between the different materials. The observation is done at 50x and 1000x magnification at 5.0 KV power. This type of analysis helps identify failure modes, such as interfacial debonding, crack propagation patterns, and plastic deformation characteristics within the multi-material composites. Understanding these fracture mechanisms provides valuable insights into material compatibility, bonding effectiveness, and potential areas for optimization in multi-material additive manufacturing processes.

3.4.2 Machine Learning for inverse design of TPMS diamond structures

A feed forward backpropagation artificial neural network (ANN) model was used in this study to predict the multi-material lattice structure properties for Model 3. Most ANN models provide a non-parametric regression method that approximates complex non-linear functions [80]. ANN models simulate biological neural networks by defining a set of neurons distributed across multiple layers, with each neuron acting as a function that transforms input data into an output [81]. A typical neural network structure comprises an input layer, one or more hidden layers, and an output layer, where each neuron in one layer is interconnected with neurons in adjacent layers [82].

Regarding the mechanism of ANN, it functions by mapping an input vector $x \in R^d$ into an output vector $y \in R^e$ through a transformation function f , which is obtained by optimizing a cost function C . The cost function represents the error between the network's predicted output $f(x)$ and the actual target value y , and is typically computed as:

$$C = \frac{1}{n} \sum C_i \quad (2)$$

where C_i is the individual loss for each training sample, and n is the number of samples. A regularization term may be added to prevent overfitting, improving generalization and stability during training [80].

The fundamental computation of an artificial neuron is defined as:

$$y = \varphi (\sum_{j=1}^d w_{xj} + b_i) \quad (3)$$

where w_j and b_i are the weights and bias for the i -th neuron, x_j represents the inputs, and φ is the activation function that introduces non-linearity into the model. The activation function ensures that the network can capture complex patterns in data. This function provides a stronger gradient compared to the standard logistic function, leading to more efficient learning and convergence. Utilizing an ANN model like this can help us predict the performance of different structures and help us in optimization and prediction of a novel multi-material mechanical metamaterial lattice structure.

The experimental data from this work was utilized to train, test and validate a feed forward ANN model. The ANN model was used to find the relationships between the material and mechanical properties for single and multi-material lattice structures. A final model with 2 hidden layers and 10 neurons was used for data training and testing - validation. The complete data set was distributed into two parts where 80% of data was used for training

and 20% of data was used for testing and validation. The validated ANN model was used to find optimal multi-material lattice structure with desired mechanical properties. Energy absorption, compression modulus and Peak load were selected as inputs while the PLA percentage and Relative density were selected as outputs (Figure 3.13). The proposed ANN model enabled effective estimation of complex force-displacement relationships while giving predictions for structural properties.

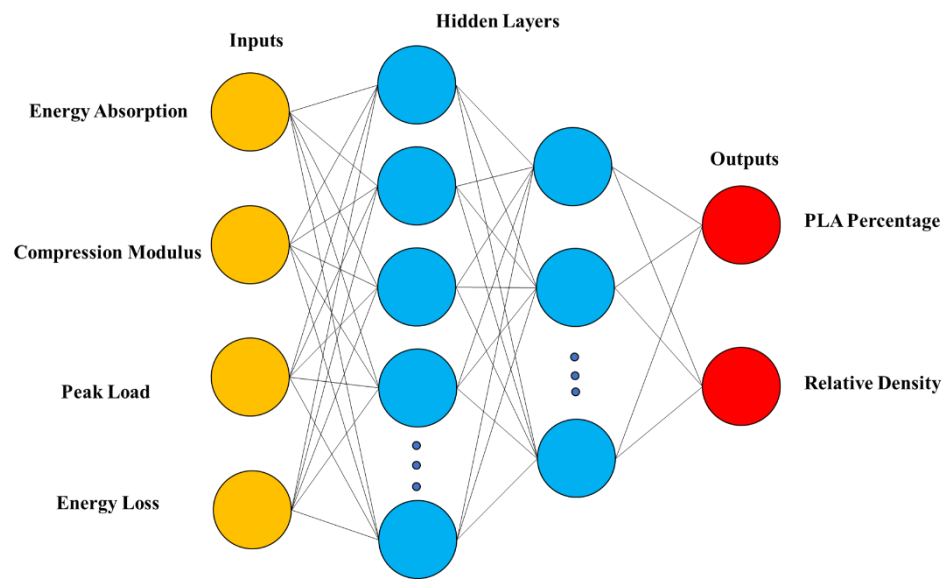


Figure 3.13. Illustration of a neural network with 2 hidden layers and 10 neurons with energy absorption, compression modulus and peak load as inputs and %PLA and Relative density as outputs.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Strut-based and plate-based cubic lattice structures

4.1.1. Deformation behavior of cubic lattice structures under compression loading

The plate-based and strut-based cubic multi-material MMs were compressed under quasi-static load until densification. All multi-material MMs at different deformations can be seen in Figure 4.1. For three different variations of total thickness, only one type of sample is shown, as all three samples showed similar behavior when compressed under quasi-static load. In Model 1-2x, before 5 mm displacement, it can be seen that the lattice structure deformed under global structural buckling, which means that there was uniform buckling in the entire structure. After 5mm, it is visible that the structure tilted and fractured significantly from multiple points. More fractures can be seen in 10mm deformation for the same sample. However, in Model 1-3x, it can be seen that there is local buckling instead of global buckling, and it is near the loading point. Due to the local buckling in the unit cells, it can be seen in 10,15, and 20mm deformations that the unit cell is fracturing one by one in a layer form instead of collapsing together at the same time. For model 1-4x, a different phenomenon was seen after compression than in the other two different samples of the structures. It can be seen that there is no visible crack in the compression testing of Model 1-4x as the structure starts to collapse under bending. This is completely different from 2x and 3x structures, where complete fracture is visible and the structure collapses under buckling. Since among all these samples, 2x, 3x, 4x, the unit cells are increasing,

hence the density is also increased. The increase in the density and unit cell mainly affects the behavior of the MMs irrespective of the multimaterial; however, with a single material such as PLA, the failure would be more disruptive at higher deformations, such as after 5 mm. For model 2-2x, a similar type of behavior is seen as Model 1-4x. The structure starts to bend from the middle at 10mm deformation. The buckling and bending increase as the deformation in the structure increases. However, in Model 2-3x and Model 2-4x, local buckling is the dominating behavior of the plate-based multi-material MM instead of the bending behavior of 2x plate-based cubic structures. This means that there is uniform distribution of load in all unit cells in Model 2- 3x and 4x as compared to 2x in plate-based multi-material MMs. The TPU is playing an important role in the deformation of all cubic structures, as it is not allowing the structures to collapse suddenly due to brittle failure and provides ductility to some extent to all structures. The next section will further evaluate this analysis based on the force-displacement curve and also how much energy is absorbed.

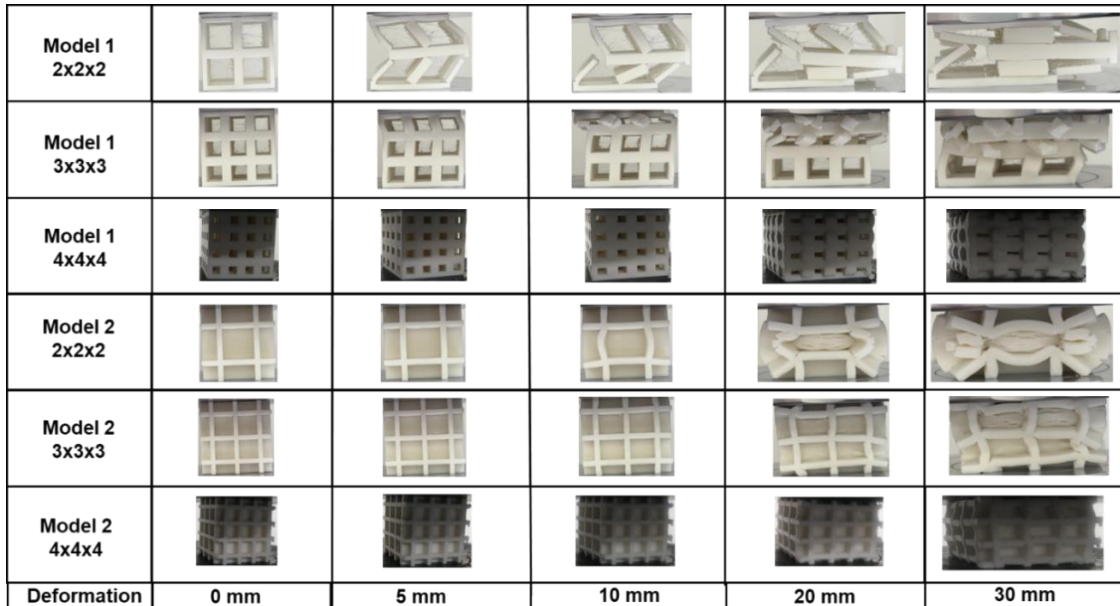


Figure 4.1. Results at 0, 5, 10, 20 and 30 mm deformation for strut based and plate based multi-material metamaterial cubic structures under quasi-statics load.

