Metal functionally graded gyroids: additive manufacturing, mechanical properties, and simulation

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Abstract
Functionally graded materials raise considerable interest in the biomedical research. In particular, gyroid structures are suitable for bone tissue engineering applications, allowing to emulate the porosity of the inner part of the bone. In this frame, the mechanical properties of 17–4 PH steel gyroids made by additive manufacturing have been investigated. Three design methods have been implemented, i.e., thickness graded, size graded, and uniform, to address the lack of knowledge in the area of stainless-steel scaffolds aiming at providing a map of the mechanical properties. Compressive mechanical properties absorbed energy and absorption efficiency have been found for the aforementioned design methods. Furthermore, defects and collapse behavior have been analyzed: imperfections have been detected in the thin-walled areas of the graded samples. Nevertheless, under given conditions, the graded samples have mechanical properties comparable to those of uniform ones, exhibiting a controlled layer-by-layer collapse mechanism and consequent weight reduction. The Gibson-Ashby models have been implemented, and the calibration coefficients have been compared with other research works. A FEM-based numerical model has been proposed to reproduce the mechanical properties of the mentioned structures finding critical issues in the representation of defects. In this frame, the resulting Gibson Ashby calibration coefficients are in good agreement with the literature and reveal the graded samples have a bending-dominating behavior sustaining larger strains than the uniform case, giving the ground for high energy absorption applications. Furthermore, the FEM analyses are in good agreement with the literature providing a reliable tool to further investigate the metal functionally graded gyroid field.

Keywords Additive manufacturing · Functionally graded materials · Lattice structures · Simulation

1 Introduction

Human bones perform crucial structural and protective roles, such as support of the body movement and protection of vital organs. Consequently, congenital or acquired injuries lead to severe health consequences. In this frame, bone tissue engineering (BTE) has been developed as a multidisciplinary field aiming at inducing bone regeneration using biomaterials, cells, and factor therapy [1, 2]. A macroscale void fraction is crucial for promoting the adhesion and mass transport of nutrients over the scaffold and achieving both osteoconductivity and osteoinductivity [3]. Thus, scaffolds must be designed as a porous structure limiting detrimental effects on the resulting mechanical properties. As a consequence, lightweight structures represent an interesting approach for the biomedical sector, owing to their significant advantages, like weight reduction, elevated strength, good shock resistance, and excellent capacity of energy absorption.

Gibson and Ashby defined a cellular structure as a material composed of an interconnected network of solid struts or plates forming the edges and faces of the cells; foams and honeycombs are included [4]. Tao et al. [5] classified cellular structures into foams, honeycombs, and lattice structures. In particular, lattices are defined as three-dimensional structures composed of interconnected cells arranged sequentially: the unit cell can be a geometric wireframe composed of interconnected struts (strut-based lattice) or a structure built using a mathematical algorithm as Schoen Gyroid [6]. The Schoen Gyroid lattice is a triply periodic minimal surface (TPMS) structure with high stiffness and strength suitable for automotive, aerospace, and biomedical industries [7–9]. These are 3D surfaces with zero mean curvature that exhibit translational symmetries in three independent directions.

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The aforementioned TPMS structures tend to exhibit high mechanical performance and low density. Gyroid lattice structures have been extensively studied considering their good energy absorption capacity and mechanical properties: in the literature, it was found that gyroid structures made of 316L stainless steel exhibited better stiffness, plateau stress, and energy absorption capability compared to body-centered cubic architectures [10]. Yang et al. found gyroid mechanical performance, such as low anisotropy with a roughly uniform stress distribution [11].

According to the purpose of more effectively exploiting the advantages of gyroid structures, the functionally graded materials (FGMs) have been considered. Cellular structures can be uniform or graded; i.e., FGM uniform lattices refer to the porous structures with uniform distribution of unit cells formed by the same topological shapes and geometric sizes; instead, FGMs are designed with a gradual composition or structure [12, 13] resulting in graded material properties [14]. Porosity in these graded structures affects mechanical and biological properties: high porosity allows nutrient flow and tissue growth. Nevertheless, pores affect the resulting mechanical properties. According to Mahmoud [15], a biomedical scaffold must be designed considering the effective bone features, with the porosity increasing towards the center [16]; the outer part (i.e., the cortical bone) has higher mechanical strength and modulus in comparison with the inner part (i.e., the cancellous or trabecular bone, resembling sponge or foam materials with lower strength) [17].

