Lattice structures in stainless steel 17-4PH manufactured via selective laser melting (SLM) process: dimensional accuracy, satellites formation, compressive response and printing parameters optimization

Alcide Bertocco1 · Gianluca Iannitti2 · Antonio Caraviello3 · Luca Esposito4

Received: 16 November 2021 / Accepted: 16 February 2022 / Published online: 23 March 2022
© The Author(s) 2022, corrected publication 2022

Abstract
By the term, lattice structures are intended topologically ordered open-celled structures consisting of one or more repeating unit cells. Technological development and especially the growth of the additive manufacturing (AM) industry allows innovative structural design, including complex lattice structure. Selective laser melting (SLM) is an AM process that enables the manufacture of space filling structures. This work investigated the influence of the most important process parameter settings on lattices printability, focusing on the geometrical accuracy, the quantity of powders adhered to the main frame (satellites) and their compression behaviour. The process parameters such as the laser power, scan speed and layer height affect vigorously the design, quality and mechanical properties of the part. The aim of the paper is to evaluate how different parameter combinations affect the cellular structures’ printing. Twenty-four lattice structures with cubic and rhombic dodecahedron unit cells made of stainless steel 17-4PH (AISI-630) were printed using different combinations of SLM process parameters. Each structure was analysed considering its geometrical, topological and mechanical properties. Finally, the best parameter combination was evaluated comparing results achieved. Although this work investigated the 17-4PH stainless steel, physical principles related to the printing process described are generally true for the SLM process. Therefore, the adopted approach could still be suitable also for all the other materials commonly used with this AM technology.

Keywords Additive manufacturing · Lattice structures · Selective laser melting · Compression behaviour · Optimization procedure · Printing parameters

1 Introduction
Cellular structures are a class of materials, which exhibit a combination of high-performance features such as high strength accompanied by a relatively low mass, good energy absorption and good thermal and acoustic insulation properties. Technological development and especially the growth of the additive manufacturing (AM) industry allows innovative structural design, using, if required, complex cellular solids. The rapid developments in additive manufacturing techniques open new horizons for the production of open cellular solids with desirable mechanical properties [1–6]. Metal cellular structures can be classified in two common types: stochastic porous structures (foams) and periodic ordered cellular lattice structures. Foams have a random distribution of open or closed voids, whereas metal periodic cellular lattices are
ordered structures generated by repeating a unit cell in a bidimensional or three-dimensional domain [7–9]. These cells are defined by the dimensions and connectivity of their constituent beam elements (or struts), which are connected at specific nodes. Struts are ideally cylindrical beams with a constant diameter that extended between two adjacent nodes (Fig. 1). Light weight lattice structures have attracted research attention due to their customizable mechanical performance and unique multi-functional characteristics, such as high specific stiffness, strength, energy dissipation and the possibility to get a negative Poisson’s ratio [10–13]. The properties of these structures are strictly related to the material from which they are made, their relative density and the topology of the unit cell could vary widely with them [14]. Also graded lattice structures are interesting the research world in the last years [15–18]. Due to the complexity of their geometry, traditional manufacturing processes are not suitable for lattices production. Additive manufacturing technologies are suitable to produce complex structures since parts are built in a layer-by-layer manner. There are many different technologies used in the metal AM field available today and they can be classified by the energy source or the way the material is being joined. Classification is also possible by the group of materials being processed, such as plastics, metals or ceramics. Also, cold spray coating processes could be classified as an AM technology [19].

Powder-bed based system is a category of AM technologies. It uses a powder deposition method consisting of a mechanism to spread a powder layer onto a substrate plate and a powder reservoir. Usually, the layers could set with a thickness value from 20 to 100 μm. Once the powder layer is distributed, it is locally melted using an energy beam applied properly. Selective laser melting (SLM) is a specific powder-bed AM technology that uses a scanning laser to sequentially melt vectors and layers of metal powders under an inert atmosphere. The significant advantage of SLM technology includes high flexibility and achievable component complexity, enabling the fabrication of highly complex lattice structures that are not otherwise manufacturable. This technology is a highly complex process, due to the large thermal gradients, local overheating, need for supports structures, and thermal powder bed. SLM is highly dimensional, with nearly 130 variables of influence on final component quality [20–22]. Some of the most important process parameters are laser beam size, laser power, laser scanning speed, hatch spacing and the layer thickness. Their combination influences the energy density brought to the powders:

\[ D = \frac{P}{vht} \]

where \( D \) is the energy density \((J/mm^3)\), \( P \) the laser power \((W)\), \( v \) the scan speed \((mm/s)\), \( t \) the layer thickness \((mm)\) and \( h \) the hatch spacing \((mm)\). Crucial for AM technologies and in particular for the SLM process is the use of support structures to build overhang section when its angle with respect to the substrate is less than certain degree.

