Bionic mechanical design and SLM manufacture of porous Ti6Al4V scaffolds for load-bearing cancellous bone implants

BO LIAO¹, CHENG XU¹, WEI LI^{1*}, DONG LU², ZHONG MIN JIN¹

¹ Tribology Research Institute, Key Laboratory for Advanced Technology of Materials of Ministry of Education,
Southwest Jiaotong University, Chengdu, China.

² Chengdu Advanced Metal Materials Industry Technology Research Institute, Chengdu, China.

In order to repair the load-bearing cancellous bone defect of the human lower extremity, the development of a porous scaffold with high porosity, appropriate pore size, low elastic modulus and high fatigue strength has been faced with great challenges. In this study, the Ti6Al4V coaxial scaffolds with five types of beam angles and three types of pore sizes were designed using CAD and fabricated with the use of SLM. The porous characteristics and mechanical properties of scaffolds were investigated systematically. The results show that the porosity of the coaxial scaffolds is 63–69%, and the pore size is 480–700 μm . Meanwhile, the elastic modulus and compressive strength of the coaxial scaffolds were 1.08–1.85 GPa, 40–88 MPa, respectively. Moreover, the fatigue strength of the coaxial scaffolds with 500–40°, 600–40°, 700–40° were 1387, 1110 and 420 MPa, respectively. The pore size and porosity of the coaxial scaffolds in our study satisfied the size requirements for bone cells growth. Meanwhile, the low elastic modulus and high fatigue strength of the scaffolds also met the bio-mechanical bearing requirements of cancellous bone implants. Our study provided a reference for the design of biomimetic cancellous bone implants with good dynamic load-bearing mechanical properties.

Key words: porous scaffolds, elastic modulus, SLM, mechanical properties, cancellous bone

1. Introduction

In recent years, load-bearing cancellous bone defects caused by trauma, congenital osteomyelitis and tumor have been the reasons for the development of the application of multiple porous scaffolds [1]–[3]. Common clinical orthopedic fillers include bone cement, allogenic bone, hydroxyapatite (HA), etc. However, their shortcomings of poor load-bearing properties [4] still pose a major challenge. Human cancellous bone is a complex porous structure with complex structure, high porosity (55–68%) and appropriate pore size (500–1200 μm) [5], which is beneficial to nutrition transport and cell growth [6]. Therefore, it is necessary to develop a load-bearing

human bone-like bionic porous scaffolds to overcome this difficulty.

Factually, metallic biomaterials have higher Young's moduli (e.g., CoCrMo: 210 GPa, Ti6Al4V: 110 GPa, and Stainless Steel 316L: 190 GPa) than that of human natural bone (trabecular bone: 0.02–2 GPa, cortical bone: 3–30 GPa) [7]–[9]. Titanium and titanium alloys are important biomaterials due to their advantages of good biocompatibility and low Young's moduli [10]. However, their mechanical properties are still higher than those of human bone, which may cause the stress shielding of implants. Porous design can effectively reduce the elastic modulus of solid titanium alloy implant. For the fabrication of porous scaffolds, there are many traditional methods, such as powder sintering [11], plasma spraying [12], electro-

* Corresponding author: Wei Li, Tribology Research Institute, Key Laboratory for Advanced Technology of Materials of Ministry of Education, Southwest Jiaotong University, Chengdu 610031, China. Phone: +86-28-87600715, fax: +86-28-87603142, e-mail: liweijiani@home.swjtu.edu.cn

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spinning methods [13], etc. However, these methods make it difficult to customize the porous parameters of scaffolds, such as pore shape, pore size, porosity, etc. In recent years, with the rapid development of additive manufacturing, the research on the preparation of porous structures using this technology has become an international hotspot. Studies have shown that selective laser melting (SLM) can accurately control the pore shape, pore size and porosity of porous scaffolds [14], making it easy to fabricate complex porous structures.