FGMs can be fabricated using a variety of processing methods. Among them, AM technology allows to strategically control the density and directionality of material deposition within a complex 3D distribution [18], thus allowing customized reconstructions in agreement with age, gender, health conditions, nutrition, and location in the body [19]. As a consequence, AM-ed scaffolds guide and support cell growth enhancing the resulting mechanical properties [20, 21]. Although many AM techniques have been reported in the literature [22, 23], laser-based powder-bed fusion [11, 24, 25] or electron beam melting [26, 27] enable the manufacture of metal biocompatible scaffolds with suitable mechanical properties and accuracy for BTE and orthopedic implants.

In the literature, the mechanical properties of gyroid structures increase with increasing wall thickness and therefore density [28]. As a consequence, considering the same material, void-free structures can show higher strength than gyroids, despite leading to component weighting and poor fluid permeability. According to the specific application, human bones are subjected to multiaxial loads; hence, scientific research needs a large amount of data in order to fully characterize the cellular structures; indeed, Kladosvilarakis et al. studied the bending mechanical behavior of TPMS structures in three distinct relative densities [29], and Polley successfully investigated the compressive fatigue behavior of TPMS structures [30]. Furthermore, Maskery et al. investigated the failure modes in Al-Si10-Mg gyroid and found that the gyroid structures are recommended for energy absorbing applications [31]. Yu et al. studied two TPMS structures, the Schwarz Primitive and Schoen Gyroid; both structures have been designed with uniform and graded density and fabricated using stereolithography. They found out that the graded Schwarz structure absorbed more energy during the compression tests, while energy absorbed in the graded gyroid structure was close to the uniform gyroid structure [32]. The study of Kelly et al. considers the effects of the gyroid design choices and concurrently the effects of SLM parameters on the structure of titanium alloy scaffold: the manufacturer’s default and customized laser parameters were used to examine the effect of input energy density on mechanical properties resulting in increased compressive and tensile fatigue behavior [33].

The Gibson-Ashby (GA) model has frequently been used to predict the mechanical response of foams processed from metal powders [34, 35]; additionally, GA models are widely adopted to investigate the field of AM-ed lattice structures [36–38]. Nevertheless, as emphasized by Maskery et al., in the field of graded structures, there is a lack of knowledge: empirical outcomes are required for lattices of different relative densities, cell types, and density. In particular, the literature on steel lattice structures is extremely limited [39]. The types of stainless steel frequently used in medicine have relatively low corrosion resistance compared to Ti-based alloys but lower manufacturing costs. Moreover, steel is the predominant material in total hip replacement and temporary implants such as fracture plates and screws. Titanium alloys have higher chemical stability; thus, they are preferred in permanent implants. Conversely, Ti alloys have a smaller density and Young modulus than biomedical steels; as a consequence, both the aforementioned metals are relevant in the biomedical domain. This article addresses the lack in the area of stainless-steel scaffolds [40], aiming at providing a map of the mechanical properties of 17–4 PH gyroid lattice structures with different densities and grading strategy. Furthermore, the Gibson-Ashby models have been developed and the calibration coefficients have been compared with other research works. Therefore, a new finite-element simulation approach, depending on the gyroid design parameters, has been also developed to reproduce the mechanical properties of the mentioned structures.

