Comparative erosion tests results of titanium alloy Ti-6Al-4V samples obtained by using 3D - printing technology and manufactured by the traditional technological method

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Abstract. Rotating blades of steam turbines and compressors operate in conditions of various damaging factors, including shock-dynamic impacts of liquid droplets contained in steam or in air. One of the most promising ways to reduce damage from water droplet erosion can be the application of the 3D - printing technology that will allow to replace damaged parts of structural elements, as well as cut repair costs and prolonging the service life of the equipment.

The aim of present work was to determine the possibility of using the 3D - printing technology of the turbine blades for use in power engineering. The main task of the work was to check samples of the material obtained by this method for water droplet erosion resistance, which is one of the regulated tests type at the turbine blades design stage.

This paper presented the results of water droplet erosion process experimental studies of the titanium alloy Ti-6Al-4V samples prepared by the method 3D - printing and by the traditional technological process at a collision velocity $C_{imp} = 300 \text{ m/s}$ with a monodisperse flow of liquid droplets with a diameter $d_d = 1000 \mu\text{m}$. Erosion tests were carried out by using a set of research equipment URI «Hydroshock rig «Erosion-M» NRU «MPEI». It has been established that the erosion resistance for the incubation period duration of the Ti-6Al-4V titanium alloy samples manufactured by the 3D - printing method is 1.4 times less than for the samples manufactured by the traditional technological process. The data obtained can be used in the future in the development of complex passive methods for protection steam turbines and compressors last stages rotating blades: creation of replaceable erosion-resistant inserts by 3D - printing with a protective coating.

1. Introduction
In present, according to available data, foreign aircraft manufacturers widely use titanium alloys, such as Ti-6Al-4V [1] to create structural elements of flying devices, in particular, compressor blades of gas turbine engines [2]. These elements are subject to water droplet erosion due to the use of primary air cooling technology supplied to the compressor inlet. This is accomplished by dispensing liquid droplets, several microns in size, in order to lower the temperature of the primary air and increase the efficiency of the installation as a whole. Thus, the problem of water droplet erosion is relevant not only for power engineering (wear of turbines wet steam stages rotating blades), but also for civil and military aviation.

One of the promising ways to reduce the cost of replacing damaged parts of power equipment, such as blades of power turbines and gas turbine engines, is the use of materials obtained with the help of additive technologies [3], the use of which [1] is gaining popularity now [4]. An advantage of additive technologies is the reduction in the time of production: according to various estimates [5], the time from design to manufacturing is reduced from 2-3 years to 5-6 months [6].

Nowadays, rapidly developing additive technologies for metal products printing have wide perspectives of use not only as prototyping of machine elements, but also their subsequent replacement. Implementation of the transition to partial or complete reconstruction of the equipment critical elements with 3D - printing technology use, which have new properties compared to the traditional methods
manufactured, is impossible without full research and testing of metals created by using additive technologies.

Today, the overwhelming number of works is aimed to study the strength characteristics of materials used for the manufacture of turbomachines structural elements by the methods of additive technologies, such as: tensile-compressive strength [7], bending [8], torsion and rupture under the action of corrosive media [9]. Another part of the research is devoted to the study of the sample parameters effect manufactured by the methods of additive technology [10], as well as the subsequent surface treatment on their strength characteristics.

Despite the large amount of data available, at present there is no information on the verification of such materials for water droplet erosion resistance. According to the guidance documents [11], this type of test is mandatory for any new manufacturing and/or hardening technology.

Proceeding from this, the problem arises of determining the fundamental patterns of erosive destruction of materials obtained by 3D - printing, promising both for the full-scale production of powerful steam turbines last stages blades and the first stages of gas turbine engines compressors, and for creating passive methods for their protection by using hardening of the surface and the application of "erosion-resistant" inserts on the periphery of the blades. (see figure 1b), acting as a promising replacement for stellite plates installed at the entrance edge (see figure 1a) in the zone most strongly affected by the impact of water droplet erosion.

![Figure 1. Scheme of stellite plates application (a) and special erosion-resistant insert (b), manufactured by 3D - printing technology.](image)

2. Experimental procedures
The manufacturer was provided with a previously developed sketch for production the erosion testing samples produced by a traditional technological method (Figure 2a). Company-manufacturer was provided model created at the CAD environment by the SolidWorks software package for production samples by using 3D - printing technology (Figure 2b).