The pore characteristics of the porous scaffolds not only affect the biomechanical properties of the porous implant, but also affect the growth of bone cell. Porosity promotes cell migration, adhesion and growth, and also cell differentiation and ECM production [2]. Higher porosity is associated with lower mechanical properties, and the porosity value can be used to customize scaffold performance [15], [16]. Pore size is also a major factor affecting scaffold behavior, cellular proliferation and ECM production. Many authors have shown that the porous scaffolds with a pore size of 300–1000 μm and a porosity of 60–95% are most conducive to bone cells growth [17]–[19]. Moreover, the human bone is in the dynamic mechanical environment and faces the stimulation of complex periodic fatigue load. Therefore, it is important to understand their fatigue behavior for the bone replacement biomaterials to experience cyclic loading. Rapillard et al. [20], [21] studied compressive fatigue behavior of human trabecular bone and cortical bone. Lambers et al. [22] identified the mechanism of microdamage accumulation in human spinal cancellous bone under cyclic fatigue loading. Yavari et al. [23] found that some of the implanted porous biomaterials showed signs of fatigue failure in *in vivo* study, with such results that bone cells could not continue to grow into the porous structure. In previous studies, cancellous bone porous scaffolds were not suitable as candidate implants for load-bearing bone defects due to the large pore size, mismatched elastic modulus and weak fatigue properties. Therefore, it is of great significance to design a porous scaffold with appropriate pore size, high porosity, low elastic modulus and high fatigue strength in the tissue engineering of load-bearing cancellous bone implant.

In this paper, in order to mimic the load-bearing capacity of tibial cancellous bone, the Ti6Al4V coaxial scaffolds with five types of beam angles and three types of pore sizes were designed. Subsequently, the coaxial scaffolds were fabricated with the use of SLM from Ti6Al4V powder. Finally, the fabrication method, mechanical properties and deformation behavior of

the coaxial scaffolds were investigated systematically. Our study is expected to provide insights into the design of load-bearing orthopedic porous implants.

2. Materials and methods

2.1. CAD model design of coaxial scaffolds

Based on the porous structure of human cancellous bone, the coaxial scaffolds were designed using software Solidworks (Dassault Systems Corp, USA). As shown in Fig. 1a, the coaxial scaffold was formed of concentric rings with a thickness of 400 μm superimposed longitudinally, and each layer ring was uniformly connected by beams with a diameter of 250 μm , forming gradient distribution porosity in the diameter direction from small to large. The entire size of the scaffold was $\Phi 10 \times 10 \text{ mm}$. The coaxial scaffolds were designed in various types including pore size (D) of 500 μm , 600 μm and 700 μm , and beam inclination angle (θ) of 0, 10, 20, 30 and 40° (Fig. 1b). The porosity of porous scaffolds plays an important role in tissue engineering and high porosity is beneficial to cell growth. Porosity can be characterized by Eq. (1),

$$P = \left(1 - \frac{M_s}{M_c}\right) \times 100\% = \left(1 - \frac{M_s}{\rho V_c}\right) \times 100\%, \quad (1)$$

where, M_s [g] is the weight of the porous scaffold, M_c [g] is the weight of the dense cylinder, V_c is the volume of the dense cylinder, ρ is the density of Ti6Al4V (4.43 g/cm^3).

2.2. Fabrication and morphological characterization of scaffolds

The coaxial scaffolds were fabricated with the use of a SLM equipment (EOS M 290-SLM, Germany). The printing material was Ti6Al4V powder (AP & C TC4 ELI, Canada) with particle size of 25–50 μm and density of 2.52 g/cm^3 . The SEM image and particle size distribution of Ti6Al4V powder were shown in Fig. 2a, b. Element proportions of Ti6Al4V powder were shown in Table 1. The laser power was 190 W, the spot diameter was 0.1 mm, the scanning distance was 0.11 mm, and the scanning speed was 1200 mm/s. After printing, all samples were annealed at 800 °C for 4 h. Cleaning of the residual powders, micro-cracks

