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Pendekatan Reka Bentuk Perancah Logam Berliang Gred Berfungsi (FGPS) untuk Menyediakan Sifat Mekanikal

(Design Approaches of Metallic Functionally Graded Porous Scaffold (FGPS) to Serve Mechanical Properties)

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ABSTRAK

Reka bentuk perencah tulang untuk implan penampung beban kekal telah menjadi satu cabaran kritikal disebabkan oleh keperluan untuk meniru sifat mekanikal dan biologi tulang asli. Perencah konvensional dengan keliangan seragam sering menyebabkan ketidakpadanan ketegaran dan perlindungan tekanan, yang boleh mengakibatkan kegagalan implan pramatang. Oleh itu, terdapat keperluan untuk strategi reka bentuk lanjutan yang mampu menyediakan keliangan terkawal dan tingkah laku mekanikal bergred. Oleh itu, kertas ini mengulas metodologi reka bentuk yang menggabungkan perancah berliang gred berfungi (FGPS) dengan seni bina permukaan minimum tiga kali periodik (TPMS) dalam perencah logam. Objektif kajian ini adalah untuk: (i) menilai keberkesanan reka bentuk berasaskan TPMS dalam menghasilkan struktur berliang saling bersambung dengan kecerunan fungsi yang diingini, dan (ii) menilai kelebihan mekanikal bagi gabungan FGPS–TPMS. Oleh yang demikian, perencah logam FGPS–TPMS menunjukkan peningkatan dalam kekuatan, penyerapan tenaga, serta pengurangan penggunaan bahan, di samping meminimumkan ketidakpadanan kekakuan dan perlindungan tekanan. Seni bina terkawal kecerunan ini menyediakan satu rangka kerja yang menjanjikan implan bioperubatan generasi baharu yang berupaya meniru topologi dan tingkah laku mekanikal tulang semula jadi dengan lebih rapat.

Kata kunci: Permukaan minimal tiga kali periodik, perancah berliang gred berfungsi, logam, pelindungan tekanan, tingkah laku mekanikal.

ABSTRACT

Designing bone scaffolds for load-bearing implants remains a critical challenge due to the need to replicate the mechanical and biological properties of native bone. Conventional scaffolds with uniform porosity often result in stiffness mismatch and stress shielding, which can lead to premature implant failure. There is therefore a need for advanced design strategies that provide controlled porosity and graded mechanical behavior. This paper reviews design methodologies that combine functionally graded porous structures (FGPS) with triply periodic minimal surface (TPMS) architectures in metallic scaffolds. The objectives are to: (i) evaluate the effectiveness of TPMS-based designs in generating interconnected porous structures with desired functional gradients, (ii) assess the mechanical advantages of FGPS–TPMS combinations. Thus, metallic FGPS–TPMS scaffolds demonstrate improved strength, energy absorption, and reduced material usage while minimizing stiffness mismatch and stress shielding. These gradient-controlled architectures provide a promising framework for next-generation biomedical implants capable of closely mimicking the topology and mechanical behavior of natural bone.

Keyword: Triply periodic minimal surfaces, functionally graded porous scaffold, metallic, stress-shielding, mechanical behavior.

INTRODUCTION

Bone possesses a complex and hierarchical structure that enables it to perform a wide range of mechanical, biological, and chemical roles. By nature, bone is dynamic, and it can adjust its structure, composition, and mass in response to mechanical stress (Milan et al., 2010). Its inherent capacity to remodel and regenerate after minor injuries or small bone loss contributes to effective healing (Yuan et al., 2019). However, when bone loss results from severe trauma, surgical tumor removal, or serious injuries, it can lead to large segmental defects that do not heal naturally (Metz et al., 2020). These types of defects surpass the bone's natural healing capacity and therefore require advanced and complex medical intervention. Despite this, researchers have discovered that addressing critical large segmental defects requires additional materials to fill the gap. The "gold standard" treatment involves autologous bone grafting (Pobloth et al., 2018). Other techniques include the Masquelet method, which incorporates an external fixator and cement (Masquelet et al., 2019). Improved surgical techniques aim to enhance treatment outcomes for complex fractures and other skeletal defects. Nonetheless, existing treatment methods come with significant limitations, including complications at the donor site, loss of bone, the need for multiple surgical procedures, and a heightened risk of infection (Ferracini et al., 2018). As an alternative, researchers have explored the use of synthetic bone substitutes, which can be directly implanted into damaged areas to facilitate bone regeneration and repair large segmental defects (Zhang et al., 2020).