2 Materials and methods

2.1 Gyroid design

The main design parameter of an elementary gyroid unit is the wavelength or unit cell size \( L_0 \). Considering a reference size \( L_0 \), the length \( L_0 \) along each axis is expressed using the scale factor \( k_i \) for the geometric expansion (Fig. 1):
The equation of a 3D gyroid lattice surface \( G \) in an \( xyz \) reference system has been considered [1]:

\[
G = \sin \left( \frac{2\pi x}{L_x} \right) \cos \left( \frac{2\pi y}{L_y} \right) + \sin \left( \frac{2\pi y}{L_y} \right) \cos \left( \frac{2\pi z}{L_z} \right) + \sin \left( \frac{2\pi z}{L_z} \right) \cos \left( \frac{2\pi x}{L_x} \right)
\]

(2)

Concerning the Eq. (3), \( T \) is the wall thickness of gyroids as shown in Fig. 1.

\[
D_i = \frac{L_i}{2} - T
\]

(3)

In this paper, the gyroid structures have been designed using nToplogy software which has several benefits:

- high-performance geometry, regardless of the complexity of the model
- software interconnectivity capabilities [41]

The specimens have a 10-mm radius and a 20-mm lightened height (Fig. 2). Three different relative densities (15%, 25%, 35%) have been considered; for each one of them, three design methods have been implemented: uniform (U), thickness graduation (TG), and void size graduation (SG). In the uniform case, all the design parameters have been taken constant along the manufacturing direction, considering no orientation effect; in the TG design, the wall thickness increases as manufacturing advances; in the SG case, the void size decreases along the building direction as a result of the concurrent variation of \( T \) and \( L_z \) (Table 1).

### 2.2 Manufacturing

Argon-atomized pre-alloyed stainless-steel powder with a mean grain size of 36 μm has been used to manufacture the gyroids. The composition is in compliance with the standard UNS S17400 chromium-copper precipitation hardening steel, offering high strength and corrosion resistance for mechanical applications [42], as well as biocompatibility [43]. The powder has been processed with LPBF fusion using a commercial EOSINT M270 laser sintering system operating in full melting mode. The levels of the governing factors (Table 2) has been set according to previous research works [44, 45].

### 2.3 Testing

The specimens have been subjected to compression tests using an MTS Landmark servo-hydraulic machine with a 250-kN
force range and 3-Hz sampling rate. An extensometer has been used to obtain accurate measurement in the elastic stage (Fig. 2). The testing method has been performed under displacement control.

2.4 Analysis

Considering the results of the compression test, the elastic modulus ($E$) and the yield strength $\sigma_y$ at 0.2% strain have been

| Relative density [%] | Cell size [mm] | Thickness [mm] |
|---------------------|----------------|-----------------|
| 15                  | $L_x = 13$     | $0.55 \div 0.90$|
|                     | $L_y = 13$     |                 |
|                     | $L_z = 13$     |                 |
| 25                  | $L_x = 8$      | $0.50 \div 0.75$|
|                     | $L_y = 8$      |                 |
|                     | $L_z = 8$      |                 |
| 35                  | $L_x = 5.5$    | $0.50 \div 0.60$|
|                     | $L_y = 5.5$    |                 |
|                     | $L_z = 4.8 \div 5.5$ |         |
evaluated. In addition, in compliance with the international reference standard [46], the plateau stress has been measured as the arithmetic mean of the stresses in the range between 20 and 30% engineering strain. Finally, the absorption efficiency \( \eta(\varepsilon) \) has been calculated as the ratio of the cumulative energy absorbed per unit volume \( (W_\varepsilon) \) up to a given strain \( \varepsilon \), and the corresponding stress \( \sigma_\varepsilon \), as suggested by Maskery et. al. [47]

\[
\eta(\varepsilon) = \frac{W_\varepsilon}{\sigma_\varepsilon} = \frac{1}{\sigma_\varepsilon} \int_0^\varepsilon \sigma d\varepsilon \quad (4)
\]

Namely, \( \varepsilon_D \) is the value of the densification strain, as proposed by several authors [48, 49]: this is considered the practical limit for energy absorption applications; indeed after this strain value, the cell structure will continue to absorb energy, but transferring stress throughout the structure as the scaffold behaves like a rigid connector. This can result in injury to the human body [38].

