Rare Metal Materials and Engineering
Volume 46, Issue 8, August 2017
Online English edition of the Chinese language journal

Cite this article as: Rare Metal Materials and Engineering, 2017, 46(8): 2041-2048.

ARTICLE

Microstructure and Mechanical Properties of Porous Titanium Based on Controlling Young's Modulus

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Abstract: The Young's modulus of implant plays an important role in reducing stress shielding. A new method called titanium mesh stacked-forced-sintering (TMSS) was applied to porous titanium, which could easily control Young's modulus and balance the mechanical properties by different porosities, pore sizes and pore distribution. The results indicate that porous titanium has different structures in different directions. It has regular macro-pores in the cross section and irregular micro-pores in the longitudinal section. The stress-strain curve of porous titanium shows smooth and stable increase at plastic deformation along the axis direction. The Young's modulus obviously decreases, when increasing the porosity, decreasing nominal pore size, or changing pore distribution from regular to staggered at the same porosity. So the Young's modulus of porous titanium can be adjusted by these architecture factors to match the different bone tissues, and the appropriate pore sizes have the potential to induce bone tissue ingrowth. The match of mechanical properties and appropriate structures can effectively promote the fixation between the implant and the bone tissue in a long term.

Key words: porous titanium; TMSS; mechanical porosity; Young's modulus; pose size; pores topological structure

Over the past few decades, titanium and its alloys have been successfully applied in dental and orthopedic implants because of their excellent mechanical properties, chemical stability, and biocompatibility[1]. However, these titanium and titanium alloys often cause stress shielding due to mismatch of Young's modulus between the bio-titanium and the surrounding bone. This mismatch can result in bone absorption and eventually the implant loosens clinical performance in a long term when it is implanted into the bone host[2,3].

As mentioned, a major problem concerning stress shielding in orthopaedic surgery is the mismatch of Young's modulus between bone (10~30 GPa) and bulk metallic titanium (110 GPa). There are two ways to reduce the stress shielding. The first one is a metallurgical method to reduce the Young's modulus. When introducing β phase in microstructure by adding β phase elements such as Ta, Nb, Zr, and Sn in titanium, the Young's modulus could decrease from 110 to 42 GPa in some beta titanium alloys achieved through different heat treatment[4-6]. Alloying can decrease the Young's modulus of titanium. However the Young's modulu is still higher than that of the natural bone[7]. The other well accepted way is introducing porous structure. The porous structure can not only imitate structure and properties of natural bone, but also facilitate proliferation of cells into the porous structure and provide space for drug and bio-factor (gene and/or protein) delivery[8]. There are many ways to fabricate porous titanium. The conventional metallurgical method is successfully used to fabricate porous titanium by titanium powder sintering[9]; however it cannot bear tensile stress and even exhibits 'brittle' property suffered the compressive load. Recently, titanium fiber sintering has been also developed to produce po-

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Received date: August 25, 2016
Foundation item: National Key Basic Research Development Program of China ("973" Program) (2012CB619101)

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rous titanium. The pore structure of porous materials, such as porosity, pores size, pores shape, and pores orientation, is investigated to influence the Young's modulus[10, 11]. However, porous titanium fabricated by this method shows low elastic modulus, and is very difficult to control the pore shape and size. New rapid prototyping methods such as 3D printing technologies allow the fabrication of porous titanium parts with complex and controlled internal architectures [12-14]. However, the oxygen and nitrogen element content is significantly increased during printing [15], which dramatically reduces the fatigued property. So it is necessary to find a way which can easily control the pore structure and mechanical properties such as Young's modulus and yield stress.

In the present study, porous titanium was fabricated using titanium mesh by the stacked-forced-sintering method, in which porosity is controlled by cold pressure, pore size changed by the size of titanium mesh, and pore distribution obtained by array ways of titanium mesh. The microstructure and mechanical behavior of porous titanium was studied. Furthermore, based on a squared pore model and the well-known Gibson-Ashby equation, the relationship between porosity, pores size, pore distribution, and mechanical properties was investigated.

1 Experiment

1.1 Design and fabrication of porous titanium

Commercial pure titanium meshes with the nominal sizes of pore which are 150, 250, 300 and 600 μm (Gr2, Fe<0.02, C<0.01, O<0.05, N<0.01, H<0.001) were used as the porous titanium source. There are two knitting ways for fabricating porous titanium, which can control the pore size through changing the distance of parallel titanium fibre, and the strut of porous titanium through changing the different diameter of the titanium fiber. The first is shown in Fig.1a, where three kinds of pore size of 250, 300 and 600 μm were knitted in this way. The other way is shown in Fig.1b, which has the pore size of 150 μm. The four titanium mesh size and struts were measured and shown in Table 1.

The titanium meshes were cut into samples with the diameter of 20 mm. Many samples were stacked layer by layer. Then they were put into a mold with the same size under different cold pressures (90~220 MPa), as shown in Table 2. Under a series of pressures, porous titanium with porosity of 35%~60% was produced. Then the prepared porous titanium was put into a vacuum furnace, heated to 1100 °C at the rate of 10 °C/min, held for 2 h, and cooled with the furnace. Max vacuum degree must exceed 10^{-2} Pa regardless of the progress of heating, holding, or cooling. Cylindrical specimens with the size of Φ6 mm×9 mm used for compressive tests were cut from the sintered billet. The rectangular-shape specimens with dimension of 6 mm × 6 mm × 9 mm were used for SEM observation.

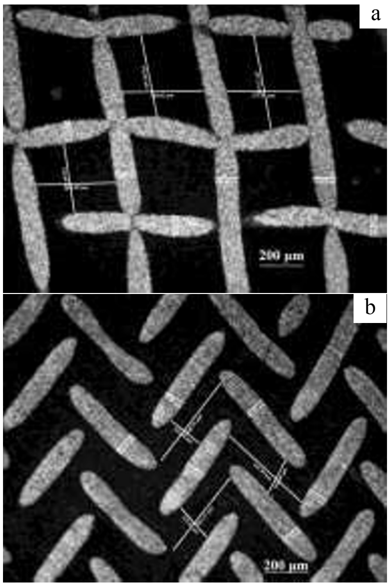

Fig.1 Optical micrographs of titanium mesh with different nominal sizes: (a) 300 μm and (b) 150 μm

Table 1 **Dimensions of pore and strut of titanium mesh (Mean±SD)**

Mesh size/μm	600	300	250	150
a_n/μm	600	300	250	150
a_m/μm	651±37	363±35	261±32	168±24
t_m/μm	242.2±4.5	165.5±3.6	103.0±2.9	96.5±3.0

Note: a_n-nominal size of pore, a_m-measure sizes of pore, t_m-measure sizes of struts

1.2 Characterization of porous titanium

The porosity, pore size distribution and average pore size were characterized using mercury intrusion porosimetry (MICROMERITICS INSTRUMENT CORPORATION). The local porous structures (pore size and pore size distribution), the joints between layers and microstructure of the titanium wire were clearly shown by scanning electron microscopy (FESEM, MIRA3, TESCAN). The compression properties of the porous titanium were evaluated by a screw-driven load frame (MTS SYSTEMS (CHINA) CO., LTD) at a crosshead speed of 0.5 mm/min. The compressive strengths and Young's modulus were calculated from the compressive stress-strain curves. Five specimens were tested to obtain the average values and their standard deviation with the same fabricated process parameters.

2 Results and Discussion

2.1 Characters of porous titanium

2.1.1 Pore architecture

The pore architecture, pore distribution and morphology