IOP Conf. Series: Materials Science and Engineering **212** (2017) 012006 doi:10.1088/1757-899X/212/1/012006

Fabrication and Mechanical Properties of Porous CP-TiUsing Selective Laser Melting (SLM)

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Abstract. Recently, porous structure has become focus for the study of implantable devices due to the superior ability of osseointegration. Meanwhile, Selective laser melting (SLM), a versatile rapid manufacturing method, is widely utilized in medical restoration field due to its flexibility. Given the information about mechanical properties and manufacturing process of porous structure is limited, the aim of this study is to investigate the manufacturing process and static mechanical properties. Therefore, regular hexahedron structures are designed and fabricated by SLM, also the dimensions and mechanical properties are evaluated by experiments. The results show that manufacturing process and design of structure have significant influence on porosity and mechanical properties. Porous structure would reduce the elastic modulus and yield strength, and the ductility of porous structure is poor than that of solid structure. Moreover, the suitable pore size is >0.7mm. In conclusion, porous implant has great potential to use in bone repair and further study should be done to obtain more information.

1. Introduction

In recent years, with the development of RP technology, selective laser melting (SLM) technique comes into being, which makes the use of high-energy density laser beam to melt the metal powder completely, layer upon layer increment, ends up with computer aided design model of the metal products[1]. SLM is an advanced AM technique that can fabricate dense parts by completely melting metal powder to produce implant with material properties closing to those of the bulk materials [2]. Fabrication by SLM can manufacture specimens with whatever geometric shapes thanks to the design freedom and high reproducibility [3]. Compared with other conventional manufacturing, SLM has irreplaceable advantages and become a hot research topic [4]. Nevertheless, the SLM study is still in its infancy, the mechanical properties, accuracy and materials are subject to further discussion.

Dental implants are widely used today as aviable and reliable alternative for tooth replacement in edentulous patients and have been drawing more and more attention due to their advantages of reliability and comfort[5-6]. With the wide-ranging application of dental implant, its initial stability has been considered to be the primary condition of the success by most of scholars [7].

However, the implants fabricated by metallic biomaterials are much stiffer than natural bone, resulting in stress shielding and even bone resorption. The bone resorption caused by stress shielding isconsidered to contribute to undesired effects. Therefore, finding optimal structures to avoid the appearance of stress shielding is necessary. Porous structures are suitable for implantation since they allow for bone ingrowth through the open porosities and improve stability with the high roughness and lower stiffness and thus avoid stress-shielding [8]. SLM using to fabricate porous structure has the advantages to combine the solid materials and porous materials in one structure.

Since the method of fabrication and design would influence the clinical effect. In this study, the effect of design, fabrication and mechanical properties are analyzed to evaluate the performance of porous structure.

2. Materials and methods

2.1. Materials
A large number of studies have demonstrated when doing small deformation and static analysis, materials used in study are assumed to be continuous, homogeneous and isotropic. Titanium is the material of choice due to its favorable mechanical and biocompatible properties, with the tensile strength and yield strength of 383MPa and 475MPa based on SLM process. CP Ti grade 2 is used in this study, chemical composition is listed in Table1, with the purity of 99.8%. In this study, spherical commercially pure grade 2 Ti powder with particle size ranging from40 µm to 60 µm is used.

Table1. Chemical composition of CP-Ti grade 2 used in the study.

Element	Ti	Fe	C	N	H
w%	Balance	0.03	0.007	0.015	0.0035

2.2. Design and fabrication
Based on reverse engineering and 3D modeling software-Solidworks 2014, experimental models are shown in Fig.1. Ti 250-750 has a theoretical strut size of 250µm and pore size of 750µm. Rectangular porous specimen with dimensions of 10.25mm*10.25mm*15mm and porosity of 77% are fabricated for accuracy and mechanical properties analysis.

