

Fatigue of Triply Periodic Minimal Surface (TPMS) Metamaterials – a Review

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Abstract A review of the fatigue behavior of triply periodic minimal surface (TPMS) metamaterials with consideration for their fabrication is presented in this paper. The review analyses the most common TPMS geometries used due to their mechanical characteristics. Production methods and the base materials used are presented with the key advantages and drawbacks. Furthermore, the mechanical characteristics of cellular structures with emphasis on TPMS geometries are described. Lastly, the state-of-the-art findings of their fatigue behavior are analyzed and explained. Based on the findings in this article, cellular geometries based on TPMS are superior to conventional cellular structures when comparing their fatigue life. Because of the smooth transitions between struts or surfaces, the stress distribution is much more uniform without stress concentration zones.

Keywords cellular structures, TPMS metamaterials, production technologies, mechanical characterization, fatigue behavior

Highlights

- The general characteristics of cellular structures, with focus on TPMS geometries, are explained.
- Fabrication techniques used to produce TPMS metamaterials are briefly introduced.
- Fatigue behavior of TPMS metamaterials is presented and compared.

1 INTRODUCTION

Cellular structures are materials composed of solid edges or faces that are arranged in patterns to fit a certain space. They are inspired by porous materials found in nature, such as bone, wood, coral and honeycombs [1]. Their main benefits are high strength and excellent energy absorption at a relatively low weight. Due to these qualities, cellular materials are being analyzed and applied in industries like aerospace, sports, automotive and medicine [2,3]. Cellular materials can be broadly categorized into three types. The first are open-cell structures (Fig. 1b). The voids and pores inside the structures are interconnected, meaning a fluid could flow freely through the material. In contrast, closed-cell structures (Fig. 1c) feature isolated voids. The third category are honeycomb cellular structures, comprised of repeating cells in two dimensions that resemble the hexagonal pattern found in natural honeycombs (Fig. 1a) [4].

However, due to the increasing number of newly engineered materials, designed to exhibit unusual or tunable mechanical, acoustic or electromagnetic properties that are known as

metamaterials [5], they can be further categorized in more detail as shown in Fig. 2. Porosity or relative density are typically used to describe metamaterials. Porosity refers to the fraction of the material's volume that is made up of voids or pores, while relative density compares the density of the cellular material to that of the solid material [2,6]. Additionally, plateau stress, densification strain and energy absorption (SEA) are critical in characterizing the mechanical response of these materials [7]. They can achieve an auxetic response with the right combination of cell topology and morphology. This means that they have a negative Poisson's ratio, so when a compressive force is applied, the material contracts laterally, unlike typical materials that expand. This behavior leads to benefits such as increased stiffness, high energy absorption and enhanced shear stiffness [8]. Geometries that exhibit this type of response are typically strut-based lattices and chiral structures. They are designed to be lightweight yet highly efficient in distributing forces. A negative aspect of these types of structures is their sharp transitions in areas where their struts meet. This can negatively affect their mechanical properties, especially whenever dynamic loads are applied [9-12].

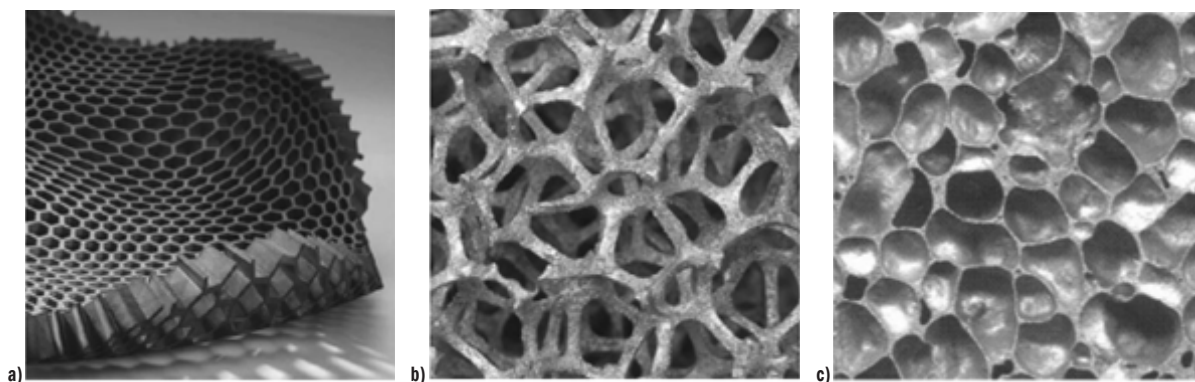


Fig. 1. a) Honeycomb, b) open-cell and c) closed-cell cellular structures, reproduced from [4]

Another type of architected cellular structures that do not have this drawback are TPMS geometries, which are usually geometrically more complex but offer highly efficient structural performance such as compressive strength, elastic modulus and energy absorption due to their smooth surface transitions [13,14].

Because of their unique properties, they have gained attention in various applications, e.g. energy absorption, thermal management, fluid mixing and biomedical engineering [15–18]. With the proper production method, unit cell selection and grading, TPMS structures were shown to closely mimic human bone's mechanical properties, such as strength, stiffness and porosity [19]. This makes them viable for manufacturing personalized bone implants [20,21]. Additionally, these mechanical properties make them suitable for applications as energy absorbers, such as components designed to assure controlled deformation during a crash in the transport industry [22]. TPMS metamaterials are not only used in mechanical applications. Certain geometries are being investigated for use in the static mixing of fluids. Their geometries enhance turbulence and mixing efficiency, making them suitable for pH control and inline coagulation applications in water treatment systems [23]. Some TPMS configurations are increasingly being integrated into heat exchangers. They improve heat transfer efficiency due to their high surface area to volume ratio, which leads to better heat transfer and thermal efficiency [17,24–27].

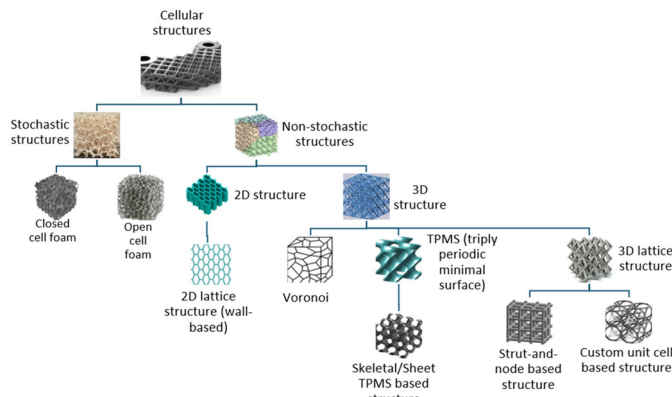


Fig. 2. Categorisation of cellular materials, reproduced from [28]

In addition to the mechanical and thermal properties of TPMS metamaterials, like other cellular materials, understanding their long-term mechanical performance under cyclic loading conditions remains essential [29]. Many of their main applications include bone implants and crash absorbers. These components are often subjected to repeated mechanical loads. Under such conditions, fatigue behavior becomes a critical design consideration, since failure may occur even before the loads reach the static mechanical limits of the structure [30]. Fatigue analysis of TPMS metamaterials is therefore vital in ensuring their long-term performance. Research on the fatigue behavior of cellular materials has slowly increased over the past years. However, TPMS metamaterials only have a handful of scientific publications that have analyzed their response under cyclic loading. This paper aims to review different types of TPMS geometries, production methods, and mechanical and fatigue properties to better understand their advantages and limitations. Lastly, outlines for future research are given.