Fig. 1. CAD structure of porous scaffolds: (a) schematic diagram of the designed coaxial scaffolds, (b) coaxial scaffolds with five types of inclination angles

Fig. 2. Evaluation of Ti6Al4V powder: (a) SEM image, (b) size distribution

Table 1. Element proportions of Ti6Al4V powder

Element	Al	C	Cu	Fe	Mg	Mo	Sn	V	Zr	H	O	N
Concentration [%]	6.52	0.015	<0.005	<0.198	<0.005	<0.010	<0.010	4.01	<0.005	0.0026	0.082	0.018

and stress concentration parts of the scaffolds were performed by using the acid solution (HF: H₂O = 1:10 ml). The porous characterization of the scaffolds was measured using a scanning electron microscopy (SEM, JSM-6390LV, Japan) and a laser confocal microscope (VK-X, Japan).

2.3. Mechanical properties of scaffolds

To obtain the static mechanical properties of the coaxial scaffolds, the compressive tests were obtained

by a static axial tensile equipment (Electronic tensile testing Machine WDW-3100, China). According to ISO: 13314, the loading speed was set at 1.5 mm/min until the porous scaffold was destroyed. Moreover, the compressive fatigue tests of the coaxial scaffolds were obtained using a dynamic compressive equipment (INSTRON E10000, America). According to ASTM F 382-2008, the compression frequency was 10 Hz, the R was 0.1, and the fatigue strength was obtained after 10^6 compression cycles. Based on Hooke's law, the elastic modulus of scaffolds can be characterized by Eq. (2):

$$E = \frac{\sigma}{\varepsilon} = \frac{F/S}{\Delta L/L}, \quad (2)$$

where, F [N] is the external load, S [mm²] is the upper surface area of the cylinder, L [mm] is the initial length of the porous scaffold, and ΔL [mm] is the compressive displacement.

2.4. Statistical analysis

In the mechanical test and porous characteristic measurement, the experimental data were expressed as mean and standard deviation. The F test (analysis of variance) was used to show the significant differ-

ence among different porous scaffolds under the same test conditions. The level of statistical significance was set to $P < 0.05$.

3. Results

3.1. SLM fabrication analysis

In Figure 3, the morphologies of the coaxial scaffolds printed using SLM are shown. The outer contour of the porous structure with different pore sizes and inclination angles can be clearly displayed. As can be seen from Fig. 3b, there were semi-melted powder and slag hanging on the beam and the layer walls of the porous scaffolds, and there was no fracture, collapse and pore blockage. In Table 2, lists the characteristic parameters of the porous scaffolds according to the measurement rules in section 2.1, are listed. The results showed that the actual measured pore sizes were 491, 595, and 688 μm , and the porosities measured were 63, 66, and 68%. In general, the whole architectures of the porous scaffolds achieved accurate reproduction of the designed geometry, and the forming ability of the porous scaffolds was reliable and controllable.

Fig. 3. Morphologies image of the printed coaxial scaffolds. (a) Three types of pore size, (b) laser confocal microscope images of scaffolds with five types of inclination angles

