Acta Biomaterialia 9 (2013) 5802–5809

Contents lists available at SciVerse ScienceDirect

Acta Biomaterialia

journal homepage: www.elsevier.com/locate/actabiomat

Novel multilayer Ti foam with cortical bone strength and cytocompatibility

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ARTICLE INFO

Article history:
Received 24 August 2012
Received in revised form 31 October 2012
Accepted 13 November 2012
Available online 29 November 2012

Keywords:
Porous Ti
Ti foam
Cortical bone
Stress shielding
Cytocompatibility

ABSTRACT

The major functions required for load-bearing orthopaedic implants are load-bearing and mechanical or biological fixation with the surrounding bone. Porous materials with appropriate mechanical properties and adequate pore structure for fixation are promising candidates for load-bearing implant material. In previous work, the authors developed a novel titanium (Ti) foam sheet 1–2 mm thick by an original slurry foaming method. In the present work, novel Ti foam is developed with mechanical properties compatible with cortical bone and biological fixation capabilities by layer-by-layer stacking of different foam sheets with volumetric porosities of 80% and 17%. The resulting multilayer Ti foam exhibited a Young's modulus of 11–12 GPa and yield strength of 150–240 MPa in compression tests. In vitro cell culture on the sample revealed good cell penetration in the higher-porosity foam (80% volumetric porosity), which reached 1.2 mm for 21 days of incubation. Cell penetration into the high-porosity layers of a multilayer sample was good and not influenced by the lower-porosity layers. Calcification was also observed in the high-porosity foam, suggesting that this Ti foam does not inhibit bone formation. Contradictory requirements for high volumetric porosity and high strength were attained by role-sharing between the foam sheets of different porosities. The unique characteristics of the present multilayer Ti foam make them attractive for application in the field of orthopaedics.

1. Introduction

As the average age of the population is increasing in the developed world, the demand for load-bearing metals for orthopaedic implants has grown drastically [1]. The major functions required of orthopaedic implants are load bearing and mechanical or biological fixation with the surrounding bone. Ti and its alloys have been used in orthopaedic implants for load-bearing applications because of their biocompatibility, good corrosion resistance and excellent mechanical properties. However, the major problem of Ti and Ti alloy implants is a mismatch of Young's modulus between bone (10–30 GPa) and Ti (110 GPa), which leads to stress-shielding and results in bone resorption and implant loosening [2]. One possible solution to this problem is the development of low-modulus Ti alloys, which, over the past 20 years, has resulted in new alloys such as TNTZ (Ti–29Nb–13Ta–4.6Zr) [3,4]. Unfortunately, the Young's modulus of human bone is too low to be reached by an alloy-designing approach. An alternative method of overcoming the mismatch of Young's modulus is the use of porous metal coating, which can reduce mismatch at the interface and achieve stable long-term biological fixation through bone ingrowths. Many types of porous metals have been developed and used to coat the surface of orthopaedic implants [5–10]. Typical fabrication methods for such porous metals are powder metallurgy [11–13], chemical vapour infiltration [14,15], space-holding [16,17], plasma spraying [18] and rapid prototyping [19–21]. Although open-pore structures have the advantages of a low Young's modulus and bone ingrowth, leading to better fixation with bone, they have the disadvantage of insufficient mechanical strength compared with that of bulk structural materials [22]. As a result, the majority of these porous metals are applied as coatings on fully dense substrates [9].

Imwinkelried [16] reported the first application of a Ti foam device for the human lumbar spine. However, the yield strengths of this Ti foam, which had a porosity of 63–50%, were 68–140 MPa under compression. This low mechanical property limited its application to the load-bearing devices for the human lumbar spine. Therefore, porous metal fabrication technology ensuring adequate strength and tailorable open-pore structure is assumed to be very important for orthopaedic implants. To achieve these contradictory requirements of adequate strength and high porosity with adequately open-pore structure, the present authors developed novel

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1742-7061/$ - see front matter © 2012 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actbio.2012.11.018

Ti foam by stacking foam sheets of different porosities layer by layer to create multilayer Ti foam. This study examines the mechanical properties of multilayer Ti foam designed to have cortical bone strength. Cell penetration capability is evaluated by in vitro experiments and compared with a control sample prepared by stacking a single type of foam sheet. In addition, cell penetration and calcification in the Ti foam sheet are examined.

2. Materials and methods

2.1. Manufacturing process and specification of Ti foam and multilayer Ti foam

An original slurry foaming method, illustrated in Fig. 1a, was used to fabricate novel Ti foam. A slurry containing Ti powder (20 μm in mean diameter), binder, foaming agent and water was prepared and coated on a carrier sheet. The sheet was treated in a foaming moisture chamber, and then moved to a drying chamber, where the foaming agent in the slurry was evaporated. Foamed green sheets were heated for debinding and then sintered in a vacuum heat-treatment furnace. This Ti foam has already been used commercially in new electrochemical applications [23].

