Influence of SLM parameters on the compressive behaviour of lattice structures in 17-4PH stainless steel

A Bertocco1*, L Esposito2, A Aurino3, D Borrelli3 and A Caraviello3

1 Department of Industrial Engineering, University of Naples Federico II, Napoli, Italy
2 Department of Chemical, Materials and Production Engineering, University of Naples Federico II, Napoli, Italy
3 Sophia High Tech S.r.l.

Abstract. Additive manufacture (AM) technologies allow innovative structural design, including complex lattice structures. Selective laser melting (SLM) is an AM process that enables the manufacture of space filling lattice structures. Lattice structures are topologically ordered, three-dimensional open-celled structures composed of one or more repeating unit cells. From a mechanical designer viewpoint, a great advantage offered by cellular materials is high strength accompanied by a relatively low mass. Due to their complex structure, fine geometry and the absence of supports structures, the setting of the best parameters to print lattice structures is difficult and could negative influence their mechanical response. This study investigated how different parameters settings influence the compression behaviour of lattice structures in stainless steel 17-4PH (AISI-630) printed by SLM. A comparison between compressive response of structures printed with different parameters is presented and considerations about their behaviour exposed.

1. Introduction

Light weight cellular 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 negative Poisson's ratio [1–3]. Metal cellular structures are a unique classification of materials, which exhibit a combination of high performances features such as high strength accompanied by a relatively low mass, good energy absorption and good thermal and acoustic insulation properties. Metal cellular structures can be classified into two common types: 1) stochastic porous structures and 2) periodic cellular lattice structures. Metal stochastic porous structures 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 [4]. The properties of these structures can vary widely, depending on the choice of the solid from which they are made, the volume fraction of the solid and the geometry of the cells [5].

Due to the complexity of their geometry, traditional manufacturing processes are not suitable for lattice production. Additive manufacturing (AM) technologies are manufacturing processes developed in the last thirty years in which 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, for example using a binder, laser or heated nozzle. Classification is also possible by the group of materials being processed, such as plastics, metals or ceramics. Cold spray coating processes could be classified as an AM technology too [6]. Powder-bed based AM system 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 have a thickness 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 powder-bed AM technology that uses a scanning laser to sequentially melt layers of powdered metal 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, supports necessity, and thermal powder bed resistance that is poorly understood and subject to significant experimental uncertainty. SLM is highly dimensional, with nearly 130 variables of influence on final component quality [7]. Laser power, laser scanning speed, hatch spacing and the layer thickness are processing parameters influencing the laser energy density (Eq. (1)):

\[ D = \frac{P}{v \cdot h \cdot t} \]  

Where:
- D : energy density [J/mm³]
- P : laser power [W]
- v : scan speed [mm/s]
- t : layer thickness [mm]
- h : hatch spacing [mm]

Another fundamental aspect to highlight is that SLM printed parts requires support structures to build overhang section if its angle respect to the substrate is less than certain degree [4]. Many works have investigated how process parameters and geometrical features influence fabrication of cellular lattice structures using the SLM process. Brooks et al. [8] studied the SLM production of 316L stainless steel lattice structures considering combination of three element types including pillar, diagonal and octahedral elements. They tested the manufacturability of the minimum angels of elements from the horizontal and found that the elements with angles lower than 30 were difficult to realize. Santorinaios et al. [9] 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.

This study investigated how different parameters settings influence the compression behavior of Cubic lattice structures in stainless steel 17-4PH (AISI-630) printed by SLM. A comparison between compressive response of structures printed with different parameters is presented and considerations about their behavior exposed. In conclusion, the compression tests are used to define the best set of parameters. Process parameters under investigation include laser power, scanning velocity, hatch spacing and contour offset.

2. Materials and methods

2.1. Material and manufacturing
Atomized 17-4PH stainless steel powder, with nominal chemical composition as reported in Table 1, and according to ASTM A564 / A564M – 13 UNS S17400 [10], were used as a starting material to produce SLM samples.
Table 1. Nominal chemical composition of 17-4PH steel powder [wt%].

|   | Fe   | C    | Mg   | P    | S    | Si   | Cr   | Ni   | Cu   |
|---|------|------|------|------|------|------|------|------|------|
|   | Balance | 0-0,07 | 0-1,00 | 0-0,04 | 0-0,03 | 0-1,00 | 15,00-17,50 | 3,00-5,00 | 3,00-5,00 |

The powder grains were spherical in shape with sizes in the range of 15–45 μm. Samples were produced by SLM using M2 Cusing-Concept Laser system.