Table 2. Porous characteristics of the coaxial scaffolds

Group	Pore size [μm]		Strut size [μm]		Porosity [%]	
	CAD	OM	CAD	OM	CAD	OM
500–0°	500	486 $\pm$ 10	250	276 $\pm$ 15	66%	63% $\pm$ 0.6
500–10°	500	486 $\pm$ 14	250	275 $\pm$ 6	66%	64% $\pm$ 0.6
500–20°	500	529 $\pm$ 13	250	275 $\pm$ 11	66%	63% $\pm$ 0.6
500–30°	500	503 $\pm$ 12	250	289 $\pm$ 7	65%	63% $\pm$ 0.5
500–40°	500	515 $\pm$ 12	250	287 $\pm$ 12	65%	63% $\pm$ 1
600–0°	600	599 $\pm$ 11	250	281 $\pm$ 10	68%	66% $\pm$ 0.6
600–10°	600	599 $\pm$ 18	250	266 $\pm$ 10	69%	66% $\pm$ 1
600–20°	600	599 $\pm$ 7	250	266 $\pm$ 6	69%	65% $\pm$ 0.6
600–30°	600	584 $\pm$ 19	250	282 $\pm$ 4	68%	64% $\pm$ 0.6
600–40°	600	594 $\pm$ 5	250	281 $\pm$ 5	68%	65% $\pm$ 1
700–0°	700	691 $\pm$ 8	250	277 $\pm$ 3	69%	68% $\pm$ 0.6
700–10°	700	688 $\pm$ 22	250	278 $\pm$ 6	71%	67% $\pm$ 1
700–20°	700	683 $\pm$ 20	250	266 $\pm$ 7	71%	68% $\pm$ 0.6
700–30°	700	674 $\pm$ 13	250	284 $\pm$ 14	71%	69% $\pm$ 1
700–40°	700	705 $\pm$ 5	250	284 $\pm$ 5	70%	67% $\pm$ 1

3.2. Mechanical properties

3.2.1. Static compressive properties

In Figure 4, the stress–strain curves of the coaxial scaffolds under the compression test are shown. Almost all stress–strain curves consist of three stages: line elastic stage, yield stage and damage stage. According to the results collected in Table 3, the elastic moduli of

the coaxial scaffolds fabricated by SLM ranged from 1.08 to 1.85 GPa, and the compressive strength ranged from 40 to 88 MPa, which matched the elastic modulus (1 GPa) and the compressive strength (50 MPa) of the human cancellous bone. In addition, in Fig. 5 it was shown that the elastic modulus all decreased with the increasing pore size, inclination angle and porosity. The yield strength and compressive strength also decreased with the increasing pore size and inclination angle.

Fig. 4. Strain-strain curves of the coaxial scaffolds with three kinds of pore sizes: (a) 500 μm , (b) 600 μm , and (c) 700 μm

Table 3. Static compressive properties of the coaxial scaffolds

Group	Elastic modulus [GPa]	Yield strength [MPa]	Compressive strength [MPa]
500 μm	1.13–1.84	62–83	78–88
600 μm	1.14–1.65	50–66	62–70
700 μm	1.05–1.55	34–55	40–59

3.3.2. Deformation behaviors

In Figure 6, the deformation energy of the coaxial scaffolds under the compression load is shown. The

deformation energy was calculated by selecting the compressive displacement from the initial point to the plastic stage. As shown in Fig. 6b, the energy decreased with the increasing pore size, and increased with the

Fig. 5. Static compression test results of coaxial scaffolds: (a) elastic modulus, (b) yield strength, (c) compressive strength, (d) relationship between elastic modulus and porosity

Fig. 6. Compressive deformation energy analysis of different coaxial scaffolds: (a) force-displacement curves, (b) compressive deformation energy, (c) maximum compressive displacement, (d) maximum compressive force

Table 4. Typical deformation state of the coaxial scaffolds during static compression tests

Pore size: 700 μm	Deformation state [%]			
	Initial state	Initial failure	Obvious damage	Totally destroyed
0°
Strain Values	0	4.5	5.8	10.8
10°
Strain Values	0	4.5	6.5	11
20°
Strain Values	0	4.5	6	9
30°
Strain Values	0	5	6.5	10
40°
Strain Values	0	6	7.5	9

Fig. 7. SEM image of fatigue fracture surface of the coaxial scaffolds beam

increasing inclination angle. In addition, the maximum compressive displacement had the same trend as the compressive deformation energy (Fig. 6c), which also decreased with the increasing pore size, and increased with the increasing inclination angle. In Figure 7, the failure position of scaffolds was mainly at

the bottom of the beam is shown, indicating that the stress concentration of the scaffolds occurred at this location. In Table 4, the typical deformation states of the coaxial scaffolds with pore size of 700 μm during the compression test are listed. It was noted that, along with the increase of strain, the coaxial scaffolds