Many works have investigated how process parameters and geometrical features influence fabrication of cellular lattice structures using the SLM process. Bertocco et al. [21] investigated the influence of many parameters on the printability of cubic lattice and how they affect their compression behaviour. Brooks et al. [23] studied the SLM production of 316L stainless steel lattice structures considering combination of three element types including pillar, diagonal and octahedral elements. They found the elements that inclined lower than 30° with respect to the horizontal plane were difficult to realize. Santorinaios et al. [24] studied open cellular lattice structures with the cell sizes of 1.25, 2.5 and 5 mm. They found that the SLM process cannot build horizontal struts. In this work, challenges of lattice structures manufacturing via SLM technologies were investigated. Printability of many lattice structures in stainless steel 17-4PH (AISI-630) printed by SLM was

| Table 1 | Nominal chemical composition of steel powder [wt%] |
|---------|-----------------------------------------------|
| Fe      | 0–0.07 | Mg   | 0–1.00 | P    | 0–0.04 | S    | 0–1.00 | Cr   | 15.00–17.50 | Ni   | 3.00–5.00 | Cu   | 3.00–5.00 |
| Balance |        |      |        |       |        |      |        |      |              |      |           |      |           |
considered. The lattice structures investigated are (i) cubic with volume fraction (VF) of 7.7%; (ii) cubic with VF = 11%; (iii) rhombic dodecahedron with VF = 21%; and (iv) cubic with VF = 13%. This work focused mainly on structures with cubic cells. This geometry was chosen because of the presence of both vertical and horizontal struts, respectively, the easier and more difficult to print. A comparison between results in terms of satellites formation, dimensional analyses and compression behaviour of structures printed with different parameter combination is proposed. By using the term satellites means the metallic powders adhered to the main structure after the printing process. An important aspect that can influence satellites formation is the thermal diffusion [25]. It occurs between loose powder and solid material due to big temperature difference, leading to powder particles sticking to the strut surface. In conclusion, the compression response and dimensional analysis are used together as a quality check of printed lattice, identifying the best set among the analysed parameters. Process parameters under investigation were laser power, scanning velocity, hatch spacing and contour offset. To analyse how these parameters directly affect the printability of lattice structures, no mechanical or thermal treatment was conducted after the printing process.

2 Materials and methods

2.1 Materials

Atomized 17-4PH (AISI630) stainless steel powder with average particle size in the range 15–45 μm was used as a starting material to produce SLM samples. According to ASTM A564 / A564M - 13 UNS S17400 [26], the chemical composition is shown in Table 1. Steel powders were provided by Carpenter Additive, a business unit of Carpenter Technology Corporation. The SEM micrograph of the stainless steel powder is shown in Fig. 2. Most of the powder particles exhibit a nearly spherical shape and smooth surfaces, but some small particles with the size of less than 10 μm stick to the bigger particles, creating some clusters.

| ID  | Unit cell      | Cell size (mm) | Struts diam. (mm) | Volume fraction (%) |
|-----|----------------|----------------|-------------------|--------------------|
| P1  | Cubic          | 5              | 0.8               | 7.7                |
| P2  | Cubic          | 3              | 0.6               | 11                 |
| P3  | Rhombic dodecahedron | 6          | 1                  | 20.5               |
| P4  | Cubic          | 10             | 1.3               | 12.8               |

Table 2 Nominal unit cells properties

Table 3 SLM parameters sets used for specimens manufacturing with a laser beam diameter and the layer thickness fixed to 150 μm and 25 μm for each set

| Set name | Power (W) | Scan speed (mm/s) | Hatch space (mm) | Contour offset (mm) | Energy density (J/mm³) |
|----------|-----------|------------------|-----------------|---------------------|-----------------------|
| PA01     | 200       | 1050             | 0.105           | 0.225               | 72.6                  |
| PA02     | 180       | 1050             | 0.105           | 0.225               | 65.3                  |
| PA03     | 200       | 1165             | 0.105           | 0.225               | 65.4                  |
| PA04     | 150       | 700              | 0.105           | 0.075               | 81.6                  |
| PA05     | 180       | 1165             | 0.105           | 0.075               | 58.9                  |
| PA06     | 130       | 900              | 0.105           | 0.040               | 55.0                  |

Table 3 SLM parameters sets used for specimens manufacturing with a laser beam diameter and the layer thickness fixed to 150 μm and 25 μm for each set

Fig. 2 SEM micrograph of the stainless steel powders
2.2 Design and manufacturing

A series of AISI630 lattice test specimens were manufactured in the same job with different printing parameters. Samples were produced by SLM using an M2 Cusing-Concept Laser system in an N environment with a residual O2 content of 0.2–0.8%. Four different types of lattice structures were printed. Three of these were with a cubic unit cell and one with a rhombic dodecahedron cell. Their nominal geometrical features are summarized in Table 2. The cubic cell was of crucial interest because of the presence of both vertical and horizontal struts. The rhombic cell consists of 24 struts at an angle of 22.5° from the building plate and 14 nodes. The latter is of industrial interest due to its high value of the packaging factor and ability to absorb great quantity of energy [27, 28]. The CAD model of the cubic cellular lattice structure was realized by nTop Platform Software and Netfabb. Strut-based topologies can be characterized by their Maxwell number, $M$, which is dependent on the number of struts, $s$, and nodes, $n$, as follows [29]:

$$M = s - 3n + 6$$  \hspace{1cm} (2)

