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Research article

Investigation of additive manufacturing of porous Ti-6Al-4V alloy: Geometry analysis for dental applications

Mohammad Hossein Malekipour Esfahani[1]*, Fatemeh Safdarian[2], Sharif Heydari[3]**

[1]*Dental Students Research Center, School of Dentistry, Isfahan University of Medical Sciences, Isfahan, Iran*
[2]*Industrial Engineering, Faculty of Engineering, Islamic Azad University (Khorasgan Branch), Isfahan, Iran*
[3]*Department of Biomedical Engineering, Kerman Branch, Islamic Azad University, Kerman, Iran*

* mh.malekipouresfahani@yahoo.com, ** sharifheydari8@gmail.com

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Abstract

This research is dedicated to reviewing porous titanium alloy structures suitable for biomedical applications. The mechanical properties of porous samples with different structures and porosity were reviewed through a static compression test to identify the type of suitable structure. In addition, high porosity is desirable due to the growth of bone tissue in the internal microstructure of the porous bony implant. Samples are normally fabricated made of Ti-6Al-4V alloy and stainless steel using selective laser melting (SLM) as an additive manufacturing process. The samples were prepared with a pore size (200, 400, and 600 µm) and cubic and trabecular topology. The actual weight of all samples was determined, which is important in identifying other characteristics. All the tested samples reached the optimal values of maximum stress and tensile strength. The most appropriate mechanical properties were observed for samples with a pore diameter of 200 µm and a cubic structure. The implants with porosity, pore size, and pore interconnectivity affect the differentiation of bone tissue.

Keywords: Selective laser melting, 3D printing, Ti-6Al-4V, Additive manufacturing, Porous Titanium

1- Introduction

Contemporary medicine uses knowledge and modern engineering facilities greatly. This is significantly reflected in the field of replacement of damaged bone parts [1-2]. Porous bony implants normally meet certain requirements. Therefore, these samples can be produced by the highest porosity, roughness, and surface modification using advanced and modern technologies [1-3]. The mechanical and biological properties of the porous implant should be as similar as possible to the original biological bone. This scaffold may not cause any special problems for the patients [2-3]. Therefore, bony metallic porous implants are expected to have a biocompatible property with the human body, which is able to conduct proper functions [2-4]. Metallic products are suitable for bone trauma and fracture. Titanium alloys are highly recommended due to their low weight compared to other metals. They have highly favorable biocompatibility and sufficient corrosion resistance. A disadvantage of Ti alloys is the relatively high elastic modulus of about 113 GPa compared to the dense human bone with 15-20 GPa, which affects the healing process for patients with sufficient bone density [3-6]. Dai et al. [4] introduced the reduction of the α phase in titanium alloys that decrease elastic modulus. The β-phase titanium alloy (E= 65 GPa) was designed and tested. Arifin et al. [5] enriched Ti material with hydroxyapatite (HA) nanoparticles to decrease elastic modulus. Also, an increase in the biological property of Ti from in vivo tests and in vitro is limited to the laboratory study. Many researchers conduct compression analysis and bending tests on porous Ti bony prosthesis with calcium phosphates (CaPs) for coating the Ti with better mechanical properties. An additive manufacturing (AM) seems to be a very promising technique for preparation of metallic implants [7-14]. Several technologies such as laser sintering (LS) or SLS, direct laser metal sintering (DMLS) and electron beam melting (EBM) are based on the rule of high-power lasers to produce effective mechanical microstructures [15-23]. SLS technology can prepare a layer-by-layer architecture defined in a pre-designed computer-aided design (CAD) model. These metallic implants with a size of 20 micro meters to 100 micro meters which can enhance the cell attachments. This process is performed with argon and nitrogen gas to prevent oxidation. The porous materials are characterized using computed tomography (CT) which is a proper as non-destructive investigation technique [6-15]. CT can be used for the size of the grain, percentages of porosity and geometry, and structure evaluation. The samples are required for heat, machining, and polishing after preparation processing. Researchers investigate the potential of SLS in the fabrication of dental solid implants. Porous Ti dental implants made using DMLS indicated more osteointegration than commercial implants. The obtained results show the preclinical meta-analysis for bone formation in dental implants [16-20]. The implants with porosity, pore size, and pore interconnectivity affect the differentiation of bone tissue. The bone implant porosity caused a reduction in mechanical performance and elastic modulus of the host bone using 3D printing. The porosity of the scaffolds for biological applications plays an important role in the acceptance of products with low porosity. In many scientific research, the authors investigated the mechanical properties of porous Ti implant with various topologies and porosities created by AM using SLS process [21-25]. However, the fabricated scaffold investigated unique heterogeneous bone substitutes by validated medical software for biomedical approaches. The current study presented the design and weight optimization of porous architecture using Ti by AM which reduce the stress shield effect for biomedical engineering applications.

2- Materials and methods

The samples were prepared from Ti-6Al-4V as listed in Tables 1. The samples were designed according to the ISO-13314 standard. The samples were designed based on the International Organization for Standardization (ISO) standard. The sample with a cylindrical shape of 10 mm × 20 mm was selected and made of Ti-6Al-4V substrate as shown in Table 1. The porous structures with trabecular and cubic shapes were fabricated with pore sizes of 200-600 µm designed by solid work with STL format.

Table 1: The elements of the titanium graded for the SLS scaffold

Component	Content (%)
Ti	90
Al	6
V	4
N, C, H, Fe, O	≤1

2-1- Preparation of 3D models

The 3D sample was designed using computer-aided design (CAD) and produced in Solid works modeling software. Fig. 1 indicates a CAD model as a base architecture.