The properties of the gyroid structures have also been analyzed with the laws proposed by Gibson and Ashby, where the normalized elastic modulus, normalized yield strength, and densification strain can be expressed as a function of the fractional density \( \rho \) of the cellular structure, i.e., the ratio of the graded density to the bulk density.

\[
\frac{E}{E_r} = C_1 \rho^n \quad (5)
\]

\[
\frac{\sigma}{\sigma_{y,r}} = C_2 \rho^m \quad (6)
\]

\[
\varepsilon_D = 1 - \alpha \rho \quad (7)
\]

The reference elastic modulus \( E_r \) and yield strength \( \sigma_{y,r} \) of the material has been set at 170 GPa and 560 MPa, respectively, resulting from the average of the mechanical properties provided by the metal powder manufacturer. Therefore, calibration parameters \( C_1, n, C_2, m, \) and \( \alpha \) have been calculated.

### 2.5 Setting up the numerical simulation

The simulation specimens have been designed for each lightening geometry with two disk-shaped bases to apply the compression boundary conditions. The uniform specimens have been redesigned considering a lightening of the uniform samples aiming at reducing the components weight with no significant reduction in mechanical properties. In this framework, with the aid of the software nTopology, the surface discretization has been performed using a triangle mesh with an average element size of 0.1 mm. Subsequently, the surface mesh has been converted into a volumetric one using a free tetrahedral mesh algorithm implemented in COMSOL Multiphysics, to handle the geometric complexity of the lightening components (Fig. 3). The geometric order of the mesh elements was quadratic (second order nodes) to increase the accuracy of the simulation (Table 3), as already described in a simulation paper [50]. The overall quality of each mesh has been evaluated in terms of skewness, which is the default measure for many mesh types: in the case of a degenerate element, it ranges between 0 and 1, the latter for a perfect triangular element. The elements have been

| Parameter                              | Value |
|----------------------------------------|-------|
| Laser power (W)                        | 195   |
| Scanning speed (m/s)                   | 0.75  |
| Hatch spacing (μm)                     | 100   |
| Scan length (mm)                       | 20    |
| Layer thickness (μm)                   | 20    |

Table 2: Values of the process parameters in laser powder-bed fusion
marked using the color scale from green to red (Fig. 4). Based on this, an average skewness value has been found for each virtual sample. The total amount of elements in each mesh, the minimum, and the average quality values are given in Table 4.

Furthermore, the software COMSOL Multiphysics has been used to simulate the behavior of the virtual samples aiming at validating the empirical procedure. The mentioned software has been chosen due to the model setting flexibility and the accuracy of the numerical analysis [51].

The essential mechanical properties as density, Young modulus, yield strength, Poisson ratio, and tangential isotropic module have been found in the literature [50].

The structural mechanics module has been implemented to study the mechanical performance in both the elastic and plastic deformation domains. The boundary conditions have been applied on the two bases emulating the settings of the empirical test: fixed displacement has been set on the upper face and a displacement with a 3 mm/min velocity has been imposed on the lower face.

The resulting values of displacement and force applied on the compressed face have been detected using two virtual surface probes, returning the respective average measurements on the nodes of the mesh (Fig. 3). The response of each probe has been analyzed with a time-step of 0.1 s over a 60 s full-time study.

3 Results

3.1 Manufacturing accuracy

Defect analysis is crucial to justify the mechanical behavior of the manufactured structures. In this framework, visible printing defects have been found for samples with a density of 15% and less significant imperfections have been detected for graded samples with a density of 25% (Table 5).

3.2 Mechanical properties

The mechanical properties have been analyzed evaluating the stress vs. strain curves, the cumulative absorption energy, the absorption efficiency, and the collapse behavior of all the manufactured gyroid structures.

According to Table 6, all the uniform samples exhibit a uniform collapse thanks to their regular geometry; on the other hand, the graded structures exhibit a sequential layer-by-layer collapse with the initial failure localized in the bottom layer, i.e., in the low-density zone (Table 6). Thus, all the graded samples lead to predictable behavior under loading. Nevertheless, the graded strategy, in both the TG and SG designs, results in a reduction in mechanical properties compared to U-structures (Table 7).

