Metallographical researches results of titanium alloy Ti-6Al-4V samples obtained by using traditional and additive technologies

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Abstract. Technologies of additive manufacturing are increasib ly used in various industries, including power engineering. It is known that the leading foreign turbo-building companies actively implement such technologies and successfully produce full-size products. Nevertheless, there are many questions related to the operation reliability of such equipment, in particular, resistance to various types of wear.

The purpose of this work was to establish the possibility of titanium alloy Ti-6Al-4V samples obtaining, which is used in turbine construction, with the help of additive technologies to solve problems on the study of their properties and comparison with similar characteristics of samples obtained by the traditional technological method.

As a result of the work, the properties of both types of samples were determined and their comparative analysis was carried out. An almost identical chemical composition of both types of samples was found to comply with the ASTM B265 standard for the Ti-6Al-4V alloy. It is shown that the hardness and microhardness of the investigated both types of samples is the same and amounted to 31 ± 5 HRC and 390 ± 10 HV0.1, respectively. The surface roughness of the «printed» samples is not less than 4 times higher than for the samples manufactured by the traditional technological method, which requires it’s additional processing for further research.

The microstructure of the alloy obtained by using additive technologies is acicular martensite formed as a result of rapid cooling from the high-temperature beta region.

1. Introduction

Today, one of the promising areas for manufacturing complex parts and components is the method of additive technology or 3D - printing of metal products [1]. Recently, there has been an increased interest in these technologies in the field of mass production, measured in hundreds of units [2]. There are a lot of products made from special materials, often complex geometry, in the aviation industry, the space industry, power engineering and a number of other industries [3].

In these industries there is an increased interest in 3D - printing technologies, as an alternative to traditional technological methods for the production of non-prototypes or prototypes, and products that will be actively used in real objects. The economic feasibility of using this kind of technology is explained by the fact that in some cases, with objective calculations of real costs, additive technologies are less expensive than traditional ones.

At the same time, not only technological quality control is important for the reliable use of additive manufacturing technologies, but also testing the product for resistance to various types of wear, to which the equipment, in particular, solid particle erosion, is exposed. This type of test is regulatory [4] and mandatory for any new manufacturing technology and / or subsequent strengthening of products exposed to gas-abrasive flow. First of all, it concerns the blades of guiding [5] and rotating devices of the powerful power gas-turbine plants compressors first stages [6] and the high and medium pressure cylinders first stages of powerful steam turbines [7].

Carrying out solid particle erosion tests will first of all give the kinetics fundamental dependencies of this process for samples obtained by using innovative additive technologies. To understand the wear
resistance of printed sample complete physical picture it's important to imagine the process of material manufacture and how great is the difference from the material manufactured by traditional method. Therefore it's necessary to preliminary studies the properties of the sample, the analysis of which can later explain the mechanism of surface destruction during the solid particles impact.

2. Equipment and research methodology specification
Using the traditional technological method (Figure 1) and additive technology (Figure 2) two batches of Ti-6Al-4V titanium alloy samples were manufactured for metallographic researches and subsequent solid particle erosion resistance tests.

The sample manufacturing process by the traditional method included the following stages:
– cutting titanium alloy Ti-6Al-4V bars with a diameter 36 mm into 5 mm long billets;
– material sampling to diameter 34 mm at length 1 mm from the sample edge;
– deburring the sample side edges and flange;
– grinding sample surface on a grinding machine to the required grade of smoothness.

During the sample manufacturing were observed the following technical requirements:
– samples were made of a single material melt with allowances and landings;
– sample heating during mechanical processing in the manufacturing process did not cause structural changes and physicochemical transformations in the metal;
– modes and sequence of the tooling minimized cold-hardening and eliminated the local overheating of the sample working surface during grinding;
– during the sample manufacturing the technological facets have been removed, and sharp edges are blunted up to radius 0.5 mm;
– sample working surface did not contain any corrosion signs, temper colors, etc.

