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Fabrication, characterization, and compressive properties of SLM-fabricated 316L triply periodic minimal surface structures

Hengliang Fan[1,2] and **Abdullah Yassin**[2]

Abstract

Triply periodic minimal surface (TPMS) structures are widely utilized in fields such as aerospace, biomedicine, and sound absorption. This study investigated the fabrication characteristics and compressive properties of 316L stainless steel TPMS structures produced via selective laser melting (SLM). Uniform and gradient Gyroid (G) and I-Wrapped Package (IWP) porous structures with different porosities and unit cell sizes were designed. Specimens were fabricated via SLM and their morphology was evaluated employing scanning electron microscopy (SEM) along with micro-computed tomography (Micro-CT). The Micro-CT and SEM images revealed no defects or broken cells, confirming that SLM can accurately manufacture TPMS porous structures. After fabrication, the actual porosities of uniform porous specimens were 1.62%–5.14% lower than their target values. Both the elastic modulus and yield strength of uniform porous structures decreased progressively with increasing porosity. Although the deformation mode of TPMS structures was unchanged by graded porosity, introducing a porosity gradient significantly increased the compressive strength and energy absorption compared to uniform porosity designs. Using Abaqus software, a finite element model was established to analyze compressive behavior, enabling simulation of the corresponding stress–strain response. The outcomes of the numerical analysis demonstrated strong agreement with the experimental observations. This study systematically compares and validates the uniform porosity and gradient porosity in the 316L TPMS lattice through experiments and finite element analysis. These findings offer guidelines for designing TPMS metamaterials tailored to various operating conditions.

Keywords
triply periodic minimal surfaces, compression properties, selective laser melting, numerical simulation, energy absorption

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Introduction

Porous structures have numerous advantages, such as excellent energy absorption properties, light weight, high specific strength, and superior thermal and acoustic insulation.[1,2] Due to their designable porosity, density, and strength, porous materials have been widely applied in various fields, including medicine,[3] civil engineering,[4] and other areas.[5] However, in traditional manufacturing processes, it is challenging to produce porous structures with controllable porosity, which remains one of the major obstacles in their development.[6] Traditional methods for preparing porous materials include gas injection, spatial fixation, template replication, and screen printing. These methods are limited to producing porous materials with low uniformity and random structures. However, these issues can be addressed by utilizing additive manufacturing technology to create porous structures with complex geometries. Recent progress in additive manufacturing (AM),[7] including fused deposition modeling (FDM),[8,9] selective laser melting (SLM),[10,11] selective laser sintering (SLS),[12,13] has enabled the precise production of lattice structures and materials with enhanced accuracy. Various studies have explored additively manufactured lattices. The classical cell solid theory proposed by Gibson and Ashby serves as the fundamental theoretical framework for studying the mechanical behavior of

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[1] School of Mechanical and Vehicle Engineering, Bengbu University, Anhui Province, China
[2] Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, Malaysia

Corresponding author:
Abdullah Yassin, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, Sarawak 94300, Malaysia.
Email: yabdulla@unimas.my

porous structures including foams and lattice materials.[14] Chen et al. examined the mechanical behavior of sheet-based gyroidal stochastic cellular structures fabricated through additive manufacturing. Their findings revealed that higher relative density enhanced both stiffness and strength, while structural failure was primarily driven by progressive layer-wise collapse caused by localized buckling and fracture.[15] Xie et al.[16] studied the compression and fatigue performance of functionally graded Ti-6Al-4V mesh structures manufactured using electron beam melting. The results indicated that graded designs, owing to their gradual stiffness transitions, exhibited superior energy absorption capacity, and enhanced fatigue resistance when compared with uniform mesh counterparts.[17] Mueller et al.[18] studied periodic and stochastic 3D lattices via additive manufacturing and found that periodic structures showed stretching-dominated behavior with high peak stress, while stochastic ones showed bending-dominated behavior with stable energy absorption. However, traditional random or regular porous structures exhibit significant limitations in terms of performance uniformity, controllability, and stress distribution.

