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Anisotropic Ti-6Al-4V gyroid scaffolds manufactured by electron beam melting (EBM) for bone implant applications

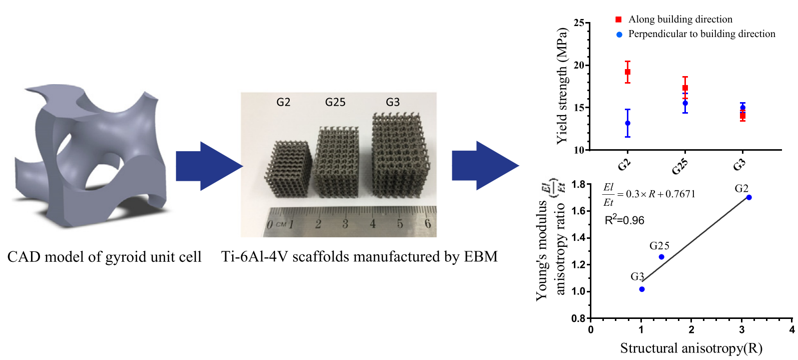
Arash Ataee [a], Yuncang Li [a], Darren Fraser [b], Guangsheng Song [c], Cuie Wen [a,*]

[a] School of Engineering, RMIT University, Bundoora, Victoria 3083, Australia
[b] High Performance Metal Industries program, CSIRO Manufacturing Flagship, Clayton, Victoria 3168, Australia
[c] School of Material Science & Engineering, Anhui University of Technology, Maanshan, Anhui 243002, China

HIGHLIGHTS

- Ti-6Al-4V triply periodic minimal surface lattices are printed by electron beam melting (EBM).
- As-built scaffolds exhibit structural anisotropy.
- The mechanical properties of the scaffolds along two orthogonal directions were significantly different.
- The strain-stress curves of the as-built gyroid scaffolds showed brittle behavior.
- The ratio of elastic modulus anisotropy in orthogonal directions was comparable to those of trabecular bone.

GRAPHICAL ABSTRACT



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ABSTRACT

Ti-6Al-4V gyroid scaffolds with high porosities in the range of 82–85% and three different unit cell sizes 2, 2.5 and 3 mm were manufactured by electron beam melting (EBM) for bone implant applications. The microstructure, mechanical properties and failure mode of the scaffolds with different sample orientations were evaluated. The as-built struts showed orthogonally orientated martensite α′ needles in columnar grains along the building direction with an average hardness of 3.89 GPa and the elastic modulus and yield strength of scaffolds ranged from 637 to 1084 MPa and from 13.1 to 19.2 MPa, respectively. The elastic modulus and yield strength along the build direction and perpendicular to building direction varied by ~70% and 49%, respectively, depending on the amount of structural anisotropy and unit cell size. The ratio of elastic modulus anisotropy in orthogonal directions was comparable to those of trabecular bone and could be in favor of bone implant applications. Furthermore, as-built scaffolds showed a mixed mode of ductile and brittle behavior under compression, and the dominant failure mode was by forming orthogonal crush bonds at the peak loads with an angle of ~45° with compression axis.

1. Introduction

The mismatch of elastic modulus between biomaterials and the adjacent bones is the main challenge to have a good fixation of implantation materials to the bone tissue. While implants need to have a low modulus to match that of bone, the implanted materials must be strong

* Corresponding author.
E-mail address: cuie.wen@rmit.edu.au (C. Wen).

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and durable enough to endure the physiological loads applied on it and expected to serve for an extended period or until lifetime without failure or revision surgery [1,2]. To date, Ti alloys and specifically Ti-6Al-4V have been broadly used for load-bearing implant applications because of their outstanding mechanical strength and excellent biocompatibility [3–7]. However, the stiffness mismatch of solid Ti-6Al-4V and bone tissue is huge which cause stress shielding. To overcome this issue open cellular foams or scaffolds have been used to reduce the elastic modulus of implants. Open cellular foams or scaffolds with an interconnected pore structure can also permit the transport of body fluids and provide better biological fixation by promoting bone tissue ingrowth into the pores of the implants and also offer smooth stress transfer between implants and bones [8,9].

Over the last few decades, achievements have been made in a design of scaffolds that mimic the architecture and mechanical behavior of natural bone. A variety of production methods has been developed to fabricate scaffolds for biomedical applications. Developments in additive manufacturing techniques have enabled the successful production of metallic scaffolds. Particularly, for biomedical applications, electron beam melting (EBM) and selective laser melting (SLM) have eliminated the numbers of manufacturing constraints like shape, size, and pore architecture [10,11]. The physiological structure of bone tissues is naturally heterogeneous and complex. Therefore instead of reproducing the exact internal microarchitecture of bones, design of scaffolds are mainly focused on the creation of simplified models which are functionally similar to the host bones in terms of porosity and mechanical properties [12].

