



Gyroid porous titanium structures: A versatile solution to be used as scaffolds in bone defect reconstruction

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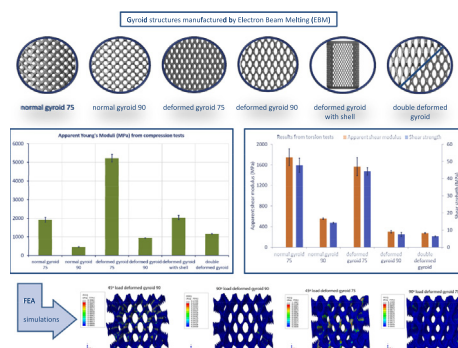
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HIGHLIGHTS

- Different gyroid porous titanium structures were characterized by mechanical testing and finite element analyses.
- Deformed gyroids showed good mechanical properties under compression loads.
- Normal gyroids presented a more homogenous mechanical behaviour under different direction loads and different types of loads.
- Gyroid scaffolds might be suitable to adapt to different load directions and different types of loads.

GRAPHICAL ABSTRACT



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ABSTRACT

Triply periodic minimal surfaces (TPMS) have emerged as a suitable tool for designing porous biomaterials. One of the well-known TPMS structures is the gyroid structure. Different types of gyroid porous structures (normal and deformed gyroid structures) with different porosities have been designed and fabricated by Electron Beam Melting technology with the purpose of analysing the mechanical properties under compression and torsion loads. Then, some of them have also been studied by finite element method for different load directions. The compression tests demonstrated that the deformed gyroids presented high stiffness and strength with loads in the longitudinal direction of the structures, especially when the deformed gyroids were reinforced with a shell. The torsion tests showed that the normal gyroids presented better torsional stiffness and strength than the deformed gyroids, with high CAD porosities (90%). However, no significant differences between both structures were found for low CAD porosities (75%). Finite element analysis showed that when the loads adopted a 45° angle with regard to the longitudinal axis of the structure, the normal gyroids presented more homogeneous behaviour than the deformed gyroids. In summary, gyroid porous titanium structures presented good and versatile stiffness and strength to be used for correction of bone defects.

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1. Introduction

In recent years, new manufacturing technologies, known as additive manufacturing (AM), have been placed on the market. They are capable of manufacturing pieces from powder achieved from different materials by means of a controlled fusion process and the consolidation of the

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material with a layer-by-layer process. One of these technologies is the so-called Electron Beam Melting (EBM), which uses titanium alloy. This technique has evolved in such a way that allows working in a trustworthy and repetitious manner with implantable titanium alloys. This has enabled the manufacturing of porous geometries in titanium, which prove a feasible solution for bone reconstruction [1]. This technology perfectly adapts to special manufacturing needs of custom-made implants [2,3]. Their application in long bone reconstructions is currently being researched, as they may present areas with high mechanical loads [4]. In addition to EBM, there are other additive manufacturing techniques based on powder-bed methods, such as selective laser melting (SLM) and selective laser sintering (SLS), which may be suitable for porous metal scaffolds [5].

The use of highly porous titanium structures represents a great differentiating element since they have evidenced good biocompatibility and shown sufficient bone ingrowth [6,7]. By using different typologies and geometry parameters, it is possible to modify the variables that contribute to the success of porous implants, such as density, porosity, porous size, stiffness, strength, etc. In addition, the lower stiffness of the porous prosthesis or implant in comparison to the solid implant mitigates the stress shielding effect that may appear in the location of the implant insertion [8,9], thus ensuring primary or mechanic stability. The closer the stiffness of the implant to that of the bone which is being replaced, the higher the stability and probability of long-term success [10]. On the other hand, porosity allows a progressive internal regeneration of the bone tissue thanks to vascularization, as it integrates the implant with the bone, ensuring secondary or biologic stability. The permeability is another major property since it allows the blood to transport cell nutrients and growth factors through porous implants [11].

Previous research has carried out experimental analysis of different types of titanium porous structures for biomedical applications. The most studied are: cubic [12–15], diamond [9,16,17], rhombic dodecahedron [12,18], and variations of these structures (truncated structures) [12]. Another type of porous structures, which has proven to be suitable for biomorphic scaffold designs, are triply periodic minimal surfaces (TPMS) [19–23]. Yan et al. [19] investigated Ti6Al4V TPMS structures for bone implants and concluded that applying porosity to the implant can reduce the equivalent stiffness (Young's modulus) and thus the stress shielding might be reduced, which, in turn, would increase the longevity of the implants. Moreover, TPMS structures have shown a good fatigue behaviour [22,23]. Due to the continuous curvature of their struts, the effect of stress concentrators at nodal points is eliminated. Another advantage is that they have a good permeability and, therefore, a suitable architecture to provide cell penetration [21,24,25].