The stress vs. strain compression curves match the trends provided by Gibson and Ashby for cellular solid foams with a linear elastic stretch in the first stage of the test, followed by a stress plateau and a final densification regime leading to increased stiffness (Figs. 5, 6, 7, 8, 9, and 10). Analyzing stress vs. strain graphs, in all the cases of 15% density and in all the graded samples with 25% of density, oscillations have been detected; these have been typically found in elastic-fragile materials of cellular solids and are due to local failures induced by manufacturing defects. On the other hand, a more regular trend has been found for the remaining samples. The overall mechanical behavior of any graded structure is generally lower than its uniform counterpart with the same density. Consequently, the reduced stiffness at the lower levels of graded structures, where thinner thickness and/or larger average void sizes are applied, is not balanced by the larger thickness and/or smaller void sizes at the upper levels. As shown in Table 7, comparing the stiffness of the uniform case with that of the SG and TG design, at 15% density, the graded strategy has detrimental effects on stiffness, as consequence of the manufacturing defects detected in Table 5; indeed, at 25% and 35% density, where the defects are less evident, the stiffness reduction (ΔE), calculated as
the ratio of the absolute value of the difference between the uniform stiffness and the graded one, to the value of the uniform stiffness, is remarkably reduced. Hence, although the graded approaches do not provide improved mechanical properties, they can be adopted in order to benefit from their sequential layer-by-layer collapse. Considering the absorption efficiency, at first, the cumulative absorbed energy is nearly linear in both the elastic and the plateau stages, hence before densification where a significant increase is experienced because the samples are reduced to compact structures. Moreover, fluctuations similar to those found for the stress vs. strain diagram have been found for samples with 15% density and 25% density (Fig. 11). As shown in Fig. 5, densification stress decreases with increasing density; thus, the complete structure failure is achieved at reduced strains with a corresponding increase in absorbed energy. In addition, considering the graphs of absorbed energy (Figs. 12, 13, 14, 15, 16, and 17), since uniform structures have shown superior mechanical properties (Fig. 11), they also require more energy to reach the same strain level of their graded counterpart. Furthermore, absorbed energy represents the area subtended by the stress–strain curve and provides information about the deformation magnitude at a certain stress level. In this context, densification strain of the structure generally decreases with increasing density; hence, the collapse of the structure is achieved at reduced deformation and increased absorbed energy. Considering the same density level, the absorbed energy curves exhibit a slight influence.

| Surface and volumetric elements, minimum quality element, overall quality, and computational size | Triangular elements | Tetrahedral elements | Minimum quality of the entire mesh | Average quality | Size [GB] |
|---|---|---|---|---|---|
| 15U | 212,482 | 162,820 | 0.1842 | 0.6637 | 3.73 |
| 15TG | 166,216 | 142,885 | 0.1906 | 0.6594 | 7.73 |
| 15SG | 226,676 | 138,078 | 0.0886 | 0.6595 | 6.93 |
| 25U | 277,742 | 189,420 | 0.0733 | 0.6697 | 7.29 |
| 25TG | 250,044 | 175,108 | 0.0472 | 0.6542 | 3.99 |
| 25SG | 327,016 | 165,496 | 0.2056 | 0.6604 | 8.16 |
| 35U | 416,268 | 326,056 | 0.1712 | 0.6617 | 13.83 |
| 35TG | 373,102 | 188,956 | 0.1711 | 0.6618 | 12.66 |
| 35SG | 395,776 | 361,104 | 0.1083 | 0.6597 | 17.26 |

| Defect analysis: example of significant imperfection of the gyroid structures | 15% density | 25% density |
|---|---|---|
| U | ![Image](image1.png) | ![Image](image2.png) |
| SG | ![Image](image3.png) | ![Image](image4.png) |
| TG | ![Image](image5.png) | ![Image](image6.png) |
from the type of grading strategy; indeed, analyzing the graphs related to the absorption efficiency (Figs. 15, 16, and 17), the curve related to the uniform case diverges from those related to the graded one, implying under the same stress–strain condition the uniform specimens are able to absorb more energy than the graded ones.