4.1.2. Force-displacement curve for cubic lattice structures

The force-displacement curve for all multi-material metamaterial cubic structures can be seen in Figure 4.2. No significant change can be seen in the linearity of the elastic region by changing the thickness of PLA and TPU in all multi-material metamaterial cubic structures. In Figure 4.2a, for Model 1-2x, a peak load at the yield point can be seen before the force values reduce to zero. This is due to the sudden fracture of the Model 1-2x structure, where the unit cell fractures immediately after yield for all three different thicknesses of the struts. A second peak appears in all three samples at around 25 mm of deformation, which can be attributed to the collapse of the structure and overlap of the top and bottom layers. From the graph, it could be seen that the Model 1-2x sample with 4.4mm total thickness exhibited the highest strength, followed by 4 mm and 3.6 mm thickness structures, respectively, as increasing the thickness of the structure increases the stiffness as well. In Figure 4.2b, a similar trend in the strength can be seen being exhibited by all three structures with different thicknesses for Model 1-3x. In these samples, however, the force does not suddenly drop to zero upon reaching the yield point. Instead, it retains a significant portion of the load. The subsequent reduction in force can be attributed to the progressive collapse of each unit cell and the onset of local buckling within them. In Figure 4.2c, the trend suggests a uniform load distribution throughout the structure, indicated by the steady increase in force with continued deformation. The absence of any force drop indicates that no progressive collapse occurs in this Model 1-4x. This can be observed for the cubic MMs, which have generally high peak values, while the structure fails abruptly after this point. However, with the increase in the thickness, it is evident that the stability of the structure has improved, which can be because of the higher thickness of the PLA,

but also TPU elasticity is contributing to this interesting behavior. Similarly, for model 2-2x, a clear drop in force can be seen for all three structures, indicating progressive collapse in the unit cells of the structure. Similar to Model 1-4x, Models 2-3x and 4x exhibit a steady increase in force with increasing deformation, indicating a uniform load distribution. However, Model 2-3x shows a slight drop in force around 25 mm of deformation, suggesting a localized collapse in the structure at that point. The stability of the Model 2 with 3x and 4x configurations is mainly due to the increase in the unit cell, but as it is observed in the physical visualization of the MMs, the TPU may contribute to avoiding the sudden drop of force or instability of the structure.

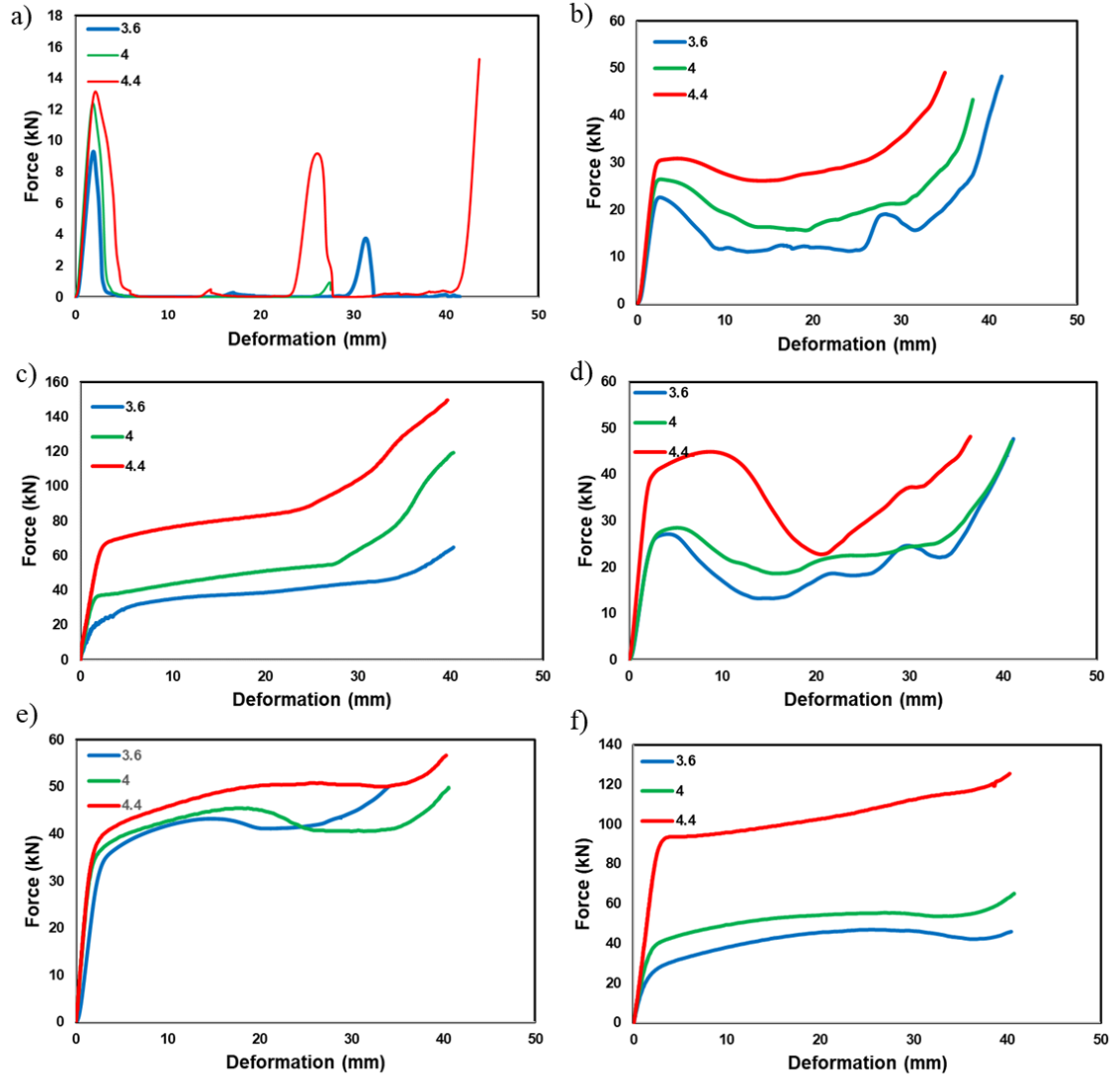


Figure 4.2. Force-deformation curves for strut-based cubic structure with a) 2x, b) 3x and c) 4x unit cell configuration and plate-based cubic structure with d) 2x, e) 3x and f) 4x unit cell configuration with 3.6, 4, and 4.4 mm thickness.

4.1.3. Peak load, compression modulus, and energy absorption

The force-deformation curves were used to calculate the mechanical properties, i.e. peak load, compression modulus, and energy absorption, to study the behavior of all multi-material meta-material cubic structures. The peak load of strut-based and plate-based multi-material cubic structure can be seen in Figure 4.3a and b analysis of the bar chart

shows that the peak load increases with the increase of unit cell configuration as well as the thickness of the overall structure. For model 1, the peak load is highest (68.79 kN) for the 4x unit cell configuration structure with 4.4 mm thickness, while it is lowest (9.36 kN) for the 2x unit cell configuration structure with 3.6 mm thickness. The same is true for plate-based cubic structure, where a 4x unit cell configuration structure with 4.4mm thickness yields the highest peak load (84.27 kN) and the 2x unit cell configuration sample with 3.6mm thickness yields the lowest peak load (26.8 kN). Comparing the peak load of the plate-based and strut-based cubic structure, it is evident that the plate-based structure can sustain a higher peak load as compared to strut-based cubic structure. The rest of the multi-material MMs samples exhibit intermediate peak load properties. A similar trend is seen for energy absorption and compression modulus of all multi-material cubic structures, where the energy absorption and compression modulus for plate-based cubic structure (3828.97 J) is higher as compared to strut-based cubic structure (2848.07 J), respectively. However, this changes for compression modulus at the highest point where the strut-based cubic structure has the highest compression modulus of 32.35 kN/mm, while plate-based cubic structure has the highest compression modulus of 30.18 kN/mm. Energy absorption for 2x model 1 is very less, which can be observed from the actual response of the MMs. 2x unit cell has a lower density than 3x and 4x, which allows the failure of the structures at lower forces. The comparison among all the MMs can be improved by normalizing the structures either by volume or by weight.