If $M < 0$, there are not enough struts to equilibrate external forces without equilibrating moments induced at the nodes, causing bending stresses in the struts and leading to bending-dominated behaviour. Whereas if $M \geq 0$, external loads are equilibrated by axial tension and compression in struts meaning that no bending occurs at nodes, making these structures stretch-dominated [30]. Due to these phenomena, stretch-dominated structures are stiff and strong, especially considering their mass, whereas bending-dominated structures are compliant and deform more consistently [31, 32]. The considered structures are $M < 0$. To evaluate how various parameters affect the quality of manufacturing process and the best set of parameters for lattice structures made in AISI630, each of the four aforementioned structures was printed using six different combinations of printing parameters. The set name and the corresponding values of parameters are presented in Table 3. The laser beam diameter and the layer thickness were imposed respectively to 150 $\mu$m and 25 $\mu$m for each set. The PA04 and PA06 sets were suggested for AISI 316L printing in [33] and [34] respectively. The other sets were chosen to analyse the impact of the laser power and scan speed changing on the manufacturability of 17-4PH stainless steel [21]. The contour offset is a purely

---

Table 4 Design of experiment

|     | P1 | P2 | P3 | P4 |
|-----|----|----|----|----|
| PA01| X  | X  | X  | X  |
| PA02| X  | X  | X  | X  |
| PA03| X  | X  | X  | X  |
| PA04| X  | X  | X  | X  |
| PA05| X  | X  | X  | X  |
| PA06| X  | X  | X  | X  |

---

Fig. 3 Structures composing the job and their coding

Fig. 4 Printed specimens
geometric parameter and it is used considering the melt pool size of the scan vectors that describe boundaries of a strut and is much higher than the laser spot size although the scan vectors are usually shifted inwards for compensation [35].

Therefore, the job was composed of 24 lattice structures and their coding is proposed in Fig. 3.

Using this approach, every single set of parameters was tested four times, with each type of structure, and each type of structure was tested six times, by using six different sets of parameters. The resulting DoE is schematized in Table 4.

2.3 Measurements and characterizations

The morphology of the SLM-fabricated lattice structures was observed by optical microscope. The dimensional analysis was carried out by using a MICRO-EPSILON laser micrometre with a maximum resolution of 1 μm. Since the lattice struts can be not uniform along their axis [36], the struts’ diameter was measured at their middle and thinnest section. For each structure, 10 strut diameters were measured, and the average values were attributed to the sample. In structures with cubic unit cell, only vertical struts were considered for measurement because horizontal ones were affected from satellites presence, as will be shown in the next paragraph. Uniaxial compression testing was performed at 1 mm/min using an Instron 5582 equipped with a 100-kN load cell and according to ISO 13314 standard for ductility testing of porous materials [37].

3 Results

3.1 Struts morphology and dimension

Printed samples before removal from the substrate are shown in Fig. 4. In Fig. 5, the dimensional analysis for all the

![Fig. 5 Influence of printing sets parameters on the struts dimensions for a P1, b P2, c P3 and d P4 structures](image-url)
printed lattice structures regrouped by their topology (P1, P2, P3 and P4) is shown. A common trend has been noticed regardless of the cells’ topology: by using sets PA01, PA02 and PA03, struts are thinner than the nominal value with an error in the range 25–40%; structures printed with PA04 and PA05 are closer to the target value; the set PA06 produces struts thicker than designed.

All the P1 lattices structures are noticeably damaged with many struts failed or affected by a great amount of satellites (Fig. 6). The P2 structures clearly showed a less defectiveness in comparison with the P1 one’s despite their struts’ nominal diameter being smaller. In these structures, very few struts failed even so satellites are still present. Details of the printed rhombic dodecahedron unit cells (P3 structures) are shown in Fig. 7.

Their struts are all printed with an angle of 26.5° form the build plate and this ensures a better printing quality if compared to structures with cubic unit cells. They are all successfully printed with no struts failed and very few satellites present. All the horizontal struts that made up the P4 structures failed. Anyway, the presence of satellites under them was small while the underside of the struts inclined of 35° was quite smooth.

3.2 Compression behaviour

Defectiveness, both microscopical and macroscopical, could strongly affect mechanical response of lattice structures. Because of this, uniaxial compression tests were used as quality check to judge the best set of printing parameters. Due to the differences in strut diameters, the compression responses were normalized to allow the direct comparison among similar structures printed by different parameter sets regardless of the dimensional error. The response of cubic structures (P1, P2 and P4) was normalized with respect to the inertia modulus. P3 structure responses were normalized with respect to the section modulus. In Fig. 8, normalized compression curves are regrouped for structure type.

4 Discussions

4.1 Struts morphology and dimension

Analysing results of the dimensional analysis, a common trend has been noticed regardless of the cell topologies. To corroborate this assumption, the errors made with respect to
the nominal strut diameters were regrouped and plotted in box-plots against the type of structure (Fig. 9) and parameter sets (Fig. 10). A box-plot is a standardized way of displaying the dataset based on a five-number summary: the minimum, the maximum, the sample median, and the first and third quartiles. The median value showed in Fig. 9 seems to be quite constant with the type of printed structure whereas it is highly dependent from the parameter set chosen (Fig. 10). When lattice structures were printed by using sets PA01, PA02 and PA03, the measured strut diameter was thinner than the nominal value with an error in the range 0.2–0.4 μm; structures printed with PA04 and PA05 had struts closer to the target value; the set PA06 produces struts bigger than designed.