There have been many attempts in the production of regular meshes having predefined internal and external architecture using SLM and EBM methods. Most of these studies are focused on regular lattice-based geometries, such as cubic [13–17], octahedral [18,19], diamond [14,20–23], rhombic dodecahedron [24], honeycomb [25], and kelvin polyhedral/tetrakaidecahedron [26]. For example, Hrabe et al. [21] manufactured Ti-6Al-4V scaffolds with diamond structure over a range of pore sizes (500–1500 μm) and relative densities (0.17–0.40) and. Li et al. [27] have studied effects of cell shape on the mechanical properties of additively manufactured Ti–6Al–4V scaffolds with porosities ranged from 58% to 88% and different unit cells (G7, cubic and rhombic dodecahedron). Further, Sun et al. [28] reported selective laser melting of stainless steel 316 L with low porosity and high build rates. Maria et al. [29] manufactured graded Ti-6Al-4V scaffolds with bcc and diamond structures and average gradient porosities of 65–21% for segmental bone defect treatments. Further, an excellent review on 3D printing of cellular scaffolds for orthopedic implants was also performed by Tan et al. [30]. The manufacturing, topological design, mechanical properties and biocompatibility of cellular Ti-6Al-4V scaffolds via SLM and SEBM methods were elucidated with highlights on current manufacturing limitations, topological shortcomings, and uncertainty of biocompatible tests [30].

However, the success of the biological fixation of the implant depends on surface characteristics, implant architecture, and topology. The surface characteristics of materials affect the osteoblast adhesion on biomaterials; therefore, the porosity, pore shape and pore size of the biomaterial play a critical role in the bone ingrowth in vivo.

Recently a class of periodic minimal surfaces belonged to implicit functions is introduced as attractive candidates for the design of biomorphic scaffold architectures [12]. These surfaces are also known as Triply Periodic Minimal Surfaces (TPMS) [31]. TPMS structures have smooth boundless surfaces that divide the space into two labyrinths in the absence of self-intersections. TPMS can be periodic in three independent directions [32] and are found in sodalite crystal structures, lyotropic liquid crystals, soluble proteins in lipid-protein water phases, diblock polymers and specific cell membranes [31].

First attempt using advance computerize-controlled fabrication method and characterization of tissue engineering scaffolds based on TPMS has been presented by Rajagopalan and Robb [33]. High-precision fabrication of TPMS-based scaffolds such as Schwarz's Diamond (D) and Schoen's Gyroid (G) has been demonstrated by [34–36]. More complex structures with different volume fractions of pores as well as functional gradient architectures have also successfully designed and manufactured by SLS [37] and SLA [38]. Most recently Yan et al. [39] have investigated the manufacturing of high porosity gyroid and diamond TPMS scaffolds having a pore size in the range of 560–1600 μm and 480–1450 μm by SLM method from Ti–6Al–4V. They showed that the TPMS scaffolds with 80–95% porosity had an elastic modulus in the ranges of 0.12–1.25 GPa which was similar to properties of cancellous bone.

Advantages of implementing TPMS structures in the design of scaffold can be summarized as follow:

- It provides computationally efficient and accurate method in design parameters such as pore size, pore shape, inner channel interconnectivity and volume fraction [12,40].
- It provides better manufacturability for layer-based additive manufacturing methods like SLM and EBM.
- It exhibits better mechanical and biological properties compared to the traditional scaffolds consist of rod-connected pore structures due to the effect of geometrical continuity and topological smoothness [40].
- It provides high surface-to-volume ratios by the simple analytical definition and could be easily wetted and intruded by a cell suspension, resulting in a more homogeneous cell distribution and a deeper cell colonization [12]. It also enhances the viability and cell migration [32,33,38,40–43].

While advantages of using TPMS structure were previously reported in literature, very limited number of studies was performed on the mechanical properties of metallic gyroid scaffolds for biomedical applications. Therefore, this research intended to investigate the effects of unit cell size on the mechanical property and microstructure of Ti-6Al-4V gyroid structures processed by EBM. Furthermore, in contrast with previous literature that mechanical properties were reported only for one direction; in this study, effects of unit cell size on the mechanical properties of scaffolds in two orthogonal directions (parallel and perpendicular to build direction) were evaluated.

For the design of scaffold for biomedical applications, it is reported that the minimum pore size for improving osseointegration is 300 μm [44] and the porosity must be above 60% with pore size ranges 300 to 1200 μm that may have better bone tissue ingrowth [1,4,45–47]. Although higher porosity permits bone ingrowth [48], the upper limit in porosity and pore size must be defined by constraints that refer to the mechanical properties of the implant and surrounding bone tissue. Therefore in this work, gyroid scaffolds with three different unit cell sizes (2 mm, 2.5 mm, and 3 mm) with porosity in ranges of around 72–74% and pore sizes of ~850–1270 μm were designed and manufactured.

2. Experimental procedures

2.1. Materials

The Ti-6Al-4V (Ti64) powder used for this work exhibits a spherical shape and smooth surface providing an excellent flowability. Powder particle distribution analysis was performed by Mastersizer 3000 (Malvern Instruments Ltd). The powders showed a particle size normally distributed between 54.4 μm (D10) and 132 μm (D90) with a mean volume diameter of 85.9 μm (D50). The elemental analysis of the Ti64 powder particles performed by Leco combustion and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) and listed in Table 1.