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Compressive anisotropy of sheet and strut based porous Ti–6Al–4V scaffolds

Helena Barber [a], Cambre N. Kelly [b], Kaitlin Nelson [b], Ken Gall [b]

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Highlights

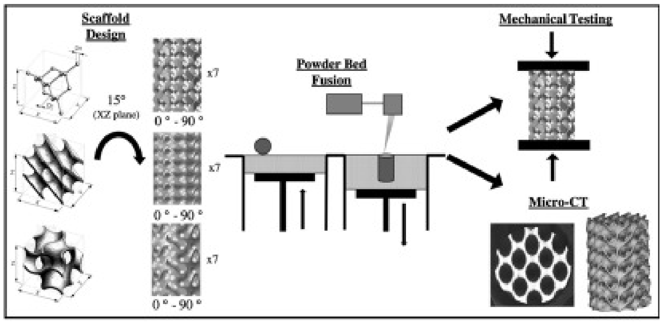
- Ti–6Al–4V scaffolds of three architectures were 3D printed via powder bed fusion.
- Unit cells were rotated in the XZ plane in 15° increments.
- Compressive strength depends on architecture and orientation.
- Sheet-based structures had higher strength than strut-based scaffolds for all orientations.
- The strut-based architecture was more than twice as anisotropic as both sheet-based architectures.

Abstract

Porous metallic scaffolds show promise in orthopedic applications due to favorable mechanical and biological properties. In vivo stress conditions on orthopedic implants are complex, often including multiaxial loading a[illegible] axis orientations. In this study, unit cell orientation was rotated in the XZ plane of a strut-based architecture, Diamond Crystal, and two sheet-based, triply periodic minimal surface (TPMS) architectures, Schwartz D and [illegible] Sheet-based architectures exhibited higher peak compressive strength, yield strength and strain at peak stress than the strut-based architecture. All three topologies demonstrated an orientational dependence in mechanical properties. There was a greater degree of anisotropy (49%) in strut-based architecture than in either TPMS architectures (18–21%). These results support the superior strength and advantageous isotropic mechanical properties of sheet-based TPMS architectures relative to strut-based architectures, as well as highlighting the importance of considering anisotropic properties of lattice scaffolds for use in tissue engineering.

Graphical abstract

Ti-6Al–4V scaffolds of three architectures. Each architecture contained seven orientations, created by rotating the unit cell in 15° increments in the XZ plane. Scaffolds were printed via powder bed fusion and were tested in static compression. Micro-CT analysis of each geometry and orientation with subsequent volumetric reconstruction and analysis was performed.



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Introduction

Porous metal implants produced by Additive Manufacturing (AM), also known as 3D printing, are rapidly gaining popularity for use in a variety of orthopedic applications due to their mechanical and biological advantages (Ricles et al., 2018). A primary advantage of porous metal implants is reducing the implant's stiffness to better match human bone, which reduces stress-shielding and improves implant longevity (Moyen et al., 1978; Huiskes et al., 1992; Oh et al., 2003; Ryan et al., 2006; Niinomi and Nakai, 2011). The interconnected porous architectures also promote bony ingrowth by encouraging cell migration, nutrient diffusion and cell growth (Van Blitterswijk et al., 1986; Schliephake et al., 1991; Otsuki et al., 2006; Rajagopalan and Robb, 2006; Ryan et al., 2006). Titanium and it's alloys are frequently used for these implants due to favorable properties including its superior biocompatibility compared to other materials, promotion of osseointegration and high strength (Geetha et al., 2009; Kaur and Singh, 2019). Furthermore, the titanium alloy Ti–6Al–4V has a high resistance to corrosion due to the formation of protective surface oxides. Baragetti et al. (2018) found that this protective effect can be compromised in aggressive environments in the presence of notch effects, which is a concern with both surface defects and the inherent internal porosity seen in additive manufacturing. This combination of increased stress concentration factors and susceptible environments could detrimentally effect corrosion fatigue of titanium implants.

Advances in AM technology have expanded the possibilities for developing implants with complex geometries containing porous regions for bony ingrowth, sold regions for structural support, and a shape that is matched to patient anatomy. Powder bed fusion (PBF) is an AM technology that allows for the conversion of a computer a design (CAD) into a three-dimensional printed geometry. Utilizing the CAD file, a high-powered laser scans ac bed of powder and selectively fuses particles in a layer by layer fashion to create the desired three-dimensiona geometry (Kelly et al., 2018). This process allows for precise control over the final geometry and the production of highly complex and patient specific structures. PBF is often used to created Ti–6Al–4V porous geometries for orthopedic implants utilized in spine, foot and ankle, arthroplasty, and reconstruction after bone tumor resection (Wong, 2016; Dekker et al., 2018; Sheha et al., 2019).

The mechanical properties of various topologies of porous architectures have been widely studied in an effort to maximize both implant durability and osseointegration. Due to the amount of control provided by PBF, one can alter a number of variables of the scaffold topology including the unit cell architecture, pore size, unit cell size, percent porosity, wall/strut thickness, and surface roughness, all of which have effects on the mechanical properties, stability, and amount of bony ingrowth into an implant (Sun et al., 2013; Yan et al., 2015; Taniguchi et al., 2016; Zaharin et al., 2018; Maszybrocka et al., 2019).