In recent years, triply periodic minimal surface (TPMS) porous structures have emerged as a novel porous structure characterized by high interconnectivity and a smooth surface. A comprehensive overview of TPMS porous structures, including multiscale design strategies, precise additive manufacturing routes, and multidisciplinary applications, is provided by Feng et al.[19] More recently, Li et al.[20] demonstrated that hybrid TPMS architectures can significantly enhance impact resistance and energy absorption under impact loading, highlighting the potential of TPMS-based hybrid designs for crashworthiness applications. Li et al.[21] provided a comprehensive review of additively manufactured metallic TPMS lattice structures, summarizing geometric design strategies, AM processes, and their multifunctional mechanical and energy absorption properties. It can be used as a scaffold for tissue engineering, a lightweight filler, or a micro-reactor. This versatility has attracted increasing attention in fields such as biomedicine and aerospace.[22,23] Alizadeh-Osgouei et al.[24] analyzed the structural features and mechanical performance of PLA gyroid scaffolds produced through fused deposition modeling, focusing on variations arising from different unit cell sizes, finding that smaller unit cells (G2) exhibited higher mechanical strength and anisotropy, with compressive and tensile behaviors suitable for bone tissue engineering applications. Chen et al. designed and SLM-fabricated uniform and porosity-graded Primitive and Gyroid TPMS structures. They found that transverse porosity grading yields slightly higher stiffness and strength than uniform lattices.[25] However, the study did not focus on the use of 316L for forming IWP structures. Zhao et al.[26] showed that SLS-fabricated Primitive PA12/HA scaffolds with radial porosity grading and 15% HA achieve optimal compressive strength, permeability, hydrophilicity, and cytocompatibility for bone tissue engineering. Ramu et al. examined the compressive response and energy absorption characteristics of AlSi10Mg TPMS lattices fabricated using selective laser melting. Their study revealed that Diamond architectures achieved higher energy absorption because of more uniform stress distribution, whereas Gyroid and Schwarz designs demonstrated distinct failure mechanisms under applied loading.[27] Thus, investigating gradient porous architectures holds significant relevance.[28] Abdelaal and Eldesouky[29] experimentally compared uniform and graded F-RD and Fischer–Koch S TPMS lattices under quasi-static compression, showing that density grading increases plateau stress and EA and delays densification compared with uniform counterparts. Noroozi et al.[30] developed innovative bone scaffolds by integrating 3D-printed PLA with alginate hydrogel containing living cells, showing that dynamic culture conditions promoted superior cell survival, growth, and differentiation compared with static environments. Ravichander et al.[31] explored the compression performance and corrosion behavior of sheet-type TPMS structures composed of 316L stainless steel, which were manufactured using the laser powder-bed fusion (LPBF) process.

In addition to experimental approaches, numerical methods have been employed for the analysis of TPMS structures. Sun et al.[32] used FEA to analyze stress distribution and deformation in Ti-6Al-4V TPMS structures, revealing that Gyroid structures had the most uniform stress distribution, contributing to their superior mechanical performance. Emir and Bahçe[33] investigated functionally graded hybrid lattice structures combining TPMS-based primitive–Gyroid and BCC–Gyroid unit cells produced by SLM, and demonstrated that hybrid grading with smoothly varying pore size can effectively tune stiffness and SEA while maintaining stable plateau deformation. Yang et al.[34] have analyzed the fabrication, compression behavior, and failure mechanisms of ABD-900AM TPMS structures via selective laser melting, demonstrating high fabrication quality and superior energy absorption compared to typical metal alloys. Kladovasilakis et al. employed finite element analysis (FEA) to simulate the stress–strain behavior of FFF-printed TPMS structures. The FEA results closely matched experimental data, accurately predicting stiffness, energy absorption, and post-softening behavior across different relative densities.[35] In general, numerical simulations offer detailed insight into failure mechanisms, which is crucial for understanding TPMS structures.

Previous studies have investigated graded Gyroid TPMS lattices in 316L stainless steel and sheet-type 316L TPMS structures, as well as TPMS architectures in other alloys and processing routes.[6,31] In contrast,