Comparison of the structure and properties of samples from TI-6AL-4V alloy received on different printers for 3D printing

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Abstract. In this work, we compared the samples obtained by additive technologies. Samples for the study were printed on two different printers using similar DMLS and DMLM technologies. Printing was carried out according to the CAD model data. The printing was performed using the manufacturer's recommended print settings. For printing, we used powders recommended by the manufacturer for these printer models. In the course of the work, the structure and roughness parameters in the initial state were compared. The heat treatment mode was selected. The effect of vacuum annealing on the structure as well as mechanical properties such as uniaxial tension, KCU and fatigue strength was investigated. Based on the results of the work, a conclusion was made about the improvement of 3D printing, as a result of which the products obtained using additive technologies after heat treatment are not inferior in properties to products obtained using industrial technology from a similar alloy.

1 Introduction

Recently, there has been an increased interest in the use of additive technologies for the production of complex-shaped parts from various materials, which are difficult to obtain using traditional industrial technologies. [1, 2] One of such materials is titanium alloys. Titanium alloys, due to a successful combination of properties such as corrosion resistance, biocompatibility, as well as strength and ductility, are widely used in various sectors of the economy, including medicine, aviation and the chemical industry [3-6].

Titanium is a difficult-to-machine material, so the use of additive technologies for the production of parts is a promising task.

Direct Metal Laser Alloy Metal (DMLS / DMLM) allows the use of layer-by-layer printing technology to produce high quality metal parts. This method of rapid 3D prototyping is one of the most commonly used for obtaining parts of complex geometries [7-10].

In works [11-15], the authors found that with the help of additive technologies with subsequent processing, it is possible to obtain blanks that are not inferior in mechanical properties to blanks obtained using traditional technologies.

The structure and properties of the final product made by direct laser metal alloying technology strongly depend on many factors, including the size of the powder fraction, printing modes, such as laser power, atmosphere, temperature in the working chamber, height of the alloyed layer and others [4, 16, 17]. This is why the properties of the final product can vary and cannot be easily predicted and guaranteed.

Therefore, the study of samples obtained by direct laser alloying of metal on various printers to assess the comparability of properties is undoubtedly an urgent task.
Materials and research methods

The studies were carried out on samples obtained by direct laser metal alloying (DMLS / DMLM). The samples were square and circular. The geometric parameters of the printed samples corresponded to the geometric parameters of the blanks for mechanical tests for uniaxial tension, fatigue strength, and impact strength. The printing was carried out from CAD data on the EOS M290 and Concept Laser M2 Cusing printers for 3D printing of metal products. Powder from titanium alloy Ti-6Al-4V, grade EOS Titanium Ti64 Grade 23 with a fraction size of -80 +20 μm and CL 41TI ELI Grade 23 with a fraction size of -45 +15, was used as a material for printing. The chemical composition of the powder is shown in table 1.

Table 1. Chemical composition of Ti-6Al-4V alloy powder (wt.-%)

| Name                        | Al   | V    | Fe  | O   | N   | C   | H   |
|-----------------------------|------|------|-----|-----|-----|-----|-----|
| CL 41TI ELI Grade 23        | 5.73 | 3.96 | 0.18| 0.12| 0.03| 0.015| 0.008|
| ASTM F136-02a               | 5.5-6.5 | 3.5-4.5 | 0.0-0.25 | 0.13 | 0.05 | 0.08 | 0.012|
| EOS Titanium Ti64 Grade 23  | 5.5  | 4.26 | 0.17| 0.11| 0.03| 0.012| 0.007|
| ASTM B348                   | 5.5-6.5 | 3.50-4.50 | 0.25 | 0.13 | 0.05 | 0.08 | 0.012|

Samples for metallographic analysis were prepared according to the standard procedure [18].

Heat treatment was carried out in a VEGA-1M vacuum furnace.

The microstructure was examined using an AXIO Observer.Alm optical microscope at magnifications up to 1000 times. The bright field method was used in air. The images were analyzed using the NEXSYS ImageExpert Pro3.6 software package.

The Rockwell hardness was measured on a BUEHLER Macromet 5100T GOST 9013-59 device.

The surface roughness was measured on a HOMMEL TESTER T500 device in accordance with GOST 2789–73.

Statistical mechanical tensile tests were carried out in accordance with GOST 1497–84 at normal temperature on a TIRA-test 2300 universal machine.

Short-term dynamic impact tests were carried out on a 2130KM03 pendulum impact machine with a limiting energy not exceeding 300 J, GOST 10708–82.

The resistance to high-cycle fatigue was determined according to GOST 25.502-79 on a UBM100 testing machine, according to the scheme of pure bending with rotation, the asymmetry coefficient \( R = -1 \), the loading frequency \( f = 50 \) Hz, the base number of cycles \( 10^7 \).