Fig. 8. Strain-strain curves of the coaxial scaffolds under different fatigue cycles: (a) 500–40°, (b) 600–40° and (c) 700–40°

Fig. 9. Fatigue strength results of the coaxial scaffolds under compression frequency of 10 Hz: (a) the curves of stress-number of cycles, (b) fatigue strength results

gradually yielded until they were completely destroyed. Moreover, with the increase of the beam angle of scaffolds, the strain at the obvious damage state increased gradually.

3.2.3. Compressive fatigue properties

In Figure 8, strain-strain curves of the coaxial scaffolds under different fatigue cycles are shown. It is found that the deformation accumulation of coaxial scaffolds was increasing during the compression fatigue process, which called the hysteresis characteristics. Moreover, under the same stress of scaffolds, the order of strain was 500–40° > 600–40° > 700–40°.

In Figure 9, the fatigue strength results of the coaxial scaffolds under compression frequency of 10 Hz. The result shows that the number of compression fatigue cycles increased with the fatigue strength decreasing. Meanwhile, the fatigue strength of 500–40°, 600–40° and 700–40° coaxial scaffolds were 1387, 1110 and 420 MPa, respectively.

4. Discussion

Cancellous bone defects often occur in the human tital bone due to different reasons. Therefore, it is necessary to develop bionic porous scaffolds with the combination of high porosity, appropriate pore size, low elastic modulus and high fatigue strength. In this paper, the Ti6Al4V coaxial scaffolds with five types of beam angles and three types of pore sizes can meet those requirements.

In the SLM printing process, the molten metal fluid was irregular before cooling, and the cooling process of the molten pool was not synchronous. The semi-melted Ti6Al4V powder may adhere to the scaffolds (Fig. 3b), causing a gap between the designed value and the measured value. Compared to the design values, the actual measured pore sizes were 491, 595, and 688 μm, and the measured porosities were 63, 66, and 68%, but met the size requirements of bone cell growth [17]–[19]. Furthermore, the coaxial scaffolds

Table 5. Comparison between the mechanical and structural properties of the coaxial scaffolds and those porous scaffolds in other studies

Material type	Pore type	Pore Size [μm]	Porosity [%]	Elastic modulus [GPa]	Compressive strength [MPa]	Fatigue strength [MPa]	Ref.
TC4	Coaxial	480–700	63–69	1.08–1.85	40–88	>420	This study
TC4	PT	413–420	50–75	5.22–34.36	94–932	15.86–264.73	[25]
TC4	Optimized	~2000	72	–	77	~22	[26]
TC4	TPMS	–	49–87	1.9–17.6	50.9–345	5.3–43.8	[14]
TC4	Cubic	1443 $\pm$ 79	63.2	14.9	155.9	75	[27]
TC4	G7	1310 $\pm$ 77.3	64.5	2.4	59.6	9.8	
TC4	Rd	1216 $\pm$ 121.4	62.1	6.3	77.2	13.9	
TC4	–	250–600	51	12.37 $\pm$ 1.46	167 $\pm$ 18	135	[28]

fabricated by SLM exist no defects such as fracture, collapse and pore blockage, indicating that the SLM technology is a reliable method to precisely customize the porous scaffolds under our design parameters.