This issue is attributed to the chosen value for the contour offset. In fact, among the assumed parameters, the only one that follows the same trend found for the strut diameter is the contour offset (Table 5). In Fig. 11, the generation process of the melt pools along the build direction is shown. The laser beam has a Gaussian energy distribution and selectively scans and melts the metal powders and generates a melt pool with an arc-shaped cross section. The intensity is greatest in the centre of the laser beam, leading to the maximum depth of the melt pools, and gradually decreases from the centre to the edge of the laser beam, hence generating the arc-shaped cross section of the melt pools. There exists a remelted heat-affected zone around the laser beam, which makes the melt pool wider than the laser beam diameter. This means if the contour of layers was scanned exactly at the nominal position, the final component will be surely bigger than the designed. The contour offset is the parameter that compensates this issue, shifting inward the laser spot. How much to move the spot depends on the melt pool wide that is influenced from the interaction between laser parameters and the material to melt. In the present work, the best dimensional accuracy was achieved when the contour offset is set at 75 μm (PA04 and PA05). Hence, the melt pool is about...
300 μm (the laser beam diameter plus twice the optimal contour offset value). In Fig. 12, an optical microscope image of a section along the building direction of a strut printed by DLMS process is showed, corroborating what is described in Fig. 11. By analysing Fig. 12, it is possible to notice the melt pools’ depth is at least 3 times greater than the layer thickness. Another crucial issue to consider is the satellites formation during the printing process. In the present work, the formation of satellites affects each printed sample, independently from the quantity of generated heat. Each parameter is studied in a wide range of values. For example, if we consider the PA04 and PA05 sets: they have opposite values of energy density and scanning speed; the power is quite different; the hatch spacing and the contour offset are parameters that affect print quality mainly in the scanning plane. Despite these features carrying to a great variation of generated heat, they have the same amount of adhered powders. Because of this, we can consider the influence of thermal diffusion phenomenon only marginal.

In the present work, it was found the smaller is the geometrical feature to print, the greater is the amount of satellites. This behaviour was ascribed to the ratio between...
the feature to print and the dimension of the melt pool. As stated above, the melt pools have an arc-shaped cross section. Their width and depth are strictly related to the interaction between the laser and the metal powders. To ensure bonding of adjacent layers, the melt pool depth must be slightly higher than the layer height to form overlaps between them. However, the circular struts with varying inclined angles are partially built on the loose powder, and thus some metal particles below each layer will be totally or partially melted and then bonded on the bottom of the layer. For any curved surfaces or inclined plane,

![Diagram](image1)

**Fig. 11** Generation process of the melt pools along the building direction

| Table 5 | Printing parameters and mean error of strut diameters |
|---------|------------------------------------------------------|
| **Set name** | **Power (W)** | **Scan speed (mm/s)** | **Hatch space (mm)** | **Contour offset (mm)** | **Strut diameter mean error (mm)** |
| **Structure P1 (cubic cell: 5 mm; struts diam: 0.8 mm)** |  |  |  |  |  |
| PA01 | 200 | 1050 | 0.105 | 0.225 | -0.280 |
| PA02 | 180 | 1050 | 0.105 | 0.225 | -0.285 |
| PA03 | 200 | 1165 | 0.105 | 0.225 | -0.279 |
| PA04 | 150 | 700 | 0.105 | 0.075 | +0.006 |
| PA05 | 180 | 1165 | 0.105 | 0.075 | +0.001 |
| PA06 | 130 | 900 | 0.105 | 0.040 | +0.090 |
| **Structure P2 (cubic cell: 3 mm; struts diam: 0.6 mm)** |  |  |  |  |  |
| PA01 | 200 | 1050 | 0.105 | 0.225 | -0.235 |
| PA02 | 180 | 1050 | 0.105 | 0.225 | -0.234 |
| PA03 | 200 | 1165 | 0.105 | 0.225 | -0.243 |
| PA04 | 150 | 700 | 0.105 | 0.075 | +0.010 |
| PA05 | 180 | 1165 | 0.105 | 0.075 | +0.009 |
| PA06 | 130 | 900 | 0.105 | 0.040 | +0.086 |
| **Structure P3 (rhombic cell: 6 mm; struts diam: 1.5 mm)** |  |  |  |  |  |
| PA01 | 200 | 1050 | 0.105 | 0.225 | -0.300 |
| PA02 | 180 | 1050 | 0.105 | 0.225 | -0.295 |
| PA03 | 200 | 1165 | 0.105 | 0.225 | -0.292 |
| PA04 | 150 | 700 | 0.105 | 0.075 | +0.002 |
| PA05 | 180 | 1165 | 0.105 | 0.075 | +0.001 |
| PA06 | 130 | 900 | 0.105 | 0.040 | +0.069 |
| **Structure P4 (cubic cell: 10 mm; struts diam: 1.3 mm)** |  |  |  |  |  |
| PA01 | 200 | 1050 | 0.105 | 0.225 | -0.310 |
| PA02 | 180 | 1050 | 0.105 | 0.225 | -0.314 |
| PA03 | 200 | 1165 | 0.105 | 0.225 | -0.319 |
| PA04 | 150 | 700 | 0.105 | 0.075 | +0.018 |
| PA05 | 180 | 1165 | 0.105 | 0.075 | +0.020 |
| PA06 | 130 | 900 | 0.105 | 0.040 | +0.078 |