A synthetic bone scaffold must meet several key criteria to effectively fulfill its intended functions. Firstly, a scaffold should feature a suitable pore size, porosity, and a gradient in density to support cell attachment and growth proliferation (Hussein et al., 2021; Onal et al., 2018). Secondly, scaffolds must exhibit sufficient mechanical strength and stiffness to maintain structural integrity and prevent stress shielding (Boccaccio et al., 2016; Prasadh & Wong, 2018). Thirdly, the scaffold material must be biodegradable and non-toxic to ensure it can be safely replaced by natural bone tissue over time (Md Saad et al., 2019). Additionally, while offering mechanical stability, the scaffold should not be excessively rigid, where excessive stiffness could lead to bone resorption or implant loosening, compromising long-term performance during everyday activities (Metz et al., 2020).

Synthetic bone scaffolds require design methodologies in order to match the design of implants with desired microstructural, mechanical, and biological properties. Bone scaffolds can be created using CAD-based methods (Ahmadi et al., 2015; Deng et al., 2021; Noordin et al., 2022; Prochor & Gryko, 2021; Rodríguez-Montaño et al., 2018), triply periodic minimal surfaces (TPMS) methods (Feng et al., 2020; Maskery et al., 2018; L. Yang et al., 2019) and structural optimization techniques (Boccaccio et al., 2018; Makowski & Kuś, 2016; Nasrullah et al., 2020; Rodríguez-Montaño et al., 2020; Vilardell et al., 2019; Wieding et al., 2014). The most common method widely used for scaffold design is the CAD-based method due to its simple structure and good mechanical properties. Cai and Xi (2008) used the CAD-based method to define pore size distribution in the bone scaffold by controlling pore morphology based on the hexahedral mesh refinement (Cai & Xi, 2008). While TPMS-based methods offer robust design capabilities, they are constrained to 3 periodic structures, poor smooth curvature, and interconnected void networks (Yang et al., 2019).

Rajagopalan and Robb (2006) introduced triply periodic minimal surfaces (TPMS) modeling, which is recognized for its intriguing topological characteristics, including smooth, continuous surfaces, a high surface area-to-volume ratio, and interconnected pore networks (Rajagopalan & Robb, 2006). Onal et al. found that TPMS structures had a porosity and modulus that are comparable to actual bone (Onal et al., 2018). Despite these advantages, challenges remain in achieving pore interconnectivity (Melchels et al., 2010) and facilitating functional grading through mathematical modelling (Hussein et al., 2024; Hussein et al., 2025). It is important to consider adequate relative density, as native bone consists of cancellous and cortical bone with varying densities, pore sizes, and porosity distributions (Gibson & Ashby, 2014). Zadpoor (2019) claimed that a gradient hierarchical arrangement of holes in bones helps to enhance the strain gradient and prevent scaffold loosening. For example, Vijayavenkataraman et al., proposed a functionally graded porous structure (FGPS) using the TPMS-based method to satisfy several geometrical parameters and mechanical properties based on a parametric optimization approach. Thus, several studies claimed that the FGPS TPMS-based method exhibited fascinating properties, such as relatively low density with high strength and excellent energy absorption (Al-Ketan et al., 2020; Hussein et al., 2024; Liu et al., 2018).