2 TPMS GEOMETRIES

2.1 Most Common TPMS Geometries

The design and geometries of TPMS structures can be tailored for specific properties. They can be adjusted to achieve desired

porosity and stiffness, making them ideal for lightweight structures or scaffolds in tissue engineering [27]. Additionally, their shapes and continuity influence local stress distributions and fatigue resistance. For example, smooth and continuous surfaces reduce stress concentrations, while sharp transitions act as fatigue crack initiation sites. Euler and Lagrange first studied the theory behind minimal surfaces in a three-dimensional space. The name refers to surfaces with a mean curvature of zero at every point [31]. Meusnier discovered the most primitive examples of this with the help of an analytical approach to calculate the mean curvature of a catenoid and helicoid [32]. These surfaces can be described using a general implicit equation of the form:

$$f(x, y, z) = C. \quad (1)$$

Equation (1) defines a surface in a three-dimensional space. For it to exhibit the mean-zero curvature and periodicity characteristic of TPMS, the function must be expressed using specific trigonometric formulations. Some of the most common examples are presented in Table 1. These trigonometric functions divide space into two domains as the equation approaches zero. The resulting domains can be identical in shape or differ from one another. By adjusting the constants within the function, the topology of the surface can be modified, resulting in different TPMS configurations. Because these types of structures are fully defined with an equation, they allow for great freedom when modelling [32–34]. The first triply periodic minimal surfaces were described by Schwarz in 1865 [31] and Neovius in 1883 [35]. They are defined as continuous, non-self-intersecting structures that extend infinitely in three principal directions. They exhibit periodicity and crystallographic space group symmetry [36]. Using this definition, Alan Schoen built upon Schwarz's foundational discoveries. The most common TPMS geometries with their implicit equations are presented in Table 1. The first surface model that fits these requirements is called Schwarz Primitive. It has two intertwined congruent labyrinths, each with the shape of an inflated tubular version of the simple cubic lattice [37]. If we replace the shape of the lattice with a diamond bond structure, we get the so-called Diamond surface [37]. The Gyroid was discovered by Alan Schoen in 1970 and is an infinitely connected triply periodic minimal surface. It is an intermediate between the aforementioned Diamond and Schwarz Primitive surfaces. This geometry is found in butterfly wings and is widely used in fluid transport and mixing [27].

Table 1. Common TPMS geometries and their corresponding equations

Name	Equation	Model
Schwarz Primitive	$\cos(x) + \cos(y) + \cos(z) = 0$	
Diamond	$\cos(x) \cdot \cos(y) \cdot \cos(z) - \sin(x) \cdot \sin(y) \cdot \sin(z) = 0$	
Gyroid	$\sin(x) \cdot \cos(y) + \sin(y) \cdot \cos(z) + \sin(z) \cdot \cos(x) = 0$	
I-Wrapped Package (I-WP)	$\cos(x) \cdot \cos(y) + \cos(y) \cdot \cos(z) + \cos(z) \cdot \cos(x) = 0$	

Lastly, the I-Wrapped Package (I-WP) was described by Alan Schoen in 1970. It is characterized by its two to four self-intersecting

Schoenflies surfaces [37]. In engineering applications, TPMS metamaterials are typically designed with relative density ranging from 0.1 to 0.5, and unit cell sizes commonly falling within the range of 1 mm to 6 mm, depending on the chosen manufacturing process [38-41].

2.2 TPMS Structure Generation

The above presented geometries are based on surfaces. To be able to test them and make physical specimens, they must be assigned a volume. There are two ways of generating a volumetric model from the sheet-based geometries. In the first instance, a thickness is assigned to the surface model. With altering the wall thickness, the relative density of the structure changes. These geometries are called sheet-based TPMS structures. The second method uses the implicit surfaces and divides the domain around them into two solids [42]. Depending on the chosen TPMS design, the resulting domains can be identical or different from one another. By adjusting the constant C in Eq. (1), it is possible to control the domains shape. Figure 3 shows how the resulting geometries differ, depending on which method was used to generate them. Further modifications made by changing the values in the implicit functions, while still retaining smooth transitions between cells can be made easily. The first modification that can be made is changing the relative density. As previously mentioned, it can be altered by changing the C constant. Suppose C is not constant, and we assign a function that changes its value depending on the location in the coordinate system. In that case, we can achieve graded structures with different relative densities and mechanical properties throughout their geometries [20].

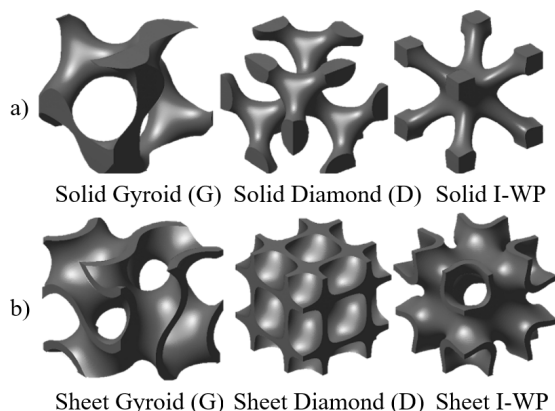


Fig. 3. Difference between: a) skeletal-TPMS metamaterials, and b) sheet-TPMS metamaterials, adapted from [43]

Another type of grading can be achieved by changing the size of individual cells. This changes the surface area and pore sizes while retaining a constant relative density. Liu et al. [40] described how this is achieved mathematically and is showcased in Fig. 4. It was observed that cell-size adjustments do not cause as substantial of a change in the mechanical properties of TPMS metamaterials as density gradients do. This is because larger cells negatively affect the mechanical properties, which is also where the geometries failed in testing. The last method is cell type grading or multimorphology. It is obtained by transitioning between different types of TPMS geometries while retaining smooth surface transitions. This is done by dividing the volume into different subdomains. If the equations that describe the unit cells have the same value at the intersections of these domains, we can achieve a continuous surface connecting them [44,45].

Graded designs not only influence mechanical stiffness but also play a role in fatigue behavior, since density, cell-size or cell-type

variations can either mitigate or amplify local strain accumulation during cyclic loads.

