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Fabrication of Ti14Nb4Sn Alloys for Bone Tissue Engineering Applications

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Abstract. In this paper, porous Ti14Nb4Sn alloys were fabricated using a space holder sintering method, resulting in a porosity of ~70%. Scanning electron microscopy (SEM) analyses revealed a combination of both macropore and micropore structures. The fabricated titanium alloy scaffolds exhibited a similar structure to that of natural bone, which is expected to improve bone implant longevity. Bacterial cells of *Pseudomonas aeruginosa* ATCC 9027 were employed for the *in vitro* test.

Introduction

Metal and its alloys, such as titanium, stainless steel, and chromium cobalt showed high mechanical strength which is suitable for load bearing bone substitute. In the case of titanium, the possibility of implant loosening due to the significant difference between the elastic modulus of dense titanium and natural bone may cause stress shielding. Elastic modulus of dense Ti alloys is in the range of 55-110 GPa which is significantly higher than that of natural bone (0.1-30 GPa) [1,2]. These drawbacks (poor osseointegration and aseptic loosening) lead to an increasing number of revision surgery [3].

One way to lower the elastic modulus is to produce a porous structure of the metallic alloy by adjusting its porosity [4, 5]. The porous structure allows bone to grow into the pores and lock the artificial implant for better fixation [6,7]. Another way to lower the elastic modulus is to introduce β-alloying elements, such as niobium and tin. Studies by Obbard *et al.* proved that the elastic modulus could be reduced by adjusting the concentration of β stabilizer (Nb, Ta and Sn) in the alloys [8]. Titanium alloys with aluminium and vanadium as a stabilizing element (Ti6Al4V) have been widely applied to various implants, however a study revealed that the release of Al and V ions can be harmful to human body (i.e. neurological disorders and cytotoxic) [9]. Thus, other alloy stabilizers have been explored to reduce the biological adverse impacts. Moreover, alloying element addition might improve the mechanical properties. Alloying elements that attract studies are tantalum (Ta), tin (Sn), niobium (Nb), and zirconium (Zr) due to their non-cytotoxicity, good biocompatibility, high corrosion resistance and completely solubility in titanium [10-12].

In recent years, the space holder sintering method has been widely used to produce porous titanium alloys. Compared to other techniques (e.g., slurry sintering, self-propagating high temperature synthesis, and rapid prototyping), this method has been proven to produce a porous structure with flexibility to choose the desired porosity by adjusting the weight of space holder particles [13-16].

Infections are inevitable when implant materials are used. Complex problems, such as pain, osteomyelitis and implant loosening will arise as antibiotics are unable to cure the infection due to the difficulty of penetration into the biofilm [17-20]. Thus, it is crucial to minimise the risk of infection by designing implant materials that lower the tendency of bacteria to attach. Studies on bacterial attachment on Nb and Sn have not been much investigated yet.

Cells of *Pseudomonas aeruginosa* were selected in this study as they have been the common opportunistic pathogenic bacteria found in infections related to orthopaedic implant surgery [21, 22]. The purpose of this study was to develop porous Ti14Nb4Sn using space holder sintering method and to investigate bacterial attachment on metallic surface.

Materials and Methods

Porous titanium alloys preparation. Titanium metal powder (purity 99.7%), tin metal powder (purity 99.9%) and niobium metal powder (purity 99.8%) with particle size less than 45 µm (Atlantic Equipment Engineers, Bergenfield, NJ, USA) were used. Firstly each component was weighed to give a desired composition of Ti14Nb4Sn. These components were mixed and blended in a planetary ball milling (Retsch, PM400) for 4 hours. This experiment used ammonium hydrogen carbonate (NH_4HCO_3) as a space holder material. The particle size chosen was 300-500 µm in diameter. The desired porosity and pore size were controlled by adjusting the initial weight ratio of NH_4HCO_3 to metal powders and the particle size of NH_4HCO_3. After mixing the ammonium hydrogen carbonate with the metal powders, the mixture was pressed into green compacts in a 50 ton hydraulic press. The next step was heat treatment process inside a high vacuum furnace with a pressure of 10^{-5} Torr. The sintering process conducted in two steps, first is to burn out the space holder material at 175 °C for 2 h, and the second step is to heat the compacts at a heating rate of 10 °C /min until 1200 °C and keep them at this temperature for 5 h.