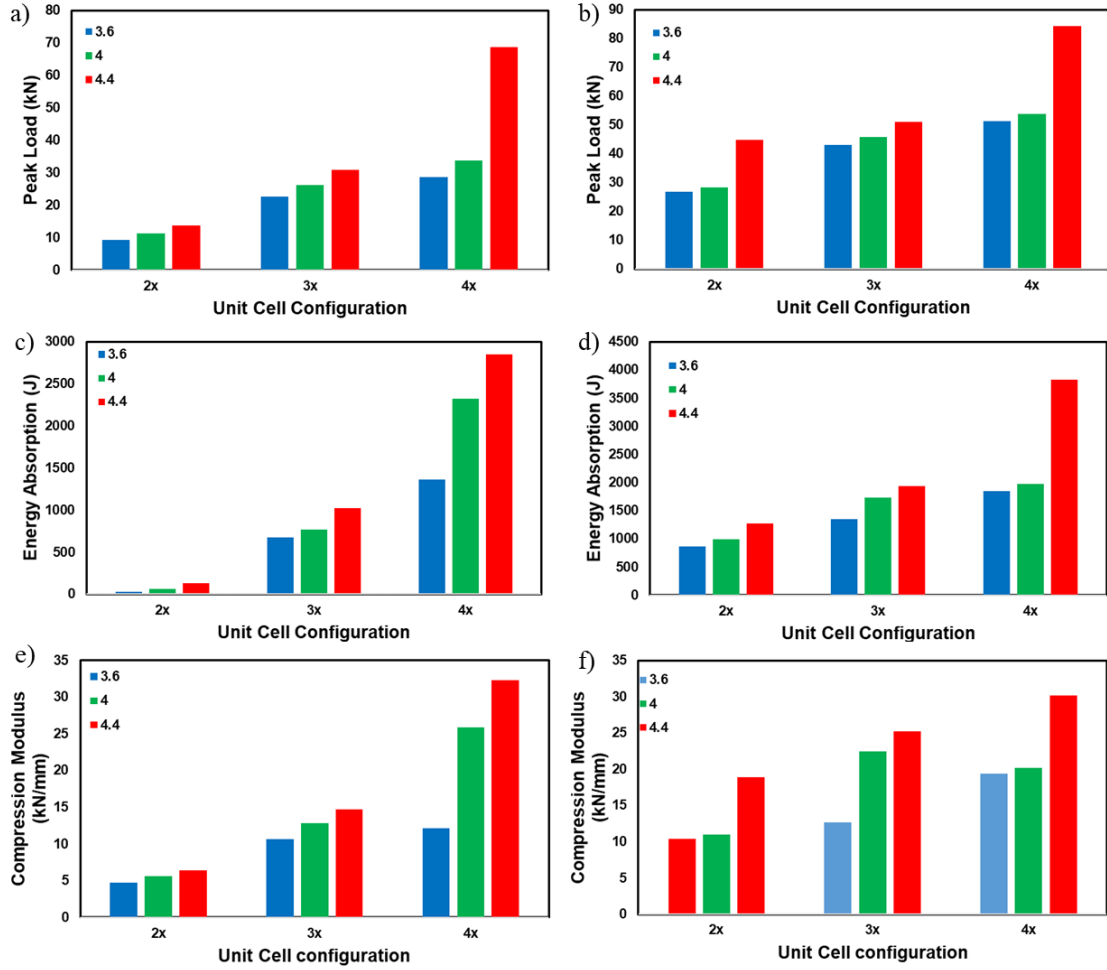


Figure 4.3. a) Peak load, c) energy absorption and e) compression modulus for strut based cubic structure and b) peak load, d) energy absorption and f) compression modulus for plate based cubic structure with 2x, 3x and 4x unit cell configuration with 3.6, 4 and 4.4 mm thickness.

4.1.4. Finite element analysis

The compression test was also simulated in ANSYS for the strut-based cubic 3x multi-material model with a thickness of 4.4 mm to computationally validate the performance of the multi-material metamaterial samples. The force–deformation curves from both the experimental and simulation results are shown in Figure 4.4a. The experimental and

simulation results exhibit good overall agreement in terms of curve trends; however, the experimental results show slightly lower force values in the plateau region. Additionally, the onset of densification occurs earlier in the simulation, which may be attributed to differences in interlocking behavior and failure patterns between the layers of the structures. However, when looking at the deformation pattern, the simulation response is very close to the experimental response of the multi-material strut-based cubic structure (Figure 4.4b). The simulated structure exhibited a buckling pattern consistent with the experimental observations. The discrepancy in force values can be attributed to several factors. Firstly, the material properties defined within the simulation software were limited to elastic and plastic behaviors and did not account for the actual fracture mechanisms observed experimentally. Secondly, manufacturing the structure through FDM inherently introduces geometric discrepancies between the original CAD design and the fabricated components, a common issue in AM processes [83]. Additionally, a mesh convergence study was not conducted in this simulation; performing such a study could potentially reduce numerical errors, although it would not fully capture the observed reduction to zero force seen experimentally. The accuracy of the simulation could be further improved by employing a material model capable of accurately predicting fracture behavior [83].

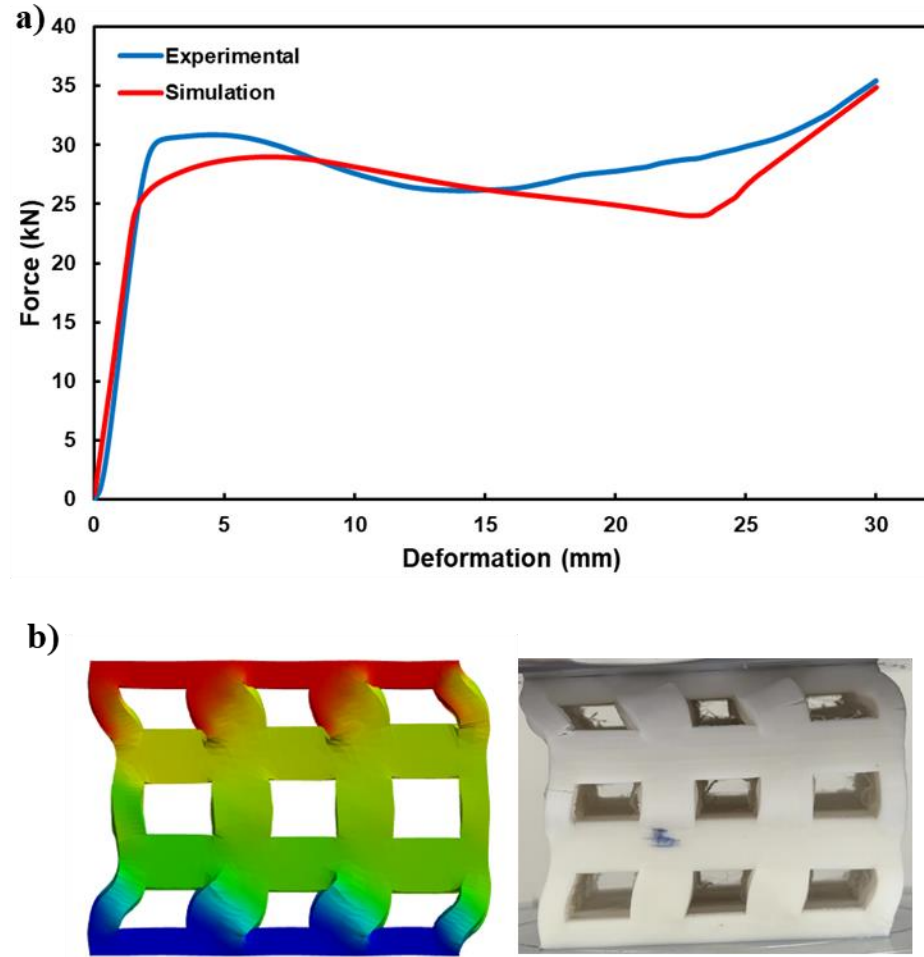


Figure 4.4. Simulation vs experimental for a) force displacement curves and b) deformation pattern for Model 1-3x with 4.4mm thickness.

4.1.5. Fracture analysis of cubic lattice structures using SEM

The SEM analysis (Figure 4.5a) of multi-material cubic structure fabricated using FDM revealed that the majority of failure occurred within the PLA region, particularly between PLA layers, which is consistent with common failure modes observed in FDM-printed thermoplastics due to weak interlayer adhesion [84]. The PLA region was exposed to higher tensile stress during loading, resulting in intra-material fractures. However, the TPU region remained well-adhered to the PLA, showing no signs of delamination at the

interface, indicating strong interfacial adhesion between the stiff and flexible phases. This is significant as multi-material 3D printing involving dissimilar materials often suffers from poor bonding due to differences in melting temperature and surface energy. The fracture surface topology varies across the sample, but a clear distinction in the deformation behavior of the two materials can be observed. The TPU region appears stretched and plastically deformed, forming elongated structures and smoother fracture planes, typical of hyper-elastic materials that absorb more energy before failure. In contrast, the PLA exhibits a more brittle fracture with sharp edges and micro voids at the crack path, confirming its lower toughness and higher stiffness. This can also be confirmed by comparing it with the zoomed image in Figure 4.5b. The SEM side view (Figure 4.5c) shows a fracture surface that is primarily localized in PLA regions, specifically between individual printed layers. This failure mode is a dominant fracture mode in FDM-printed thermoplastics, with the fracture propagating along the layered structure. The visible stair-step structure indicates the layer-by-layer deposition process, and the fracture appears to have propagated along these boundaries. The failure appears more energy-absorbing, suggesting that the PLA layers may have undergone plastic deformation before fracturing. This behavior could be attributed to the presence of TPU in the structure, which may have altered the stress distribution during loading. TPU is observed to be stretched and elongated, particularly at the interface with PLA, reinforcing its hyper-elastic characteristics. This tendency to deform plastically and maintain continuity under stress is beneficial for energy dissipation and can improve the overall toughness of multi-material structures. The SEM micrograph of a plate-based cubic multi-material structure (Figure 4.5e), consisting of PLA as the outer shell and TPU as the core, reveals a fracture propagating through the TPU region. The

internal void-like features and continuous crack path suggest that the TPU material was the initiating point of failure, possibly due to excessive localized deformation under mechanical loading which can also be seen in Figure 4.5e. TPU, being a hyperelastic and softer material, tends to undergo large strains, leading to stress concentration and crack initiation, especially when confined by a stiffer outer shell-like PLA. Elongated voids aligned along the interface and within the TPU core indicate that under tensile or flexural loading, the TPU experienced internal tearing or cavitation, a failure mechanism often observed in soft elastomers. These voids may have originated due to strain-induced decohesion within TPU or insufficient infill density during the printing process. Despite the failure originating within TPU, the PLA-TPU interface remains intact, suggesting that interfacial adhesion was not the weak link in this failure. The fracture surface exhibits well-defined layer lines of PLA in the upper region, indicative of the FDM process, confirming that the failure propagated entirely through the TPU region without influencing the surrounding PLA shell. This behavior is particularly relevant for plate-based designs, where flexural stresses are concentrated on the inner core.