![Figure 2. Sketch of the experimental samples (a) and it’s 3D - model (b).](image)
For experimental researches were produced the samples of titanium alloy Ti-6Al-4V (this alloy contains up to 90% of the mass titanium fraction, 6.75% aluminum and 4.5% vanadium and other trace elements) using «Concept Laser Mlab_cusing» printer by means of selective laser sintering technology. The form of the «grown» samples at special printer platform is shown in Figure 3a. After manufacturing, the samples were removed from the tooling and the working surface was grinded to remove the excess material remaining after printing (see figure 3b).

![a)](image1)
![b)](image2)

**Figure 3.** Titanium alloy Ti-6Al-4V samples, manufactured by the 3D-printing method.

Samples form produced by traditional technological method of the hot rolled titanium alloy Ti-6Al-4V twig (the chemical composition is presented in Table 1) by means of turning, milling and grinding is shown in Figure. 4.

**Table 1.** The chemical composition of the titanium alloy Ti-6Al-4V.

| Element | Ti | Al | Mo | V  | Zr | Fe | N  | C  | H  | O  | Si | Admixtures |
|---------|----|----|----|----|----|----|----|----|----|----|----|-------------|
| Composition, % | Base | 5.9 | 4.1 | 0.07 | 0.2 | 0.03 | 0.07 | 0.01 | 0.1 | 0.04 | < 0.3 |

Tests of both types titanium alloy Ti-6Al-4V samples were carried out with research equipment of the URI «Hydroshock rig «Erosion-M» NRU «MPEI». Hydroshock rig – is rotary test rig that works as follows: two test samples are affixed to the ends of a titanium alloy rod rotating in a vacuum chamber and intersect a vertical liquid droplets flow emerging from a special drops generator. The samples were tested in pairs, i.e. one titanium alloy Ti-6Al-4V sample obtained by the 3D-printing method and manufactured by a conventional technological method were simultaneously tested in one experiment.

![image3]

**Figure 4.** Titanium alloy Ti-6Al-4V samples, manufactured in the traditional way.

Experimental studies were carried out at a collision rate \( C_{imp} = 300 \text{ m/s} \) of sample with droplets \( d_c = 1000 \mu \text{m} \). The time for samples testing varied. Six different exposure times at least were selected to construct an erosion curve. To perform a comparative analysis of the erosion tests results, the sample mass loss \( \Delta m_i \), (g) as a function exposure time at the test rig t, (s) was made.

The sample mass loss was calculated of according to formula:

\[
\Delta m_i = m_0 - m_i
\]

where, \( m_0 \) is the initial samples weight; \( m_i \) is the sample mass after experiment; \( i \) is the experiment number.

The results of the tests are presented as a function \( \Delta m = f(t) \), with the display of experimental points and the relative error to determining \( \Delta m \), is \( \delta m = 5\% \).
3. Results and discussion
After the manufacture both types of sample were made metallographic sections to reveal differences in the specimen microstructure (Figure 5).

![Image a](image1.png) ![Image b](image2.png)

**Figure 5.** Image of the titanium alloy Ti-6Al-4V sample microstructure manufactured in a conventional process (a) and with additive technology (b).

The alloy obtained by the traditional method (Figure 5a) is represented by a two-phase structure \((\alpha + \beta)\). In this case, the structure is characterized by the presence of heterogeneity in the shape and size of the grains-among the crystallites of the elongated shape, it is possible to observe \(\alpha\) - phase grains close to equiaxial. It can be assumed that such heterogeneity arose as a result of the action of the thermal deformation cycle during the manufacture or subsequent thermal treatment of the alloy. An alloy made by using additive technologies (Figure 5b) has a characteristic for this combination of material and technology disperse needle-shaped martensitic structure.

Kinetic erosion curves at \(\Delta m = f(t)\) coordinates (Figure 6) were obtained as a result of the tests series of titanium alloy Ti-6Al-4V samples produced by 3D-printing and the traditional technological method at the impact samples velocity \(C_{imp} = 300 \text{ m/s}\) with liquid droplets with the diameter \(d_d = 1000 \mu\text{m}\).

![Image of graph](image3.png)

**Figure 6.** The erosion wear curves of titanium alloy Ti-6Al-4V samples obtained by the 3D-printing method (1) and manufactured by the traditional technological method (2) at the impact velocity \(C_{imp} = 300 \text{ m/s}\) and a droplet diameter \(d_d = 1000 \mu\text{m}\).

