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A comparative study on mechanical properties of porous titanium implant

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Abstract:

Background: Porous titanium scaffolds are promising candidates for bone reconstruction. In the load-bearing applications, predicting the mechanical properties of scaffolds are important.

Materials and methods: In this study, we developed a titanium scaffold with 55, 65 and 75% porosity using powder metallurgy technique, to investigate the effect of porosity on the mechanical properties of scaffold. The micro-structure of the scaffolds were studied using scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses. The plateau stress of titanium scaffolds was measured using compression test and compared to an analytical model.

Results and discussion: According to the SEM results, by increasing the porosity of scaffold from 55 to 75%, the thickness of struts became thinner. While results of XRD analysis did not indicate any impurity at fabricated scaffolds, the results of experimentally measured and analytically calculated plateau stress of titanium scaffolds, differ significantly, particularly at higher porosities (i.e. 75%).

Key words: Titanium scaffold; Porosity; Mechanical properties, Bone.

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Introduction

One of the major problems with current orthopedic implants is deficiency of having fixed implant/tissue interfaces, which results in implant wear [1]. Movement of the wear products and displacement of implant will cause infection, and ultimately death of surrounding bone tissue [1]. Fixation of an implant within a tissue is possible in several ways include: (i) mechanical fixation using bolts, nuts and wires, etc. [2], biological fixation using bioactive molecules and growth factors to help tissue ingrowth within the porous surfaces of an implant [2] and biochemical fixation using chemical bonding of tissue with bioactive materials.

Due to a high toughness and strength, metals are suitable choices for load bearing implantation in the body especially for bone [2]. However, high density, high elasticity, fast corrosion which causes ion release, and non-bioactivity, are the common problems of metallic biomaterials which need to be addressed.

To overcome the problem of high density and high elasticity of metals, increasing the porosity in the metal structure is a suitable technique. In addition to the reduction in both density and elastic coefficient, increasing the porosity will improve the biological fixation of implant [1].

The most commonly used metal biomaterial is titanium and its alloys [1, 3], 316 stainless steel [3] and cobalt-chromium alloys with elastic coefficient of 105, 205-210, and 230 GPa, respectively [1, 3]. Among metallic biomaterials, titanium has low elasticity [4, 5], excellent corrosion resistance [3] and fatigue life [6]. However, to minimize the stress shielding phenomenon, the elasticity of the bone and bone implant should be similar. The elastic coefficient of the cortical bone is reported in various values of 15 GPa [7], 30-30 GPa [1] and 10-40 GPa [3] by different researchers, while the elastic coefficient of the cancellous bone is reported 3 GPa [7] and the elastic coefficient of the bone is generally reported about 0.1-30 GPa [8]. So the reduction of titanium elasticity is an essential necessity for the researchers.

Li et al. prepared titanium scaffolds with different amount and size of pores through rapid prototyping (three-dimensional fibers deposition) and after implantation in the spine of the goat showed that by increasing porosity and pore size, the bone in-growth in the scaffold had been facilitated [9].

Although, porosity can improve bone-implant integration, it can adversely affect the mechanical properties of scaffold. Mathematical modeling can be used to predict the mechanical properties of porous scaffolds.

According to Mangipudi et al., in metallic scaffolding with irregular pores, the probability of stress concentration in the sharp corner of the pores and early failure is more than the metal scaffolds with spherical pores. So the shape of the pores has an important influence on the mechanical properties of the metal scaffold [10]. Therefore, morphology of pores in metal implants is important, especially when these implants are under cyclic loads, and the problem of fatigue can also be raised. In addition to the shape of the pores, the uniformity of size and distribution of the pores are also important throughout the scaffold.

In this study, the effect of porosity on the mechanical properties of titanium scaffold, was studied and compared to an analytical model.

Materials and Methods

Titanium Scaffolds Fabrication

A powder metallurgy-space holder method was used to fabricate titanium scaffolds. Spacer was used from sodium chloride (NaCl: Aryan Chemical, Iran). The commercially pure titanium powder of grade 4 with a particle size of smaller than 50 microns (Baoji Unique Titanium Industry Co. LTD- China) was used for the metallic matrix according to the manufacturer's analysis certificate according to Table 1.

Table 1. Nominal composition of raw titanium powder.