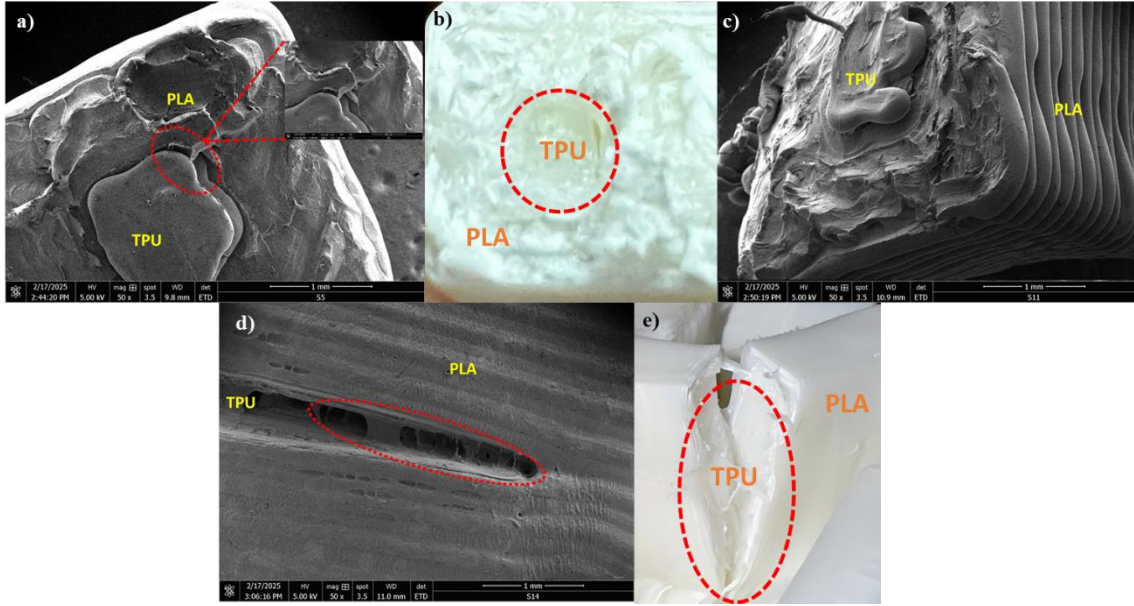


Figure 4.5. SEM images of fracture surfaces in strut-based multi-material cubic structure showing (a) top view of layer failure of PLA–TPU interface, (c) side view of interlayer fracture propagation along PLA with TPU deformation, and plate-based structure showing (d) TPU core failure in plate-based structure with preserved PLA–TPU adhesion and zoomed images of the fracture points of (b) strut-based and (e) plate-based multi-material cubic structures.

4.2 Multi-material TPMS diamond lattice structures

4.2.1 Deformation behavior of TPMS lattice structures under compression loading

The single and multi-material lattice diamond structures were compressed under quasi-static load up to 18 mm to extract the force-displacement curves and analyze the effect of different percentages of PLA and TPU on the quasi-static compressive response. Figure 4.6 illustrates the deformation of single and multi-material lattice structures with 0%, 25%, 50%, 75%, and 100% PLA at 0 mm, 5 mm, 10 mm, and 15 mm. The results after 15 mm were not shown as the onset of densification was observed without any fracture. As all relative densities exhibited similar responses, only samples with 40% relative densities are shown in Figure 4.6.

Compared to single material lattice structures, the deformation mechanism in the single material structures can be observed by studying the diagonal diamond layers. The initial samples (e.g. PLA 0% - 0 mm) show perfect diagonal layers; however, under compressive loads, these layers show increasing deformation, leading to progressive buckling and densification of the material under compressive load. As a hyperelastic material, the buckling and onset of densification is clearly visible in the PLA 0% - 15 mm samples (Figure 4.6). On the other hand, lattice structures with 100% PLA showed both buckling and shear band formation. The presence of shear bands in 100% PLA samples are clearly visible in the PLA 100% - 15 mm samples.

It is well known that material imperfections lead to buckling at loads lower than the Euler critical load [85]. Deformation in PLA samples show that PLA creates a belly when compressed due to buckling, shear band formation, and non-uniform stress distribution [86]. On the other hand, a similar type of buckling effect is seen in TPU structures triggered by the destabilization and the onset of bending and buckling mechanisms within one of the structural layers of the body [87]. In a perfect deformation, the single material lattice structure should deform as a column without bulge formation due to even stress distribution. However, it can be seen that the single material (PLA and TPU) structures show buckling with a clear bulge due to localized buckling observed in these samples (PLA 0% and PLA 100%).

Analysis of multi-material lattice structures do not show any visible deformation patterns till 5 mm deformation. Unlike single material lattice structures, the multi material lattice structures do not show any sign of buckling. Therefore, the multi-material structure prevents instability showing better homogeneous compression where the load is distributed linearly throughout the structures. However, a slight deformation can be observed in the 75% and 100% PLA samples, particularly at the top left and bottom right of the lattice structures. This change in deformation patterns is due to the presence of PLA in the lattice structure where the deformation in PLA causes the structure to deform plastically. This is different from the diamond structures made of PLA and TPU blend by Liu et al. [6] where it showed both shear band formation and buckling.

The deformation patterns for multi-material lattice structures are exaggerated at higher PLA % and is evident in the PLA 75% - 10 mm samples where the waviness in diagonal lines is more apparent. In PLA 0%, 25% and 50% lattice structures, the waviness is introduced in the structure at 10 mm. However, a higher waviness is observed in the PLA 75% - 10 mm and PLA 100% - 10 mm lattice structures. The same is true for deformations at 15mm where the pattern of diagonal lines is highly distorted at 75% and 100% PLA – 15 mm as compared to other lattice structures. In all deformations, TPU acts as an elastic material and allows for higher deformation under load while PLA acts as a stiffener in the lattice structure.

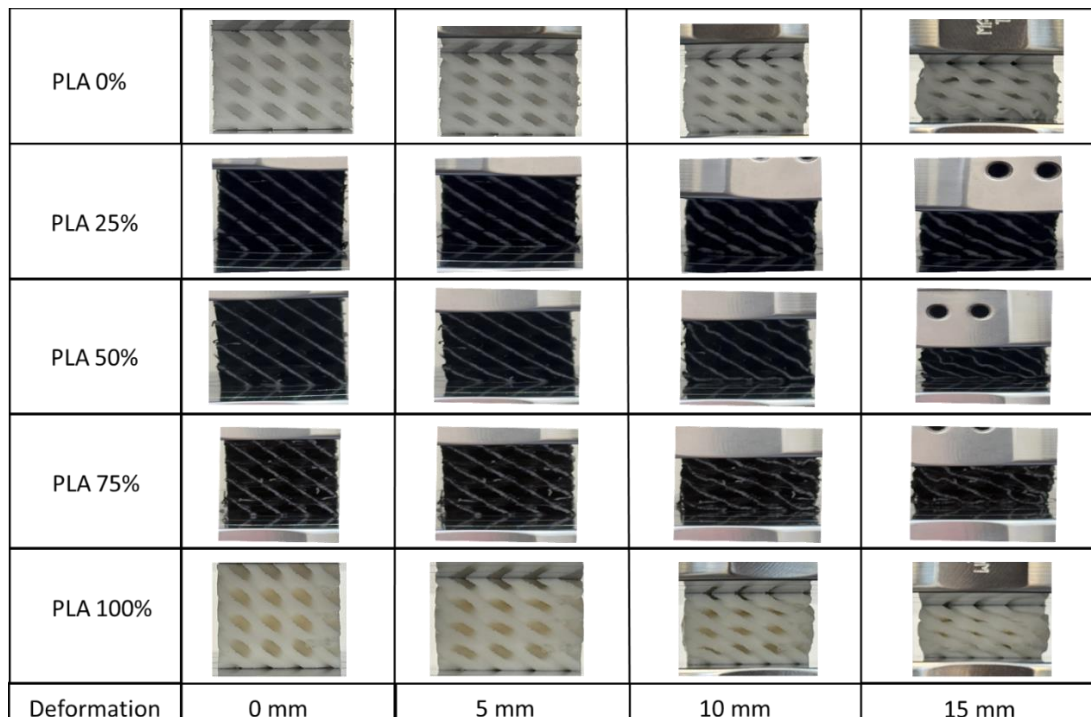


Figure 4.6. Results at 0 mm, 5 mm, 10 mm and 15 mm deformations for single and multi-material diamond structures with 40% relative density during compression testing.

