JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 46 (2015) 104–114

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Research Paper

Fabrication, pore structure and compressive behavior of anisotropic porous titanium for human trabecular bone implant applications

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ARTICLE INFO

Article history:
Received 11 October 2014
Received in revised form
19 February 2015
Accepted 20 February 2015
Available online 3 March 2015

Keywords:
Porous titanium
Biomaterials
Diffusion bonding
Pore structure
Compressive behavior

ABSTRACT

Porous titanium with average pore size of 100–650 μm and porosity of 30–70% was fabricated by diffusion bonding of titanium meshes. Pore structure was characterized by Micro-CT scan and SEM. Compressive behavior of porous titanium in the out-of-plane direction was studied. The effect of porosity and pore size on the compressive properties was also discussed based on the deformation mode. The results reveal that the fabrication process can control the porosity precisely. The average pore size of porous titanium can be tailored by adjusting the pore size of titanium meshes. The fabricated porous titanium possesses an anisotropic structure with square pores in the in-plane direction and elongated pores in the out-of-plane direction. The compressive Young's modulus and yield stress are in the range of 1–7.5 GPa and 10–110 MPa, respectively. The dominant compressive deformation mode is buckling of mesh wires, but some uncoordinated buckling is present in porous titanium with lower porosity. Relationship between compressive properties and porosity conforms well to the Gibson–Ashby model. The effect of pore size on compressive properties is fundamentally ascribed to the aspect ratio of titanium meshes. Porous titanium with 60–70% porosity has potential for trabecular bone implant applications.

1. Introduction

Titanium and its alloys are promising materials used for bone implants because of their unique properties such as high specific strength, excellent biocompatibility and corrosion resistance (Geetha et al., 2009; Niinomi et al., 2012). Unfortunately, the mechanical incompatibility between solid titanium and human bone has limited their applications. For instance, Young's modulus of human bone (less than 30 GPa) is much lower than that of the solid titanium (about 110 GPa) (Gepreel and Niinomi, 2013; Niinomi, 2008). This mismatch in Young's modulus may lead to bone resorption and implant loosening associated with the "stress shielding" effect. In the past decades, a large amount of studies have been made to decrease Young's modulus of titanium and the measures mainly include the following two aspects. The first one is addition of alloying elements such as Nb, Zr and Sn to form a metastable beta structure in titanium alloys (Nie et al., 2014;

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http://dx.doi.org/10.1016/j.jmbbm.2015.02.023
1751-6161/

Zhao et al., 2013). The second one is introduction of a bone-like porous structure in titanium to form porous titanium (Rao et al., 2014; Ryan et al., 2008; Sallica-Leva et al., 2013). Porous structure in titanium is favored to decrease Young's modulus by increasing porosity, which can solve problems associated with the "stress shielding" effect (He et al., 2012). In addition, porous titanium can promote the transport of body fluid and stimulate bone ingrowth, which is helpful to improve the fixation of implants to the bone (Karageorgiou and Kaplan, 2005; Ryan et al., 2006).

In recent years, extensive studies have been done on porous titanium and they mainly focus on the fabrication processes (He et al., 2012; Yook et al., 2012), mechanical compatibility (Ahmadi et al., 2014; Sallica-Leva et al., 2013), surface modification (Takemoto et al., 2006) and biocompatibility (Fukuda et al., 2011; Xue et al., 2007). As to the fabrication process, Dunand et al. and Ryan et al. have reviewed the fabrication methods of porous metallic biomaterials (Dunand, 2004; Ryan et al., 2006). Various fabrication methods such as powder sintering (Li et al., 2012; Oh et al., 2003), freeze casting (Chino and Dunand, 2008; Jung et al., 2013; Yook et al., 2009, 2012), space-holder method (Jha et al., 2013; Ye and Dunand, 2010) and rapid prototyping (Campoli et al., 2013; Heinl et al., 2008; Mullen et al., 2009; Van Bael et al., 2012) have been proposed and employed to produce porous metallic biomaterials with mechanical properties compatible with bone. It is well known that a pore structure (including porosity, pore morphology, pore size and its distribution) has substantial influence in the mechanical compatibility and biocompatibility of porous biomaterials. Among the above parameters, porosity is one of the most important. According to the Gibson–Ashby model (Gibson and Ashby, 1997), mechanical properties such as Young's modulus and yield stress are greatly related to porosity. Since the Young's modulus and yield stress are two key parameters for designing porous implants, it is important for the fabrication process possessing excellent design and accurate control of the porosity. In addition, elongated pores in the porous titanium attract much more attention than equiaxed pores due to their morphological similarity to the anisotropic porous structure of bones, which can reduce "stress shielding" effect more effectively (Jorgensen and Dunand, 2011; Weiner and Wagner, 1998). Up to now, many fabrication processes have been proposed to prepare porous titanium with elongated pores, such as freeze casting and rapid prototyping. Freeze casting is a simple method to produce high aspect ratio pores in titanium, but the fabricated porous titanium has high oxygen content and poor mechanical properties (Chino and Dunand, 2008). In recent years, rapid prototyping has been paid much more attention for fabricating porous titanium. Rapid prototyping is a flexible fabrication process based on a CAD model. However, the fabricated porous titanium sometimes has defects such as impurities, inclusions and unmelted powders, which may deteriorate the mechanical properties (He et al., 2012; Sallica-Leva et al., 2013).