### Table 6
Strain progress under compression loading for each sample up to the densification regime

|      | 0% | 5% | 10% | 20% | 30% | 40% | 50% | 60% | 70% |
|------|----|----|-----|-----|-----|-----|-----|-----|-----|
| 15   | U  |    |     |     |     |     |     |     |     |
|      | TG |    |     |     |     |     |     |     |     |
|      | SG |    |     |     |     |     |     |     |     |
| 25   | U  |    |     |     |     |     |     |     |     |
|      | TG |    |     |     |     |     |     |     |     |
|      | SG |    |     |     |     |     |     |     |     |
| 35   | U  |    |     |     |     |     |     |     |     |
|      | TG |    |     |     |     |     |     |     |     |
|      | SG |    |     |     |     |     |     |     |     |

Table 7 Gyroid structures mechanical properties under compressive load: elastic modulus ($E$), yield strength ($Y_t$), plateau stress ($\sigma_{pl}$), densification strain ($\epsilon_d$), absorption energy ($W_d$), stiffness reduction ($\Delta E$)

|      | $E$ (GPa) | $Y_t$ (MPa) | $\sigma_{pl}$ (MPa) | $\epsilon_d$ (%) | $W_d$ (MJ/m$^3$) | $\Delta E$ (%) |
|------|-----------|-------------|---------------------|------------------|------------------|----------------|
| 15U  | 4.9       | 12          | 16.6                | 76               | 21.5             | /              |
| 15SG | 2.3       | 7           | 15.3                | 77               | 22.1             | 53             |
| 15TG | 1.2       | 11          | 15.2                | 75               | 20.5             | 76             |
| 25U  | 8.5       | 29          | 57.8                | 65               | 40.2             | /              |
| 25SG | 7.9       | 11          | 45.8                | 60               | 33.9             | 7              |
| 25TG | 7.5       | 19          | 44.9                | 60               | 39.9             | 12             |
| 35U  | 12.8      | 47          | 110.5               | 51               | 52.4             | /              |
| 35SG | 11.8      | 40          | 81.7                | 50               | 42.04            | 8              |
| 35TG | 9.7       | 37          | 92.9                | 40               | 33.5             | 24             |
3.3 Gibson-Ashby models

GA laws have been used in order to further analyze the mechanical behavior of the specimens for each grading strategy (Figs. 18, 19, 20, and 21): mechanical properties increase with increasing relative density, as well as, densification strain decrease. As a consequence, according to the experimental outcomes, the uniform samples require more energy to be deformed than the graded ones. Indeed, mechanical properties, yield strength and elastic modulus, increase with increasing component density and are proved to be reproducible with GA models. Conversely, densification strain decreases with increasing density as under the same load, denser components, and therefore components with larger resistant sections deform less.

The coefficients $C_1$ and $C_2$ are geometrical parameters; conversely, the scaling exponents $n$ and $m$ indicate the mode of deformation. A value of less than 2 for the modulus and less than 1.5 for the strength denotes stretching dominating deformation, while a value greater than 2 for the modulus and greater than 1.5 for the strength denotes bending-dominating deformation [52]. In this frame, the graded samples show a bending-dominating behavior sustaining larger strains than the uniform case, giving the ground for high energy absorption applications.

The obtained calibration coefficients are in good agreement with the expected values reported in the work of Gibson and Ashby [53]. Deviations can be ascribed to the different native application; indeed, GA model was developed for applications in cellular structures such as foams without any grading method. Furthermore, the calibration coefficients have been compared with other works in the literature in the field of gyroid grading structures: higher values for both $C_2$ and $m$ can be found when computing a regression law that contemplates different failure mechanisms (Table 8). The regression equation is strongly influenced by the cell type, the design approach, the material, and the manufacturing.
technology, with a considerable effect on the calibration parameters. As a consequence, several experiments are required to collect a sufficient amount of data in order to industrialize the FGM structures.

3.4 Results of the numerical simulation

For each condition of design, the stress vs. strain diagram has been obtained. The resulting mechanical properties are reported in Table 9.

At first, the simulated yield strength for graded specimens at 15% density is missing due to their irregular geometry; indeed, the graded strategy leads to extremely thin regions resulting in over-concentration of stress (Fig. 22), i.e., singularity areas, inhibiting the simulation convergence. Of course, in the case of empirical compression tests, the effect of singularities is a non-limiting condition as compression continues even after crack initiation. These cracks are undetectable during the laboratory test, and they can also be interpreted as noise in the compression process. The over-concentration of stress occurs mainly at 15% density due to the extreme reduction in wall thickness. As a consequence, it is inferred that the most reliable conditions are the ones with higher density.