From the literature, there are three types of gradients for FGPS, including linear, radial, and conical graded structures. Boccaccio et al., (2016) developed a linear cell size grading system based on a mechanobiological optimization algorithm to obtain the optimal porosity distribution for maximal bone growth. Other than that, Onal et al., (2018) and Montazerian et al., (2019) proposed radially graded structural porosity as a design that can enhance load-bearing capacity and more efficiently meet mechanobiological criteria. Their results revealed that their structures greatly improved compressive strength and toughness while maintaining an appropriate elastic modulus. Thus, Afshar et al., discovered the impacts of linear and radially FGR scaffolds on the deformation mechanism and compressive mechanical characteristics. They highlighted that the radial gradient patterns (perpendicular to the loading direction) provide higher deformability and high failure strain compared to linear-gradient patterns. However, studies indicate that conical graded structures outperform both linear and radial graded, as well as uniform porosity structures, in mechanical response and deformation behavior (Hussein et al., 2024). Overall, it clearly highlighted that the grading distribution has better matched the topological and mechanical properties of human bone. Prior to the development of functionally graded structures, research related to metallic implant materials in bone tissue engineering (BTE) has recently attracted a lot of attention.

This article reviews the current progress in design methodologies for metallic functionally graded TPMS scaffolds aimed at improving mechanical performance. The objectives are to: (i) evaluate the effectiveness of TPMS-based designs in generating interconnected porous structures with desired functional gradients, and (ii) assess the mechanical advantages of combining FGPS with TPMS architectures in enhancing strength, energy absorption, and biomechanical compatibility. The review emphasizes the importance of 4 optimizing the internal gradient architecture of scaffolds to improve their functional performance and concludes by highlighting the potential of metallic scaffolds as reliable clinical solutions for large segmental bone defects.

METHODOLOGY DESIGN OF REGULAR UNIT CELLS

Most of the studies focus on designing the internal geometry of scaffolds using regular unit cells arranged in a repeated pattern. As shown in Table 1, the design methods of regular porous structures include the computer-aided design (CAD)-based unit cell method (Deng et al., 2021; Prochor & Gryko, 2021), the triply periodic minimal surface (TPMS) method (Feng et al., 2020; Maskery et al., 2018; Yang et al., 2019) according to their specific software.

CAD-BASED METHOD

The CAD-based method is a manual design approach that is widely recognized as the most common method used for scaffold design. Based on the modelling principles illustrated in Figure 1, CAD methods used implicit modelling approaches to build the whole scaffolds. For example, Rodríguez-Montaño et al. (2020) designed unit cells using CAD modelling techniques, then analyzed them using Abaqus software. Each unit cell featured a spherical cavity and cylindrical interconnections oriented along the orthogonal directions of the coordinate axes. To create a porous structure, a Boolean subtraction operation was applied by removing the volumes of spheres and cylinders from a cubic domain. Although CAD-based design methods allow for precise geometric control, they still present limitations in managing the spatial distribution of heterogeneous pore architectures, which is critical for achieving the desired mechanical and biological performance in scaffolds.

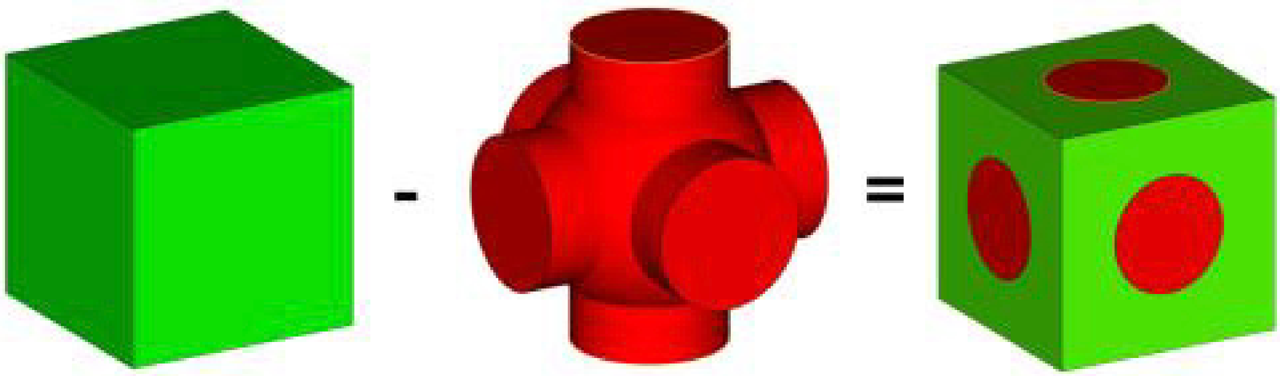


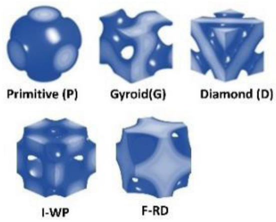
FIGURE 1. CAD-based regular periodic lattice structure