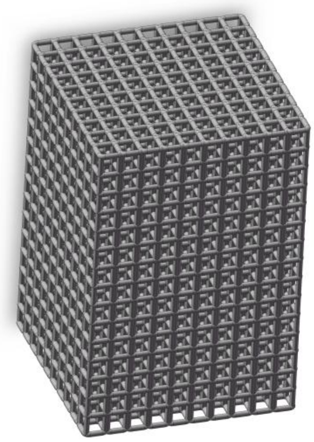

Figure 1. Additively manufactured porous CP Ti structures: 3D CAD visual representation

SLM125HL YLR-100-WC of SLM Solution is used to study SLM technique in this study. The sizes of the table are 125 mm×125 mm×75 mm, and the processing speed is 15cm^3/h, layer thickness could be controlled from 20µm to 75µm, the scanning spot size is in the range of 70~130µm, the

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minimum processing thickness is from 140μm to 160μm. Based on the experimental results, the optimum technical parameters are shown in Table2.

Table2. Processing parameters of SLM technique.

process parameters	laser powder	scanning interval	scanning speed	layer thickness	Scanning spot
value	100w	0.13mm	255mm/s	70μm	87μm

2.3. *Mechanical testing*
Static mechanical testing for five rectangular specimens of porous structures is carried out based on the standard ISO 13314:2011. All tests are done using MTS Landmark370.10 by applying a constant deformation rate of 0.1mm/s (Fig.2).

3. Results

3.1. *Accuracy of manufacturing for dimensions and porosity*
Five specimens are fabricated by SLM and measurement results of dimensions by werth SCOPE-CHECK 300 composite optical measuring machine are shown in Table 3. The average dimension of pore is 0.66812mm and strut is 0.33262mm, with the average difference of 0.08mm. Archimedes measurements of five rectangular samples are used to evaluate actual porosity. Theoretical density of pure Ti is 4.5 g/cm^3 in this study. As a result, the actual porosity of pure Ti specimen is 72%, closing to the theoretical porosity of 77%.

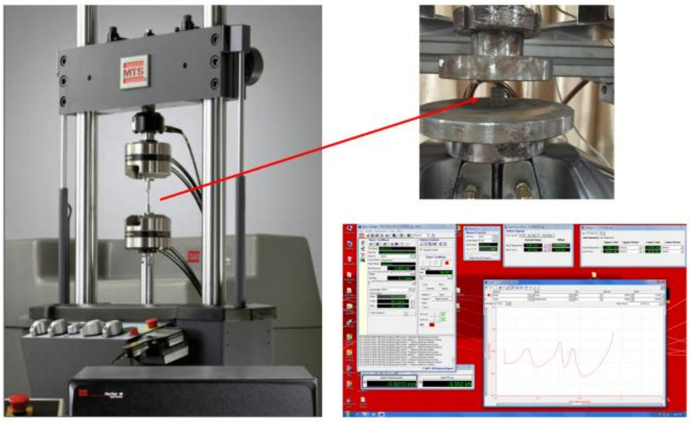

Figure 2. Machine and parameters of mechanical testing.

Table3. Dimensions of specimens by SLM (mm).

	Specimen-1	Specimen-2	Specimen-3	Specimen-4	Specimen-5
Pore	0.6652	0.6634	0.6723	0.6712	0.6685
Strut	0.3361	0.3354	0.3256	0.3317	0.3343

3.2. *Static mechanical testing*
The results of the static compression testing are summarized in Fig.3. A representative curve of strain-stress during static compression testing is shown to analyze the static mechanical properties. Different from the compression of solid structure, maximum compressive stress and strain could be registered due to the poor ductility of the porous CP Ti material. The maximum compressive stress is 186MPa, and σ_{pl} (the arithmetical mean of the stresses between 20% and 30% compressive strain)is87MPa.

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Elastic gradient (the slope of linear deformation region within 20% and 70%plateau stress) is registered as 83.45GPa.In this context, the quasi-elastic gradient will not be referred to as stiffness. Eventually, σ_y(yield stress) is calculated as 170.3MPa based on the above data.