In addition to their mechanical response, these geometrical choices also determine how TPMS structures can be produced. For example, sheet-based designs have thin walls needing higher resolutions to achieve smooth transitions when compared to skeletal-based structures. Graded or multimorphology designs add further challenges, as variations in cell size and topology can prove too challenging for certain manufacturing processes. Because of this, the next section presents the main technologies used to produce TPMS structures.

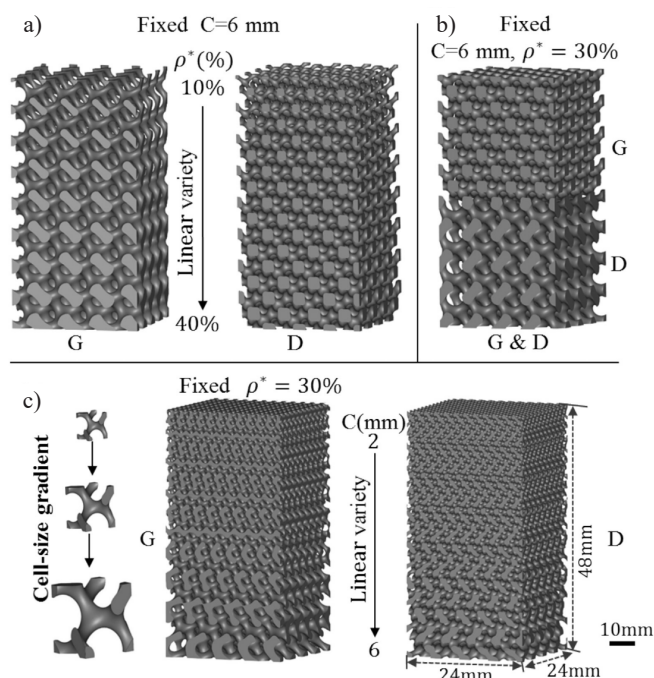


Fig. 4. Designed models of gradient samples; a) in relative density, b) in heterostructure and c) in cell size. Reproduced from [40]

3 PRODUCTION TECHNOLOGIES OF TPMS STRUCTURES

Because of their complexity, TPMS structures can only be produced with limited technologies. The most common and widespread is additive manufacturing (AM). It enables the creation of complex geometries that are difficult or impossible to achieve with traditional methods. Even with the advancements in AM technologies, the porous features and complex geometries still represent a challenge for layer-by-layer manufacturing [27].

3.1 Powder Bed Fusion – Laser Beam/Metals (PBF-LB/M)

PBF-LB/M, sometimes referred to as selective laser melting (SLM), is a type of laser powder bed fusion (LPBF), which falls under the broader category of powder bed fusion (PBF) technologies. In PBF-LB/M fabrication, a high-power laser is used to fully melt metallic powders to create structures. Not all of the powder gets melted. The remaining media supports the next layers [27]. With PBF-LB/M, both the size of the laser spot and material grain size influence the quality of the final product. The most commonly used materials in PBF-LB/M manufacturing are Ti6Al4V and 316L stainless steel [46-49]. Metals are used instead of polymers for applications that require greater strength. Another advantage of these two materials is their corrosion resistance and biocompatibility, making them

excellent for use in medical fields as porous bone scaffolds [47,49]. The aerospace industry is another sector that has been utilizing AM metamaterials made with PBF-LB/M for less demanding, lightweight components, with TPMS geometries slowly being integrated [50]. The manufacturing accuracy of TPMS structures with PBF-LB/M is influenced by the designed thickness and overhang angle, mainly because of unmelted material particles sticking to the surface [51]. These regions accelerate fatigue crack initiation and should be removed or minimized with post-treatments to improve fatigue life [18,46].

3.2 Powder Bed Fusion – Laser Beam/Polymers (PBF-LB/P)

As the name suggests, PBF-LB/P works on the same principle as PBF-LB/M technologies, but this process only sinters or bonds the material together without fully melting it. Commonly used materials include semi-crystalline and amorphous polymers, ceramics, metals such as Ti6Al4V and CoCr, and various polymer composites. The resulting parts are somewhat porous, making them suitable for vibration absorption [27]. They are also of a good enough quality to be compared to the ideal geometries used in numerical tests. Their mechanical characteristics are greatly influenced by the relative density and porosity of the sintered material [52]. The main advantage of this method is the possibility of mixing different types of powder material, enhancing their mechanical properties, and achieving controlled degradation [53].

3.3 Vat Photopolymerization – Photoinitiated (VPP-PI)

A different approach to additive manufacturing is VPP-PI. It uses a photosensitive liquid material that cures layer by layer using ultraviolet or another special light source [27]. The designs can be produced with high accuracy depending on the size of the light spot, and mechanical properties depend on the specimen's geometry and post-curing time [54]. The main drawback of this technique is the limited number of materials that can be utilized, but this number is slowly growing with materials such as Biomed Amber making their appearance [55]. Instead of using a light spot to trace each layer, a screen can also be used to project an entire layer at once. This approach reduces build times while maintaining high precision. This process's main limitation is the projection's resolution, as the pixel size determines the print accuracy. Additionally, the build volume is generally smaller than when using a laser due to the projection system [27]. Despite these limitations, it is being used to produce and analyze complex TPMS geometries intended for use as electromagnetic absorbers in the field of high-temperature electromagnetic wave absorption [56]. Although this method produces smoother surfaces, the limited material options restrict usability and research, even though surface quality suggests potential improvements in fatigue life over powder-based approaches.

3.4 Material Extrusion – Thermal Rheological Behavior/Polymers (MEX-TRB/P)

Probably the most well-known additive manufacturing method is fused deposition modelling, or MES-TRB/P. This is most used in commercially available AM technologies. Material is melted and extruded layer by layer to build the desired part. This type of manufacturing is of lower precision than VPP-PI or PBF-LB/M, and many support structures are needed, resulting in wasted material and rough surface finishes [27]. Despite its limitations, MEX-TRB/P offers an effective way of producing geometries quickly and for a relatively low price from polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) or similar polymer materials and comparing

results of different types of geometries [57]. An advantage of this production method is the possibility of reasonably quickly constructing specimens from two or more other materials, creating so-called interpenetrating phase composites (IPC) [58].

