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Full length article

Fatigue behavior of As-built selective laser melted titanium scaffolds with sheet-based gyroid microarchitecture for bone tissue engineering

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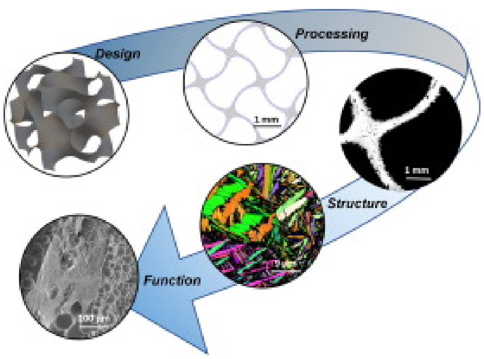
Abstract

Selective laser melting (SLM) has enabled the production of porous titanium structures with biological and mechanical properties that mimic bone for orthopedic applications. These porous structures have a reduced effective stiffness which leads to improved mechanotransduction between the implant and bone. Triply periodic minimal surfaces (TMPS), specifically the sheet-based gyroid structures, have improved compressive fatigue resistance due lack of stress concentrations. Sheet-based gyroid microarchitectures also have high surface area, permeability, and zero mean curvature. This study examines the effects of the gyroid microarchitectural design in parallel with SLM parameters on structure and function of as-built titanium alloy (Ti6Al4V ELI) scaffolds. Scaffold design was varied by varying unit cell size and wall thickness to produce scaffolds with porosity within the range of trabecular bone (50–90%). Manufacturer's default and refined laser parameters were used to examine the effect of input energy density on mechanical properties. Scaffolds exhibited a stretching-dominated deformation behavior under both compressive and tensile loading, and porosity dependent stiffness and strength. Internal void defects were observed within the walls of the gyroids structure, serving as sites for crack initiation leading to failure. Refinement of laser parameters resulted in increased compressive and tensile fatigue behavior, particularly for thicker walled gyroid microarchitectures, while thinner walls showed no significant change. The observed properties of as-built gyroid sheet microarchitectures indicates that these structures have potential for use in bone engineering applications. Furthermore, these results highlight the importance of parallel design and processing optimization for complex sheet-based porous structures produced via SLM.

Statement of Significance

Selective laser melting (SLM) is an additive manufacturing technology which produces complex porous scaffolds for orthopedic applications. Titanium alloy scaffolds with novel sheet-based gyroid microarchitectures were produced via SLM and evaluated for mechanical performance including fatigue behavior. Gyroid structures are function based topologies have been hypothesized to be promising for tissue engineering scaffolds due to the high surface area to volume ratio, zero mean curvature, and high permeability. This paper presents the effects of scaffold design and processing parameters in parallel, a novel study in the field on bone tissue scaffolds produced via additive manufacturing. Additionally, the comparison of compressive and tensile behavior of scaffolds presented is important in characterizing behavior and failure mechanisms of porous metals which undergo complex loading in orthopedic applications.

Graphical abstract



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Introduction

Triply periodic minimal surfaces (TPMS) have recently gained interest as the basis for novel topological structures for porous titanium scaffolds in tissue engineering applications. TPMS structures, including the gyroid, primitive, and diamond result from repeating periodic functions and are known for zero mean curvature of the surfaces [1]. The function-defined surface can be enclosed to generate skeletal microarchitectures or thickened to create sheet-based microarchitectures, like the gyroid sheet structures shown in Fig. 1. Porous scaffolds designed based on TPMS unit cells exhibit a unique combination of mechanical and biological properties, which can be tuned to mimic trabecular bone for orthopedic applications [2], [3], [4].

Although the mathematical basis of TPMS structures has been studied for decades [1], it is not until recently that 3D printing methods have enabled the fabrication of these complex architectures with the high precision, reproducibility, and at a cost reasonable for medical applications. Traditional manufacturing methods such as machining or metal injection molding have been used to create porous titanium scaffolds, but with limited control over the microarchitecture and surface features [5], [6]. More recently, additive manufacturing (AM) has enabled evolution of scaffold designs to increase complexity at both a macro-scale (patient specific geometry) and micro-scale (porous topology and surface topography).

Selective laser melting (SLM) is an AM technology that enables the fabrication of complex lattice structures from titanium or other metals. During the SLM process, powder is swept across a build platform in a thin layer. A laser energy source then selectively melts the material in planar cross-sections by CAD-defined scanning vectors; the process is repeated, and parts are built up in a layer wise fashion. The flexibility to create and control many combinations of scaffold design via SLM is unparalleled by other more traditional manufacturing methods. By altering the sheet-based TPMS unit cell (i.e. gyroid, Schwarz P, Schwarz D, etc.), unit cell size, or wall thickness applied, the porosity and resulting properties of the printed scaffold can be specified for a given application [7]. Evaluation of this new family of lattice structures will allow specification of microscale designs to define resulting macroscale properties such as strength, stiffness, surface area, and permeability [8], [9].

