Investigation of the influence of geometry and technological parameters of production on the structure and properties of spherical cellular structures obtained by selective laser melting

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Abstract

In this work, we studied the SLM process of obtaining spherical cellular structures from corrosion-resistant steel 03X16H15M3 (316L). The dependences of the microstructure and mechanical properties on the geometry and scanning strategy were studied for spherical cellular structures of 2 types: “Hollow spherical unit cell” with a calculated volume of voids of 69% and “Spherical unit cell” with a calculated volume of voids of 50%. Sample size was 10x10x10 mm. Investigations of the influence parameters of the laser scanning strategies have revealed the dependence of spherical geometry cellular structures and properties of the samples from the scanning strategy. A different course of the deformation curves and different values of the yield strength are obtained depending on the geometry and growth mode of spherical cellular structures. The minimum value of the yield strength is showed by a sample with a volume of voids equal to 60%. Comparison of the cellular structures of other samples with a difference in the volume of voids of 10%, resulting from the use of different strategies and modes of laser processing, showed that the yield strength of the samples may differ 1.5 times with the same initial geometry CAD model.

1 Introduction

Methods of obtaining metal products using laser additive technologies are actively developing in the world. Direct laser-growing technologies (DMD) are used mainly for the production of large-sized products that do not require high geometry detail [1], as well as for the manufacture of products with a gradient of properties [2].

The selective laser melting allows to obtain products with a high “print resolution” [3], but with overall dimensions limited by the dimensions of the building platform and working chamber. The SLM technology is of great interest for manufacturing details that have passed topological optimization, which, on the one hand, reduces the detail weight and makes its use in the construction of more effective, on the other hand significantly complicates the detail geometry, and thus make it difficult or completely impossible the process of its production using traditional methods (casting, rolling, welding) [4].

A typical example of the above is the topological optimization of products using cellular structures with a cell size of less than 1 mm, which can only be made using the SLM process [5]. The mechanical properties of cellular structures are strongly dependent on the parameters of the cell, and in particular the volume of voids. With an increase in the proportion of voids, mechanical properties decrease, and for different types of cells, these dependencies are different in nature [6-8]. At the same time, the small thicknesses of the elements of cellular structures, due to the different heat transfer conditions, require for their production to use...
laser processing modes different from those used for massive details [9,10]. Using an optimal mode of laser processing, it is possible to obtain cellular structures with a geometry corresponding to the CAD model, with minimal defects, which ultimately ensures the final properties of products close to the calculated ones.

In this paper, we studied the SLM process of obtaining spherical cellular structures and their microstructure and properties depending on the geometry and scanning strategies.

2 Methods

2.1 Material

The powder of corrosion-resistant steel 03X16N15M3 (316L) was used for the SLP process. The powder composition is given in Table 1. The powder micrograph is shown in Figure 1. In this work, a powder with a particle size of 5-45 μm was used. The powder flowability is 16.1 s, the bulk density is 4.47 g/cm³. Form factor 1.2: rounded powder.

Table 1 The chemical composition of powder wt.%

|   | Fe | C | Si | Mn | Cr | Ni | Mo | S | P |
|---|----|---|----|----|----|----|----|---|---|
| Matrix | to 0.03 | to 0.6 | to 0.8 | 15.0–17.0 | 14.0–16.0 | 2.5–3.0 | to 0.015 | to 0.02 |

Figure 1. Particles of powders of steel.

2.2 Cellular structures

Spherical cellular structures of 2 types were investigated: “Hollow spherical unit cell” (Sample No. 1) with a calculated volume of voids 69% (Figure 2a) and “Spherical unit cell” (Samples No. 2-1 and 2-2) with a calculated volume of voids 50% (Figure 2b). The size of the samples is 10x10x10 mm. The generation of cellular structures was carried out using software developed by FSU RFNC-VNIIEF.
2.3 Growing samples

Samples were obtained using the SLM280 unit. Growing modes are presented in table 2.

Table 2 – Modes of growing samples

| Parameter                          | Sample №1 | Sample №2-1 | Sample №2-2 |
|-----------------------------------|-----------|-------------|-------------|
| Laser power, Wt                   | 100       | 100         | 100         |
| Scanning speed, mm/s              | 565       | 565         | 565         |
| Distance between tracks, mm       | -         | -           | 0.09        |
| Number of laser passes            | 1         | 1           | 2           |

Figure 2. CAD models of samples of cellular structures: a) hollow spherical unit cell (sample 2); b) spherical unit cell (sample 2-1, 2-2).
### Table 1

| Parameter                                | Value 1 | Value 2 | Value 3 |
|------------------------------------------|---------|---------|---------|
| First pass from the detail edge, mm     | 0.02    | 0.02    | 0.09    |
| Laser power, Wt                          | 100     | 100     | 175     |
| Scanning speed, mm/s                     | 565     | 565     | 750     |
| Distance between tracks, mm              | 0.12    | 0.12    | 0.08    |

2.4 Microstructure investigations

The microstructure of the samples was investigated using an electronic scanning microscope TESCAN VEGA LMH with an x-ray energy dispersive microanalysis system of Oxford Instruments Advanced AZtecEnergy.

The EBSD analysis of the alloys was investigated using the NordlysMax2 detector (Oxford Instruments Advanced AZtecEnergy). The MAD was 0.5.