3.5 AM-assisted/Hybrid Casting

A newer way of manufacturing cellular structures is so-called hybrid casting. The first step in the process is creating an AM model of metamaterial samples using castable wax resin. The samples are connected to each other with channels (Fig. 5a). A mold is then created with Ransom & Randolph "Platinum Investment & Binder" around the wax structure, followed by a burnout cycle (Fig. 5b and c). The resulting mold can be used to cast complex geometries such as TPMS structures. The process is described in more detail in the work of Singh et al. [59]. When TPMS structures made with this new hybrid technology were compared with ones created with PBF, the cast specimens exhibited a longer fatigue life. This improvement is primarily attributed to smoother surfaces, reduced porosity and more rounded geometrical transitions achieved by the casting process. These microstructural and geometric advantages, in turn, result in less fatigue ratcheting and strain accumulation during cyclic loading. The same authors have used this new process to embed the specimens within another material, creating IPCs [60]. Interestingly, they observed that the mechanical response of Al-ceramic and steel-Al interpenetrating phase composites considerably differs from the performance of the base materials. This production method could significantly increase the availability of cellular structures and their use in real-world applications, since casting enables the production of many products at a lower cost.

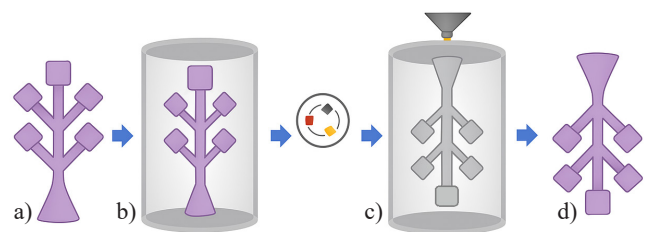


Fig. 5. Schematic of the hybrid casting production process; a) additively manufactured wax resin samples, b) creation of mold used for casting, c) casting of specimens, and d) cast specimens

4 MECHANICAL CHARACTERIZATION OF TPMS STRUCTURES

Mechanical characterization of TPMS structures is commonly performed under quasi-static loading; however, many of the observed mechanisms, such as buckling, densification and deformation mode (stretching- or bending-dominated), directly affect fatigue resistance.

It is essential to analyze the structures across multiple orders of magnitude to characterize cellular materials and understand their deformation behavior. At the macroscopic level, entire components or representative test samples typically comprise at least 5 to 7 cells (3 cells for 2D geometries [61]) in each direction are used in an analysis. This scale allows for the statistical evaluation of mechanical properties, such as elastic modulus, Poisson's ratio and plateau stress. When analyzing at the mesoscopic scale, the focus shifts to individual cells within the material. They are influenced by the geometry, choice of base material, and, in some cases, gases caught in the cells. The last microscopic scale describes the base material from which the cellular structures are made. This includes chemical elements, pores and possible inclusions. When analyzing cellular materials, it is

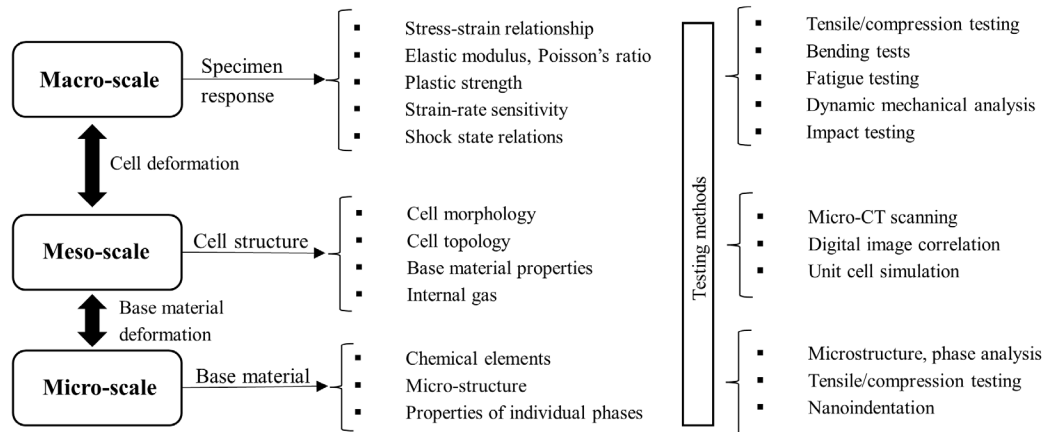


Fig. 6. Properties and characteristics at different scales for cellular materials

essential to understand the connections between the different orders of magnitude to be able to examine the mechanical response. The mechanisms at the micro and meso scales determine macroscopic properties. For instance, global macroscopic deformation reflects the nominal strain observed in the material. In contrast, local macroscopic deformation corresponds to the global response at the mesoscopic level or the deformation behavior of individual cells. The exact correlation between mesoscopic local strain and microscopic global strain can be made, representing the base material strain [62]. Properties, characteristics and testing methods at different scales for cellular materials are graphically presented in Fig. 6.

A typical compressive stress-strain response of cellular structures can be divided into three distinct deformation stages, as illustrated in Fig. 7. The initial elastic stage is known as the pre-collapse stage and is characterized by a nearly linear response of the material. This is caused by the elastic deformation of cell walls in the material. When the strain in the material reaches a point where it starts to deform plastically, and the cells begin to buckle, bend or collapse, it enters the so-called plateau stage. It is characterized by a significant increase in strain with minimal increase in stress, resulting in a nearly horizontal stress-strain response. This phase is responsible for the material's energy absorption capabilities. As the deformation increases, the cellular structure becomes increasingly compressed and compact, leading to the densification stage. In this final phase, the collapsed cell walls come in contact with each other, and the material acts more like a solid specimen. This results in a steep rise in the stress-strain curve, so-called densification [63–66].

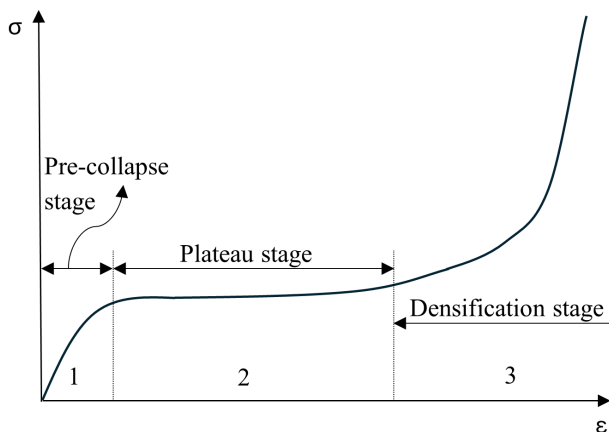


Fig. 7. Characteristic quasi-static compressive stress-strain curve for cellular materials