TPMS-BASED METHOD

A mathematical modelling method was applied to design triply periodic minimal surfaces (TPMS). TPMS structures are made up of two sub-spaces with a smooth and non-intersecting surface. According to Yoo (2011), TPMS comprises infinite and periodic in three independent directions with a mean curvature of zero. TPMS have garnered significant attention recently for their smooth shells, high surface area-to-volume ratio, and interpenetrating void networks, aimed at enhancing the mechanical properties of structures that mimic natural bone (Afshar et al., 2018; Al-Ketan et al., 2020). There are several types of TPMS unit cells, such as primitive (P-type), gyroid (G-type), diamond (D-type), I-WP, and F-RD (Al-Ketan & Abu Al-Rub, 2020).

The simplest and most used method to describe the nodal coordinates that designate a minimal surface is the level-set approximation approach. Level-set equations are sets of trigonometric functions that collectively satisfy the equality φP(x,y,z)=C. Examples of commonly used level-set equations in literature are provided below, with corresponding surfaces shown in Table 1.

TABLE 1. Design methods of regular porous structures

	Design methods	Type of modelling	Designs	Tools	Refs
1.	CAD-based	Implicit modelling		SOLIDWORKS, ABAQUS, CATIA, UG, Pro/E, Magics, CASTS	(Feng et al., 2020; Yang et al., 2019)
2.	TPMS-based	Mathematical modelling		MATLAB, MathMods, PYTHON script, Grasshopper, and Rhinoceros	(Feng et al., 2020; Maskery et al., 2018; Yang et al., 2019)

Primitive (P) $$\varphi P(x, y, z) = \cos(X) \cdot \cos(Y) + \cos(Y) \cdot \cos(Z) + \cos(Z) \cdot \cos(X) = C \quad (1)$$

Gyroid (G) $$\varphi G(x, y, z) = \sin(X) \cdot \cos(Y) + \sin(Z) \cdot \cos(X) + \sin(Y) \cdot \cos(Z) = C \quad (2)$$

Diamond (D) $$\varphi D(x, y, z) = \cos(X) \cdot \cos(Y) \cdot \cos(Z) - \sin(X) \cdot \sin(Y) \cdot \sin(Z) = C \quad (3)$$

F-RD $$\varphi F{-}RD(x, y, z) = 4[\cos(X) \cdot \cos(Y) \cdot \cos(Z)] - [\cos(2X) \cdot \cos(2Y) + \cos(2Z) \cdot \cos(2X) + \cos(2Y) \cdot \cos(2Z)] = C \quad (4)$$

I-WP $$\varphi I{-}WP(x, y, z) = 2[\cos(X) \cdot \cos(Y) + \cos(Y) \cdot \cos(Z) + \cos(Z) \cdot \cos(X)] - [\cos(2X) + \cos(2Y) + \cos(2Z)] = C \quad (5)$$

In these equations, $X = 2\alpha\pi x$, $Y = 2\beta\pi y$, $Z = 2\gamma\pi z$, α , β , γ are constants related to three spatial directions in the x, y, and z, respectively.