Technical data after recommended heat treatment are reported in Table 2. The heat treatment consists of an annealing at temperatures of 1025 – 1055°C, followed by a rapid cooling down in water, air or oil. Heat up to 480°C and maintain temperature for 1 hour. Subsequently allow the component cooling down at ambient atmosphere. Samples realized was tested as built and the heat treatment were not carried out. All samples were built in an N environment with a residual O₂ content of 0,2-0,8%.

The cubic unit cell was used to generate periodic cellular lattice structures with box shape and overall dimensions of (30x30x20) mm. The unit cell size was 3 mm, the struts diameter 0,6mm and the volume fraction 11%. The CAD model of the cubic cellular lattice structure was realized by nTop Platform Software and is shown in Fig. 1. This geometry was chosen because of the presence of both vertical and horizontal struts, respectively the easier and more difficult to realize in AM processes.

Table 2. 17-4 PH technical data after recommended heat treatment.

| Yield Point R\(_{0,2}\) | Tensile Strength | Elongation A | Thermal Conductivity | Hardness |
|--------------------------|------------------|--------------|----------------------|----------|
| 1170 MPa                 | 1310 MPa         | 10%          | 16 W/mK              | 388HB    |

Figure 1. Lattice structure CAD model.

To investigate the influence of SLM parameters on the manufacturability and the mechanical response of aforementioned structures, six different sets of parameters are used to realized six samples, one specimen for each set (Table 3). The laser beam diameter and the layer thickness were fixed respectively to 150μm and 25μm for each set. The PA04 and PA06 was respectively used in [11] and [12] for AISI 316L printing, while the other sets were chosen to analyse the impact of the power and scan speed changing on the manufacturability of 17-4PH stainless steel. The contour offset is a purely geometric parameter and it is used considering that the melt pool size of the scan vectors that describe
boundaries of a strut, is much higher than the laser spot size although the scan vectors are usually shifted inwards for compensation [13].

Table 3. SLM parameters sets used for specimens manufacturing.

| 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                   |

2.2. Measurements and characterizations
An optical microscope was used to investigate the morphology of the SLM-fabricated lattice structures and to check the strut sizes. As the strut diameter of the lattice is not uniform along its axis, we took the diameter of the middle and thinnest section of the struts as strut size [14]. By using the microscope images, for each structure 10 strut diameters were measured, and the average values was attributed to the sample. Only vertical struts were considered for this operation because horizontal ones were affected from satellites (adhered powders) presence, as will be show in the next paragraph.

Uniaxial compression testing was performed at 1mm/min using a calibrated electromechanical 200 kN Instron machine according to ISO 13314 standard for ductility testing of porous materials [15].

3. Results and discussion

3.1. Morphology of the Struts
As shown in Fig.2 the structure was printed correctly with each set. Only few horizontal struts are broken. From the figure is also visible that the horizontal struts are affected from a great amount of powder adhered at the bottom surface side.
In figure can be also noticed that the horizontal struts are affected from a great amount of powder adhered at the bottom surface side. The PA04 and PA05 parameters seems to be less affected from satellites presence whereas the PA06 is the most one. The vertical struts were well printed with each set. A magnified profile of the horizontal struts for each sample is reported in Fig. 3. The structural continuity is guaranteed for each parameter while the ideal cylindrical geometry is better reproduced with parameters PA04 and PA05. In addition, the axis of horizontal struts realized with the set PA06 is less straight in comparison with the others. An important aspect, found in literature, that can influence satellites formation, is the thermal diffusion. It occurs between loose powder and solid material due to big temperature difference, leading to powder particles sticking to the strut surface [17]. In this 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. 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, they are equal in terms of quantity of adhered powders. Because of this we can consider the influence of thermal diffusion phenomenon only marginal.

The CAD model of the strut is sliced in many layers which are then printed one by one and combined together to form the circular shape. For any curved surfaces or inclined plane, the effect of layer by layer build is noticed as stair step, which is referred to as stair stepping effect, leading to the staircase-shaped profile of the circular strut as shown in Fig. 4 [4]. 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 [16].
Figure 3. Microscopic images of the horizontal struts.

Due to the staircase-shaped profile, circular struts are partially built on the loose powder. To ensure bonding of adjacent layers, the melt pool depth must be slightly higher than the layer height to form overlaps between layers as shown in Fig. 4(b). 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. 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.

Figure 4 (a) High magnification SEM micrograph of the strut and (b) schematic illustration of the SLM manufacturing process of the circular strut [4].