Deformation velocity is another critical factor that influences the mechanical response of cellular materials. Under quasi-static loading conditions, where the deformation occurs at a very low strain rate, materials typically have a homogeneous response throughout their entire volume. In this regime, the structures deform uniformly until local instabilities or imperfections cause the collapse of individual layers or regions. On the other hand, when the specimens are subjected to high-speed loading, such as impact or impulse, the material exhibits a different behavior [62]. It usually becomes stiffer, and the deformation localizes at the point of loading. Instead of a uniform collapse, a localized deformation forms at the loading point, known as a so-called shock front [67]. This behavior is essential in applications involving fast, dynamic loads where a lot of energy must be absorbed quickly, such as in a crash [62,68]. When subjected to a macroscopic load, static or dynamic, cellular structures can deform by a combination of bending, twisting or stretching [69]. If the struts support mainly axial loads and collapse by stretching, the geometry is referred to as stretching-dominated. In contrast, if the deformation occurs primarily through bending of the struts or cell walls, the structure is considered bending-dominated. Most cellular solids, such as metal foams, are bending-dominated. Consequently, they exhibit lower strength and stiffness compared to stretching-dominated geometries [70]. Another way of determining what mechanism is more prevalent in a geometry is by plotting their mechanical properties obtained from uniaxial tests using the Gibson–Ashby scaling power law [2]:

$$M = C\bar{\rho}^n. \quad (2)$$

In this relation, M is the normalized mechanical property, and $\bar{\rho}$ is the relative density. The parameters C and n are obtained by fitting experimental data, with the exponent n in particular serving as an indicator of the dominant deformation mechanism [71]. If the value of n is below 2, then the geometry is stretching-dominated, while anything above is considered bending-dominated. Following this criterion, sheet-based TPMS metamaterials are stretching-dominated, while skeletal-based geometries are bending-dominated, with the exception being the skeletal gyroid [70].

Knowing these deformation mechanisms allows us to evaluate advanced cellular geometries such as TPMS, which offer unique mechanical advantages to conventional materials. As already mentioned, their properties are influenced by the manufacturing process, material selection and unit cell geometry. Unlike conventional strut-based geometries, their uninterrupted surfaces enhance their mechanical efficiency under various loading conditions. Several studies have been conducted proving this fact [63–66]. They

all concluded that TPMS structures outperform other designs when subjected to compressive and tensile loads, with the Diamond and Gyroid sheet geometries outperforming other structures.

Table 2 shows the mechanical properties of several cellular materials made from Ti6Al4V under quasi-static compressive loading. The base material was selected due to its excellent corrosion resistance, favorable strength-to-weight ratio and AM capabilities, making it common in the field of cellular structures. Structures made from materials with comparable properties can be expected to exhibit similar performance under equivalent conditions. Elastic modulus and strength of TPMS metamaterials are greatly influenced by the type of unit cell and base material selection. How the shape of the unit cell affects the elastic modulus is graphically presented in Fig. 8, which was prepared by the authors based on the data reported in the literature and summarized in Table 2. The results demonstrate that for a given relative density, TPMS structures such as Gyroid and I-WP achieve a significantly higher elastic modulus compared to strut-based lattices. Strut-based geometries generally show lower stiffness but can still offer comparable compressive strength depending on density. Open-cell foams exhibit the lowest strength values, confirming the superior load-bearing capacity of TPMS structures. Using PBF-LB/M with Ti6Al4V alloy, Gain et al. [20] were able to closely mimic the elastic modulus, compressive strength and tensile strength of human cortical bone with graded TPMS metamaterials. A similar study was conducted by Wang et al. [21], where cubic, octet and TPMS gyroid lattice structures were fabricated to mimic natural bone. The gyroid structure was found to have the highest elastic modulus and yield strength.

Porosity is another parameter influencing the mechanical characteristics of TPMS structures, and it was investigated by Cai et al. [72]. Results comparing the different iterations showed that both yield strength and modulus of elasticity decreased when porosity was increased. Another observation was that the failure mechanism changed. While low-porosity geometries broke down via buckling, high-porosity specimens endured micro-fractures under load. The introduction of functionally graded porosity with a varying density across different regions of the structure was demonstrated to enhance mechanical strength and energy absorption capacity by Liu et al. [40], Zhang et al. [73] and Shi et al. [44]. This results from mitigating stress concentrations and providing a more uniform load distribution. Since porosity influences crack initiation and propagation, these results link structural design and fatigue strength. Higher porosity often reduces fatigue life due to stress concentration and easier crack initiation.

Several studies have emerged in recent years exploring possible alternative designs and their advantages. Isotropy would be an excellent characteristic for load-bearing and energy-absorption implications, meaning the material has the same response under loads in all orientations. Fu et al. [74] designed and tested such structures by performing Boolean operations. The new isotropic hollow cellular structures had a higher Young's modulus and better energy absorption properties than the original designs. In works [44,45], hybrid designs have been shown to improve energy absorption efficiency and yield strength under both static and dynamic loading conditions.

Table 2. Compressive mechanical characteristics of common cellular and TPMS shapes made from Ti6Al4V

The shape of base cell	Relative density [-]	Compressive strength	Elastic modulus E [GPa]	Ref.
Gyroid (TPMS)	0.1-0.4	16.44-275.17	1.21-10.60	[75-77]
I-WP (TPMS)	0.1-0.4	9.81-306.62	0.94-3.2	[77]
Diamond (strut-based)	0.13-0.4	21.00-118.80	0.4-6.5	[78,79]
Cubic (strut-based)	0.3-0.6	7.28-163.02	0.57-14.59	[80]
Foam (open-cell)	0.08-0.1	3.80-4.50	0.19-0.49	[81]

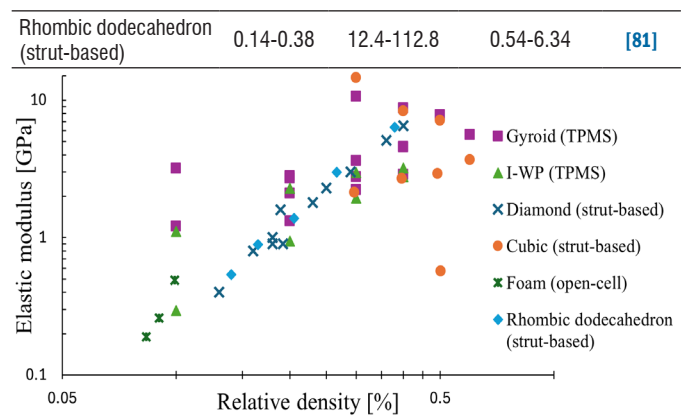


Fig. 8. Graphical comparison of elastic modulus of different cellular structures made from Ti6Al4V

5 FATIGUE BEHAVIOR OF TPMS STRUCTURES

When designing cellular structures, their fatigue behavior has become a critical consideration, particularly for those that are intended to be used in load-bearing applications. As highlighted by Benedetti et al. [82] in their literature review, the majority of fatigue design methods rely on experiments, which are time-consuming, expensive and able to handle only selected architectures and materials. While there are theoretical approaches, they can result in inappropriate estimates of the material parameters [83]. They did highlight, however, that with the amount of numerical methods, machine learning algorithms and data-driven approaches being developed in recent years, they could predict complex nonlinear relationships. Despite this promise, predictive modelling of TPMS fatigue life remains challenging. Classical finite element analysis can capture stress distributions, but it struggles to account for manufacturing defects, surface roughness and microstructural variability. This makes purely numerical predictions unreliable without experimental calibration. By training on experimental datasets, data-driven methods, including machine learning, could capture complex mechanisms and fatigue response. However, such models require large datasets and careful validation. The integration of physics-based simulations with machine learning is therefore emerging as a promising direction. Reflecting these challenges, Nečemer et al. [29] also noted that the fatigue performance of cellular materials under cyclic loading remains underexplored and requires further investigation. While TPMS metamaterials exhibit substantial potential as lightweight structural materials, their fatigue behavior is still limited and warrants further investigation. They are especially of interest because of their smooth transitions between struts, avoiding stress concentrations which could promote better fatigue life. Most studies until now have focused on the impact of manufacturing and topology on their mechanical response [63-66]. Even though these types of structures are being investigated for use in applications where damage is a result of repetitive, low-intensity loads, only a handful of studies have been conducted [30]. In this section, relevant scientific articles on the fatigue behavior of TPMS metamaterials are presented.