![Figure 1. Samples made by traditional technological method.](image1)

Samples produced by using additive technologies were made of titanium powder Ti-6Al-4V Grade 5. The manufacturing process consisted of the following: device for applying and leveling the layer removed the powder layer from the feeder and distributed it uniformly over the substrate surface. After that, the laser beam scanned this layer surface and formed a product by sintering. At the end of powder layer scanning the platform with manufacturing product has been gone down for deposited layer thickness and the platform with powder has been raised, and the process of applying the powder layer and scanning repeated.

![Figure 2. Sample’s computer model (a) and samples produced by additive technologies (b).](image2)
After this process consummation unused powder deleted from platform. The chemical compositions of the both materials types are shown in Table 1.

| Element     | Ti-6Al-4V Powder | Ti-6Al-4V Bar |
|-------------|------------------|---------------|
| Titanium (Ti)| 88÷90            | 89.2          |
| Aluminum (Al)| 5.5÷6.5         | 5.9           |
| Vanadium (V)| 3.5÷4.5          | 4.1           |
| Iron (Fe)   | < 0.25           | 0.2           |
| Oxygen (O)  | < 0.13           | 0.1           |
| Carbon (C)  | < 0.08           | 0.07          |
| Nitrogen (N)| < 0.05           | 0.03          |
| Hydrogen (H)| < 0.012          | 0.01          |

The following measuring equipment URI «Hydroshock rig «Erosion-M» was used to implement the planned metallographic studies:
– TESCAN MIRA 3 LMU scanning field emission electron microscope - to study the both sample types morphology and structure;
– X-Max 50 X-ray energy dispersive spectrometer (EDS) - to obtain the full spectrum of X-ray elements radiation, to carry out qualitative and quantitative elemental analysis of metallographic samples sections with locality on the order of 1 μm;
– Dektak 150 mechanical profilometer - to study the surface morphology, evaluation the material wear of the experimental sample after tribological tests, construction and analysis the surface profiles;
– DuraScan 20 hardness tester for small loads - to determine the surface microhardness in accordance with GOST 9450 76, ISO 6507 and ASTM E384 standards;
– M4C hardness tester - to control the material macrohardness in accordance with the Vickers hardness test method – GOST 2999-75 standard (also ISO 6507, ASTM E-10 standards) at a load of 10 kgf;
– TRB-S-CE-0000 tribometer – to determine the friction coefficient of sample by the «Ball-plane» method in the chosen load values, speed and mileage length.

Following machines by Buehler GmbH company were used to prepare sample for researches: an abrasive cutting machine with a linear movable cutter system PowerMet 3000, an automatic press Simplimet 1000, cold casting apparatus Cast n° Vac 1000 and a grinding machine Beta with an automatic nozzle Vector and a modular system of liquid distribution PriMet 3000.

The structure of both samples types after obtaining the metallographic section and it’s subsequent etching was studied at the TESCAN MIRA 3 LMU scanning field emission electron microscope. For metallographic analysis were used a series of standards: GOST 10243-75 «Steel. Methods of testing and macrostructure evaluation»; GOST 8233-56 «Steel. Standards of microstructure»; GOST 5639-82 «Steels and alloys. Methods for the detection and determination the grain size».

Tribological tests of samples were conducted at the following conditions:
– movement scheme - linear reciprocating sample motion relative to a stationary counterbody with a specified displacement amplitude;
– displacement rate – 0.05 m/s;
– applied load– 1 N;
– stroke length (displacement amplitude) – 2 mm;
– mileage length (friction path) – 200 m;
– counterbody – ball Ø6 mm, material – WC.

3. Results and discussion
The metallographical sections of the titanium alloy Ti-6Al-4V samples produced by additive technologies and by traditional technological method are shown in Figure 3 and Figure 4.
Figure 3. Microstructure image of titanium alloy Ti-6Al-4V sample produced by additive technologies at various multiplications

Figure 4. Microstructure image of titanium alloy Ti-6Al-4V sample produced by traditional technological method at various multiplications

The microstructure of the alloy obtained by using additive technologies is acicular martensite formed as a result of rapid cooling from the high-temperature beta region. The microstructure of the alloy manufactured by the traditional process is represented by elongated in the direction of deformation alpha-phase grains with beta-phase streaks located along their boundaries.