Characterization. The microstructure of porous titanium alloys was observed and imaged using field emission scanning electron microscopy (FESEM) (ZEISS SUPRA 40VP) and elemental analysis of porous titanium alloys were investigated using energy dispersive X-ray spectroscopy (EDS) (Oxford Instruments INCAx-act 250 system).

Preparation. Four samples (titanium, tin, niobium, and TiNbSn) were used in this study. Subsequent surface treatment of each sample was performed. The discs were gently wet grounded using silicon carbide paper (600 grit) and followed by 1200 grit, then 15, 9, 6, 1 µm diamond compounds were used respectively for fine polishing. All metallic discs were then ultrasonically cleaned using ethanol for 5 minutes. The surface roughness value was measured using a stylus profiler (Alpha Step D-120, KLA Tencor, USA).

Contact angle measurement. Surface wettability test was performed using contact angle measurement by sessile drop method. Contact angle was acquired for water using an FTA 1000c (First Ten Ångstrom Inc., U.S.) instrument. The FTA Windows Mode 4 software was used for the recorded image analysis and subsequently the contact angle measurement.

Bacterial attachment study Bacterial strains of *Pseudomonas aeruginosa* ATCC 9027 were grown overnight at 37 ºC in nutrient broth (Oxoid). The metallic samples were immersed in 5 mL of bacterial suspension for incubation [19]. After incubation, each sample was washed with copious amount MilliQ water to remove non-attached cells and allowed to air dry for 45 minutes prior to any analysis.

Microscopy and image analysis Each sample was gold coated using a Neocoating instrument. Bacterial adhesion on these surfaces was evaluated using scanning electron microscopy (SEM). SEM examinations of samples with bacteria attached were conducted at 1,000× and 2,500× magnifications. Images with 2,500× magnification were used for calculating the number of bacteria attached to the titanium, niobium, tin, and TiNbSn surfaces following the same SEM procedure previously reported [19].

Results and Discussion

Fabrication of Ti14Nb4Sn. Space holder sintering by powder metallurgy is a technique to produce highly porous structures with well controlled pore size and porosity. Pore size and porosity are the major concern in producing porous scaffolds as they influence both the mechanical properties of implants (e.g., elastic moduli) and the biological performance of the implant material.

SEM images of the fabricated porous titanium alloys, as shown in Fig. 1(a)-(b), exhibited a combination of both macropores and micropores on the surface. The micropore size ranges from 0.5 to 10 µm, while the macropore size ranges from 50 to700 µm. Samples with higher porosities showed more interconnected features and more accessible inner surfaces. It is believed that the optimal pore sizes to ensure vascularization and bone in growth are 100-400 µm.

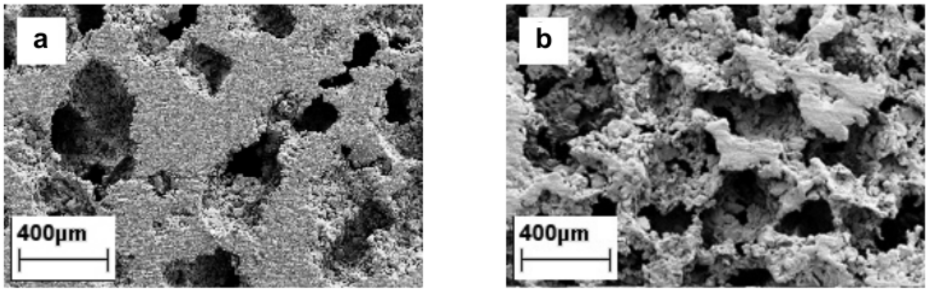

Fig.1 Morphology of porous Ti14Nb4Sn alloys with different porosity (a) 55% and (b) 79%

