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Compressive behaviour of gyroid lattice structures for human cancellous bone implant applications

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ABSTRACT

Electron beam melting (EBM) was used to fabricate porous titanium alloy structures. The elastic modulus of these porous structures was similar to the elastic modulus of the cancellous human bone. Two types of cellular lattice structures were manufactured and tested: gyroids and diamonds. The design of the gyroid structures was determined by the main angle of the struts with respect to the axial direction. Thus, structures with angles of between 19 and 68.5° were manufactured. The aim of the design was to reduce the amount of material needed to fabricate a structure with the desired angles to increase the range of stiffness of the scaffolds. Compression tests were conducted to obtain the elastic modulus and the strength. Both parameters increased as the angle decreased. Finally, the specific strength of the gyroid structures was compared with that of the diamond structures and other types of structures. It is shown that, for angles lower than 35°, the gyroid structures had a high strength to weight ratios.

1. Introduction

Recently developed additive manufacturing (AM) techniques allow the production of porous titanium biomaterials. The most commonly used techniques for this material are selective laser melting (SLM) and electron beam melting (EBM). The main advantage of these techniques, as compared to others, is their ability to manufacture interconnected porous biomaterials with predictable and pre-determined unit cells. This means that the possibility to combine designs of different unit cells will open up a broad field with many opportunities for optimal design of orthopaedic implants [1–3]. Some authors highlight the advantages of EBM over SLM due to its capability to manufacture dense parts in less time [1,4]. However, other authors conclude that structures fabricated by SLM show better mechanical properties for a given relative density in comparison to those fabricated by EBM [5]. In this paper, the EBM process, developed by Arcam AB (Krokslätts Fabriker 27A, SE-43137 Mölndal, Sweden), has been used to fabricate non-stochastic lattice structures.

The current trend is to fabricate patient-tailored implants for which some researchers have proposed different types of three-dimensional structures with an interconnected porosity. The aim of fabricating this kind of structures is, on one hand, to provide the right environment for tissue growth and vascularization and, on the other hand, to reach specific mechanical properties, such as an elastic modulus similar to that of the human bone [6,7], the latter reducing the stress shielding effects after implantation [6,8]. Therefore, it is necessary to build lighter implants with an elastic modulus similar to the replaced bone.

The goals of this paper were to study the mechanical behaviour of the gyroid structures with regard to their strut orientation and to compare the specific strength (compressive strength against density) of those structures with other previously developed structure types. The main hypothesis is that, with a proper orientation of the struts in gyroid structures, lighter and more resistant implants can be obtained. While the suitability of SLM for the fabrication of high strength and low mass gyroid structures made of 316L stainless steel [9,10] or titanium alloy Ti-6Al-4V [11,12] is well established, little is known about the suitability of gyroid structures fabricated by EBM for medical applications.

2. Experimental procedure

Several three-dimensional porous structures (gyroid-type and diamond-type) were designed and manufactured using EBM techniques. The general procedure for the component generation layer by layer has already been described by other authors [8,13]. Titanium powder (Ti-6Al-4V) was used as raw material (elastic modulus: 110 GPa, Poisson's ratio: 0.3, density: 4.42 g/cm^3). Mechanical testing of the bulk material according to ASTM E8M-13a Standard Test Methods for Tension Testing of Metallic Materials confirms these assumptions.

A total of sixteen gyroid structures with dimensions of 21 × 21 × 21 mm were designed and fabricated. The main variable incorporated in the geometry was the angle formed between the struts

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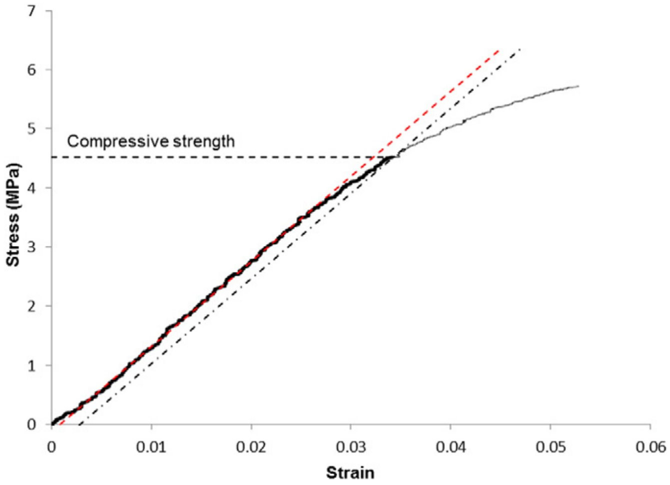

