Stiffness of 316L stainless steel support structures proposed for the SLM process

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Abstract. The subject of the article is to compare and evaluate the stiffness of the proposed structures relative to the section of the individual rods. The study is applicable to the additive technology of metal production by the 316L (1.4404) by SLM method. In the SLM process the design supports serves as the transporter of the heat generated in the melting bath to the substrate, the secondary function of the structures is for support the powder layer. The article focuses on the supportive function and weight ratio. A total of 4 structures were designed in iteration with three different rod diameters. During construction, the suitability of structures for the SLM method was determined and then the samples were subjected to a mechanical tensile test and the mechanical properties evaluated. In conclusion the most appropriate structure for the supportive function was identified.

Keywords: Stiffness, support, structures, SLM, lattice

1 Introduction

With ever-expanding 3D metal printing technology, it is devoted more and more attention to supporting structures in terms of material savings in their production. Especially in the production of overhangs with an angle of less than 45 °, in the SLM (Selective Laser Melting) process, the area is supported by the metallic powder only, resulting in the sticking of the surrounding particle powder to the component and the significant deterioration of the resulting surface of the material. This phenomenon is due to the poor heat transfer capacity of the powder and the accumulation of too much energy in the area around the overhang. For parts with overhang created without supporting structures additionally occur due to sudden heating of the laser and subsequent rapid solidification of the internal stress and deformation. The aim is to eliminate these undesirable effects. One of the ways to achieve this is to effectively orient the component in the building chamber so that the overhang angle during the construction is in a horizontal position. This option is not always feasible, and there is another option to reduce unwanted phenomena, namely to design a suitable supporting structure that will adequately dissipate heat, securely hold the part in the desired position, and be easily removable. Since the support structures are of no other significance than the above-mentioned reasons, it is a waste of material, when the components are disposed of and

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unused. The entire production process is costly and therefore it is necessary to design structures where the minimum material is used and consumed as little energy as possible.

M.F Ashby [1] states in his study that the main structural properties of the lattice of structures significantly influence choice of material, topology and relative density of the grid. Other properties that can affect properties include powder morphology, laser power setting, layer thickness, and scanning speed. Gumruk and Mines [2] examined the lattice of the BCC (Body Centered Cubic) and designed a theoretical model for the pressure test, resulting in the finding that the effects of block nodes and shear became very important for large d/L (small cell size) rather than small aspect range ($d/L < 0.1$). The structure of BCC was dealt with by Hasan et al. [3], where he found that the subsequent heat treatment of titanium alloys improved the microstructural properties of scattered impurities. Another variation of BCC grids examined by Smith and Guan [4] focused on the BCCz (Body Centered Cubic with vertical pillars) grid and found that stiffness and yield strength lattices improved markedly when the ratio of one cell was reduced over the others. Another specific structure for the SLM process is the gyroid structure and its variations. Among the first to examine this structure were Yan and Hao [5], their finding was that the effective yield strength dropped with increasing cell size. Variations of the gyroid, called double gyroid lattices, were dealt with by Maskery et al. [6], the conclusion was that more smaller cells could withstand more burdens and fewer cracks, and that heat treatment eliminates diagonal cuts and can accommodate more impact energy. The most important conclusion of the study, however, was that the double gyroid can absorb 3 times more energy than the BCC lattice.

The aim of the experiment is to determine the optimal shape of the structure's lattice in relation to the material used and the stiffness of the structure. The results will be useful for further application in the formation of overhangs and subsequent supporting structures. A similar experiment was carried out by the team around A. Hussein [7], where they found low volume lattice supports are faster to build and efficient for material saving and supports having a larger gap involving greater deformation and manufacturing failure. Our experiment takes this finding into account and works with other shapes and volumes of lattice structures. The main motivation for the experiment was the cost savings of printing the lattice of structures in the SLM process and testing the mechanical properties of the structures in academic conditions.