The defining characteristic of TPMS metamaterials is their topology, which dictates how they deform under loading. Different types of TPMS unit cells have been evaluated for their fatigue performance, stress distribution and failure mechanisms. This is presented in Table 3, where common TPMS and regular cellular structures are presented with their fatigue properties. Fatigue strength is the maximum stress a material can withstand for a specified number of loading cycles without failure, while the fatigue ratio, or sometimes called fatigue endurance ratio, is the fatigue strength

Table 3. Fatigue properties of different metamaterials

The shape of base cell	Material	Relative density [-]	Ultimate cycles	Fatigue strength [MPa]	Fatigue ratio [-]	Ref.
Gyroid (TPMS)	316L	0.15	2·10 ⁶	9.1	0.35	[30]
Gyroid (TPMS)	316L	0.15	2·10 ⁶	11.7	0.45	[30]
Gyroid (TPMS)	Ti6Al4V	0.31	106	14.3	0.18	[84]
Diamond (TPMS)	Ti6Al4V	0.31	106	18.4	0.17	[84]
Schwarz Primitive (TPMS)	Ti6Al4V	0.31	106	13.6	0.21	[84]
I-WP (TPMS)	NiTi	/	106	2.08	0.33	[85]
BCC (strut-based)	NiTi	/	106	1.88	0.34	[85]
Cubic (strut-based)	Ti6Al4V	0.37	107	75	0.48	[86]
Rhombic dodecahedron (strut-based)	Ti6Al4V	0.8	107	13.9	0.2	[86]

divided by yield strength. It can be observed that there is a large variation in fatigue ratios between Ti6Al4V and 316L Gyroid structures. This can be attributed to a number of factors, with the most influential being the high ultimate strength of Ti6Al4V compared to 316L stainless steel. Others may include surface quality of specimens, porosity, relative density and testing parameters. Yang et al. [30] investigated a Gyroid structure fabricated with PBF-LB/M and subjected to compression-compression cyclic fatigue. Their study concluded that TPMS geometries have a higher fatigue resistance than strut-based lattice structures, primarily due to their stretch-dominated deformation mechanism. The failure analysis showed that fatigue cracks formed at nodal intersections, leading to 45° diagonal fracture bands. A similar result was achieved by Soro et al. [84] under tension-tension loading conditions for three different TPMS geometries. They also outperformed regular strut-based lattices, with fatigue cracks initiating at the surface, highlighting the importance of post-treatment. Jiang et al. [87] performed experimental testing and finite element analysis (FEA) on four TPMS metamaterials (Gyroid, Diamond, I-WP, Schwarz Primitive) to evaluate their torsional and fatigue resistance. They found that the Schwarz Primitive shape exhibits superior torsional and fatigue resistance. I-WP structures showed lower torsional fatigue resistance because of their bending-dominated deformation. This failure was initiated at the curved junctions, with stress concentrations occurring in all four structures during the compression process. These aligned closely with the regions exhibiting larger strain. The same four TPMS geometries were analyzed by Bobbert et al. [88] under compression-compression loading. The change in loading conditions resulted in the Schwarz Primitive geometry having the shortest fatigue life, while all the other specimens varied between $1 \cdot 10^5$ cycles and $7 \cdot 10^5$ cycles. The samples

failed under a 45° angle, aligning with the observations made by Yang et al. [30] under the same loading conditions. Importantly, they highlighted a greater fatigue resistance compared to other AM porous materials. Even when loaded with stress levels as high as 60 % of their yield stress, some variants managed to exceed the usual threshold of $1 \cdot 10^6$ cycles used for these types of AM materials. Another study comparing different geometries was conducted by Singh et al. [59]. They compared Gyroid and I-WP metamaterials made from AlSi10Mg using powder bed fusion (PBF). They were subjected to load-controlled cyclic loading. They found that Gyroid designs outperformed I-WP specimens. Overall, they had comparable or lower fatigue ratcheting and higher stiffness. In particular, the Gyroid structures with 30 % relative density consistently demonstrated longer fatigue lives with lower comparable damage metrics. Overall, these studies indicate that the fatigue performance of TPMS metamaterials is largely determined by the topology and deformation mode, with stretching-dominated geometries such as Gyroid being better suited for compression and tension loading, while the Primitive geometry exhibits better fatigue life when subjected to bending loads. Bending-dominated geometries, such as I-WP, on the other hand, tend to concentrate stresses at curved junctions, making them less efficient under loads and more prone to earlier fatigue failure.

Mechanical performance, surface quality, and fatigue behavior are all impacted by the manufacturing process used to produce specimens. Because of this, several publications were conducted to determine how the different technologies affect fatigue life. Tilton et al. [89] investigated TPMS scaffolds fabricated with Ti6Al4V via PBF. The process left behind unwanted surface characteristics like partially melted powder and their agglomerations. These unwanted surface characteristics were initiation sites for fatigue failure. A