Fig. 2. Stress-strain curve obtained after compression tests for the G 55° structures. The red straight line determines the elastic modulus and the black dashed line represents the 0.2% offset yield strength to obtain the compressive strength.

and the axial direction (Fig. 1). Structures with angles of 19°, 21.5°, 26°, 35°, 45°, 55°, 64°, 68.5° were produced (two specimens of each angle). Structures were selected from previous tests whose elastic moduli were similar to those of the cancellous bone, with values between 10 and 1570 MPa [14]. The gyroid unit cells were generated in K3Dsurf software (http://k3dsurf.sourceforge.net). The unit cells were then imported into 3D Studio Max software (Autodesk, Inc., United States) which, through custom developed scripts, were used to fill the desired volume. Additional series of scripts and operators were developed to create anisotropic structures in accordance with the required specifications. Furthermore, six diamond structures with dimensions of $21 \times 21 \times 21$ mm were fabricated with the following characteristics: R:0.3–S:2.5; R:0.35–S:4; R:0.5–S:4; named D1, D2, D3 respectively (two specimens of each one), where R is the strut radius in mm and S the cell size in mm. As with the gyroid structures, the diamond structures were selected with an elastic modulus similar to the elastic modulus of the cancellous bone. The size of the struts was measured using a stereomicroscope Olympus SZX10 (Olympus Corporation, Tokyo, Japan). The measurements were processed with specific microscope software in order to obtain the diameter of the struts and the size of the pores. The measured values of both the diameter of the struts and the size of the pores differed less than 10% from the nominal value.

Uniaxial compression tests were conducted at a speed of 0.5 mm/min according to ASTM E9-09 Standard Test Methods of Compression Testing. The upper head was articulated and the load was applied onto the plain plate placed on the upper and lower sides of the specimens. All the specimens were loaded until failure. Fig. 2 shows the typical curve of stress versus strain obtained in compression tests. Both stress and strain were obtained in accordance with the initial cross sectional area and the initial length of each structure, respectively (ASTM E9). The elastic modulus of each specimen was obtained as the slope of the linear part of each stress-strain curve, as shown in Fig. 2. The compressive strength of each sample was identified with the 0.2% offset yield strength, i.e., the stress at which the stress–strain curve for axial loading deviates by a strain of 0.2% from the linear-elastic region (Fig. 2). The specific strength of the structures was calculated as the ratio between the compressive strength and the apparent density. To obtain the apparent density, the structures were measured, obtaining the apparent volume, and weighed on a precision balance scale (50 g ± 0.01 g). All measurements were carried out at room temperature (20 ± 2 °C).

3. Results and discussion

The compression tests carried out on the gyroid specimens showed a wide range of elastic moduli (E), between 59.12 and 700.36 MPa (Fig. 3). Those values were within the range of the elastic moduli for human cancellous bone tissue (10 to 1570 MPa) [14]. The maximum elastic modulus value was achieved with the gyroid structures of 19°, and the minimum value was achieved with the 68.5° structures. Angles higher than 68.5° were not analysed due to poor mechanical properties ($E < 60$ MPa) and technical limitations when manufacturing with higher angles. High correlation ($R^2 = 0.99$) was achieved through an exponential decay between the stiffness of the structures and the angle of the struts. The compressive strength values of the gyroid structures ranged from 1.69 MPa to 13.19 MPa (Fig. 4), which are similar to the values of the cancellous bone (1.5 to 38 MPa) [14]. A linear correlation ($R^2 = 0.97$) between the compressive strength values and the strut angle was found.

One of the main goals of this work was to obtain porous structures with an improved strength to weight ratios, designing structures with stiffness similar to that of the cancellous bone by modifying the strut angle of the gyroid structures. Different structures designed for this work and by other authors were compared following the concept of specific strength (Fig. 5). The maximum value of the specific strength for the gyroid structures was 49.4 MPa/(g/cm^3), corresponding to the 19° gyroid structure, while the minimum value was 5.82 MPa/(g/cm^3), corresponding to the 68.5° gyroid structure. Structures with orientation angles lower than 35° achieved better specific strength than diamond and rhombic dodecahedron structures (Fig. 5) [8,15]. The specific strength of the diamond structures obtained in this study is within the range from 16.84 to 33.57 MPa/(g/cm^3) showed in other studies [8, 15]. In that regard, Cheng et al. revealed the high specific strength of the rhombic dodecahedron structures in comparison with the metallic stochastic foams [15]. However, Challis et al. developed a new structure called "optimised scaffold" which showed better strength to weight ratios than the gyroid scaffolds [11]. Nevertheless, those structures were fabricated by SLM and the stiffness values were higher than those of the cancellous bone. On the other hand, the same authors studied the specific modulus, which is the relation between the elastic modulus and the density. In this paper, that parameter was not studied since the aim was to obtain structures with stiffness values similar to the elastic modulus of the cancellous bone, and optimize such structures with regard to the specific strength.