![Image](image2)

**Fig. 12** Optical microscope image of a section along the building direction of a strut printed by DLMS process [25]
the effect of layer-by-layer build is noticed as a stair step, which is referred to as a stair stepping effect, leading to the staircase-shaped profile of the circular strut as shown in Fig. 13. The stair stepping effect has a great influence on the surface quality of SLM parts, and can be diminished by decreasing the layer thickness, but this increases the time required to complete the fabrication [38].

The portion of the layer built on the loose powder is named overhang. In Fig. 14, the relationship among the layer thickness \( h \), the building angle \( \theta \) and overhang \( s \) is outlined. It is possible calculate the overhang as:

\[
s = h \cdot \tan(\theta)
\] (3)

The overhang is proportional to the layer thickness by a coefficient depending on the building angle. The greater is the overhang, the greater is the area affected from satellites formation. Hence for a given building angle, decreasing the layer thickness the quantity of adhered powders decrease. To confirm what was said, in Fig. 15, a lattice structure with struts inclined of 45° and printed by PA01 but using a layer thickness of 50 \( \mu m \) instead of 25 \( \mu m \) is showed. Despite the building angle of the struts is small, the amount of satellites is clearly greater than what it is showed in Fig. 7 for the rhombic dodecahedron cell (building angle 64.5°).

In Table 6, the values of overhang calculated in both cases are reported. The different combination of building angle and layer thickness leads to the same value of the 's' leading us to state that, for a given value of the overhang, the layer height plays a crucial role in satellites formation. The overhang value governs the extension of the area affected by the satellites presence while the layer height determine their quantity. The bigger is the layer height, the greater must be the melt pool depth to grant the metallurgic continuity between adjacent layers and so the melt pool overall dimension increases. This yields a worst print resolution. When a horizontal strut is printed, its first layer is totally supported by the loose powder. In Fig. 16, a qualitative comparison between the dimensions of the first layer of a struts of 1 mm and the melt pool is showed. It was assumed that a laser beam diameter of 150 \( \mu m \) and a layer thickness of 50 \( \mu m \) yield a melt pool 300 \( \mu m \) wide and 250 \( \mu m \) depth. It is clear the melt pool is wider and deeper then the geometry to print and this leads to scan not only desired powder but also the adjacent one, hence to satellites formation. Surely using a layer thickness as small as possible, in combination with smaller laser beam diameter available, the amount of adhered powders would decrease significantly.

| Table 6  | Effects of building angle and layer thickness on the overhang dimension |
|----------|-------------------------------------------------------------------------|
| PA01     | Struts building angle \( (\theta) \) | Layer thickness \( (h) \) | Overhang \( s = h \cdot \tan(\theta) \) |
| Structure in Fig. 15 | 45° | 50.0 \( \mu m \) | 50.0 \( \mu m \) |
| Rhombic dodecahedron (structure P3) | 63.5° | 25 \( \mu m \) | 50.1 \( \mu m \) |
4.2 Compression behaviour

Uniaxial compression tests were carried out to verify the macroscopic response of the lattice structures. Defectiveness, both microscopical and macroscopical, could strongly affect mechanical response of porous materials. Waviness of the struts, the variation in their cross-section shape, and dimensional errors as well as porosity and lack of fusion are typical issues of lattice structures manufacturing via SLM. These defects contribute all together to the macroscopic response. Hence, compression tests were used as quality check for the defectiveness of printed structures. The obtained variation of the strut diameters due to the different contour offset values does not allow to direct compare compression curves. Because of this, a normalization by a geometrical factor of data was carried out. This approach has enabled to analyse compression data regardless of dimensional errors. For structures with cubic unit cells, the normalization was carried considering the load-bearing capacity of the structures is mainly due to the vertical struts whose failure mode is buckling as shown in Fig. 17. In these cases, Euler’s critical load given by:

\[
P = \frac{E \cdot J \cdot \pi^2}{l^2}
\]

where \(E\) is the Young modulus, \(J\) the inertia modulus and \(l\) the cell dimension, will vary since the inertia modulus depends on the strut diameter parameter. For this reason, the normalization was carried out by using the inertia modulus.