FUNCTIONALLY GRADED POROUS SCAFFOLD (FGPS)

Recently, researchers have broadened their exploration of gradient pore architecture, leading to the development of functionally graded porous scaffold (FGPS) design architectures (Afshar et al., 2018; Al-Ketan et al., 2020; Wang et al., 2019; Yu et al., 2019). FGPS architectures have the ability to mimic native bone due to their excellent morphological, mechanical, and biological properties (Afshar et al., 2018; Al-Ketan et al., 2020). According to the literature, there are three design patterns of FGPS named linear, radial, and conical graded structures. Recently, Hussein et al. (2024), were the first to discover conical graded structures by integrating linear and radial graded designs, as shown in Figure 2. The equations below illustrate the implicit functions established for Schwarz-Primitive based on each density grading structure: x, y, and z represent the three spatial directions, and the parameter k denotes the lattice periodicities, defined as k = 2aπ/L. The parameter a represents the number of repeated cells, while L is the length of Linear graded: the unit cell in the lattice structure. R indicates linear graded values in the z-direction, S represents radial graded values, and T signifies the diameter of the pores.

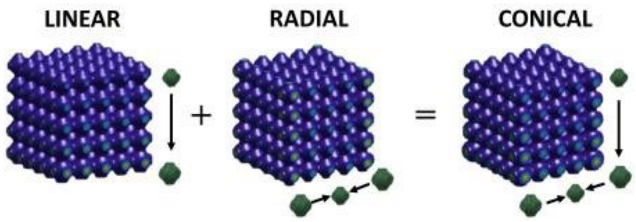


FIGURE 2. Concept design of conical graded structure.

Linear graded:

$$\varphi L(x,y,z) = cos(kx) \cdot cos(ky) + cos(ky) \cdot cos(kz) + cos(kz) \cdot cos(kx) - R(z) + T \quad (6)$$

Radial graded:

$$\varphi R(x,y,z) = cos(kx) \cdot cos(ky) + cos(ky) \cdot cos(kz) + cos(kz) \cdot cos(kx) - S(x2 + y2)2 + T \quad (7)$$

Conical graded:

$$\varphi M(x,y,z) = \cos(kx) \cdot \cos(ky) + \cos(ky) \cdot \cos(kz) + \cos(kz) \cdot \cos(kx) - R(z) - S(x2 + y2)2 + T \quad (8)$$

MECHANICAL PERFORMANCES OF FGPS ARCHITECTURE

Scaffolds having a functionally graded structure could be a feasible alternative for developing implants with specific and controllable mechanical properties (Vijayavenkataraman et al., 2018; Xiong et al., 2020). Zhou et al., have proposed linearly FGPS to alter maximum energy absorption and stiffness. Meanwhile, Montazerian et al., (2019) proposed radially graded structural porosity as a design that can enhance load-bearing capacity and more efficiently meet mechanobiological criteria. Afshar et al., found that radially density grading, with the smaller pore sizes at the center (dense in) of the structure, gave results that were reasonably similar to real bone density (Afshar et al., 2018). Despite this, research shows that both linear and radial graded structures result in a layer-by-layer collapse deformation process during compression tests (Mahmoud et al., 2021; Onal et al., 2018). Additionally, conical graded structures also exhibit a layer-by-layer collapse deformation, which improves fatigue resistance compared to random fracture occurrence throughout the scaffolds (Hussein et al., 2024). According to Hussein et al., conical graded remarkably outperforms the linear and radial graded in terms of mechanical properties and energy absorption (Hussein et al., 2024). However, these studies used PLA material, which has low mechanical properties and is only suitable for prototype structures. Therefore, metallic FGPS structures should be further explored due to their excellent mechanical properties, which enable them to withstand external loads in load-bearing applications.