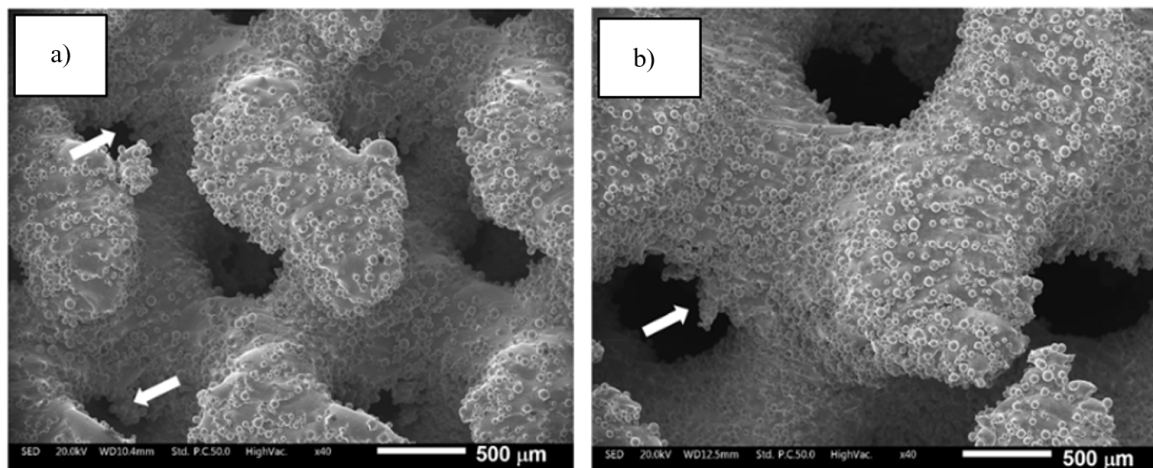


Fig. 9. SEM micrograph of TPMS metamaterials with: a) 1.5 mm, and b) 2.5 mm unit cell size, adapted from [90]

similar study was done by Ren et al. [85], but with nickel-titanium as the base material. Similar results were achieved with unmelted or partially melted particles on the surface of the structures. Cracks appear at the root of powder particles attached to the surface. The I-WP lattice structure seemed to slightly benefit in avoiding powder adhesion. Even though AM has come a long way, it still has some limitations. In a study by Emanuelli et al. [90], TPMS samples made with PBF from β -Ti21S alloy were investigated. They concluded that this material exhibits promising mechanical and biological properties for femoral implants. However, its main drawback was poor printability, which impacted pore size and fatigue resistance. They also highlighted surface irregularities and agglomerations, pointed out in Fig. 9, caused by unmelted material particles.

Studies on possible post-treatment methods that would improve surface quality, reduce stress concentrations, and eliminate manufacturing defects have been conducted to try to mitigate some of the inherent drawbacks of AM technologies. Liu et al. [91] studied the impact of high isostatic pressing (HIP) and electropolishing (ELP) on the fatigue life of diamond and gyroid TPMS structures. HIP is a process in which high pressures are applied at elevated temperatures to enhance the material's ductility and improve mechanical performance. This process resulted in a decline in surface roughness, reduced micro porosities, and released residual stresses in the Ti6Al4V specimens. Because of this, the fatigue ratio of bending-dominated TPMS structures improved from 0.11 to 0.26 and from 0.59 to 0.69 for the stretching-dominated structures. As in previous

studies, the absence of surface particles enhanced the fatigue resistance by reducing crack initiation zones. Similar results were achieved by Singh et al. [59]. They examined heat-treated AlSi10Mg TPMS structures fabricated with PBF. The process significantly improved the fatigue resistance compared to as-built structures. This was due to a slower fatigue damage accumulation in the heat-treated samples. The most significant effect was seen in Gyroid 30 % density geometries. These findings confirm that different heat treatments effectively enhance the fatigue life of TPMS structures made with AM methods. Other methods to improve the surface quality of specimens are chemical etching, shot peening, and sandblasting. Araya-Calvo et al. [76] compared as-built and chemically etched Ti6Al4V structures and concluded that the post-treated samples had an approximately 20 % improved fatigue resistance. They also demonstrated better biocompatibility and surface morphology. The effect of chemical etching is shown in Fig. 10. The as-built specimens show a significantly rough surface due to the adhesion of partially melted powder particles. The post-treatment resulted in a smoother surface, which resulted in improved fatigue resistance.

An advantage of mechanical post-treatments such as shot peening and sandblasting is the compressive residual stresses they leave behind on the surface, which was investigated by Jiang et al. [92] and Was et al. [93]. These delay crack initiation and extend fatigue life. This was studied by Yang et al. [30] on sandblasted Gyroid structures. The fatigue resistance increased from 0.35 for the as-built samples to 0.45 for the sandblasted specimens. In addition to the residual

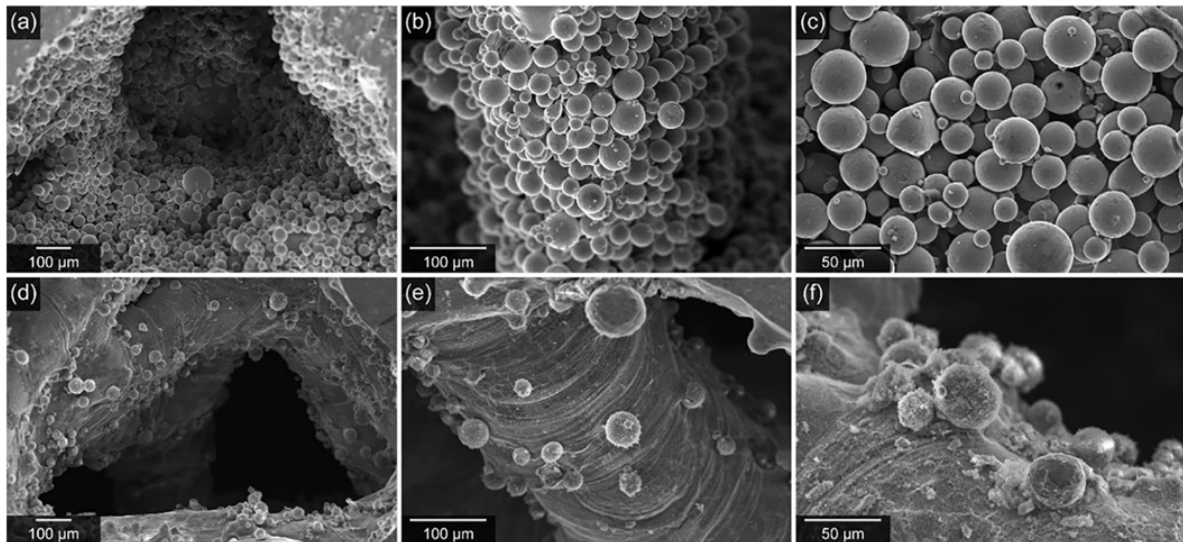


Fig. 10. Comparison of a) b) c) as-built with d) e) f) chemically etched specimens, reproduced from [76]

Table 4. Summary table of post-processes with their mechanisms and effect on fatigue life

Post-processing method	Mechanism	Effect on fatigue life	Reference
Hot isostatic pressing (HIP) (applied in combination with ELP)	Removes microporosity, relieves residual stress, improves ductility	Improved fatigue ratio from 0.11 to 0.26 (Gyroid) and from 0.59 to 0.69 (Diamond)	Liu et al. [91]
Electropolishing (ELP) (applied in combination with HIP)	Reduces surface roughness, removes powder particles	Improved fatigue ratio from 0.11 to 0.26 (Gyroid) and from 0.59 to 0.69 (Diamond)	Liu et al. [91]
Heat treatment	Slows fatigue damage accumulation, improves microstructure	Improved fatigue life due to lower fatigue ratcheting	Singh et al. [59]
Chemical etching	Smooths surface, removes powder particles	Improved fatigue resistance, especially at lower stress levels	Araya-Calvo et al. [76]
Sandblasting	Removes powder particles, introduces compressive residual stress	Fatigue resistance increased from 0.35 to 0.45	Yang et al. [30]
Shot peening	Removes powder particles, introduces compressive residual stress	Extended fatigue life because of delayed crack initiation	Jian et al. [92], Was et al. [93]

stresses, the process removed partially melted powder particles, reducing stress concentrations and crack initiation zones. Their results show that surface treatments are a highly effective way of mitigating fatigue failure, especially when working with AM-fabricated TPMS structures. Table 4 summarizes the main post-processing methods investigated for TPMS structures. In it, the mechanisms by which each technique improves fatigue life are highlighted, and results are presented to provide a clearer overview.