Based on space-holder method, there are two types of pores, macro-pores which obtained from the size of the space holders and micro-pores which obtained from the dimension of the titanium powder particles. Micropores could allow the scaffold to be impregnated with various coatings. Bone structure consists of macro, micro and nano scale features with each function and characteristics. Macropore provides mechanical anisotropy characteristic, and micro-scale porosity gives sufficient vascularisation and cell migration, while nanoscale acts as cell and mineral binding architecture [23]. The shape of the pores exhibited irregular and spherical pores.

Porosity enhances interlocking process for stability, immobility of the new implant. It is influenced by several factors, namely the particle size of metallic powder and sintering pressure [23]. Decreasing the particle size reduces the porosity due to surface energy per unit volume. Small diameter particles with high specific surface area have higher energy, and thus sintering process of the particles is much quicker. The porosity of the samples ranges from 55% to 79%. It is noted that the best porosity level of the implant should be chosen to give an optimum performance of mechanical properties and in vitro biodegradation behaviour. For example, higher porosity decreases the strength of porous material. Elemental analysis using EDS was performed concurrently with the SEM examination to identify chemical composition of the samples. EDS analysis demonstrated agreement in metal component of alloys of Ti14Nb4Sn.

Surface roughness, contact angle measurement, and bacterial attachment. The roughness, contact angle measurement, and number of cells retained of titanium, niobium, tin, and TiNbSn samples are shown in Table 1.

It is clearly shown that titanium sample exhibited the smoothest surface topography compared to other materials after receiving same surface treatment. From wettability test, all samples showed no statistical difference, with contact angle values ranging 77-82 degrees ($p > 0.05$). A statistically significant difference in the number of cells attached on Sn was also observed ($p < 0.05$). It is essential to point out the highest number of *P. aeruginosa* cells were adhered on the Sn surface.

Table 1 Surface roughness, contact angle, and number of cells values for Ti, Nb, Sn, and TiNbSn

Samples	**R_a (µm)**	**Contact angle (θ degree)**	**Retained Cells × 10^3 (number of cells/mm^2)**
Ti	0.15 ± 0.04	76.9 ± 1.0	7.3 ± 1.9
Nb	0.47 ± 0.09	78.0 ± 2.8	6.4 ± 1.7
Sn	0.26 ± 0.05	82.7 ± 4.2	110 ± 5.8
TiNbSn	0.45 ± 0.07[a]	80.4 ± 2.8	16.2 ±4.4

[a] ± standard deviation values

The aim of bacterial attachment study was to examine the *P. aeruginosa* adherence onto titanium alloy and each alloying elements (Ti, Nb and Sn). Surface wettability is one property that was believed to influence bacteria adhesion on the surface. Surface wettability test was performed by contact angle measurement. It is widely known that low contact angle represents hydrophilic features (< 90°), while contact angle higher than 90° indicates hydrophobic. From table 1, it was observed that Sn showed slightly higher contact angle than other materials, which also exhibited the highest number of *P. aeruginosa* cells attached on the Sn surface. In other studies, *P. aeruginosa* cells were reported to preferably attach on hydrophobic Ti surfaces [20]. However, based on the contact angle measurement results which are not significantly different, the number of cells attached was highly different. It can be suggested that surface wettability did not play a significant role in bacterial attachment onto these materials. A comparative analysis of the results revealed that there were no correlation between surface roughness of these different materials and the number of cells that attached. It could be suggested that only chemistry played a significant role in bacteria attachment. As it is shown in table 1, Sn surface was proved preferable for *P. aeruginosa* cells to attach compared to other materials. It is also understood that the number of cells attached on TiNbSn was higher than Ti and Nb due to the Sn presence as the alloying element.