One of the well-known TPMS is the gyroid structure [26]. Yan et al. [27] evaluated 316 L stainless steel gyroid cellular lattice structures, manufactured by SLM, and concluded that both the yield strength and the Young's modulus increase with the increment in the volume fraction. Olivares et al. [25] claimed that the structures with less layer perpendicular to the fluid vectors (such as gyroid structures) may be suitable for cell attachment by providing a larger area submitted to an adequate range of mechanical stimuli. In a previous work, we studied the compressive behaviour of gyroid porous structures with regard to their strut orientation, and we concluded that for certain angles, the gyroid structures showed a good strength to weight ratios [28]. In the same way, Challis et al. [29] found that gyroid structures had high specific strength and stiffness; nevertheless, they proposed an optimised structure that revealed better Young's modulus and compressive strength to weight ratios than those of gyroid structures. In the abovementioned studies, mechanical tests were performed only in axial direction and consequently, the behaviour in other directions or other types of mechanical loads, such as torsion, remains unknown.

Different types of gyroid porous structures (normal gyroid structures and deformed gyroid structures) with different porosities were designed and fabricated for the purpose of analysing the stiffness and

the strength under compression and torsion loads. Then, some of them were studied by finite element method for different load directions. The hypothesis is that gyroid porous structures might be suitable to better resist the different types of load that could appear if they were used as bone scaffolds.

2. Materials and methods

2.1. Design and fabrication

Several gyroid porous structures were designed following Eqs. (1):

$$F(x, y, z) = a (\sin x \cos x) + b (\sin x \cos z) + c (\sin z \cos y) + \alpha \quad (1)$$

Where a , b and c are chosen to deform the gyroid. The constant α is chosen to give the desired solid fraction, and x , y and z are the three spatial directions that each range over an interval of length 2π to generate a single unit cell. Two types of gyroid porous structures with different porosity were studied: normal gyroid and deformed gyroid. The shape of the pores of the normal gyroid structures were spherical, whereas the deformed gyroid structures were ellipsoidal with the largest radius in the direction of the longitudinal axis. Two special structures were also designed: the first was the same as the deformed gyroid 90, but adding a small shell (1 mm thickness) to its edges to reinforce it; the second was a deformed gyroid on two planes, i.e., with different projections on two orthogonal planes. Fig. 1 shows photographs of the different structures and CAD with the shape and size of its pores. The gyroid unit cells were generated in K3Dsurf software (<http://k3dsurf.sourceforge.net>). They 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 specification.

The structures were manufactured using EBM developed by Arcam AB (Krokslätts Fabriker, Mölndal, Sweden). To that end, they were built layer-by-layer (50 μm) on a stainless steel start plate and selectively melted according to the input geometry with a beam current of 44 mA. A voltage of 60 kV and electron beam size of 200 μm were used and the process was kept under vacuum at 10^{-3} mbar, controlled by using helium as a regulating gas. A constant temperature of roughly 700 °C was maintained inside the vacuum chamber throughout the build. Titanium alloy (Ti6Al4V) powder was used as raw material, with an average particle diameter of 50 μm . No heat treatment or other post processing was applied to the samples.

To obtain the apparent density, the structures were measured (obtaining the apparent volume) and weighed on a precision balance scale (50 g $\pm$ 0.01 g). All measurements were carried out at room temperature (20 $\pm$ 2 °C). The porosity P was calculated as:

$$P = (1 - \rho/\rho_0) \cdot 100\% \quad (2)$$

where ρ is the apparent density and ρ_0 is the bulk alloy density (4.42 g/cm³) [1].

2.2. Mechanical testing

Two kinds of mechanical testing were carried out: uniaxial compression tests and torsion tests.

The compression tests were carried out following the international standard ISO 13314: Mechanical testing of metals - Ductility testing - Compression test for porous and cellular metals. The number of each type of porous structure tested was 5. Each test was conducted at a speed of 0.5 mm/min. The upper head was articulated and the load was applied onto the plain plates placed on the upper and lower sides of the specimens. The measurement of the load was obtained with the load cell of the test machine itself. However, in order to measure

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