In Fig. 18, a representative compression test response for structures with cubic unit cell is presented and analysed. As it is possible to see, the curve is about periodic until the final densification. A sequence of a higher peak followed by a lower peak is shown. The first and higher peaks correspond to the simultaneous buckling of two adjacent ‘floors’ of the structure. After the buckling is started, only the weakest one continues its deformation process. This step corresponds in the graph to the decreasing load between first and second peaks. The load decreases because the more the struts of a floor are deformed, the easier it is to continue their deformation. When the weakest floor is totally deformed, the load rises and the second floor starts its compression. Because the initiation of the buckling of the second this floor was already started under the first peak of load, the second peak is lower than the first one [21]. If only one peak of load is
experienced, it means that only one floor was under a buckling deformation mechanism as in Fig. 17.

In structure P3 (rhombic dodecahedron unit cell), struts are mainly load in bending. In Fig. 19, the loading scheme is showed with an angle $\theta$ of 26.5°. Because of this, for these structures, the normalization of the load was performed by the section modulus. The experimental stress-strain curves obtained for the P3 structures are similar in form to those of the cellular foam structures, where there is a steep rise in the elastic region followed by a stress plateau. The latter continues until the onset of densification, which in turn is associated with another abrupt rise in stress. Observing compression curves obtained for P3 structures, it is clear the choice of printing parameters could strongly affect both elastic and plateau regions. The higher are the values of stiffness and plateau, the better is considered the printing result. The PA01 set generally leads to a better compression behaviour. It is true regardless of type of structure considered.

![Fig. 18 Deformation steps during compression tests of structures P1, P2 and P4](image1)

![Fig. 19 Load (F) and stress (S) distribution in struts belonging to a rhombic dodecahedron cell during a compression test](image2)
5 Conclusion

In this work, challenges of lattice structures manufacturing via SLM technologies were investigated. Stainless steel 17-4PH (AISI630) was used as starting material for the lattice structures production. The adopted approach is still suitable also for other materials commonly used in metal 3D printing industry. Four different types of lattice structures were printed, three of these with a cubic unit cell and one with a rhombic dodecahedron cell. The cubic cell was of crucial interest because of the presence of both vertical and horizontal struts, respectively the easier and more complex to realize in AM processes. The rhombic cell consists of 24 struts at an angle of 22.5° from the building plate and 14 nodes. It is of industrial interest due to its high value of the packaging factor and ability to absorb great quantity of energy in compression. To evaluate the best set of parameters for lattice structures printing, each of the four structures were printed using six different combination of printing parameters. The laser beam diameter and the layer thickness were fixed respectively to 150 μm and 25 μm for each set. In all, 24 structures were printed. Using this approach, every single set of parameters was tested four times, with each type of structure, and each type of structure was tested six times using six different sets of parameters. On every single structure many analyses were carried out: evaluation of satellites formation, dimensional analysis, and compression tests. The aim was to evaluate the best parameters set for the 17-4PH lattice structures manufacturing via SLM technology. In structures with cubic unit cells, vertical struts were printed with no macroscopic defects, whereas the horizontal struts were affected from satellites presence and waviness of their axis. Despite these problems, the structural integrity is guaranteed. In structures with a rhombic unit cell, results were clearly better with few satellites under the struts. Layer height and the diameter of the laser beam directly affect the melt pool dimension. This was identified as the main parameter governing the print resolution, influencing satellites formation. The building angle is strictly related to the overhang extension; therefore for a given value of the layer height, it determines the area subject to adhesion of metal powders. Hence, it was considered as another parameter controlling the satellites formation. As stated in [24], in this work, it was confirmed the manufacture via SLM of lattice structures with horizontal struts was inaccurate and of poor quality. A dimensional analysis was conducted. The results showed that sets PA04 and PA05 were the best in terms of dimensional accuracy. It was found that only the contour offset value affects sensitively the strut dimension. It was considered as a purely geometrical parameter affecting only the strut diameter and not able to influence the mechanical response of the structures. The best value found for the contour offset was 75 μm. All samples were mechanically tested in compression. Initially, it was found that the mechanical response, as obvious, was mainly affected by the dimension of the struts. Normalizing the raw compression curves by the moment of inertia, for the structures with cubic unit cell, and by the section modulus for the structures with rhombic unit cell, more information about all sets of parameters has been provided. Thanks to the normalization, it was possible to analyse the different sets independently from the dimension of the struts; therefore, the influence of the contour offset was excluded, and the effect of the other parameters was studied. The set PA01 is the best in terms of mechanical response. Joining dimensional and compression results and considering that the contour offset cannot influence the normalized response of the mechanical tests, the best parameter set found for a layer height of 25 μm was PA01 + contour offset = 75 μm.

Author contributions A. Bertocco and G. Iannitti carried out the experiments and analysed the data. A. Bertocco wrote the manuscript with support from L. Esposito and A. Caraviello. A. Caraviello fabricated the samples. L. Esposito and A. Caraviello supervised the project. A. Bertocco and G. Iannitti conceived the original idea.

Funding Open access funding provided by Università degli Studi di Napoli Federico II within the CRUI-CARE Agreement.

Data availability Some of the findings of this work are available within the article.

Code availability Not applicable.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication We confirm that this work is original and has not been published elsewhere, nor it is currently under consideration for publication elsewhere. All the authors listed have agreed to publish the manuscript that is enclosed.