After obtaining images of transverse sections and studying their structure, an analysis of the samples elemental composition was performed using the energy-dispersive microanalysis. In this case, spectrum of X-ray radiation were taken in different regions. The spectrum characterizes the relative intensities of the sample characteristic radiation lines, allows qualitatively to reveal the presence of various elements in it, and also estimate their relative content. Thus, on the basis of the obtained spectrum, was determined the elements content in the samples. The results of manufactured samples chemical composition analysis are shown in Table 2.

Table 2. Alloy surface components

| No | Samples characteristic                  | Compositions, % |
|----|----------------------------------------|-----------------|
|    |                                       | Al  | Ti  | V   |
| 1  | (Ti-6Al-4V, additive technologies)     | 5.19| 91.1| 3.74|
| 2  | (Ti-6Al-4V, traditional method)        | 5.97| 89.4| 4.61|

The element analysis carried out showed that the main material of the manufactured samples of both types is titanium, it’s content varies in the range 89-92%, the aluminum content is about 5.2-9.9%, the vanadium content is about 3.7-7.6%. The results of tribological tests are shown in Table 3.
Table 3. The friction coefficient change as a function of the sample’s surface mean free path.

| Material          | Ti-6Al-4V (traditional method) | Ti-6Al-4V (additive technologies) |
|-------------------|-------------------------------|-----------------------------------|
| Average friction coefficient $\mu_{av}$ | 0.5                           | 0.5                               |

Conducted researches have shown that both types of samples showed the same value of the average coefficient of friction. This circumstance attests to the high quality of the Ti-6Al-4V powder layers «sintering» and allows us to assert that for this parameter such method of obtaining a sample or billet is not inferior to the well-known hot-rolling process.

The roughness was determined from five profiles, measured at different parts of the each sample surface. The following roughness parameters were calculated: the arithmetic mean deviation of the profile (Ra) and the height of the profile unevenness measured at ten points (Rz). The obtained surface profiles of Ti-6Al-4V titanium alloy samples, manufactured by using additive technologies and the traditional technological method, are shown in Figure 5.

![Table 4. Results of the roughness, hardness and macrohardness measurement of the test samples surface](image)

| No | Samples characteristic          | Ra, $\mu m$ | Rz, $\mu m$ | HV 0.1 | HRC |
|----|---------------------------------|------------|-------------|--------|-----|
| 1  | (Ti-6Al-4V, additive technologies) | 6.59       | 45.3        | 390±10 | 31±5 |
| 2  | (Ti-6Al-4V, traditional method)  | 1.67       | 9.2         | 390±40 | 31±5 |

From presented profilograms it can be see that the surface roughness of the samples produced by additive technologies with respect to parameters Ra and Rz not less than in 4 times higher than those for samples manufactured by the traditional method.
4. Conclusions
The complex of metallographic studies showed that the titanium alloy Ti-6Al-4V composition, which is widely used at present for the manufacture of parts by additive technologies, matches the requirements of the ASTM B265 standard.
Manufactured samples have significant differences in microstructure. In the case of additive technologies, this is acicular martensite; in the case of using the traditional method, the microstructure of the alloy is represented by elongated in the direction of deformation alpha-phase grains with beta-phase streaks located along their boundaries.
The values of hardness, microhardness and average coefficient of friction in both types of samples are the same. The results of measuring the roughness of Ra or Rz indicate that the surface of products manufactured by using additive technologies must be further processed.
The obtained data can be used as a necessary knowledge base for carrying out experimental studies of the resistance to hard abrasive particles impact and the surface destruction mechanisms description of samples manufactured by using additive technologies, under different conditions.

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