Figure 2 shows representative of bacteria attachment patterns on Ti and TiNbSn surfaces. This investigation has shown that niobium and titanium are relatively good alloying elements for bone tissue engineering applications. However, despite the biocompatibility feature of Sn, it is suggested that the amount of Sn as an alloying element should be limited, as it attracted *P. aeruginosa* to attach on the surface.

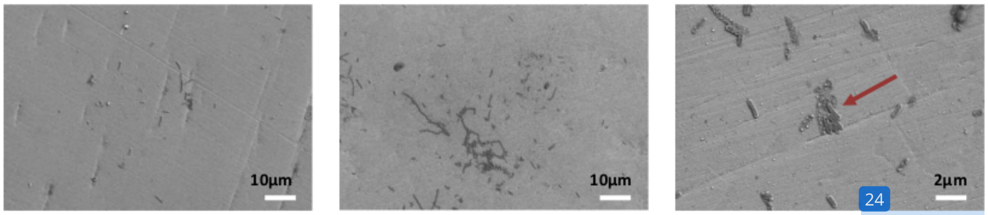

Fig. 2 Representative *P. aeruginosa* attachment patterns (a) SEM images on Ti surface; (b) SEM images on TiNbSn surface; (c) SEM images on TiNbSn.

Conclusion

The porous Ti14Nb4Sn has been successfully fabricated by space holder sintering method. Porosity ranges from 55 to 79% with pore sizes of 100-600 μm. The result gained from SEM showed both micro-pore and macro-pore structures. These findings suggest that porous Ti14Nb4Sn alloys are one of the promising materials for bone tissue engineering applications. From bacterial attachment experiment, it is recommended to limit the amount of Sn as an alloying element due to its nature on attracting *P. aeruginosa*. Future work will focus on surface modifications of these alloys to enhance osseointegration, followed with an in vitro test to assess its biocompatibility.

References

[1] M. Geetha, A.K. Singh, R. Asokamani, and A.K. Gogia, Ti based biomaterials, the ultimate choice for orthopaedic implants – A review, Progress in Material Science. 54 (3) (2000) 397-425.

[2] B.R. Levine, S. Sporer, R.A. Poggie, C.J.D. Valle, and J.J. Jacobs, Experimental and clinical performance of porous tantalum in orthopaedic surgery, Biomaterials. 27 (2006) 4671-4681.

[3] P.F.M. Choong, The challenges of joint replacement surgery in 21st century, ANZ Journal of Surgery. 79 (10) (2009) 669-671.

[4] K. Lee and S.B. Goodman, Current state and future of joints replacement in the hip and knee, Expert Review of Medical Device. 5 (3) (2008) 383-393.

[5] R.M. Meneghini, C. Meyer, C.A. Buckley, A.D. Hanssen, D.G. Lewallen, Mechanical stability of novel highly porous metal acetabular components in revision total hip arthroplasty, Journal of Arthroplasty. 25 (3) (2010) 337-341.

[6] U. Muller, T. Imwinkelried, M. Horst, M. Sievers, and U. Graf-Hausner, Do human osteoblasts grow into open-porous titanium? , European Cells and Materials. 11 (2006) 8

[7] X. Zou, H.Li, M. Bunger, N. Egund, M. Lind, and C. Bunger, Bone ingrowth characteristics of porous tantalum and carbon fiberinterbody devices: An experimental study in pigs, Spine Journal. 4 (1) (2004) 99-105.

[8] E.G. Obbard, Y.L. Hao, T. Akahori, R.J. Talling, M. Niinomi, D. Dye and R. Yang,Mechanics of superelasticity in Ti-30Nb-(8-10)Ta-5Zr alloy, Acta Materialia. 58 (10) (2010) 3557-3567.