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.
References

1. Ahmadi SM, Campoli G, Amin Yavari S, Sajadi B, Wauthle R, Sajjadi B, Weinans H, Zadpoor AA (2014) Mechanical behavior of regular open-cell porous biomaterials made of diamond lattice unit cells. J Mech Behav Biomed Mater 34:106–115. https://doi.org/10.1016/j.jmbbm.2014.02.003

2. Ahmadi SM, Hedayati R, Li Y, Lietaert K, Tümer N, Fatemi A, Rans CD, Pouran B, Weinans H, Zadpoor AA (2018) Fatigue performance of additively manufactured meta-biomaterials: The effects of topology and material type. Acta Biomater 65:292–304. https://doi.org/10.1016/j.actbio.2017.11.014

3. Ahn D, Kim H, Lee S (2009) Surface roughness prediction using measured data and interpolation in layered manufacturing. J Mater Process Technol 209(2):664–671. https://doi.org/10.1016/j.jmatprot.2008.02.050

4. Amin Yavari S, Wauthle R, Van Der Stok J, Riemslag AC, Janssen M, Mulier M, Kruth JP, Schrooten J, Weinans H, Zadpoor AA (2013) Fatigue behavior of porous biomaterials manufactured using selective laser melting. Mater Sci Eng C 33(8):4849–4858. http://doi.org/10.1016/j.msec.2013.08.006

5. ASTM-A564 (2010) Standard specification for hot-rolled and cold-finished age-hardening stainless steel bars and shapes. ASTM International pp 1–7. http://doi.org/10.1520/A0564

6. Bai L, Gong C, Chen X, Zheng J, Xin L, Xiong Y, Wu X, Hu M, Li K, Sun Y (2021) Quasi-Static compressive responses and fatigue behaviour of Ti-6Al-4V graded lattice structures fabricated by laser powder bed fusion. Mater Des 210:110110. https://doi.org/10.1016/j.matdes.2021.110110

7. Bertocco A, Esposito L, Aurino A, Borrelli D, Caravelli A (2021) Influence of SLM parameters on the compressive behaviour of lattice structures in 17-4PH stainless steel. IOP Conference Series Materials Science and Engineering 1(303)

8. Brooks W, Sutcliffe C, Cantwell W, Fox P, Todd J, Mines R (2005) Rapid design and manufacture of ultralight cellular materials

9. Evans AG, Hutchinson JW, Fleck NA, Ashby MF, Wadley HN (2001) The topological design of multifunctional ceramic metals. Prog Mater Sci 46(3-4):309–327. https://doi.org/10.1016/S0079-6425(00)00016-5

10. Gibson LJ (1989) Modelling the mechanical behavior of cellular materials. Mater Sci Eng A 110(C):1–36. http://doi.org/10.1016/0921-5093(89)90154-8

11. Gibson LJMA (1997) Cellular solids: structure and properties, vol 22, second edi edn. Cambridge University Press. http://doi.org/10.1016/0021-9290(89)90056-0

12. Hanks B, Berthel J, Frecker M, Simpson TW (2020) Mechanical properties of additively manufactured metal lattice structures: Data review and design interface. Addit Manuf 35(November 2019):101301. https://doi.org/10.1016/j.addma.2020.101301

13. Heinl P, Körner C, Singer RF (2008) Selective electron beam melting of cellular titanium: mechanical properties. Adv Eng Mater 10(9):882–888. https://doi.org/10.1002/adem.200800137

14. ISO 13314 (2011) ISO 13314 mechanical testing of metals, ductility testing, compression test for porous and cellular metals. Reference number ISO

15. Köhnen P, Haase C, Bültmann J, Ziegler S, Schleifenbaum JH, Bleck W (2018) Mechanical properties and deformation behavior of additively manufactured lattice structures of stainless steel. Mater Des 145:205–217. https://doi.org/10.1016/j.matdes.2018.02.062

16. Kooistra GW, Deshpande VS, Wadley HN (2004) Compressive behavior of age hardenable tetrahedral lattice truss structures made from aluminium. Acta Mater 52(14):4229–4237. https://doi.org/10.1016/j.actamat.2004.05.039

17. Kumar A, Collini L, Daurel A, Jeng JY (2020) Design and additive manufacturing of closed cells from supportless lattice structure. Addit Manuf 33(January):101168. https://doi.org/10.1016/j.addma.2020.101168

18. Leary M, Mazur M, Elambaseril J, McMillan M, Chirent T, Sun Y, Qian M, Easton M, Brandt M (2016) Selective laser melting (SLM) of AISi12Mg lattice structures. Mater Des 98:344–357. http://doi.org/10.1016/j.matdes.2016.02.127

19. Leary M, Mazur M, Williams H, Yang E, Alghamdi A, Lozanovski B, Zhang X, Shidid D, Farahbod-Sternali L, Witt G, Kelbassa I, Choong P, Qian M, Brandt M (2018) Inconel 625 lattice structures manufactured by selective laser melting (SLM): Mechanical properties, deformation and failure modes. Mater Des 157:179–199. https://doi.org/10.1016/j.matdes.2018.06.010