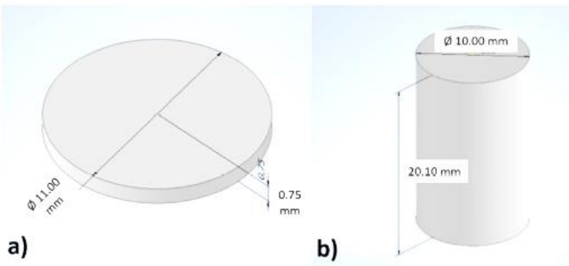

Fig. 1 Computer-aided design (CAD) models of (a) base and (b) sample.

Semi-automatic production of porous sample microstructure can be produced by Autodesk software and the CAD models with a height of 3 mm with the STL format as input data for the AM process. Fig. 2 shows 3D CAD models with specific types of porous structures with trabecular and cubic structures as shown in Fig. 2

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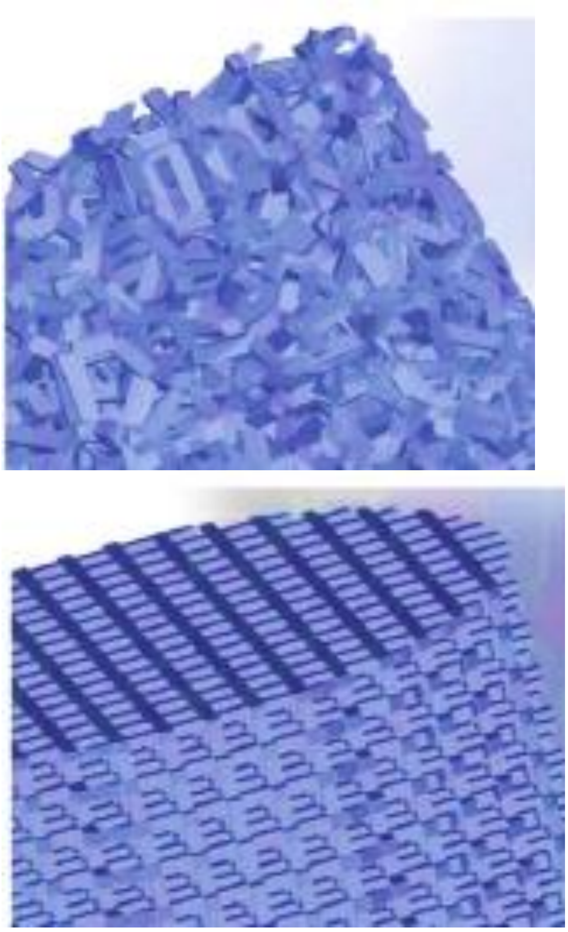

Fig. 2 The surface component of (a) trabecular and (b) cubic structures.

2-2- Post-processing of 3D printed samples

All samples were post-processed after sintering and cleaning the samples. The annealing process for Ti alloy reached 800-850°C after 4 hours. The samples were placed in the annealing chamber till the sample's temperature reduced gradually for 90 minutes. Before printing, the parameters of the SLM manufacturing process were adjusted. The mechanical properties of the samples such as yield strength, tensile strength and elastic modulus increase with decreasing the pore size. Based on the obtained results, it can be concluded that trabecular structures with larger pore sizes are more suitable for preparing the scaffold with suitable mechanical features in accordance with bone features.

2-3- General finding

Cylindrical specimens with a diameter of 10 mm were fabricated with three types of honeycomb structure, orthogonal structure, and layer structure with a pore size of 500 µm to 600 µm. The obtained results indicate the porous microstructure significantly decreases the stress shielding effect. The results indicate the compressive strength in the range of 163 MPa to 286 MPa and elastic modulus from 14.5 GPa to 38.5 GPa similar to the values of cortical bone. Arabnejad et al. [24] considered tetrahedral and octahedral topologies made of Ti-6Al-4V alloy by SLM technology with a pore size of 500 µm for the tetrahedron and 500 µm for the octahedron. One of the important factors in the formation of porous microstructures is the size of individual pores. The different size of the porous scaffold has an important effect on the permeability of cells and nutrients in the pores of the material. Itala et al. [25] performed research on Ti prostheses implanted in the femur bone of rabbits which has the optimal pore size for bone growth in the range of 100 µm to 400 µm. Ti substrate were applied in rabbit tibia bone with the porosity about 65% with pore sizes of 300-900 µm. The porous implants in cancellous bone have a significant cell growth in a microstructure with a pore size of 900 µm compared to a structure with a pore size of 300 µm. Several studies indicated that a porous structure significantly supports to decrease the stress-shielding effect and increases the growth of the bone implant with required mechanical features [26-42].

3- Conclusion

The mechanical properties are an important insight for the successful approaches of the porous implant using titanium for dental implants. However, the mechanical properties of titanium scaffold varied from those of porous bone. These changes can be greatly eliminated by the suitable microstructure of the Ti product, which does not negatively affect other desired features of the prosthesis when applied to biological tissues. The presented study was carried out with the aim of preparing samples with reduced weight and suppressing the stress shielding effect by introducing various types of porous structures. Porous scaffolds with different pore sizes (200, 400, and 600 µm) for trabecular and cubic approaches were produced through the SLM technique. The highest porosity and the lowest weight were obtained in trabecular samples with a pore size of 600 µm. In the future, samples can be coated with ceramics or polymers to improve their biological and mechanical properties and cultured with biological tissue to study the process of bone integration, bone overgrowth, and adaptation.

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