The sample surface topography change dynamics after water droplet erosion tests over time is shown in Table 2.
Table 2. Changes in the experimental samples surface topography after erosion tests.

| Material mark                      | Test time, min |
|------------------------------------|----------------|
| Ti-6Al-4V (Traditional method)     | 0  2.5  5  7.5 10 12.5  15 20  25 30 |
| Ti-6Al-4V (3D-printing)            | 0   2.5   5   7.5  10  12.5  15  20  25  30 |

As a result of the carried out experimental studies and subsequent processing of the obtained data, it was found that under the given experimental conditions:
– the duration of the incubation period for Ti-6Al-4V titanium alloy samples manufactured by the traditional technological method is 2 minutes;
– the duration of the incubation period for Ti-6Al-4V titanium alloy samples made by 3D-printing is 1.5 minutes.

Comparing the relative erosion resistance of titanium alloy Ti-6Al-4V samples obtained by 3D printing and manufactured by the traditional technological method was carried out according to the incubation period duration characterizing the time before the surface destruction began (see figure 7).

Obtained results analysis showed that the relative erosion resistance of the titanium alloy samples produced by the traditional method in the incubation period duration is higher than for titanium alloy Ti-6Al-4V samples manufactured by 3D-printing at least in 1.4 times.
4. Conclusions
Conducted researches illustrates that it is possible to make titanium alloy Ti-6Al-4V samples of the required geometry and chemical composition by using 3D - printing technology.

The relative erosion resistance over the incubation period duration of the titanium alloy Ti-6Al-4V samples manufactured in a traditional technological way is higher than for Ti-6Al-4V titanium alloy samples manufactured using 3D - printing at least than in 1.4 times.

Determination the erosive destruction dependencies of the metal specimens created with 3D - printing technology, with both another collision speeds and droplet diameter values is a solutions for creating technological possibilities for increasing the efficiency of using various passive anti-erosion methods of protection: creating easily replaceable inserts with protective coating for the peripheral part of blades. It is possible to use inserts from a titanium alloy created by using 3D - printing technology to replace stellite plates, but additional tests are necessary.

Further carrying out erosion tests of titanium alloy Ti-6Al-4V samples manufactured by 3D - printing with various hardening options will allow to determine the optimal composition of the protective coating for this material, increasing it’s resistance to the water droplet erosion and allow to realize the possibility of complex protection using.

Gratitude
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References
[1] Navrotsky V, Graichen A and Brodin H Industrialization of 3D printing (additive manufacturing) for gas turbine components repair and manufacturing // VGB PowerTech №12, 48-52 (2015).
[2] https://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/additive manufacturing-3d-printed-gas-turbine-blades.html Breakthrough with 3D printed Gas Turbine Blades
[3] Wycisk E, Solbach A, Siddique S, Herzog D, Walther F and Emmelmann C Effects of Defects in Laser Additive Manufactured Ti-6Al-4V on Fatigue Properties // Physics Procedia 56, 371-78 (2014).
[4] Zopp C, Blümner S, Schubert F and Kroll P Processing of a metastable titanium alloy (Ti-5553) by selective laser melting Ain Shams // Engineering Journal 8 475–79 (2017).
[5] Sufiariova V S, Popovicha A A, Borisova E V, Polozova I A, Masayloa D V and Orlov A V The effect of layer thickness at selective laser melting // Procedia Engineering 174, 126 - 34 (2017).
[6] Dovbysh V M, Zabednov P V and Zlenko M A Additivnye technologii i izdeliya iz metalla [Additive technologies and metal products]. FGUP NAMI, FGUP Vneshtechnika, SPbGPU. — Retrieved from http://nami.ru/uploads/docs/centr_technology_docs/55a62fc89524bAT_metall.pdf [in Russian].
[7] Babentsova L P and Antsiferova I V Quality and ecology of selective laser sintering technology // MASTER’S JOURNAL № 1, 87-92 (2017).
[8] Edwards P and Ramulo M Fatigue performance evaluation of selective laser melted Ti-6Al–4V // Materials Science & Engineering A 598, 327-37 (2014).
[9] Konečná R, Kunz L, Bača A and Nicoletto G Long fatigue crack growth in Ti6Al4V produced by direct metal laser sintering // Procedia Engineering 160, 69 - 76 (2016).
[10] Chandramohan P, Shepherd B, Obadde B A and Olubambi P A Laser additive manufactured Ti–6Al–4V alloy: tribology and corrosion studies // Int J Adv Manuf Technol 92, 1051-61 (2017).
[11] RD 153-34.1-17.462-00. Methodical instructions on the procedure for evaluating the performance of steam turbines working blades at the manufacture process, operation and repair.
[12] Mednikov A F, Ryzhenkov V A, Seleznnev L I and Lebedeva A I Studying the variation of parameters characterizing the material surface during the droplet erosion incubation period //Thermal Engineering. 2012. V.59. № 5. P. 414-20.