4.2.2 Force-displacement curve for TPMS lattice structure

The analysis of load-deformation curves helps in the analysis of mechanical properties of the single and multi-material material lattice structure. The quasi-static compression tests yielded the force-displacement curves for single and multi-material diamond structures based on PLA-TPU distribution and relative density (Figure 4.7). These results further demonstrate the role of material distribution in the diamond lattice structures at different relative densities under quasi-static load. Figure 4.7a show the force – displacement curves for different material distribution at 40% relative density. Results show that all structures exhibit a linear elastic region which varied with the percentage of PLA and TPU. It is also evident that the lattice structures deform more linearly as the percentage of TPU increased. This can be explained by the hyperelastic nature of TPU [47]. Analysis of 100% PLA results also show a slight drop in the plateau region that is caused by localized buckling in the lattice structure (Figure 4.6a). A similar trend is also observed in samples with 50% (Figure 4.7b) and 60% (Figure 4.7c) relative densities. However, the load-relaxation is much lower for the 50% and 60% samples. These observations suggest a higher localized buckling at 40% relative density as compared to the 50% and 60% relative density samples. In addition, it can be concluded that an increase in relative density led to uniform load distribution [88].

The peak load will be the maximum load sustained by the lattice structure before failure or significant deformation. The stiffer the material, the more force it requires to deform the structure, hence higher will be the peak load. PLA being the stiffer material should require higher force while the TPU being the hyperelastic material should require the minimum force to deform the lattice structure. The multi-material lattice structure should have peak

load in-between these two structures depending upon the percentage of TPU and PLA. Another useful property which can be calculated from force-displacement curves is compression modulus which can tell us about the behavior of a structure under quasi-static compression load. The modulus is usually higher for PLA as compared to TPU due to its ability to break rather than deform and resistance to deformation under compressive load whereas TPU undergoes large deformation before fracture increasing the compression modulus of the overall body [89]. Energy absorption will also be measured to better understand the behavior of single and multi-material lattice structures in absorbing and dissipating energy under compression. Looking at another study, it can be estimated that energy absorption should also be the highest for PLA as the material is stiffer and stronger than TPU and the multi-material lattice structure should also perform on the basis of the percentage of TPU and PLA [90].

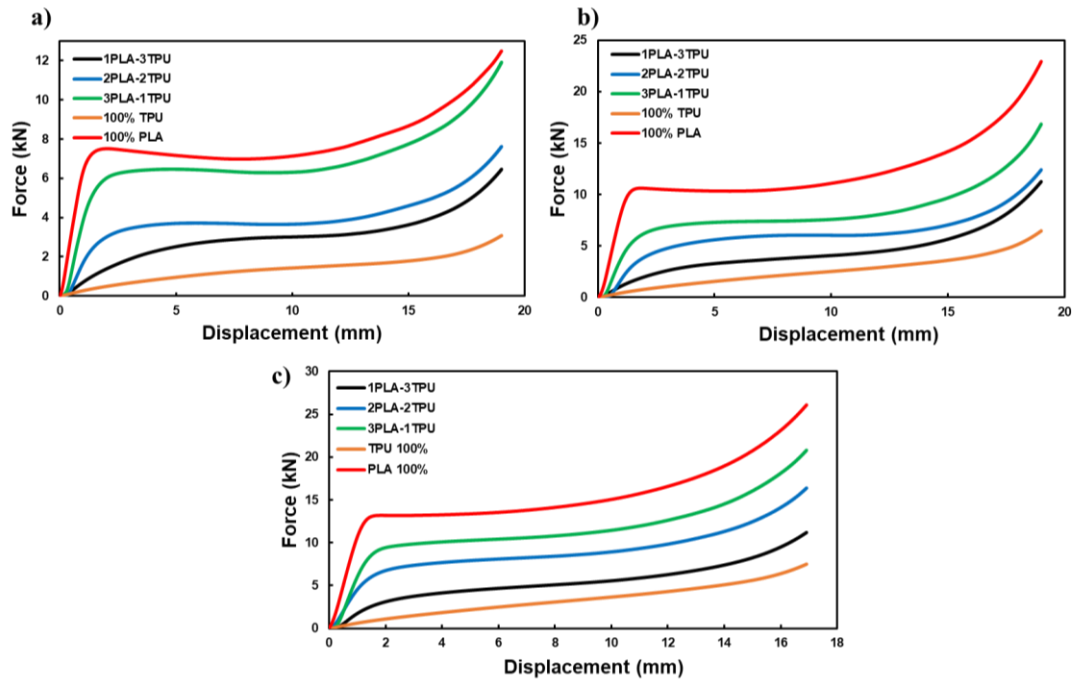


Figure 4.7. Force - displacements curves for all single and multi-material diamond structures with (a) 40%, (b) 50% and (c) 60% relative density up-to 16mm compression.

4.2.3 Peak load, compression modulus, and energy absorption

Deformation (Figure 4.6) and force-displacement (Figure 4.7) results provide the trends during deformation. However, further mechanical properties can be extracted from these results to quantify the differences in the mechanical properties between the single and multi-material diamond lattice structures. The compression modulus was calculated to determine the ability of the lattice structures to resist deformation under compressive load in the elastic region [91]. The compression modulus values for all single and multi-material diamond structures with 40%, 50% and 60% relative densities (Figure 4.8a) show a positive correlation between the compression modulus and PLA%. For TPU lattice structures, the compression modulus was calculated as 0.27, 0.42 and 0.45 kN/mm respectively which shows a direct relationship between the relative density and the compression modulus. However, the compression modulus for PLA structures was calculated as 6.54, 8.05 and 10.71 kN/mm for 40%, 50% and 60% relative density, respectively. PLA compression moduli were higher than any multi-material structure due to the presence of TPU that resulted in reduced stiffness [92]. The compression modulus of all multi-material lattice structures was between the TPU and PLA structures. This suggests that lattice stiffness is a function of relative density and PLA%. The presence of TPU in the multi-material structures delayed the yield resulting in lower compression modulus. A similar observation was also recorded for the relative densities where a higher relative density resulted in a higher compression modulus.

Similarly, energy absorption of all single and multi-material diamond structures was also calculated up to 16 mm. The energy absorption for all single and multi-material diamond

structures with 40%, 50% and 60% relative densities can be seen in Figure 4.8b. Similar to compression modulus, energy absorption increases with an increase in PLA%. The value of energy absorption for 100% TPU was calculated as 20.49, 37.12 and 55.55 J for 40%, 50% and 60% relative density, respectively. This was much less than the 100% PLA lattice which exhibited an energy absorption of 124.14, 189.07 and 258.56 J for 40%, 50%, and 60% samples, respectively. Similar to peak force, all multi-material structures showed energy absorption between the 100% TPU and PLA structures ranging from 54.91 to 196.13 J. Although the higher strength of PLA increased the energy absorption for higher PLA to TPU diamond structures, it should be noted that TPU played an important role for the progressive deformation of the multi-material structures (Figure 4.6) [5].

Figure 4.8c compares peak load values for all single and multi-material diamond structures with 40%, 50% and 60% relative densities. Analysis of results shows that the 100% PLA lattice structures reached a peak load of 7.5 kN while the 100% TPU lattice structures reached a peak load of 1.8 kN before densification. This was due to the higher stiffness exhibited by PLA samples [93]. Similarly, the 100% PLA diamond structures with 50% and 60% relative densities sustained a peak load of 10.5 kN and 13.1 kN, respectively while 100% TPU diamond structures could only sustain a peak load of 3.7 kN and 4.5 kN, respectively. Peak loads for the multi-material PLA-TPU lattice structures were observed to be between the single material PLA and TPU lattice structures [47]. These results show that the effect of TPU in PLA structures does not result in the formation of any new bonds between the two materials. The increase in peak load is a direct result of PLA%.

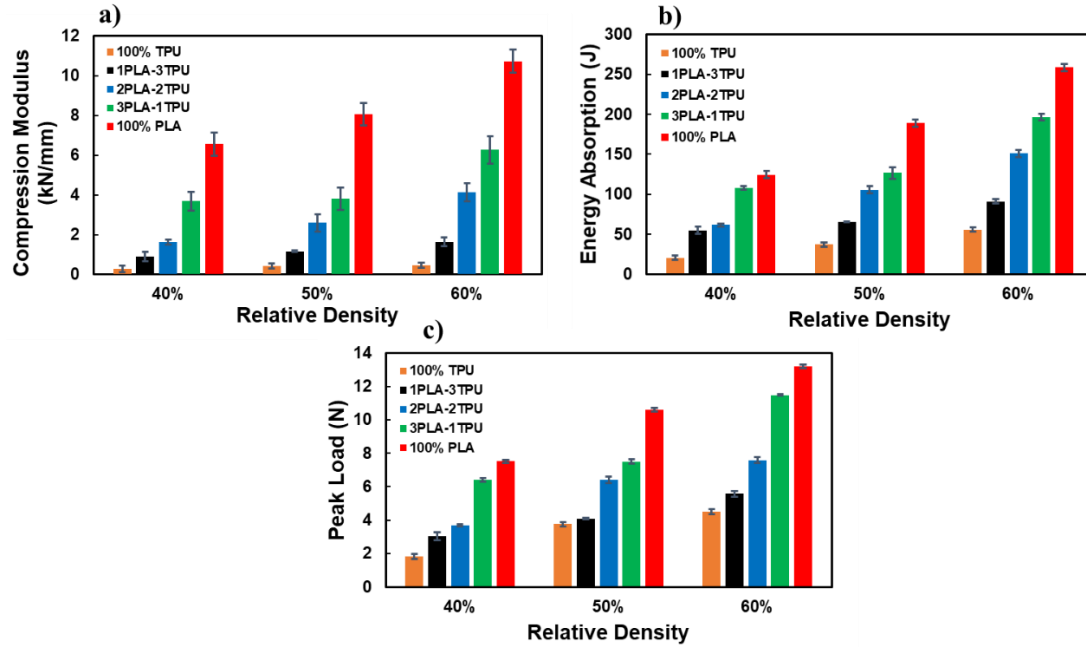


Figure 4.8. Bar charts for (a) compression modulus, (b) energy absorption and (c) peak load for single and multi-material lattice structures with 40%, 50% and 60% relative density.