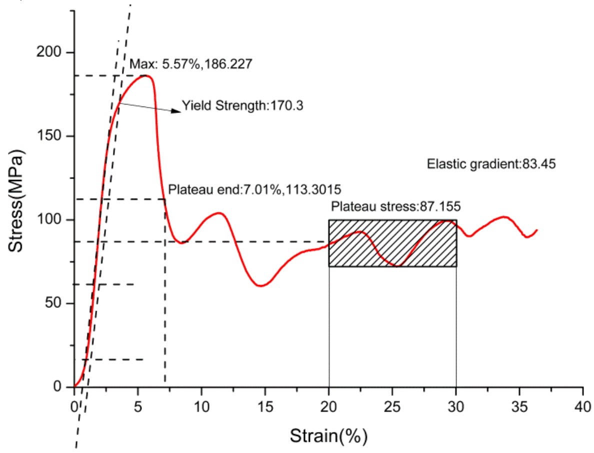

Figure 3. Strain-stress curve of static compression testing.

4. Discussion

4.1. Effect of design

Previous studies have illustrated that increasing the porosity would reduce stiffness of biomaterials. Highly porous biomaterials and large pore size provide ample space for bone ingrowth. Based on early studies, the minimum pore size is considered to be ~100um because of cell size, migration requirements and transport[9].However, acceleration studies suggest the pore size should be >300um. Small pores favored hypoxic conditions and induced osteochondral formation before osteogenesis, while large pores, that are well-vascularized, lead to direct osteogenesis (without preceding cartilage formation). Subsequent studies have shown researchers create scaffolds with pore sizes between 500 and 710 um to promote bone formation.Combined with the results by Ishaug-Riley SL, Bael SV, Otsuki B and Li JP, the proper size of pore is >0.7mm.

In static compression testing, it is observed that CP Ti porous structures continuously deform under increased compressive load, eventually reaching a first local maximum. This mechanical behavior is very similar to what is reported Ti6Al4V. The elastic gradient is not suitable for replacing elastic modulus of implant. Therefore, the formula (1) of Ashby and Gibson by previous study is used to recalculate the elastic modulus [10].

$$E^* = E * (1 - \varphi)^2 \quad (1)$$

Where $E^*$and E are the relative elastic modulus of porous structure and elastic modulus of metal, φ is the porosity. In this study, E^* is considered as 8.6GPa based on the porosity of 72% and the elastic of CP Ti 110GPa. The value of 8.6GPa is close to that of bone tissue (13.7GPa), resulting in a reduction of stress shielding.

4.2. Effect of fabrication on mechanical properties

In this study, CP Ti porous structures based on hexahedral unit cell with the porosity of 77% are fabricated to evaluate the processing precision and mechanical properties. In this study, accuracy of manufacturing is the main factor influencing the porosity and pore size, eventually changing the mechanical properties and osseointegration. Therefore, to control the processing precision is significant for implantable devices. Powder adhesion is an inevitable problem leading to bad accuracy of pore size and porosity in SLM process. In addition, there is a certain temperature gradient between layer and layer, melting channel and melting channel. This temperature gradient can lead to interior residual stress, eventually results in dimensional difference and even deformation. Therefore, the laser energy input should enough to melt the powderabsolutely, the phenomenon of powder adhesion would be reduced.Also, heat treatment and optimization of technical parameters are used to reduce or eliminate residual stress.

Although the static stress shielding and biocompatibility have shown some improvement with porous structure, the fatigue performance is the most significant factor for implantable devices. Therefore, further study of fatigue testing should be done to evaluate the fatigue performance and feasibility.

5. Conclusion

1. According to the results, with 0.75-mm pore size, the errors of porosity only 5% and the elastic modulus is close to natural bone tissue. Therefore, the pore size of 0.75 is acceptable.
2. The yield strength of this structure is 170.3MPa, which is more than maximum yield stress of bone tissue(165MPa). This structure is reasonable.
3. The stress-strain curve of porous structure by SLM is different from that of common solid structure. Porous structure is with poor ductility.

Since bone replacement biomaterials usually experience cyclic loading, it is important to understand their fatigue behavior and take further study.

Acknowledgments
This work is supported by Science and technology plan program of Guangzhou (No. 2017010160546); Science & Technology Plan Project of Guangzhou (No.201604020147); 2016 International science and technology cooperation project of Nansha;Foshan city cooperation projects (No.2014HT10008).

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