Interestingly, the stiffness of the uniform condition is higher than the graded one, both in the simulated and in the experimental scenario: in the experimental case, this is ascribed to printing imperfections. Nevertheless, since the same performance results from the simulation as well, where a defect-free sample is considered, it must be concluded that the regions of increased thickness in FG samples are not adequate to compensate the reduced stiffness of the thinner regions. Furthermore, according to experimental tests, graded structures exhibit a controlled layer-by-layer failure mechanism (Fig. 23).

The mismatch between simulated and actual value is in agreement with results obtained in the literature for TMPS structures [59, 60]. This substantial deviation results from the

Fig. 7 Stress vs. strain curves in the size graded design

Fig. 8 Graph of the stress vs. strain curve with emphasis on the elastic and plateau section (SG)
**Fig. 9** Stress vs. strain curves in the thickness graded design

**Fig. 10** Graph of the stress vs. strain curve with emphasis on the elastic and plateau section (TG)

**Fig. 11** Summary graph of the mechanical properties of all the samples included in the experimental plan
**Fig. 12** Absorbed energy vs. strain curve for each design strategy at 15% fractional density

**Fig. 13** Absorbed energy vs. strain curve for each design strategy at 25% fractional density

**Fig. 14** Absorbed energy vs. strain curve for each design strategy at 35% fractional density
**Fig. 15** Absorbed efficiency vs. strain curve for each design strategy at 15% fractional density

![Graph](image1)

**Fig. 16** Absorbed efficiency vs. strain curve for each design strategy at 25% fractional density

![Graph](image2)

**Fig. 17** Absorbed efficiency vs. strain curve for each design strategy at 35% fractional density

![Graph](image3)
Fig. 18 Gibson-Ashby models of normalized elastic modulus and yield strength in the uniform case

Fig. 19 Gibson-Ashby models of normalized elastic modulus and yield strength in the SG case

Fig. 20 Gibson-Ashby models of normalized elastic modulus and yield strength in the TG case
The fundamental differences between the real specimen and the simulated one, the real sample presenting defects that cannot be reproduced in the software. In addition, the poor surface finish of the as-built components can trigger cracking.

As regards the condition with 35% density, it is worth noting that the TG structures exhibit a simulated elastic modulus higher than the SG ones, since the gradation of the wavelength along the manufacturing direction compensates the detrimental effects induced by the imperfections concentrated in the thin-walled area, thus resulting in a higher overall strength. Therefore, in the actual sample, TG specimens have defects mainly distributed in the thin-walled area, these producing evident impact on the overall performance of the specimen, limiting the benefits induced by the TG gradation strategy.

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**Fig. 21** Gibson Ashby model of densification strain

**Table 8** GA calibration coefficients compared with experimental or numerical studies for TPMS structures

| Features of the structures | Calibration parameters of the Gibson-Ashby laws | Coefficients $R^2$ |
|-----------------------------|-----------------------------------------------|--------------------|
| Material Process Cell type  | $C_1$ $n$ $C_2$ $m$ $\alpha$                  | For E For $\sigma_y$ For $\alpha$ |
| 17-4 PH LPBF TPMS, U        | 0.24 1.12 0.47 1.62 1.42                       | 0.998 0.997 0.995 |
| 17-4 PH LPBF TPMS, SG       | 0.62 2.00 0.44 1.96 1.67                       | 0.952 0.912 0.993 |
| 17-4 PH LPBF TPMS, TG       | 1.11 2.60 0.26 1.40 1.49                       | 0.909 0.971 0.978 |
| [53] Ti6Al4V LPBF TPMS-gyroid | 0.19 1.71 1.31 1.83 | 0.997 0.997 |
| [54] AISI 316L LPBF TPMS-gyroid | 0.19-0.25 2* 1.60-2.82 1.5* 2.51-2.66 | 0.994 0.993 |
| [55] Ti6Al4V LPBF TPMS-diamond | 0.24 1.9 0.53 1.51 | 0.7655 0.681 |
| [56] Ti6Al4V LPBF, EBM TPMS-gyroid | 0.18 1.59 0.58 1.68 | 0.994 0.999 |
| [57] TiB graded LPBF TPMS-gyroid | 0.24 1.5 2.12 2.3 | 0.996 0.997 |
| [58] Ti6Al4V LPBF TPMS-based | 0.21 1.68 1.4 1.72 | 0.996 0.997 |