Relatively little investigation has been made on the effect of loading direction on vertical compressive strength over a diverse set of unit cell topologies. As seen in Fig. 1A, Diamond Crystal is a strut-based architecture with the unit cell consisting of fourteen nodes and sixteen edges, and the length of each edge defined as $\frac{\sqrt{3}}{4}c$, in which c is the unit cell size. Although it has been debated in the literature whether Diamond Crystal, a strut-based geometry, has anisotropic properties, its anisotropy has not been directly compared to other architectures (Ahmadi et al., 2014; Wauthle et al., 2015; Soul et al., 2018; Cutolo et al., 2020). Schwartz D and Gyroid are both sheet-based scaffolds based on triply periodic minimal surfaces (TPMS), which have previously been described in recent literature to have superior mechanical properties compared to traditional strut-based architectures, and may also have a relatively high degree of isotropy (Kapfer et al., 2011; Yoo and Kim, 2015). TPMS structures are generated by mathematical formulae. A unit cell with Schwartz D (Eq (Ahmadi et al., 2014).) architecture is depicted in Fig. 1B, while Gyroid (Eq (Al-Ketan et al., 2018).) is depicted in Fig. 1C.$\sin(x)\sin(y)\sin(z)+\sin(x)\cos(y)\cos(z)+\cos(x)\sin(y)\cos(z)+\cos(x)\cos(y)\sin(z)=0$.$\cos(x)\sin(y)+\cos(y)\sin(z)+\cos(z)\sin(y)=0$

TPMS structures have a mean curvature of zero in three directions and resembles the natural curvature of trabecular bone, reducing local stress concentrations (Schoen, 1970; E. Yang et al., 2019a). As a result, sheet-based TPMS structures have been found to have higher toughness, strength and fatigue resistance than their strut-based counterparts (Bobbert et al., 2017; Al-Ketan et al., 2018; Kelly et al., 2019). The mechanical behavior of TPMS structures has been described by a few studies as changes in Young's modulus and compressive strength dependent on unit cell orientation (Ataee et al., 2018; Bonatti and Mohr, 2019; L. Yang et al., 2019b). In each of these studies, compressive properties of gyroid or TPMS-like structures were evaluated in at most three orientations, making it challenging to follow a trend with incremental rotation of the unit cells in the compressive axis. Yánez et al. (2016) held unit cell orientation constant and altered the design of the base gyroid unit cell to create eight test samples with sheets at varying angles with respect to the axial direction. It was found that the orientation of the gyroid architecture had a significant effect on compressive strength.

In this study, Ti–6Al–4V scaffolds were designed with two different sheet-based TPMS topologies, Schwartz D and Gyroid, to be compared to a strut-based architecture, Diamond Crystal. The projection of the unit cell in the XZ plane was rotated in 15-degree increments from 0° to 90° to evaluate trends in the effect of unit cell orientation on compressive strength. Orthopedic implants must be able to withstand complex stress environments, including loading in orientations different from the primary axis of the unit cell. This makes the anisotropy of unit cell architectures an important consideration in evaluating the overall strength of an implant. Additionally, direct comparison of a strut-based architecture to sheet-based TPMS architectures demonstrated a significant difference in mechanical properties and degree of anisotropy between the two architecture types.

Section snippets

Scaffold preparation

Cylindrical scaffold specimens (d=10mm, length=15mm) were designed using 3DXpert (3D Systems) with Diamond Crystal, Schwartz D, and Gyroid to be 75% porosity, which is in the range of trabecular bone and allows sufficient room for bony integration in an implant (Sikavitsas et al., 2001). Each architecture was designed based on repeating unit cells with size of 5 mm×5 mm x 5 mm, and with the orientation held constant in the XY plane. The projection in the XZ plane was rotated in…

Printing accuracy

All architectures and orientations printed well with no obvious print failures. Fig. 1 depicts a single unit cell of each architecture, while Fig. 2 depicts images of scaffolds for each test scaffold and representative images of the reconstructed scaffolds in the XZ plane. All scaffolds appeared consistent with the CAD file and no “macroscopic” lattice defects from the printing process were observed.

Boundary distortion stress view analysis is depicted in Fig. 3. This analysis provides a visual…

Discussion

This study examined the mechanical properties of PBF lattice titanium geometries as the unit cells were rotated with respect to the build direction in the XZ plane. Porous metallic scaffolds have numerable biological and mechanical advantages. As applications for these implants are becoming more widely used in orthopedics, it is important to optimize the mechanical properties for implant stability and longevity. Due to complex loading environments in vivo, the anisotropy of different lattice…

Conclusions

Advances in additive manufacturing has allowed for the production of complex porous architectures with many beneficial mechanical and biological properties for use in orthopedic applications. Porous lattice structures promote osseointegration and increase implant longevity by reducing elastic modulus and stress shielding. Lattice structures can have varying mechanical properties based on the loading axis relative to axis of the primary unit cell. As in vivo conditions are not limited to load…

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CRediT authorship contribution statement

Helena Barber: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Cambre N. Kelly:** Conceptualization, Methodology, Writing - review & editing, Visualization. **Kaitlin Nelson:** Conceptualization, Methodology, Investigation, Writing - review & editing, Visualization. **Ken Gall:** Conceptualization, Methodology, Resources, Writing - review & editing, Visualization, Supervision, Project administration.…

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: restor3d…

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