Increased porosity of titanium structures results in a reduced stiffness and improved mechanotransduction between implant and bone. However, this improvement comes with a tradeoff of reduced monotonic and fatigue strength. Study of these tradeoffs for porous SLM titanium has gained increasing focus, including computational, theoretical and experimental methods [2], [9], [10], [11], [12], [13]. Recent results have indicated that TPMS structures have significantly improved compressive fatigue resistance compared to beam (strut-node) based architectures [2], [14], [15]. This improvement is likely due to reduction of stress concentrations at strut-node interfaces in the beam-based topologies, which do not exist in the continuous curvature of TPMS structures [2]. Although the primary loading mode in orthopedic implants (and trabecular bone) is compression, stress concentrations in a porous structure can lead to local tensile stresses [2], [13], [16]. The macroscopic compressive loads typically experienced by orthopedic devices result in varied local tensile stresses, which are dependent on not only the loading scenario, but also the implant microarchitecture. In addition, devices that are primarily under compressive loads can experience bending loads resulting in significant local tensile stresses for all architectures. Thus, assessment of fatigue behavior and failure modes in both far-field compression and tension is necessary. Study of printing laser parameters and resulting part density, microstructure, and mechanical properties is also an active area of research [17], [18], [19]. However, the cross-sections of the continuous sheet geometry of TPMS structures that make up the scan paths during SLM differ from those of solid parts or even beam-based lattices. This difference in geometry warrants further investigation into ideal SLM printing parameters for varied TPMS lattice topology to optimize performance.

In this study, titanium alloy (Ti6Al4V) scaffolds of sheet-based gyroid microarchitecture were fabricated via SLM and both scaffold design and printing parameters were varied to be studied in parallel. The gyroid structure was selected due to its high surface area to volume ratio, smooth transitions between unit cells, and self-supporting nature for printability. The chosen unit cell size and wall thickness were changed to design scaffolds of porosity targeted to that of bone, namely from 50 to 85%. The chosen unit cell sizes and wall thickness were selected to produce pore sizes appropriate for orthopedic applications. Laser scanning parameters were altered to understand the effect on microstructure and mechanical properties of printed gyroid scaffolds of varied wall thickness. Gyroid scaffolds were tested in tension and compression, under monotonic and fatigue loading to characterize the mechanical properties as affected by the topological design and laser parameters. Characterization of the as-built microstructure and fracture surfaces enabled understanding of the mechanical properties resulting from varied gyroid wall thickness or laser parameters used. Although it is well known that heat treatment and hot isostatic pressing (HIP) improves the relative properties of printed metals, the current study only considers the properties of as-built samples without surface or heat treatment. The examination of as-built structures establishes a baseline for the microstructure and mechanical properties of the gyroid structure without any post-processing. This fundamental structure and property knowledge enable consideration of as-printed structures and also sets the baseline microstructures for future heat treatment studies.

Section snippets

Additive manufacturing and sample post-processing

Test specimens were fabricated via SLM (direct metal printing) of Ti-6Al-4V ELI powder on a titanium substrate in an inert argon atmosphere using a 3D Systems DMP ProX 320. All specimens were built within a validated area of the build platform in the same direction of loading for mechanical testing with a layer thickness of 30 μm. Cubic (12 mm × 12 mm × 12 mm) samples were used for all compression testing, and dogbones with cubic gage section (6 mm × 6 mm × 6 mm) were used for all tensile…

Effect of varied gyroid topology on printed microarchitecture and microstructure

Microarchitecture of the gyroid structure was varied by altering unit cell size (4 × 4 × 4 or 6 × 6 × 6) and wall thickness (0.25, 0.5, or 1.0 mm) to generate fully interconnected porous structures with porosity in the range of trabecular bone (50–90%) [20]. By increasing unit cell size, porosity increased, and surface area decreased. Conversely, with increasing wall thickness, porosity decreased, and surface area increased. The variation of these two design parameters, and their ratio to one…

Discussion

Recently, investigation of TPMS structures fabricated in various materials via 3D printing methods including, SLA, SLM, and PolyJet have been reported [2], [9], [25], [26], [27], [28]. These 3D printed TPMS topologies can act as tissue engineering scaffolds, providing space for biological ingrowth and appropriate mechanical properties including stress distribution throughout the construct [2], [3]. In order to characterize mechanical behavior relative to bone, sheet-based gyroid structures were …

Conclusion

In the current study, the fatigue behavior of sheet-based gyroid scaffolds manufactured by SLM from Ti-6Al-4V powder has been investigated. The main results can be summarized as follows:

- The current sheet-based gyroid scaffolds had stiffness within the range of trabecular and cortical bone depending on porosity, and strengths appropriate to bear high load. Furthermore, a favorable stretching-dominated deformation behavior was observed by power-law fitting of mechanical properties observed under...

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