4.2.4 Analysis of the complete cycle to capture energy loss

As energy loss was also studied in this work, Figure 4.9 shows the shape recovery after the load was removed. It can be seen that all single and multi-material samples exhibited a level of recovery. This retention was inversely proportional to the PLA % where increasing the PLA% decreased the ability of the structure to recover. The most shape retention with minimal energy loss was observed by the 100% TPU lattice structure due to its hyperelastic response [94], [95]. On the other hand, 100% PLA samples showed maximum energy loss (Figure 4.9). However, the addition of TPU in PLA lattice structures decreased this energy loss. This unique behavior can also be attributed to the lattice geometry (diamond structure) used in this work [96]. Therefore, the responses in energy loss can be attributed to the

material and lattice structure independently. It can be seen that PLA 0% lattice structure recovered most of its energy after compressing it to 15 mm.

Analysis of the multi-material structures show that the white diagonal TPU lines in the PLA 25% samples could not recover to the original shape due to local onset of bending. During recovery, this resulted in uneven surface as seen in Figure 4.9. The same trends were observed for all multi-material samples with varying TPU% and relative densities. However, a higher deviation was observed with higher TPU% (PLA 25%). It should also be noted that none of the multi-material structures showed any fracture during recovery which highlights the importance of TPU in enabling the energy absorption response of PLA-TPU lattice structures.

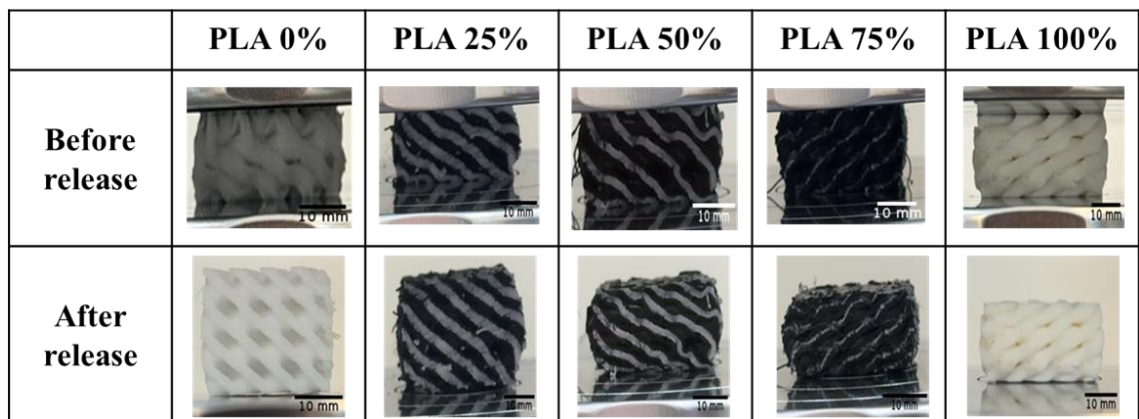


Figure 4.9. Behavior of single and multi-material lattice structures with 40% relative density before (top) and after (bottom) releasing load in compression testing

4.2.5 Force-displacement curves energy loss calculation

Figure 4.10a, b and c show the complete cycle for force-deformation curves for 40,50 and 50% relative density, respectively. Figure 4.10d presents the energy loss % for the single and multi-material diamond lattice structures. It can be seen that for the same relative density, the energy loss increased with an increase in PLA%. However, a similar energy

loss was observed for samples with varying relative densities. For example, 50% PLA lattice structures showed an energy loss of 92.52%, 91.36% and 90.77% for 40%, 50% and 60%, relative densities respectively that resulted in recovery from 15 mm to 10.35, 10.5 and 10.2 mm, respectively. Therefore, it can be concluded that the energy loss does not account for the initial energy in the system and therefore is a function of the material and lattice structure rather than the density of the material. The PLA - 0% structures showed the lowest energy loss (62.02%) while the PLA - 100% structures exhibited the highest energy loss (97.06%).

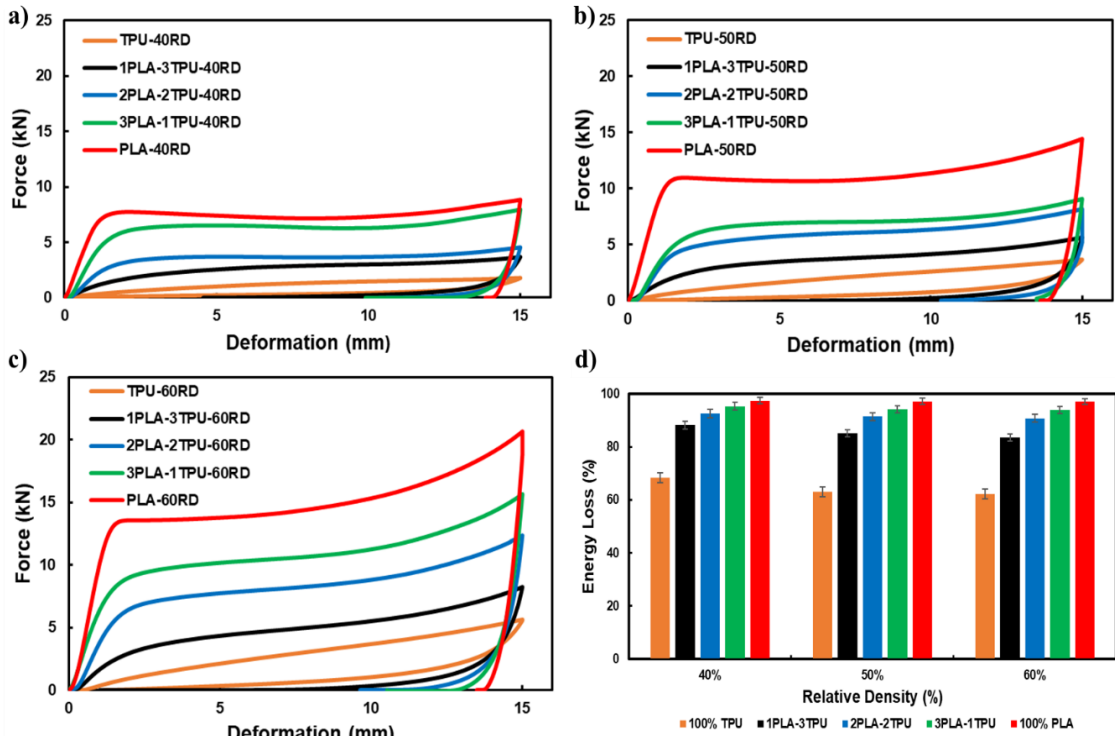


Figure 4.10. Force - deformation curves for a complete cycle of compression with (a) 40%, (b) 50% and (c) 60% relative density and (d) Energy Loss% for all single and multi-material diamond structures.

4.2.6 Inverse design

The mechanical properties presented in the previous section show the overall behavior of the single and multi-material lattice structures with changes in material composition and relative densities. The results from single and multi-material lattice structures determined the mechanical properties of the structure at different relative densities with different percentages of PLA and TPU. After the calculation of mechanical properties i.e. peak load, compression modulus, energy absorption and energy loss%, a general trend can be established between the mechanical properties and design parameters. This will help in the optimization and prediction of multi-material diamond lattice structure parameters by using the design parameters (relative density and PLA %) as inputs and predicting the required mechanical properties (peak force, compression modulus, energy absorption and energy loss%) as outputs. In this work, the optimized multi-material lattice structures were designed based on a feed forward back propagation ANN. The proposed ANN will be established to determine the design parameters for single or multi-material diamond lattice structures.

4.2.7 Training of the model from experimental values

The inputs to the proposed ANN model are shown in Figure 3.13. Results show peak load (PL), compression modulus (CM), energy absorption (EA) and energy loss% (EL) from all single and multi-material lattice structures. It should be noted that all mechanical properties are plotted with their respective material composition and relative densities. The compression modulus and peak load are shown on the left y-axis while the energy absorption and loss are shown on the right y-axis. The extrapolated trends observed in Figure 4.11 highlight the non-linearity between the various mechanical properties.

Therefore, any optimization attempt requires a flexible and robust mechanism to predict the required structures for any given properties.