**Table 9** Properties extracted by simulations and percentage mismatch to the experimental values

| Sample | Young modulus (MPa) | Yield strength (MPa) | Mismatch on Young modulus (%) | Mismatch on yield strength (%) |
|--------|---------------------|----------------------|--------------------------------|-------------------------------|
| 15U    | 5.2                 | –                    | 5.1                            | –                             |
| 15TG   | 5.0                 | –                    | 75.9                           | –                             |
| 15SG   | 3.8                 | 20.2                 | 39.2                           | 65.3                          |
| 25U    | 12.7                | 54.9                 | 23.7                           | 47.2                          |
| 25TG   | 11.6                | 55.0                 | 35.4                           | 62.6                          |
| 25SG   | 8.9                 | 50.8                 | 11.2                           | 78.3                          |
| 35U    | 16.3                | 95.9                 | 21.5                           | 51.0                          |
| 35TG   | 15.6                | 66.7                 | 38.0                           | 44.5                          |
| 35SG   | 13.9                | 78.0                 | 14.9                           | 48.7                          |
In this work, the mechanical behavior, the failure process, and the energy absorption characteristics of the functionally graded gyroid have been studied through a combination of experimental and numerical methods. In this framework, the samples with 15% and 25% density showed a higher percentage of defects in the thin-walled areas than the 35% ones, as in the low-density case additive technologies work to the limit of allowed dimensions. A map of the mechanical properties of 17–4 PH gyroid lattice structures under different densities and grading strategy has been obtained exhibiting a slight reduction in mechanical properties in the graded condition. Nevertheless, the functionally graded material showed a different collapse process under compression from uniform structures, failure coming sequentially starting with the least dense regions. Furthermore, the Gibson-Ashby coefficient have been obtained with good agreement in the literature, providing a reliable model to predict the behavior of the graded sample exhibiting a bending-dominating deformation suitable for high energy absorption applications. The compression behavior has been simulated through FEM tools obtaining promising results, but a mismatch between experimental tests and simulations occurs due to singularities in the wall area and lack of modeling of defects, although in agreement with the literature for TMPS structures. Finally, the resulting gyroids provide a layer-by-layer controlled failure mechanism with overall good mechanical behavior.

4 Conclusions

In this work, the mechanical behavior, the failure process, and the energy absorption characteristics of the functionally graded gyroid have been studied through a combination of experimental and numerical methods. In this framework, the samples with 15% and 25% density showed a higher percentage of defects in the thin-walled areas than the 35% ones, as in the low-density case additive technologies work to the limit of allowed dimensions. A map of the mechanical properties of 17–4 PH gyroid lattice structures under different densities and grading strategy has been obtained exhibiting a slight reduction in mechanical properties in the graded condition. Nevertheless, the functionally graded material showed a different collapse process under compression from uniform structures, failure coming sequentially starting with the least dense regions. Furthermore, the Gibson-Ashby coefficient have been obtained with good agreement in the literature, providing a reliable model to predict the behavior of the graded sample exhibiting a bending-dominating deformation suitable for high energy absorption applications. The compression behavior has been simulated through FEM tools obtaining promising results, but a mismatch between experimental tests and simulations occurs due to singularities in the wall area and lack of modeling of defects, although in agreement with the literature for TMPS structures. Finally, the resulting gyroids provide a layer-by-layer controlled failure mechanism with overall good mechanical behavior.
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Availability of data and material Data required to reproduce these findings have been given in the text. If needed, they can be shared upon request.

Code availability Data required to reproduce the code for the optimization are given in the text. If needed they can be shared upon request.

Declarations

Ethics approval This material is the authors’ own original work, which has not been previously published elsewhere.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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