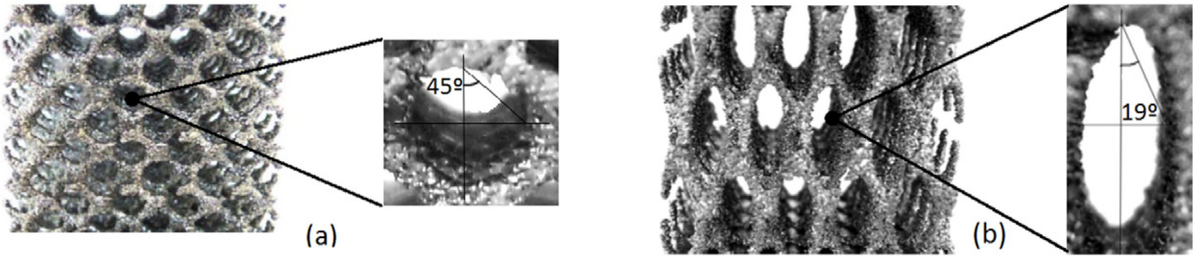

Fig. 1. Examples of two gyroid structures fabricated by EBM. (a) Specimen with angle between the struts and the axial direction of 45°. (b) Specimen with angle between the struts and the axial direction of 19°.

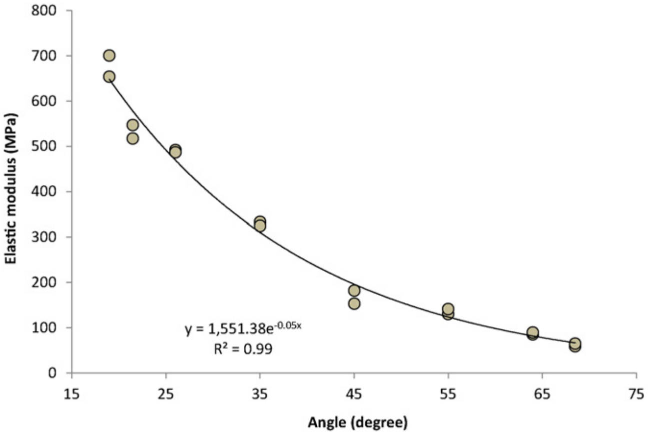

Fig. 3. Elastic modulus related to the angle of the gyroid structures. Exponential correlation curve is plotted with the fitting equation and R^2 value.

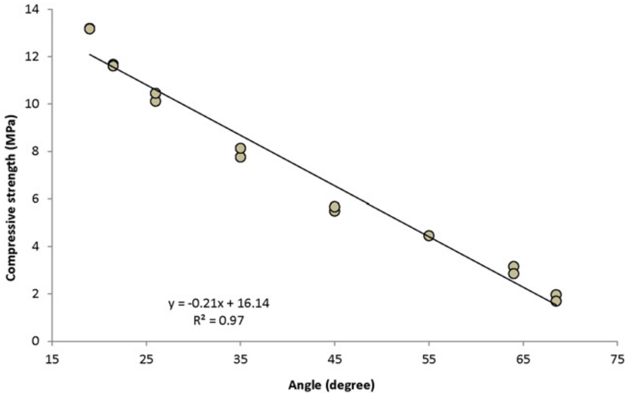

Fig. 4. Compressive strength related to the angle of the gyroid structures. Linear correlation is plotted with the fitting equation and R^2 value.

In this study, gyroid lattice structures with angles between 19 and 68.5° were selected. In this regard, angles smaller than 19° were not fabricated since the structure would present a severe anisotropy with poor mechanical properties in the perpendicular direction of the load, having inherent limitations in the implantation applicability. On the other hand, angles greater than 68.5° would not only lead to structures with little or none load bearing capabilities but also to complications in the manufacturing process. Additive manufacturing uses powder as raw material and fuses together a layer of few micrometres of material at each step of fabrication. In this way, greater angles would lead to a smaller overlap of the particles that conform the raw material, creating structures with poor reliability and increasing the probability of imperfections.