In the SLM printing process, the irregular molten metal and the asynchronous cooling process of the molten pool may cause the strength differences of the beams. Thus, with the collapse of different weak parts of the beams, the porous layers were compacted with each other, causing the stress–strain curves to fluctuate up and down in the damage stage (Fig. 4). The stress–strain curves were similar to the previous studies [24]. Moreover, the elastic modulus, yield strength and compressive strength of the coaxial scaffolds all decreased with the increasing pore size, inclination angle and porosity (Fig. 5). On the one hand, the increase of pore size and porosity led to a decrease in the number of beams under the same volume, reducing the compression and deformation resistance of the scaffolds, so as to make the scaffolds more prone to fracture. On the other hand, the increase of the beam inclination angle reduced the axial load on the scaffold beams, which may have caused stress concentration at the beam bottom, resulting in the reduction of compression deformation energy of the coaxial scaffolds with the increase in the pore size (Fig. 6b). As shown in Table 4, with the increasing inclination angle of the beams, the extended compression strain values of the scaffolds in the damage state also increased, resulting in the increase of deformation energy. This indicates that the coaxial scaffolds with appropriate pore size and beam inclination angle can efficiently reduce the stress shielding rate and promote the growth of bone cells. As shown in Fig. 7, due to the plastic deformation of beam under static compression load, there were more dimples and a few extruded dislocation layers at the

fracture of the beam. It led to the transformation of the coaxial scaffolds from the linear elastic deformation stage to the yield stage, and finally to the destruction of the whole structure due to the stress concentration of the beams.

The mechanical environment of human skeleton is dynamic, so the dynamic fatigue characteristics of porous implants should also be considered. In Figure 5, it can be seen that the three kinds of coaxial scaffolds of 500–40°, 600–40°, and 700–40° have the lowest mechanical properties. Therefore, we only need to analyse compression fatigue on them to evaluate the dynamic mechanical bionic properties of the coaxial scaffolds. In the process of dynamic compression, with the increase of the number of compression cycles, the strain of coaxial scaffolds gradually accumulates, which cannot be recovered quickly, and finally leads to fatigue fracture. The phenomenon was similar to the compressive fatigue behavior of human cancellous [20]. Among the three kinds of structures, the strain accumulation of the 700–40° structure is the most obvious, and obvious deformation will occur under the action of very small stress. The results show that the large pore size and the large beam angle have the risk of premature collapse. However, Figure 9 shows that the fatigue strength of the 700–40° structure is 420 MPa, which is still stronger than the strength (about 50 MPa) of natural human cancellous bone [20], [21]. Compared to Ti6Al4V porous scaffolds for orthopedic applications, built so far by other researches (Table 5), the coaxial scaffolds possesses suitable pore size (480–700 μm) and porosity (63–69%), favorable elastic modulus (1.08–1.85 GPa) and higher fatigue strength (420–1387 MPa) to facilitate osseointegration. The results illustrate the coaxial structure is a suitable porous scaffold for load-bearing orthopedic applications.

5. Conclusions

In this paper, the functionally coaxial scaffolds, characterized by high porosity, appropriate pore size, low Young's modulus and high fatigue strength were designed and fabricated by SLM. The fabrication morphological, mechanical properties and deformation behavior of the coaxial scaffolds were investigated systematically. The conclusions can be summarized as follows:

1. The Ti6Al4V coaxial scaffolds with five types of beam angles and three types of pore sizes were precisely fabricated by SLM with pore size of 500–700 μm and porosity of 63–69%, which met the size requirements of bone cells growth. Moreover, the SLM was a reliable technology to precisely customize the porous scaffolds with complex porous morphology.
2. The coaxial scaffolds had an elastic modulus of 1.08–1.85 GPa and a compressive strength of 40–88 MPa, which matched the elastic modulus (1 GPa) and the compressive strength (50 MPa) of the human cancellous bone. In addition, the elastic modulus and compressive strength of the porous scaffolds can be changed by adjusting the porosity, pore diameter and beam inclination angle to achieve the purpose of mechanical bionics.
3. Among all coaxial scaffolds, the fatigue strength of 500–40°, 600–40° and 700–40° coaxial scaffolds with the weakest static mechanical properties were 1387, 1110 and 420 MPa, respectively. It is verifiable that the coaxial scaffolds can satisfy the dynamic bio-mechanical bearing requirements of cancellous bone implants.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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