Element	Fe	N	O	H	C	Ti
Wt.%	0.07 >	0.02 >	0.4 >	0.02 >	0.02 >	Balance

In order to fabricate titanium scaffolds, the raw titanium powder (volume fractions of 55, 65 and 75%) was mixed with particles of spacer agents and then pressed in a mold at a pressure of 200 MPa. The specimens were then heated at 200 °C for 2 h, then at 800 °C for 2 h, and finally at temperature of 1100 °C for 2 h under a vacuum of 1×10-4 Torr using a vacuum furnace (YARAN YHV5047).Samples were eventually cooled down until ambient temperature in the furnace under the same vacuum conditions. The heating and cooling rates were set at 5^{0}C/min. The spacer agent was removed by dipping samples in distilled water at ambient temperature for 40 h.

Titanium Scaffolds Characterizations

Microstructure

Scanning electron microscopy (SEM: Philips XL-30) was used to study the microstructure include distribution of pores and surface morphology of titanium scaffolds. The voltage of electron gun was set on 20 kv.

Phase analysis

X-ray diffraction (XRD: Philips, X'Pert-MPD, Netherland) was used to measure the phases formed in the scaffolds. The diffraction pattern was obtained by a Cu-Kα lamp with a wavelength of 1.54060 angstroms in the range of 20◦<2θ <80◦ with the step size of 0.05 degrees and the time per step of 1 s.

Mechanical properties

Compressive properties of titanium scaffolds were investigated according to ISO 13314 [11]. The mechanical properties of cylindrical samples (D= 6, H= 9 mm) were studied using a universal testing machine (INSTRON 5566S, USA, at Nagasaki University, Japan) at crosshead speed of 0.5 mm/min at ambient temperature. After plotting the strain-strain diagram of each sample, the plateau stress (i.e. σpl or mean stress in strains between 10 and 20%, according to the mentioned standard) was calculated [11].

Experiments were performed in triplicate and the average values were reported. The results obtained from compression test of the scaffolds were compared with the analytical values. The Mori-Tanaka model (equation 1) was used to predict the mechanical properties of scaffolds with different porosities [13]:

Equation 1 $$\frac{K}{K_0} = \frac{1-p}{1+cp}$$

Where, k and k0 are the plateau stress of the scaffold and the yield strength of the matrix metal, respectively. The constant p is the porosity of scaffold and the constant c is a constant number.

Results and discussion

Microstructure

SEM imaging of titanium scaffolds with 55, 65 and 75% porosity was presented in Fig. 1. According to Fig. 1, by increasing the porosity of scaffold from 55 to 75%, the thickness of struts decreased and the interconnectivity of pores also increased. Although, having more porosity has been shown to be more favor for cellular growth into the scaffold, the mechanical properties of scaffold reduces significantly. Hence, an optimum porosity should be considered for development of a scaffold to have both cellular growth and tissue integration as well as mechanical properties. Furthermore, SEM imaging at higher magnification shows the presence of micro pores with the size of about 10 micrometer at the struts of macro pores, which can facilitate cell nutrition and waste removal in vivo.

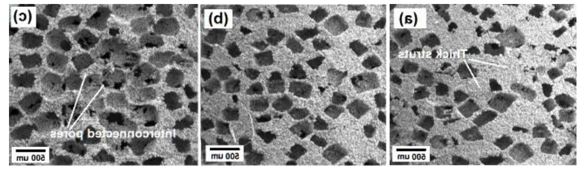

Fig 1. SEM images from our titanium scaffolds with (a) 55%, (b) 65%, and c) 75% porosity. Struts and interconnected pores have been indicated by arrows.

Phases analysis

X-ray diffraction pattern in Fig. 2 shows the phases formed in our titanium scaffolds. Since contaminations in the scaffolds influence on the mechanical properties of the scaffold, it is important to ensure the absence of impurities, particularly when mechanical properties is studied. As indicated in Fig. 2, the fabricated titanium scaffolds were not contained any phases other than pure titanium. Since the results of all three samples are the same, only the results of scaffold including 65% porosity are presented. In Fig. 2, the gray lines indicate the location of the titanium peaks according to the reference card (PDF No.: 00-005-682). It should be noted that the peak spots of the graph are exactly the same as the standard peaks, and the sample is composed of only titanium.

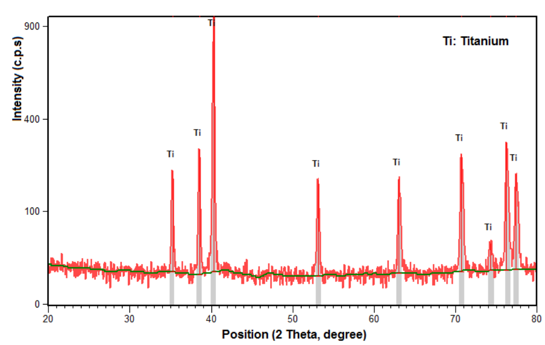

Fig 2. X-ray diffraction pattern for fabricated titanium scaffold.