Results of experiments and their discussion

At the initial stage of the work, the microstructure was investigated and the hardness and roughness of the surface of the samples were measured immediately after 3D printing (in the initial state). The studies were carried out in two directions: printing direction (PD) and transverse direction (TD) (figure 1).
In the initial state in the direction of printing, the structure of the samples is represented by practically equiaxed $\beta$-grains (figure 2 a, c), and the intragranular structure is represented by $\alpha'$-martensite (figure 2 e, f). The $\beta$-grain size differs slightly and the average size after printing on the EOS M290 printer is 120 $\mu$m, and on the Concept Laser M2 Cusing printer – 100 $\mu$m. The somewhat smaller size of the $\beta$-grain is apparently due to the use of a finer fraction of the powder.
If in the direction of printing the β-phase grains have an equiaxed shape, then in the transverse direction they are elongated in the direction of sample growth (figure 2 b, d). The average β-grain length is 245 μm on the EOS M290 and 215 μm on the Concept Laser M2 Cusing. The slight difference, as in the previous case, is apparently due to the use of powder of different fractions.

Studies have shown that the surface roughness of the samples is practically independent of the powder fraction. When printed on the EOS M290, the roughness (Rz) was 61.5 microns, and on the Concept Laser M2 Cusing it was 59.3 microns.

Previous studies [19, 20] showed that the values of hardness depend on the direction of measurement, and the difference in values can reach 5-6 units. HRC. On samples obtained on two printers, differences in hardness values, both among themselves and in two directions, were not found, and it was 35-37 units. HRC.

At the next stage of the work, the effect of heat treatment on the formation of the structure and mechanical properties of samples from the titanium alloy Ti-6Al-4V was investigated. Analysis of the literature data showed that most often the annealing of samples obtained by 3D printing is carried out in the temperature range from 800° to 850°C with a holding time from 4 to 1 hour. Therefore, an average temperature of 820 °C was chosen for research. Annealing was carried out in vacuum for 2 hours.

Since the annealing was carried out in the (α + β) -region, the size of the initial β-grain did not change (figure 3 a-d). The intragranular structure has changed, which is now represented by the α-phase, which has a lamellar morphology, which is inherited from martensite, and a small amount of the β-phase (figure 3 e, f). The hardness of the samples, measured in two directions, after annealing decreased to 34 units. HRC.
At the final stage of the work, mechanical tests of the samples were carried out after vacuum annealing. The test results are presented in table 2.

The tests carried out have shown that the samples obtained on different printers have close values of the ultimate strength and plasticity. Samples obtained on the Concept Laser M2 Cusing printer are inferior in terms of relative constriction (by 13%) and impact strength (by 25%), but all of them are at a sufficiently high level and are not inferior to the mechanical properties of deformed semi-finished products obtained using traditional technologies from an alloy VT6 (Ti-6Al-4V) (table 2).
In an earlier work, the authors found that the formation of an intragranular lamellar morphology of the α-phase and imperfection of 3D printing after annealing lead to low values of fatigue strength, and the number of cycles before fracture of samples of the same type at the same stress could differ by two orders of magnitude [21]. The fatigue strength values obtained in this work indicate the improvement of the 3D printing technology: almost all samples withstood 10,000,000 cycles at a stress of 400 MPa and were removed without destruction, despite the lamellar morphology of the phase-phase. The results are listed in table 2.

Table 2. Mechanical properties of samples made of Ti-6Al-4V alloy after annealing at 820°C for 2 hours

| 3D-printer name       | Tensile strength [Rm] (MPa) | Yield strength [Rp0.2] (MPa) | Elongation at break [%] | Reduction of area [%] | KCU, [MJ/m²] | Fatigue strength, 400 [Mpa] |
|-----------------------|-----------------------------|-------------------------------|------------------------|-----------------------|--------------|-----------------------------|
| EOS M290              | 1010                        | 980                           | 16,5                   | 54                    | 0,67         | $10^7$                      |
|                       |                             |                               |                        |                       |              | $10^7$                      |
| Concept Laser M2 Cusing | 1020                        | 960                           | 16,5                   | 47                    | 0,50         | $10^7$                      |
|                       |                             |                               |                        |                       |              | $10^7$                      |
| ASTM F3001            | 860                         | 795                           | 10                     | -                     | -            | $1,7\times10^6$             |
| Deformed bar from VT6 alloy (GOST 26492-85) | $\geq 885$ | - | $\geq 8$ | $\geq 25$ | $\geq 0,25$ | - |

* Remove without destruction

4 Conclusion

Thus, the studies carried out have shown that the samples obtained on the EOS M290 and Concept Laser M2 Cusing printers by direct laser metal alloying, in spite of the almost two-fold difference in the size of the initial powder fractions, have an identical structure in the initial and annealed states and close mechanical values. Properties that are not inferior to the mechanical properties of rods made of titanium alloy VT6 (Ti-6Al-4V), obtained by traditional industrial technology.

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