From the biomaterial perspective, in vivo studies to analyse the suitability of titanium porous structures for clinical applications have shown an adequate osteointegration and tissue regeneration inside the structures [16,17]. However, little is known about the long term applicability of such structures due to stress shielding effect that leads to the loss of bone mass and the associated pathologies. At the microscopic level, titanium structures fabricated by additive manufacturing offer an adequate substrate that favours cell proliferation and differentiation [18]. In addition, it has been shown that stiff substrates lead to an osteoblastic commitment of the cells [19]. Surface curvature also has an influence in tissue growth [20] and cell differentiation [21], although it can be considered a neglect in the structures presented in this work since the dimensions are several orders of magnitude larger than those of the previous studies. In this way, the angle of the struts could rather provide a guide for tissue growth than influencing cell behaviour in a specific manner.

Even though bone tissue has the capability to heal in most of the clinical situations, large bone defect and joint replacement still remain as a challenge. In this way there is a wide variety of biomedical implants with porous structures and manufactured with EBM technology that are under investigation, as for example, customized hip and knee implants [3,22,23] or large bone defect [24]. The titanium structures presented in our work showed an appropriate load bearing capability that could facilitate early load transfer to the substituted tissue and a porous structure that could increase the integration between the implant and the bone. These factors together could reduce the rehabilitation time, increasing the life quality of the patient and the associated costs.

Previous studies revealed that non-axial load cases can strongly modify the mechanical response of the structures [8]. In this study, mechanical tests were performed only in axial direction and consequently, the behaviour in other directions remains unknown. Therefore, the

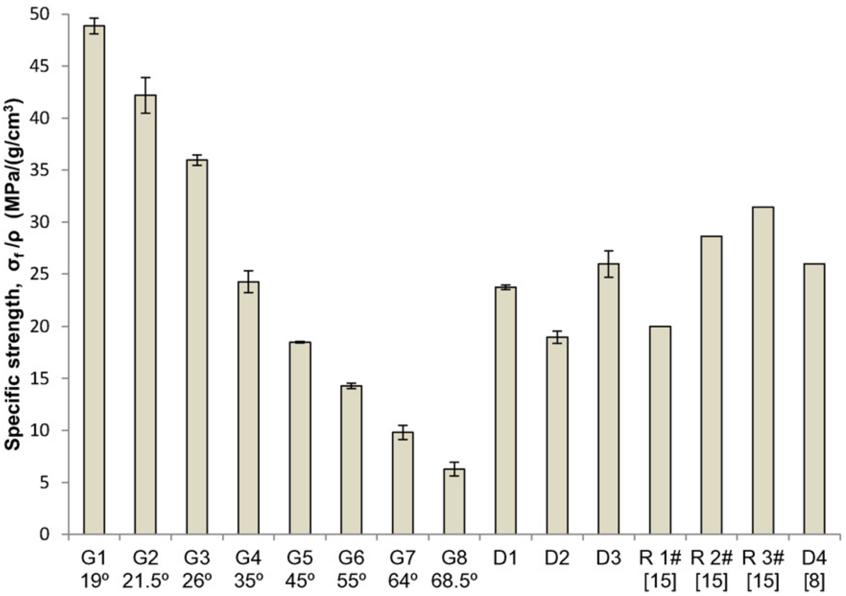

Fig. 5. Specific strength (mean and standard deviation) from porous titanium structures. "G" identifies gyroid structures with different angles; "D" identifies diamond structures with different porosities; and "R" identifies rhombic dodecahedron structures with different porosities. The numbers into brackets represent data from the literature [8,15].

selection of the most suitable type of structure will depend on the main direction of the load in the implantation site. On the other hand, only two scaffolds per group were tested, making an insufficient number for exhaustive statistical analysis. However, the accuracy and reproducibility of the manufacturing system in previous studies makes this aspect not critical [11,25].

Another limitation of this study is that the EBM process may lead to fabrication irregularities such as surface roughness, variations in the strut surface, void spaces or unmelted material [4,25,26]. Those irregularities frequently generate stress concentrators that can affect the mechanical behaviour, especially when repeated loading is applied [27]; however, there are processes that could improve the affected structures, such as the Hot Isostatic Pressing (HIP), whose standard treatment should be applied on Ti-6Al-4V components in orthopaedic implants [28,29]. Further research could be focused on fatigue tests in order to evaluate the dynamic behaviour of gyroid structures fabricated by EBM for medical applications [27,30].

4. Conclusions

The elastic modulus of gyroid Ti-6Al-4V structures manufactured by electron beam melting was similar to the elastic modulus of the cancellous human bone. A high correlation was obtained between the elastic modulus and the strut angle, as well as between the compressive strength and the strut angle. Interestingly, as the strut angle decreased, both the elastic modulus and the compressive strength increased. The specific strength of the gyroid structures was compared with other types of structures studied in this paper and by other authors, concluding that for certain angles, the gyroid structures showed a better strength to weight ratios.

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