As-fabricated Ti foam sheets were 0.2–2 mm thick and possessed a prescribed porosity and pore diameter. The volumetric porosity of the foam P was estimated by

$$P = 1 - (\rho^*/\rho_s)$$

where ρ^* is the measured apparent density of foam, and ρ_s is the density of bulk Ti.

Because the Ti foam had a sheet shape, it was possible to stack them easily, despite their different volumetric porosities. Table 1 lists the test samples prepared by stacking the Ti foam sheets. Designation letters indicate Ti foam with high (H), middle (M) or low (L) volumetric porosity. Designation numbers indicate the approximate thickness in millimetres of the corresponding Ti foam in the stacked sheet. The "multilayer" type consists of two different volumetric porosity sheets, and the "stacked" type consists of the same volumetric porosity sheets. Table 2 lists the chemical composition of Ti powder and Ti foam. A photograph and microscopic images of H2L1, multilayer Ti foam composed of high volumetric porosity sheet (H, 80%) and low volumetric porosity sheet (L, 17%), are shown in Fig. 1b–d. As specified in Table 1, H2L1 consisted of four pairs of eight sheets: high volumetric porosity sheet with a thickness of 2 mm and low volumetric porosity sheet with a thickness of 1 mm alternated four times. The sample was sintered in a vacuum heat-treatment furnace. In the case of M2L2, M denotes a middle volumetric porosity sheet of 62%, and 2 denotes a thickness of 2 mm. Similarly, H2 was composed of a single type of 2-mm-thick high volumetric porosity Ti foam sheet. H2 data were obtained during a previous work [23].

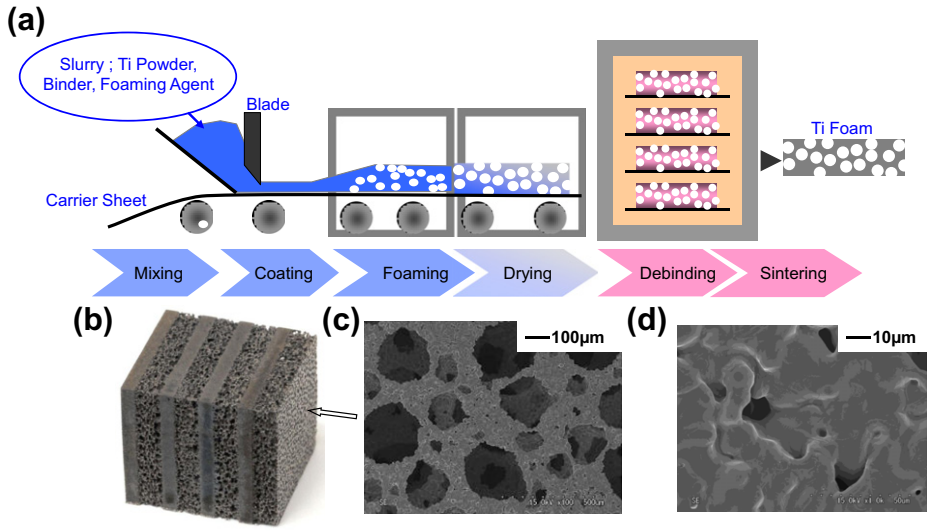

Fig. 1. (a) Illustration of the slurry foaming method; (b) photograph of a multilayer Ti foam sample; (c) and (d) scanning electron microscopy images of the arrow surface of (b) in (c) low and (d) high magnification.

Table 1
Specifications of multilayer and stacked Ti foam samples.

Designation	Type	Total porosity[a] (%)	No. of repetitions	Ti foam A[b]			Ti foam B[b]		
				D_A (μm)	P_A (%)	T_A (mm)	D_B (μm)	P_B (%)	T_B (mm)
H1M1	Multilayer	72	6	320	80	1	320	63	1
H2L1	Multilayer	57	4	320	80	2	–[c]	17	1
H1L1	Multilayer	42	6	380	80	1	–[c]	17	1
M2L2	Multilayer	38	3	340	62	2	–[c]	17	2[d]
H2[e]	Stacked	80	6	300	80	2	–	–	–
M2	Stacked	62	6	340	62	2	–	–	–

D, average pore diameter; P, porosity; T, thickness. Designation letters indicate Ti foam with high (H), middle (M) or low (L) volumetric porosity. Designation numbers indicate the approximate thickness of the corresponding Ti foam in the stacked sheet.

[a] Total porosity of multilayer and stacked foam was slightly lower than the initial porosity of Ti foam A and B, because of the stacking sintering process.

[b] Properties of Ti foam A and foam B are measured in the sheet condition.

[c] Pore diameter of the foam with low porosity was difficult to measure by optical microscopy.

[d] Ti foam L was stacked using two sheets of L1.

[e] Data of stacked sample H2 was obtained in previous work [23].