Among the potential applications of TPMS cellular structures, the biomedical field has the most studies, particularly for use as bone scaffolds [94–96]. Slowly, they are also being considered for dental implants, as numerically investigated by Kök et al. [97]. Compared to standard dental implants, they showed 15 % less stress-shielding and still complied with the number of cycles required by DIN EN ISO 14801, resulting in a 45 % reduction in weight.

6 CONCLUSIONS

This review of recent studies confirms that TPMS structures are a versatile class of cellular structures with a broad potential. Their continuous geometry based on mathematical equations offers advantages in terms of mechanical properties, unit cell design, and tunability. Compared to traditional strut-based cellular structures, they demonstrate superior mechanical performance under static and dynamic loads because of their smoother stress distribution, especially in the Gyroid and Diamond unit cell shapes. They also mitigate failure caused by stress concentrations, which are common in strut-based designs.

A general observation across the analyzed studies is that the mechanical properties of TPMS structures depend not only on the relative density and cell type but can also be significantly enhanced by improving surface quality and reducing unit cell size. Because they are almost entirely fabricated with AM technologies, the resulting specimens have unwanted leftover material particles, and their agglomerations stuck to the surfaces. This implies that post-processing treatments such as sandblasting, electropolishing, and chemical treatments are essential for achieving consistent results. It can be expected that newer approaches like plasma electropolishing will also become increasingly relevant for producing smoother surfaces and improving fatigue performance in TPMS structures. Research in applications such as medicine, energy, sound absorption, dental implants, vibration absorption, static mixing, and heat transfer highlights the benefits of the tunable geometry of TPMS metamaterials. These diverse areas of study suggest a broad potential in future technologies.

The paper gives an overview of the fatigue behavior of TPMS cellular structures with consideration for their fabrication and characterization. Based on the reviewed literature, we can draw the following conclusions:

- TPMS geometries consistently outperform conventional strut-based lattice structures in both static and dynamic loading scenarios. The best-performing unit cell geometries are Gyroid and Diamond structures.
- The properties of TPMS metamaterials are closely tied to the manufacturing process. Most are fabricated with AM methods that introduce surface imperfections that must be reduced with post-treatments to improve fatigue life.
- Advanced TPMS design strategies, such as different types of grading and multimorphology designs, enable mechanical tuning. These allow the development of application-specific materials.

Although considerable progress has been made in optimising the mechanical properties of TPMS metamaterials through unit cell design, there is considerable potential for further improvements,

especially with grading strategies, hybrid geometries, and multi-material integration. In conclusion, TPMS metamaterials represent structurally efficient, customizable and application-specific cellular materials that show promising results for use in fields such as biomedical engineering, energy absorption applications, and thermal management.

7 SUGGESTIONS FOR FUTURE RESEARCH WORK

Despite significant research in the design and mechanical characterization of TPMS metamaterials, not much emphasis has been placed on their fatigue behavior which is evident in the limited number of publications. Future work should firstly focus on achieving good reproductivity. This could be done by using specimens of similar size, relative density and production methods if possible. The results would give us a more general understanding of their properties and be a good foundation for analyzing more complex factors. After this a logical next step would be to analyze how different mean stresses and strains affect their fatigue life. Most tests up to this point have been uniaxial which is sufficient if the loads are mostly in one direction. With more complex spaces being filled with TPMS metamaterials, multiaxial tests should be considered for future work. Outside factors such as impacts could cause deformations and failure in directions not accounted for in uniaxial tests. Lastly, because these types of structures can be utilized as fluid mixers and heat exchangers, studying the effects that temperature has on its fatigue life could prove beneficial to prevent premature failure caused by temperature fluctuations.

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Utrujanje metamaterialov na osnovi trojno-periodi nih minimalnih povr in (TPMS) - Pregled

Povzetek  lanek predstavlja celovit pregled obna anja metamaterialov, zasnovanih na trojno-periodi nih minimalnih povr inah (TPMS), pri obremenitvah zaradi utrujanja, s posebnim poudarkom na vplivu tehnologije njihove izdelave. V prispevku so podrobno analizirane razli ne geometrije TPMS, ki so v zadnjih letih pridobile veliko pozornosti zaradi izjemnega razmerja med trdnostjo in maso ter sposobnosti nadzora mehanskih lastnosti s prilagajanjem geometrijskih parametrov. Predstavljene so sodobne metode izdelave TPMS struktur s poudarkom na dodajalnih tehnologijah, kjer je za osnovni material privzeta titanova in jeklena zlitina. Za vsak material so navedene klju ne prednosti, omejitve in vpliv proizvodnega procesa na kon ne mehanske lastnosti struktur. Poleg tega  lanek obravnava mehanske zna ilnosti celi nih gradiv, pri  emer je poseben poudarek namenjen TPMS strukturam, ki zaradi svoje topologije omogo ajo enakomerno porazdelitev napetosti in visoko absorpcijo mehanske energije. V nadaljevanju so predstavljene najnove e raziskave in ugotovitve glede vedenja TPMS metamaterialov pri utrujanju. Analiza ka e, da TPMS celi ne strukture izkazujejo bistveno bol o odpornost proti utrujanju v primerjavi s konvencionalnimi celi nimi metamateriali. Klju ni razlog za to je njihova gladka, zvezna geometrija brez ostrih robov ali sti nih to k, kar zman  uje koncentracijo napetosti in omogo a bolj homogeno porazdelitev napetosti skozi celotno strukturo. Na podlagi predstavljenih rezultatov lahko zaklju imo, da TPMS metamateriali predstavljajo perspektivno smer razvoja naprednih lahkih konstrukcijskih materialov, ki zdru ujejo visoko trdnost, odpornost proti utrujanju in prilagodljivost geometrije glede na specifi ne zahteve uporabe.

Klju ne besede celi ne strukture, TPMS metamateriali, proizvodne tehnologije, mehanska karakterizacija, obna anje pri utrujanju