Mechanical properties of titanium scaffolds

Using the compression test, the stress-strain curve for the samples was plotted in a graph. Research shows that, the stress-strain curve of porous metals consists of three regions include (i) an elastic deformation region, (ii) a plateau stress region, and (iii) a densification region [11]. In the elastic deformation region, the stress-strain curve is linear. All above-mentioned regions are also detectable in our stress-strain plots (Fig. 3).

In Fig. 3, the stress-strain curves of the scaffold obtained from compression test are presented. The results of the analysis of the graphs according to ISO 13314 [11] are presented in Table 2. Also, the predicted values (analytical) of the mechanical properties of the scaffolds according to the Mori-Tanaka equation are presented in Table 2.

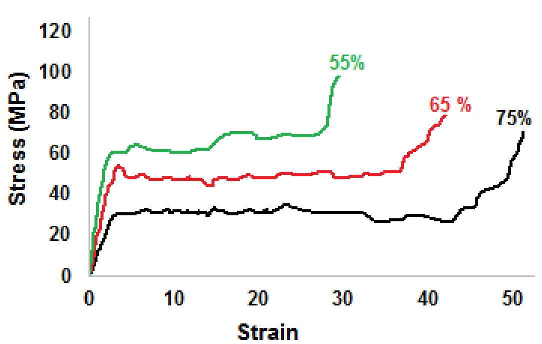

Fig 3. Engineering stress-strain curves of titanium scaffolds with 55, 65, and 75% porosity.

Table 2. Results of mechanical properties and analytical values for titanium scaffolds.

Porosity (%)	Experimental plateau stress (MPa)	Analytical plateau stress (MPa)
55	65±5	140
65	48±4	99
75	31±4	65

As shown in Fig. 3, with increasing porosity of the scaffold from 55 to 75 %, the plateau stress decreased from 64 to 31 MPa. While according to the Mori-Tanaka model and considering k0= 650 MPa and c=2 [13], the plateau stresses of the titanium scaffolds with 55, 65 and 75% porosity obtained 140, 99 and 65 MPa, respectively. It is evident that there is large difference between experimental and analytical values of plateau stress.

The c constant in the Mori-Tanaka model, should be 7.77, 10.7 and 17 for titanium scaffolds including 55, 65 and 75% porosity, respectively, to make a good coordination between experimental results and analytical values.

The results of analytical modeling and experimental tests of some researchers have shown that the distribution of pores and the uniformity of their distribution have a significant effect on the mechanical properties of metallic scaffolds. Therefore, in the fabrication of metallic scaffolds for load bearing applications, uniform distribution of pores is important [13]. However, from a biological perspective, the optimal diameter of the pores of a porous scaffold is about 200 to 500 µm with the porosity percentage of 40-80% [14].

It is necessary that these pores are interconnected to facilitate the cells penetration and mass transfer (i.e. oxygen and nutrients) into the center of implant [4]. Although, with the increase of porosity and pore size, bone tissue ingrowth is facilitated, the mechanical properties of scaffolds decrease. Hence, the upper limit of the pore sizes is limited by the mechanical properties of the scaffold and its lower limit is limited by the bone-ingrowth ability within the scaffold [14]. The shape of the titanium scaffold pores does not have any significant effect on cell proliferation and is only effective in the mechanical properties of the scaffold [15]. With increasing titanium scaffold porosity, its mechanical properties decrease [16].

Manonukul et al. fabricated titanium scaffolds including 84% porosity with a coefficient of elasticity of 0.58 GPa, which according to the Mori-Tanaka model, coefficient should be about 33 GPa. Manonukul declared this difference is related to the heterogeneity of the dimensions of the titanium scaffold pores [17]. Wenjuan et al. mentioned the low mechanical properties of titanium scaffolds in their research in relation to the Gibson-Ashby model, the presence of micro pores in the struts of macro pores [18]. According to our recent research [19], the pore morphology also has a significant effect on the mechanical properties of scaffolds, suggesting this parameter needs to be considered in analytical models.

Conclusion

A titanium scaffold with different porosity has been successfully produced by the powder metallurgy-space holder method, which was free from impurities. Mechanical properties of scaffolds show that with increasing scaffold porosity from 55 to 75%, their plateau stress decreased from 64 to 31 Mpa, which confirmed porosity has an important effect on the mechanical properties of the titanium scaffold. Comparing the experimental results with mathematical analysis, we concluded that the Mori-Tanaka model predicts higher values of plateau stresses than that of experimental values, at all ranges of porosities.

Conflict of Interest Statement

The authors have no conflicting financial interest.

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