2 Experimental details (settings)

For the purpose of the experiment, four different lattice structures in iterations with three different beam diameters were designed using different softwares. For modeling basic cube and handles was used Solid Edge and for the creating lattice structures was used nTopology software. The first test structure was a basic SC (Simple Cubic) structure that was used more or less for comparative purposes, as it follows from its very nature that it is not suitable for SLM printing because of horizontal beams that are not self-supporting. The structure is formed by moving the base cube along its elongated edges. The second structure was BCC (Body Centered Cubic) consisting of a cube with particles in the vertices and particles in the center of the cube. The structure was already investigated earlier by Ushijima et. al. [8], but the different diameters of individual beams have not been verified. This arrangement of bars appears to be suitable for printing according to the shape, due to the self-supporting bars at an angle of 45° . Another test structure (Tetragon Vertex) has already been more complicated in the arrangement of beams, this is a quadrangle where the rods from the center point to the corners of the regular tetrahedron and form an angle of 109° and the joining of the edges of the tetrahedron results in an eighth shape wall. The lattice walls are made up of four general triangles and are a so-called Platonic body. The last tested structure was also a tetragon, but centered on the center, which created an interesting structure suitable for printing. All lattice

structures were applied to a 17 x 17 x 17 mm cube pattern, for which a clamp holder was formed for mechanical properties testing. The individual beam diameters were 0.5; 0.7; 1 mm. Used material stainless steel 316L (1.4404). Table 1 shows the structures in the modeling software and their size of the individual beams.

Table 1. Used structures and their parameters

Structure 1 - Simple Cubic
Beam diameter	Percent volume
		0.5 mm	5.68 %
		0.7 mm	10.85 %
		1 mm	21.39 %
Structure 2 - Body Centered Cubic
Beam diameter	Percent volume
		0.5 mm	3.40 %
		0.7 mm	6.49 %
		1 mm	12.99 %
Structure 3 - Tetragon Vertex
Beam diameter	Percent volume
		0.5 mm	4.84 %
		0.7 mm	9.30 %
		1 mm	18.44 %
Structure 4 - Tetragon Edge
Beam diameter	Percent volume
		0.5 mm	12.33 %
		0.7 mm	23.35 %
		1 mm	45.06 %

All structures were made under the same set conditions (laser performance, scanning speed, hatch distance) and the same strategy of scanning was used, namely "Meander" because of its universal use. The samples produced were then cut off by a belt saw from the substrate and no thermal finishing was applied.

3 Results

Visual inspection was determined as the first evaluation criterion for printed structures. The inspection has been carried out since the very beginning of the press, where no complications have been observed and the build has not been interrupted once. But on cut off samples some fabrication defects can be observed. There was a phenomenon called "warping", which can be caused in two ways. The first reason for this is the heat stress caused by rapid metal solidification, where the thermal stress exceeds the strength of the material and plastic deformation occurs. This phenomenon occurs on the upper layer, which lies below the powder metal and according to Zhao et al. [9], a bending angle is produced towards the laser beam, Zhao found that the thermal residual stress is centered on both edges of the scan path, and the low scanning speed can lead to high cooling rates, resulting in higher thermal residual stresses. Zhang et al. [10] recommends that the substrate preheat temperature be adjusted and remelted to reduce it. Another option is to change the laser scanning strategy. The second reason for the emergence of warping when a part of the curve begins to overlap is the lack of support that does not support the previous layers, which is probably the reason for our defect. Warping occurred only with two structures, namely BCC and Tetragon Vertex with a diameter of beam 0.5 mm, see Fig. 1.

Fig. 1. Warp defect

Another defect that has been observed is "dross formation" This defect results in increased surface roughness and change of overhang geometry, moreover it is a difficult predictable defect and it is difficult to understand the underlying mechanism of formation of dross defect during overhanging. Kovalev and Gurin [11] in their study state that dross formation occurs when the laser scans the already formed layer and the thermal conduction speed is too high, unlike when the laser scans the powder layer and the heat conduction speed is much lower than the fixed created layer. This is often the case when overpowering occurs when the absorbed energy is higher and this results in the melt pool being enlarged and, due to the effects of gravitational and capillary forces, plunging deeper into the powder. The defect manifested itself on the first tested structure of SC, see Fig. 2.