With respect to the mechanical behavior, many researchers have investigated the effect of porosity on mechanical properties of porous titanium and its alloys (Cheng et al., 2012; Parthasarathy et al., 2010). For instance, Imwinkelried studied the static compression, bending, torsion, tension and cyclic compression properties of porous titanium fabricated by a space-holder method, which is concluded that the stiffness and strength of porous titanium with 50–80% porosity are in the range of properties of natural bone (Imwinkelried, 2007). Rao et al. discussed the Vickers hardness and compressive properties of porous Ti–Nb–Zr alloys, and found that Vickers hardness and compressive properties can be tailored by porosity (Rao et al., 2014). However, there are few studies related to the effect of pore size on mechanical properties. It is well known that pore size has effect on the bone ingrowth and biocompatibility of porous implants. Results from Xue et al. and Fukuda et al. concluded that porous titanium with pore size in the range of 100–600 μm exhibited the optimum ability to allow cell growth into the pore structure (Fukuda et al., 2011; Xue et al., 2007). In order to find out the mechanical compatibility in the range of this optimum pore size, it is necessary to investigate the effect of pore size on the mechanical properties of porous titanium.

Table 1 – Pore size and wire diameter of three types of titanium meshes.

No.	Pore size/μm	Wire diameter/μm	Aspect ratio[a]
1#	350 ± 9	109 ± 7	0.31
2#	541 ± 23	222 ± 7	0.41
3#	697 ± 11	245 ± 4	0.35

[a] Aspect ratio of titanium mesh means the ratio of wire diameter to length in a single pore. Wire length in a single pore is equal to pore size.

In this paper, anisotropic porous titanium with porosity of 30–70% and average pore size of 100–650 μm was fabricated by diffusion bonding of titanium meshes. Pore structure was characterized by Micro-CT scan and SEM. The compressive properties and deformation mode of porous titanium in the out-of-plane direction were studied. Relationship between porosity and compressive properties was analyzed by the Gibson–Ashby model. In addition, the effect of pore size on the compressive properties was discussed based on deformation mode. Porous titanium having potential for trabecular bone implant applications was provided.

2. Material and methods

2.1. *Fabrication of anisotropic porous titanium*

Porous titanium was fabricated by vacuum diffusion bonding of titanium meshes. Three types of titanium meshes (marked as No. 1#, 2# and 3#) with square pore shape and different pore size are used as starting materials. Structural parameters of these three types of titanium meshes are shown in Table 1. Table 2 shows chemical composition of the titanium meshes. Before diffusion bonding, mesh surface was treated with following processes: (i) etched in 3% HF+30% HNO_3 solution for 10–15 s; (ii) rinsed in deionized water for 15–20 min; (iii) ultrasonically cleaned in absolute ethanol for 15–20 min; (iv) dried in furnace at 80 °C for 1 h. Fig. 1 shows schematic diagram of structure for porous titanium fabricated by diffusion bonding of titanium meshes. As shown in Fig. 1, certain numbers of surface-treated meshes with dimension of $L \times W$ (mm) was stacked layer by