20. Lei H, Li C, Meng J, Zhou H, Liu Y, Zhang X, Wang P, Fang D (2019) Evaluation of compressive properties of SLM-fabricated multi-layer lattice structures by experimental test and μ-CT-based finite element analysis. Mater Des 169:107685. https://doi.org/10.1016/j.matdes.2019.107685

21. Li SJ, Xu QS, Wang Z, Hou WT, HAO YL, Yang R, Murr LE (2014) Influence of cell shape on mechanical properties of Ti-6Al-4V meshes fabricated by electron beam melting method. Acta Biomater 10(10):4537–4547. https://doi.org/10.1016/j.actbio.2014.06.010

22. Li X, Wang C, Zhang W, Li Y (2009) Fabrication and characterization of porous Ti6Al4V parts for biomedical applications using electron beam melting process. Mater Lett 63(3-4):403–405. http://doi.org/10.1016/j.matlet.2008.10.065

23. Liu X, Wada T, Suzuki A, Takata N, Kobashi M, Kato M (2021) Understanding and suppressing shear band formation in strut-based lattice structures manufactured by laser powder bed fusion. Mater Des 199:109416. https://doi.org/10.1016/j.matdes.2020.109416

24. Liverani E, Toschi S, Ceschini L, Fortunato A (2017) Effect of selective laser melting (SLM) process parameters on microstructure and mechanical properties of 316L austenitic stainless steel. J Mater Process Technol 249(November 2016):255–263. http://doi.org/10.1016/j.jmatprot.2017.05.042

25. Macanochie T, Leary M, Lozanovski B, Zhang X, Qian M, Faruque O, Brandt M (2019) SLM lattice structures: Properties, performance, applications and challenges. Mater Des 183:108137. https://doi.org/10.1016/j.matdes.2019.108137

26. Nakajima H (2007) Fabrication, properties and application of porous metals with directional pores. Prog Mater Sci 52(7):1091–1173. https://doi.org/10.1016/j.pmatsci.2006.09.001

27. Ponader S, Von Wilmowsky C, Widemayer M, Lutz R, Heinl P, Körner C, Singer RF, Nkenke E, Neukam FW, Schlegel KA (2010) In vivo performance of selective electron beam-melted Ti-6Al-4V structures. Journal of Biomedical Materials Research - Part A 92(1):56–62. https://doi.org/10.1002/jbmr.a.32337

28. Santanaiaos M, Brooks W, Sutcliffe CJ, Mines RA (2006) Crush behaviour of open cellular lattice structures manufactured using selective laser melting. WIT Transactions on the Built Environment 85:481–490. https://doi.org/10.2495/HPSM06047

29. Simsek Ü, Ozdemir M, Sendur P (2021) An efficient design methodology for graded surface-based lattice structures using free-size optimization and enhanced mapping method. Mater Des 210:110039. https://doi.org/10.1016/j.matdes.2021.110039

30. Van Bael S, Kerckhofs G, Moesen M, Pyka G, Schrooten J, Kruth JP (2011) Micro-CT-based improvement of geometrical and mechanical controllability of selective laser melted Ti6Al4V porous structures. Mater Sci Eng A 528(24):7423–7431. https://doi.org/10.1016/j.msea.2011.06.045

31. Viscusi A, Bruno M, Esposito L, Testa G (2020) An experimental/numerical study of bonding mechanism in cold spray technology
32. Deshpande VS, Fleck MANA (2001) Effective properties of the octet-truss lattice material. J Mech Phys Solids 49(4):1747–1769
33. Wang D, Yang Y, Liu R, Xiao D, Sun J (2013) Study on the designing rules and processability of porous structure based on selective laser melting (SLM). J Mater Process Technol 213(10):1734–1742. http://doi.org/10.1016/j.jmatprotec.2013.05.001
34. Wang X, Zhu L, Sun L, Li N (2021) Optimization of graded filleted lattice structures subject to yield and buckling constraints. Mater Des 206:109746. https://doi.org/10.1016/j.matdes.2021.109746
35. Yan C, Hao L, Hussein A, Bubb SL, Young P, Raymont D (2014a) Evaluation of light-weight AlSi10Mg periodic cellular lattice structures fabricated via direct metal laser sintering. J Mater Process Technol 214(4):856–864. http://doi.org/10.1016/j.jmatprotec.2013.12.004
36. Yan C, Hao L, Hussein A, Young P, Raymont D (2014b) Advanced lightweight 316L stainless steel cellular lattice structures fabricated via selective laser melting. Mater Des 55:533–541. http://doi.org/10.1016/j.matdes.2013.10.027
37. Yan C, Hao L, Hussein A, Young P, Huang J, Zhu W (2015) Microstructure and mechanical properties of aluminium alloy cellular lattice structures manufactured by direct metal laser sintering. Mater Sci Eng A 628:238–246. http://doi.org/10.1016/j.msea.2015.01.063
38. Zadpoor AA (2019) Mechanical performance of additively manufactured meta-biomaterials. Acta Biomater 85:41–59. https://doi.org/10.1016/j.actbio.2018.12.038

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.