2.5 Compression tests

The mechanical properties of the samples were determined from the results of compression tests using a universal Zwick / Roell Z250 test machine.

### 3 Results and discussion

The obtained samples of cellular structures are presented on Figure 3.

![Figure 3](image)

**Figure 3.** Samples with cellular structures: a) hollow spherical unit cell; b) Spherical unit cell (Mode 1); c) Spherical unit cell (Mode 2).

Figure 4 shows the top (a-c) and side (d-f) surfaces of cellular structures from scanning electron microscope.
Figure 4. Surfaces of samples of cellular structures: (a, d) hollow spherical unit cell; (b, e) spherical unit cell, Mode 1; (c, f) spherical unit cell, Mode 2.

It can be seen that all the samples side and top surface are different. The spherical elements of cellular structures have clear outlines from the upper surface, while on the side surface in the holes one can see the presence of “hanging” areas, which were formed as a result of excessive melting of the powder layer under the laser.

Moreover, the greatest number of them is observed in the sample of the Spherical unit cell, manufactured according to the mode No. 2 with a greater energy input during the laser processing. At the same time, there is a difference in the cell size in the samples of the Spherical unit cell obtained according to modes No. 1 and No. 2. The first sample has a greater wall thickness and, accordingly, a smaller diameter of voids, which is associated with different distances between the laser trajectories in the primary circuit and in the product.

The results of the comparison of the cells of the obtained samples with the CAD model are presented in Figures 5, 6.
Figure 5. Hollow spherical unit cell. Comparison of sample sizes with CAD model.

Thus, the parameters of the laser scanning strategy with the SLM process strongly influence the geometry of spherical cellular structures. With a wrong choice of strategy, the sizes of cellular structures can differ greatly from the CAD model, which affects the mechanical properties.
Figure 6. Comparison of sample sizes with CAD model: (a, d) spherical unit cell (Mode 1); (b, e) spherical unit cell (Mode 2); (c, f) – CAD model of Mode 1 and Mode 2.

Figure 7 shows the microstructure of the investigated cellular structures. It can be seen that the Hollow spherical unit cell and Spherical unit cell structures (Mode 2) are characterized by the minimum number of internal defects in the form of pores. Porous structure is present in cellular structures of the Spherical unit cell (Mode 1), although the geometry is closest to the CAD model.
Figure 7. Microstructure of samples of cellular structures: (a, d) hollow spherical unit cell; (b, e) spherical unit cell, Mode 1; (c, f) spherical unit cell, Mode 2.

The results of the EBSD sample analysis are presented in Figure 8. As can be seen, the structure has a grain structure with an average grain size presented in Table 3.
Figure 8. EBSD analysis of the cross section of the samples with different cellular structures - the grain structure of the sample with different grains orientations and the grains size distribution in the region: a, d - cellular structures of sample 1; b, e - cellular structures of sample 2-1; c, f - cellular structures of sample 2-2

Table 3 The grains size of samples with different cellular structures

| Cellular structure | Average grain size, µm |
|--------------------|------------------------|
| 1                  | 30 ± 5                 |
| 2-1                | 20 ± 3                 |
| 2-2                | 27 ± 3                 |

Compression tests were carried out on the samples in the initial state without heat treatment to a compression ratio of 50%, the destruction of the samples after the test was not observed. The deformation curves are presented in Figure 9. The values of the yield strength, the maximum load for the samples, as well as data on the calculated and actual volume of voids in the samples are presented in Table 4.

Figure 9. The results of compression test.
Table 4 The results of compression tests

| Cellular structure | \( F_{0.2}, \text{ MPa} \) | \( F_{\text{max}}, \text{ kg} \) | Shortening, % | Void volume, % |
|-------------------|-----------------|-----------------|--------------|--------------|
| 1                 | 91              | 2839            | 50           | 69           |
| 2-1               | 143             | 7356            | 50           | 50           |
| 2-2               | 97              | 5664            | 50           | 50           |

It can be seen that a different course of the deformation curves and different values of yield strength were observed depending on the geometry and mode of growth of spherical cellular structures. The minimum value is showed by the sample 1, for which the actual volume of voids was 60%. When comparing cellular structures 2-1 and 2-2 with a difference in the volume of voids of 10%, resulting from the use of different strategies and modes of laser treatment, the yield strength of sample 2-1 is 1.5 times higher than that of sample 2-2, with the same initial geometry CAD model.

4. Conclusions

1. The possibility of obtaining spherical cellular structures from stainless steel 03X16H15M3 (316L) by the SLP method is shown.
2. The dependences of the microstructure and mechanical properties on the geometry and scanning strategy were studied of spherical cellular structures of 2 types: “Hollow spherical unit cell” with a calculated volume of voids of 69% and Spherical unit cell with a calculated volume of voids of 50%.
3. Investigations of the influence of the laser scanning strategy parameters revealed the dependence of the geometry of spherical cellular structures and the properties of samples. A different course of deformation curves and different values of the yield strength were obtained depending on the geometry and growth mode of spherical cellular structures. The minimum value of the yield strength was showed by a sample with a volume of voids equal to 60%. Comparison of the cellular structures of other samples with a difference in the volume of voids of 10%, resulting from the use of different strategies and modes of laser processing, showed that the yield strength of the samples may differ 1.5 times with the same initial geometry CAD model.

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