Fig. 2. Dross formation defect

For the next evaluation criterion, the maximum load of the structures that they can withstand without a visible violation was investigated. A standard tensile test was chosen at a load speed of 5 mm/min. Testing was carried out on a desk, two-column, computer-controlled testometric M500-50CT at a room temperature of 21 ° C. Graphs were obtained from the obtained results, where the individual member thicknesses were compared.

Fig. 3. Comparison of tensile test of the beam diameter 0.5 mm

Fig. 4. Comparison of tensile test of the beam diameter 0.7 mm

Fig. 5. Comparison of tensile test of the beam diameter 1 mm

It can be seen from the graphs (Fig. 3, 4, 5) that with the increasing thickness of the rods the necessary force is increased to break the samples. The largest load on all three beam diameters it takes most by the Tetragon Edge, but it also occupies the largest percentage volume of all structures tested, so it is a logical result. Interestingly, the results of other structures, predominantly the Tetragon Vertex and Body Centered Cubic structures, hold a similar percentage of the volume, yet the Tetragon Vertex structure, which held almost twice as much load, was significantly more robust. The Simple Cubic Structure has also achieved good results due to the position of the rod on the Z axis. The latest interesting finding is that the smaller the diameter of the rod, the longer the relative elongation and thus the time that the structure breaks.

The last and most important assessment criterion was the relative stiffness of the structures, or the Young modulus of elasticity. The Young's modulus of elasticity is the constant characteristic of the substance and indicates its strength and deformation potential. The higher the value of the module, the higher the voltage required to achieve a certain deformation, always gets positive values. To determine the modulus of elasticity from our experiment, the relative elongation and load forces from the Testometric instrument and the calculation according to formula (1) were used. Calculated values are shown in Table 2.

$$E = \frac{F}{S} : \Delta l$$

(1)

Where:

- E

– Modulus of elasticity

F

– Load force

S

– Sample area

Δl

– Elongation

[GPa]

[N]

[mm]

[mm]

Table 2. Calculated modulus of elasticity

	Beam diameter [mm]		
	0.5	0.7	1
	Modulus of elasticity of structures [GPa]		
Structure 1	1.68	2.28	9.01
Structure 2	0.84	1.69	3.5
Structure 3	5.63	9.07	4.64
Structure 4	1.49	2.02	6.12

The table shows that the greatest values of the modulus of elasticity are achieved by Structure 3 (TET Vertex), which additionally occupies the smallest percentage of the material volume, on the other hand, the worst values of the modulus of elasticity reach Structure 2 (BCC). Of all the data, one can observe the dependence that the larger the diameter of the beam, the overall stiffness is better.

4 Conclusion

Additive production permits the creation of complicated shapes of components that cannot be manufactured by other methods or special preparations are needed. One of the great advantages of additive production is the formation of a lattice of structures that can replace the solid material inside the body and thereby reduce overall weight and material consumption. Lattice structures can also be used for so-called support when they support surfaces. The shapes, sizes and possibilities of fabrication of structures are many, this article aimed to create 4 structures with different diameter of the connecting members. The model structures were printed using the SLM (Selective Laser Melting) method on the Renishaw AM400 under constant conditions. The suitability of the use of the individual structures was assessed using established criteria where the most important criterion was the stiffness of the structure, depending on the percentage of material consumed. The stiffness was determined according to the tensile test, the data was processed into charts and tables.

From the results obtained, several partial conclusions can be drawn:

- 1) When printing the structures of BCC and Tetragon Vertex with a diameter of 0.5 mm, there was a warping effect and when printing the structure of SC there was cross formation defect
- 2) Depending on the percentage of material consumed, the Tetragon Vertex Structure can withstand the greatest load to the breaking of the beams
- 3) The smaller the diameter of the beam, the higher the relative elongation
- 4) The highest rigidity was seen in the Tetragon Vertex structure (0.7 mm) and the worst structure BCC (0.5 mm)

Overall, the most appropriate structure, depending on the consumed material, is structure no. 3 Tetragon Vertex with a diameter of 0.7 mm and a percentage volume of 9.3%. This structure should be further investigated and further tests and experiments should be carried out.

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