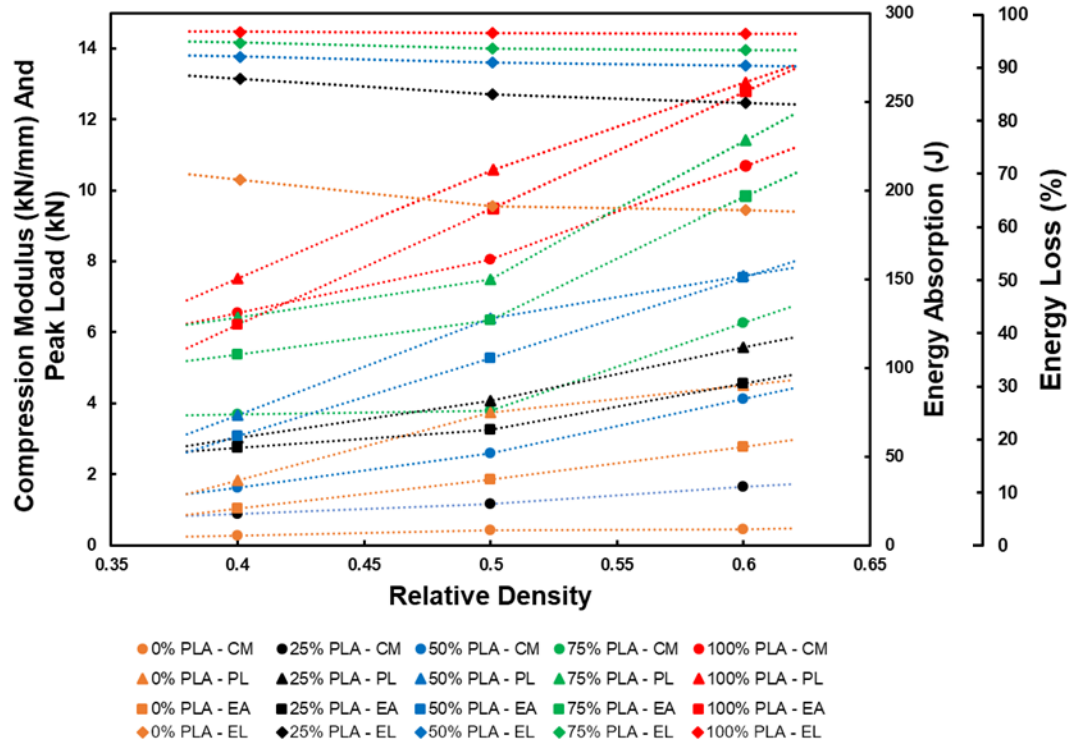


Figure 4.11. Combined graph for the mechanical behavior of single and multi-material diamond lattice structures with different relative densities. Results for Compression modulus (CM), Peak load (PL), Energy absorption (EA), and energy loss % (EL) are shown.

A relationship between the mechanical characteristics (elastic modulus, energy absorption, peak stress and energy loss%) and the design parameters (material ratio and relative density) can be established by various methods such as regression, machine learning tools, analytical models etc. [64]. However, in this work, an artificial neural network (ANN) model was used to predict the multi-material lattice parameters to achieve the desired objectives. The elastic modulus, energy absorption, peak stress and energy loss% were

taken as inputs to the ANN model while the material ratio and relative density were defined as the model outputs. The overall goal of the ANN model was to establish a relationship between the mechanical properties and the design parameters.

An ANN model with two hidden layers was used in this work to predict the various lattice parameters. The neural network's hyperparameters were established via a parametric analysis with a learning rate of 0.0045 and 4000 epochs that resulted in a training and validation loss of 0.01 and 0.05, respectively. The training for the proposed ANN model was conducted on 80% of the available data while the remaining 20% dataset was used for testing and validation. The overall ANN model showed a mean squared error % of 2.25% for relative density and 1.55% for PLA % with a R-squared of 0.91.

4.2.8 Prediction and validation of the ML

The Figure 4.12 shows the performance evaluation of the ANN model for the training, validation and testing datasets. The ANN model demonstrates a strong ability to predict PLA% and Relative Density accurately. The results show strong predictions for the training dataset for both outputs. However, slight deviations were observed in the validation and testing data sets. Minor errors are expected in prediction of validation and testing data points due to the inherent variability in data [97]. Comparison of the PLA% and Relative Density predictions shows higher errors in the relative density predictions. The results illustrate the predictive capabilities and robustness of the ANN model that effectively captures the underlying relationships between inputs and outputs.

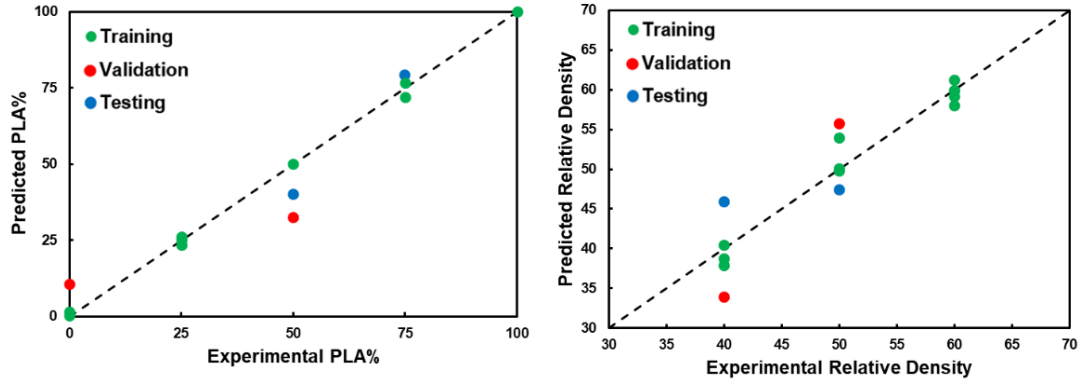


Figure 4.12. (a) Experimental and predicted PLA% and (b) Experimental and predicted Relative Density.

The predictive capabilities of the proposed ANN model confirm its applicability for inverse design of multi-material lattice structures. The validation results shown in Figure 4.12 shows excellent predictions. However, it is important to test the proposed ANN model with completely new objectives to highlight its flexibility and accuracy to achieve the desirable mechanical properties. This will enable the customization of diamond lattice structures for any given application. Five test samples with varying objectives for the mechanical properties were used to verify the ANN performance (Table 4.1). In the first phase, lattice structures with different peak load (PK), compression modulus (CM), energy absorption (EA), and energy loss% (EL) were designed. The corresponding design parameters (relative density and PLA %) for the desired objectives (PK, CM, EA, EL) are also shown in Table 4.1.

Table 4.1. Predicted values by using mechanical properties as input and getting relative density and PLA% as output by customized ML model.

Sample no.	Predicted Mechanical Property	Expected Result	Output Relative Density (%)	Output PLA percentage (%)
PL	Peak Load	4 kN	36.11	59.28
CM	Compression Modulus	2.60 kN/mm	74.54	25.52
EA	Energy Absorption	192 J	74.81	46.28
EL	Energy Loss%	85 %	50.61	33.85

4.2.9 Mechanical properties of the lattice structures from the inverse design

The predicted lattice structures from the proposed ANN model that achieved the desired mechanical properties were additively manufactured to validate the proposed ANN multi-material lattice structures. The samples were tested for up to 18mm under uniaxial compression to assess the model performance under peak load (PK), compression modulus (CM), energy absorption (EA) and energy loss (EL). The force-displacement curves from the validation samples are shown in Figure 4.13. The EL results show a complete cycle as energy loss% was only studied for this sample. The results show that the PL sample exhibited the required peak force. A plateau region can be observed in EL and PL while EA and CM samples did not show any visible plateau region showcasing progressively

stiff behavior. The results from the force-displacement curves were studied and the predicted mechanical properties were calculated from the predicted ANN multi-material diamond structures.

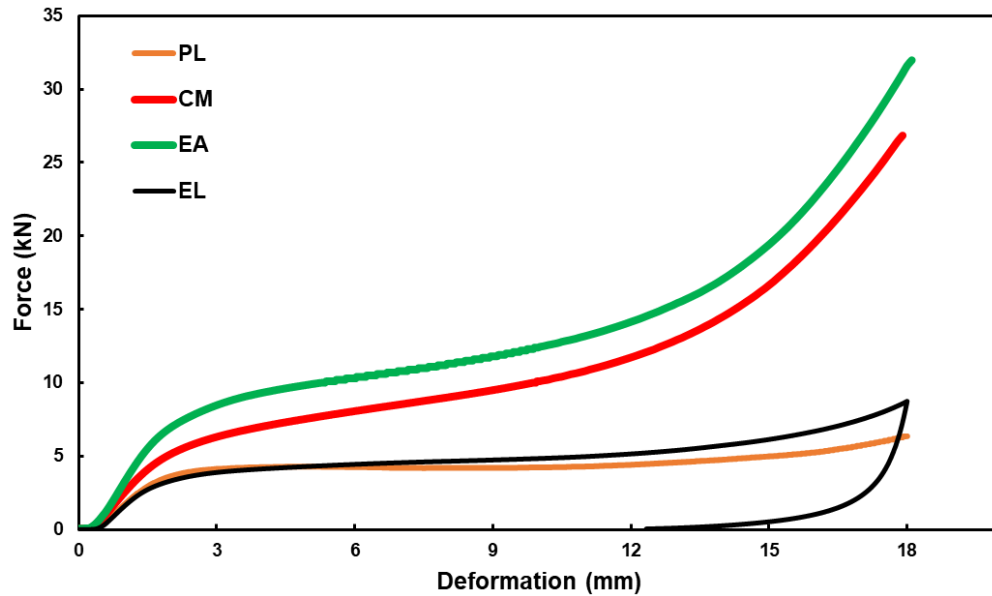


Figure 4.13. Force – displacements curve for all 4 multi-material diamond validation samples.