[9] Y.Okazaki, S. Rao, S. Asao, T. Tateishi, S.I. Katsuda, and Y. Furuki, Effects of Ti, Al, and V concentrations on cell viability, Materials Transaction. 39(10)(1998) 1053-1062.

[10] C.E. Wen, Y. Yamada, and P.D. Hodgson, Fabrication of novel TiZr alloy foams for biomedical applications, Material Science & Engineering C – Biomimetic and Supramolecular Systems. 26 (8) (2006) 1439-1444.

[11] Y. Li, C. Wong, J. Liong, P. Hodgson, and C. Wen, Cytotoxicity of titanium and titanium alloying elements, Journal of Dental Research. 89 (5) (2010) 493-497.

[12] G. Adamek and J. Jakubowicz, Microstructure of the mechanically alloyed and electrochemically etched Ti-6Al-4V and Ti-15Zr-4Nb nanocrystalline alloys, Material Chemistry and Physics. 124 (2-3) (2010), 1198-1204.

[13] Y. Li, J. Xiong, C.S. Wong, P.D. Hodgson and C. Wen, Ti6Ta4Sn alloy and subsequent scaffolding for bone tissue engineering, Tissue Engineering Part A. 15(10) (2009) 3151-3159.

[14] I.H. Oh, N. Nomura, and S. Hanada, Mechanical properties of porous titanium compacts prepared by powder sintering, ScriptaMaterialia. 49 (12) (2003), 1197-1202.

[15] S.H. Masood, J.P. Singh, Y. Morsi, The design and manufacturing of porous scaffolds for tissue engineering using rapid prototyping, International Journal of Advanced Manufacturing Technology. 27 (3-4) (2005) 415-420.

[16] S. Wu, X. Liu, Y.L. Chan, C.Y. Chung, P.K. Chu, C.L. Chu, K.O. Lam, K.W.K. Yeung, W.W. Lu, K.D.K. Luk, and K.M.C. Cheung, In vitro bioactivity and osteoblast response on chemically modified biomedical porous NiTi synthesized by capsule-free hot isotatic pressing, Surface and Coatings Technology. 202 (11) (2008) 2458-2462.

[17] J.W. Costerton, P.S. Stewart,and E.P. Greenberg, Bacterial biofilms: A common cause of persistent infections, Science. 284 (5418) (1999) 1318-1322.

[18] D. Campoccia, L. Montanaro, and C.R. Arciola, The significance of infection related to orthopedic devices and issues of antibiotic resistance, Biomaterials. 27 (2006) 2331-2339.

[19] V.K. Truong, S. Rundell, R. Lapovok, Y. Estrin, J.Y. Wang, C.C. Berndt, D.G. Barnes, C.J. Fluke, R.J. Crawford, and E.P. Ivanova, Effect of ultrafine-grained titanium surfaces on adhesion of bacteria, Appl. Microbiol. Biotechnol, 83 (2009) 925-937.

[20] V.K. Truong, R. Lapovok, Y. Estrin, J.Y. Wang, C. Fluke, R.J. Crawford, and E.P. Ivanova, The influence of nano-scale surface roughness on bacterial adhesion to ultrafine-grained titanium, Biomaterials 31 (2010) 3674-3683.

[21] C. Dividio, A. Carnevale, First report on an acute purulent maxillary sinusitis caused by *Pseudomonas aeruginosa* secondary to dental implant placement in an immunocompetent patient, Br Dental 211 (2011) 205-207.

[22] C.K. Stover, X.Q. Pham, Complete genome sequence of *Pseudomonas aeruginosa* PA01, an opportunistic pathogen, Nature. 406 (2000) 959-964.

[23] X.J. Wang, Y.C. Li, J.Y. Xiong, P.D. Hodgson and C. Wen, Porous TiNbZr alloy scaffolds for biomedical applications, Acta Biomaterialia. 5 (9) (2009) 3616-3624.

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