METALLIC IMPLANTS OF FGPS

Prior to the introduction of functionally graded structures, there has been a lot of interest in research into metallic implant materials in bone tissue engineering (BTE). For example, porous metallic implant materials such as magnesium, stainless steel, cobalt-chromium alloy, titanium alloy, iron, aluminum, and tantalum have been commonly used in the orthopedic field for load-bearing applications. As shown in Table 2, these materials possess excellent mechanical properties in terms of elastic modulus, fracture toughness, and fatigue strength (Yuan et al., 2019). Fatigue strength refers to a material's ability to withstand repeated cyclic stresses, which plays a crucial role in determining the long-term performance of an implant under continuous loading conditions. Studies from Xiong et al., (2020) highlighted that the mechanical properties of metallic implants are stronger than actual tissue metallic implants and can be employed especially in load-bearing applications due to their excellent strength. However, the excellent mechanical properties of metallic implants could have a high risk of stress shielding effects. According to the type of metallic implants, Table 2 depicts the benefits, drawbacks, and consequences. At` present, titanium alloy (Ti-6Al-4V) and cobalt-chromium alloy (CoCr) have been widely utilized in orthopedic applications because of their great mechanical properties for dynamically loaded porous implants (Aherwar et al., 2016; Jonge et al., 2019). Consequently, proposed patterns of porosity distribution in functionally graded scaffolds help to reduce the mechanical properties of the scaffold and resemble the qualities of real bone.

Recently, FGPS based on TPMS structures has been widely studied by altering porosity, pore size, and strut for balancing the elastic modulus between metallic implants and actual tissues. The differences across the materials are noticeable in their post-yield behavior. Despite this, implant stiffness reduction is important because it improves load distribution and remodelling conditions (Xiong et al., 2020; Zadpoor, 2019). Consequently, this helps prevent stress shielding-related issues, including bone resorption and loosening of the implant. As noted by Metz et al., (2020) metallic scaffolds must strike a balance, they should not be excessively rigid but must still offer sufficient mechanical support and long-term stability to withstand normal physiological loads (Metz et al., 2020). Their excellent yield strength helps prevent implant failure, making them well-suited for load-bearing applications (Xiao et al., 2018).

CONCLUSIONS

This paper provides a comprehensive review of advanced scaffold design approaches that integrate functionally graded porous structures (FGPS) and triply periodic minimal surface (TPMS) architectures in metallic biomaterials. These techniques enable precise control over porosity and mechanical gradients, resulting in improved mechanical strength, energy absorption, and fatigue resistance, closely mimicking the hierarchical structure of native bone. The integration of computational modeling and experimental validation highlights the potential of FGPS–TPMS scaffolds for repairing large bone defects and improving long-term implant stability.

Future research should emphasize optimizing fabrication processes, refining gradient configurations, and validating in vivo performance to accelerate clinical translation of these next-generation scaffolds for load-bearing bone applications. Additionally, such research contributes to student development and cultivates an entrepreneurial mindset, promoting innovation in biomedical engineering.

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TABLE 2. An overview of the mechanical properties, benefits, drawbacks, and consequences of metallic implants.

Material	Density (g/ cm^3)	Young's Modulus (GPa)	Yield Strength (MPa)	Poisson's Rat	Advantages	Disadvantages	Consequences	References
Magnesium	1.74-2.0	41-45	65-100	0.35	• Biodegradable metal • High degradation rate • Biocompatibility	• Poor corrosion resistance	• Implant mechanical failure and repeated surgery	(Cheng et al., 2016; Jasmawati et al., 2017)
Aluminium (AlSi10Mg)	1-10.2	63	280	0.33	• Biocompatibility • Lightweight • High strength	• High energy absorption	• Body reaction and adverse effects in the organic system	(Ullah et al., 2016)
Iron	5.63	200	145.7	0.29	• Excellent mechanical properties • High corrosion resistance	• Low degradation rate	• Releasing non-compatible metallic ions and allergic reactions	(Noordin et al., 2020)
Stainless steel (316L)	8.0	206	267.2	0.3	• Excellent mechanical properties	• High-stress concentrations	• Implant failure, pain to the patient, and repeated surgery	(Jin et al., 2020)
Coablt chronuium	8.3-9.2	210-253	448-1606	0.3	• Wear resistence	• Superior modulus • Low degradation rate	• Stress shielding effect, loosening, failure, repeated surgery	(Aherwar et al., 2016)
Titanium (Ti6A14V)	4.4-4.5	113.8	970	0.32	• Biocopatibility	• Low energy absorbtion • High corrosion	• Severe inflammatory response, destruction of healthy bone	(Shi Id et al., 2021)
Tantalum	-	188-190	138-345	-				(Guo et al., 2023)

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