The ANN model predictions were compared to the experimental ANN multi-material lattice structure results. Table 4.2 illustrates the expected and experimental mechanical properties of the validation samples. All samples showed excellent predictions where the PL, EA, CM and EL samples exhibited an error from -3.8 to 5.6%. Overall, the experimental outcomes demonstrated that the validation samples showed excellent predictions. Therefore, it can be concluded that the proposed ANN model can be used for inverse design of multi-material lattice structures to achieve the desired mechanical properties.

Table 4.2. illustrates the expected and experimental mechanical properties of the multi-material diamond validation samples.

Sample no.	Predicted Mechanical Property	Expected Result	Experimental Result	Error (%)
PL	Peak Load	4 kN	4.24 kN	5.6
CM	Compression Modulus	2.60 kN/mm	2.66 kN/mm	2.25
EA	Energy Absorption	192 J	184.69 J	-3.8
EL	Energy Loss%	85 %	91 %	1.18

4.3 A proposed Novel TPMS Diamond multimaterial MM lattice structure

Based on extensive experimental findings and predictions from an Artificial Neural Network (ANN) model, a novel multi-material mechanical metamaterial was proposed. This structure utilizes a Triply Periodic Minimal Surface (TPMS)-based diamond lattice configuration fabricated using PLA and TPU, offering flexibility and energy absorption. The ANN predicted optimal design parameters with a relative density of approximately 64.67% and a PLA percentage of 56.48%, targeting specific mechanical properties: a peak load of 10 kN, compression modulus of 4.34 kN/mm, energy absorption of 160 J, and energy loss of 90%. The force-displacement curve of the proposed novel multi-material lattice structure namely COM can be seen in Figure 4.14.

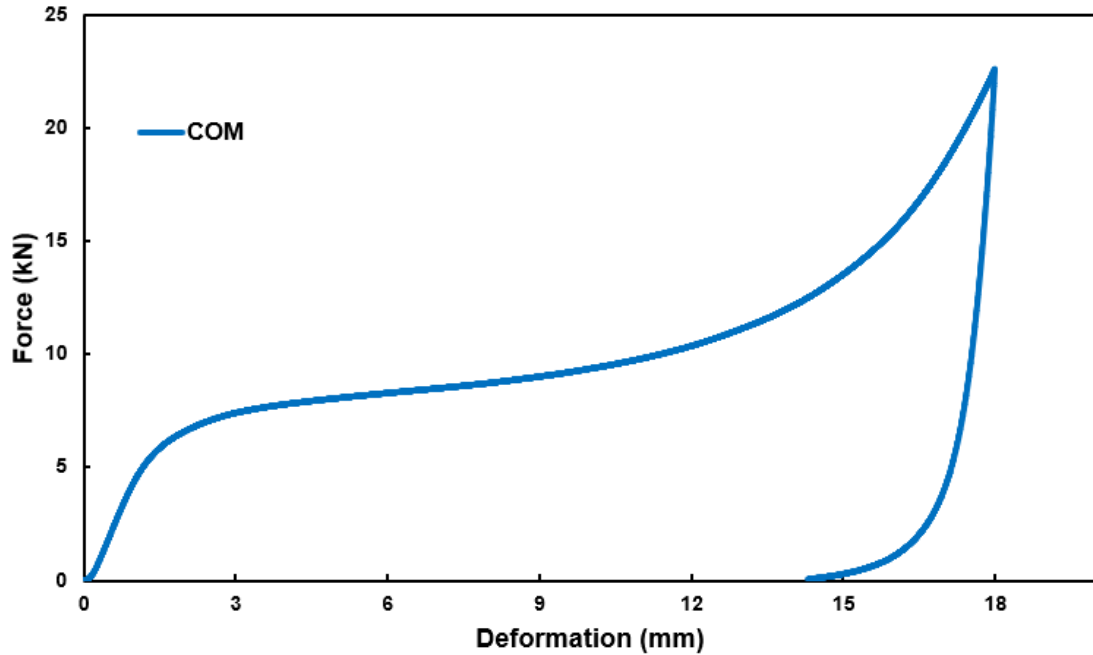


Figure 4.14. Force – displacements curve for the proposed novel multi-material diamond MM lattice structure.

To experimentally verify these predictions, the proposed multi-material lattice structure was fabricated using Fused Deposition Modeling (FDM), strictly adhering to the ANN-predicted relative density and material composition. Mechanical characterization through compression testing demonstrated strong agreement between predicted and experimental values. Specifically, the experimentally measured peak load (10.47 kN) closely matched the ANN prediction, showing only a 4.49% deviation. The compression modulus (4.27 kN/mm) exhibited minimal error (-1.64%), confirming accurate prediction capabilities. Although the experimental energy absorption (198.77 J) exceeded the predicted value by 19.5%, this outcome represents an advantageous enhancement in mechanical performance. Additionally, the energy loss percentage (93.5%) closely aligned with the predicted value, exhibiting only a slight deviation of 3.74%.

The validated performance of this novel multi-material lattice structure highlights its significant potential for various applications requiring enhanced mechanical properties, such as automotive safety systems, aerospace lightweight components, protective gear, and biomedical implants. Its tailored mechanical responses, optimized through ANN-driven design methodologies, demonstrate promising practical applicability, particularly relevant to industries within Saudi Arabia aiming for advanced manufacturing innovation and customization capabilities. Future studies may further refine these structures, explore additional material combinations, and assess performance under diverse loading conditions.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

This thesis addresses the significant knowledge gap in multi-material mechanical metamaterials by investigating how combining materials can enhance multifunctional mechanical properties over traditional single-material designs. The study is divided into two parts based on lattice structure types. The first part explores strut-based and plate-based cubic structures made from PLA and TPU with varying thicknesses and unit cell configurations, tested under quasi-static compression. The second part focuses on single- and multi-material diamond TPMS lattices, incorporating a feedforward backpropagation artificial neural network (ANN) for inverse design based on desired mechanical properties.

Compression tests revealed that all three cubic unit cell types exhibited distinct behaviors. For example, Model 1-3x showed cell-by-cell collapse which is advantageous for energy absorption. TPU contributed to ductile deformation, while PLA increased stiffness. Force-deformation curves indicated that mechanical properties could be tuned by altering material composition and geometry. Numerical simulations showed strong agreement with experimental results, validating the model. SEM analysis revealed failure patterns: PLA showed interlayer fractures in strut-based structures, while TPU remained ductile and well-bonded, confirming strong interfacial adhesion. In plate-based structures, cracks propagated through TPU cores, indicating optimized multi-material printing.

In the diamond lattice structures, increased PLA% led to higher stiffness and peak load, while increased TPU% and relative density improved strength and linearity. The 100% PLA structure at 60% relative density achieved the highest peak load (13.18 kN), while the 100% TPU structure at 40% had the lowest (1.82 kN). Energy absorption and compression modulus followed similar trends. Energy loss was lowest for 100% TPU at 60% density (62.24%) and highest for 100% PLA at 40% density (97.42%). PLA% had a greater impact on energy recovery than relative density. ANN predictions for optimal design parameters (PLA% and density) closely matched experimental results, with minimal error (−3.8% to 5.6%) which was able to predict a novel multimaterial Diamond lattice structure with desirable properties.

The combined use of PLA and TPU resulted in structures with tunable strength, energy absorption, and shape recovery, making them ideal for impact-resistant applications like automotive components and protective gear. Additionally, the integration of machine learning demonstrated precise control over mechanical properties, supporting rapid prototyping for diverse industrial applications.

5.2. Recommendations

- The relative density in the TPMS diamond lattice structures can be further explored to find more data points for the ANN model for better accuracy.
- Other types of meta-materials can be explored and tested using multi-material additive manufacturing which can increase our understanding of multi-material behavior of structure. Also, this can help us in increasing the efficacy of our ANN

model by giving it data of other types of lattice structure as well.

- For the strut-based and plate-based cubic lattice structure, the ratio of PLA and TPU and wall thickness can be further experimented to get a better understanding of the structures.
- The data from the Model 1 and Model 2 can be incorporated in the ANN model and can be tested to predict a structure out of any one of the three experimented model which can give the most desirable results.
- Combinations of other soft hard materials like ABS and TPU with lower hardness can be tried to examine the results in multi-material meta-material additive manufacturing.

5.3. Achievements

From this work, we were able to submit two Journal Papers which shall add value to the field of additive manufacturing. Following is the list of published and submitted works.

[1] M. Abbas, U. Ali and A. Nazir, “Design, additive manufacturing, and machine learning prediction of multi-material diamond TPMS structure for improved mechanical performance” – submitted to Progress in Additive Manufacturing Journal.

[2] M. Abbas, K. Azher and A. Nazir, “Multi-material Integration for Multifunctional Enhancement of Additively Manufactured Cubic Strut and Plate-Lattice Structures” – in final draft and ready to be submitted to a journal.

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