3.2. Dimensional analysis

In Fig. 5 is shown the dimensional analysis on the diameter of vertical struts. By using sets PA01, PA02 and PA03, struts are thinner than the designed value and their diameter is quite constant with an error $e \approx 39\%$. The sets PA04 and PA05 lead to a diameter value closer to the designed one and, as for previous sets, their value is quite constant with an error $e \approx 1.8\%$. Finally, the set PA06 produces struts larger than designed. This trend can be ascribed to the contour offset. As explained previously, the contour offset is a purely geometric parameter and it is used considering that the melt pool size of the scan vectors that describe boundaries of a strut, is much higher than the laser spot size.
The imagine in Fig. 6 shows the generation process of the melt pools along the build direction. 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 [17]. 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 width that is influenced from the interaction between laser parameters and material to melt. In this work, best results are obtained when the contour offset is set at 75$\mu$m. Hence the melt pool is about 300$\mu$m, the double of the laser beam diameter.

Another important issue to emphasize links together dimensional analysis to morphology of the horizontal struts. Structures printed with the sets PA01, PA02 and PA03 have thinner struts due to the excessive contour offset used. The ratio of struts diameter to laser beam diameter is about 2, whereas for PA04 and PA05 is about 4. The smaller is this ratio the worst is the print quality and it is manifest in Fig.3, mainly for the horizontal struts.

**Figure 5.** Analysis of diameter measurements of the vertical struts.

**Figure 6.** Generation process of the melt pools along the building direction [17]
3.3. Compression behaviour

Load vs displacement curves obtained from the compression tests re reported in Fig.7.

As expected, the mechanical response is strongly influenced from the vertical struts diameter that carry the most load, thus compression curves are scattered as the dimensional results. The set PA05 seems to be slightly better than the PA04 while the PA03 is the better among the lower three sets. As explained above, the dimension of the diameter of the vertical struts is influenced by the right choice of the contour offset and therefore the compression behaviour too. To analyse the effect of the other parameters on the mechanical response of printed structures, a normalization of raw data was carried out. For a correct normalization process, it was noticed that the failure mode in vertical struts is for buckling mode (Fig.8); therefore, the Eulerian approach to consider the critical load can be used. In addition, all the samples have the same cell length and architecture, hence the only parameter that change in the Euler’s formula, in accordance with the diameter of the struts, is the moment of inertia. The normalization of load was carried out by using the moment of inertia. Results of this operation are reported in Fig.9.

Figure 8. Buckling failure in vertical struts for the specimen printed with the set PA04.

Normalized compression curves are very different from raw ones. The set PA01 turns out to be the one with higher maximum load. The stiffness of specimens is also changed. The sets PA04 and PA05, considered the bests in dimensional analysis, have the load peak 50% lower than the PA01.
In Fig. 10 a representative compression test graph is presented and analysed. As is possible to see the curve is about periodic until the final densification. A sequence of an higher peak followed by a lower peak is shown. The first and higher peak correspond to the simultaneous buckling of two adjacent levels of the structure. After the buckling is started, only the weakest level continues its deformation process. This step corresponds in the graph to the decreasing load between first and second peak. The load decreases because the more the level is deformed the more is simple to continue deformation. When the weakest level is totally deformed the load rise up and the second level starting its compression. The initiation of the buckling was already started under the first peak of load; therefore, the second peak is lower than the first one. If only one peak of load is present, it means that only one layer was under buckling deformation mechanism as in Fig. 8.

**Figure 9** Compression force normalized by the moment of inertia of the vertical strut.
4. Conclusions

This study investigated how different parameters settings influence the compression behavior of Cubic lattice structures, made in stainless steel 17-4PH (AISI-630) and printed by SLM. The unit cell was 3mm large and the nominal diameter of struts was 0.6mm. This geometry was chosen because of the presence of both vertical and horizontal struts, respectively the easier and more difficult to realize in AM processes. To study the parameters influence, six different sets of parameters were chosen and for each of them one sample was printed.

By studying optical images of printed samples, it was found that both vertical and horizontal struts were printed successfully. The vertical struts are printed with no macroscopic defects, whereas the horizontal struts were affected from satellites presence and their axis isn’t straight. Despite these problems the structural integrity is guaranteed.

A dimensional analysis was conducted. For each structure 10 strut diameters were measured, and the average values was attributed to the sample. Only vertical struts were used for this operation because the shape of the horizontal ones is affected from satellites presence. The results show that sets PA04 and PA05 are the bests in terms of dimensional accuracy. It was found that only contour offset choice affect sensitively the struts’ dimension. The best value found for the contour offset is 75µm.

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 vertical struts. Normalizing the raw compression curves by the moment of inertia, 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 parameters set found was: PA01 + contour offset= 75µm. It would be useful test this approach on more geometries with different features and evaluate if the results will confirm what was found in this work.
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