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DETERMINING THE PROPERTIES OF GAS TURBINE ENGINE COMPONENTS MANUFACTURED FROM VT6 TITANIUM ALLOY POWDER (TI-6AL-4V) BY USING ADDITIVE ELECTRON BEAM TECHNOLOGY

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This study considers components manufactured by additive electron beam manufacturing (EBM) from Ti-6Al-4V (VT6) titanium alloy powder. This material is one of the most widely used in aircraft engine production due to its combination of high weldability, strength, as well as resistance to fatigue loading. The task addressed is to achieve consistently high density, structural uniformity, and stable operational properties in gas turbine engines (GTEs) components manufactured from VT6 alloy by the EBM method.

To fabricate specimens, a digital model was constructed in Materialise Magics, while layer-by-layer analysis and optimization of process parameters were carried out in Simufact Additive. Using the EBM process, experimental specimens were produced, including four GTE blades, a turbine wheel, and control samples.

The chemical composition confirmed full compliance of the parts with the VT6 (Ti-6Al-4V) alloy standard. The microstructure is characterized by a lamellar α′-phase with a minor fraction of β-phase; the α-phase exhibits an acicular morphology with crystal thickness ranging from 0.5 to 1.5 μm. A uniform distribution of alloying elements, as well as the absence of segregation and porosity, was observed. The average microhardness value HV100 was determined to be 3.71 GPa.

The results confirmed that the manufactured parts met the requirements for GTE components, demonstrating high density, strength, and operational reliability. The integration of simulation with subsequent EBM fabrication, optimization of process parameters, and the use of produced VT6 powder enabled the production of parts with zero porosity and stable microstructure. The components also showed controlled texture and high geometric accuracy. This confirms the effectiveness of the proposed approach and highlights its potential for scaling into serial production of critical components with predictable performance characteristics

Keywords: additive electron beam technology, VT6 alloy, Ti-6Al-4V, gas turbine engine, properties

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1. Introduction

Innovative technologies for manufacturing metal products using rapid prototyping open up new opportunities for the production of parts with regulated geometry and structure. Electron-beam additive manufacturing methods have been introduced into industry relatively recently. But they have already proven their effectiveness and prospects for the manufacture of a wide range of structural elements in high-tech industries – aerospace, energy engineering, the defense sector, and biomedical engineering.

The fundamental basis of such technologies is the step-by-step fusion of metal powder in a vacuum environment under the influence of a focused electron beam. This method provides a direct transition from digital models obtained by computer-aided design (CAD) to three-dimensional objects. It is important that it allows the use of a wide range of metals and alloys, including refractory and chemically active materials, among which titanium alloys occupy a special place.

The design and implementation of electron-beam installations and technologies focused on the use of certified domestic raw materials is of significant scientific and practical importance. This creates prerequisites for the development of cooperation with enterprises in the aerospace complex of Ukraine, in particular, DP “KB “Pivdenne”, AT “Motor Sich”, AT “Ivchenko-Progress”, TOV “LRZ “Motor”. Research conducted at the E. O. Paton Electric Welding Institute is aimed at reducing the time of introduction of new products into mass production, expanding their range, and designing fundamentally new types of articles with predictable properties. Such articles cannot be made without the use of 3D printing methods [1].

The introduction of additive technologies in aircraft construction is a particularly promising area. Aircraft engines mainly consist of metal components, for which high specific strength indicators are decisive while minimizing mass. Titanium alloys are actively used in the structural elements of the compressor, engine frames, and other components. The share of such materials in modern aircraft engines exceeds 30%, which emphasizes their strategic role in ensuring the reliability and efficiency of aircraft equipment.

The most difficult operating conditions are characteristic of GTE blades and turbine rotor, which operate under combined high loads and temperatures. In this context, one of the key scientific tasks of modern engine construction is the use of heat-resistant titanium alloys with improved resistance to low-cycle fatigue and creep [2].

Scientific research into this area is relevant as the practical implementation of resource-saving additive electron-beam technologies aimed at designing high-strength titanium components for aerospace equipment that meet modern requirements for reliability, durability, and operational efficiency is of particular importance.

2. Literature review and problem statement

In [3], the use of additive technologies for the manufacture of gas turbine engine (GTE) components from Inconel 625 nickel alloy powders is investigated. The potential for designing GTE blades of complex geometry is considered. It is emphasized that even in the presence of insignificant porosity, such products retain high strength. It is noted that additive methods are breakthrough in terms of production capabilities. However, issues related to the use of titanium alloys for the production of GTE parts remain unresolved.

Titanium alloy VT6 (Ti-6Al-4V) is one of the most common materials in the production of aircraft engine components due to the combination of high weldability, significant strength indicators, and increased resistance to fatigue loads [4]. In [5], the results of studies on geometric parameters, microstructure, and mechanical properties of gas turbine engine blades manufactured by the additive method using the Ti-6Al-4V alloy are reported. As an energy source for forming the material, laser radiation was applied, using Selective Laser Melting (SLM) technology. It was found that the tensile strength of samples manufactured using the SLM method is about 770 MPa, which corresponds to the level of conventionally processed Ti-6Al-4V alloys. At the same time, the material is characterized by a finer grain structure, which positively affects the mechanical properties. However, the issues of increasing the mechanical properties of products manufactured using additive methods compared to established technologies remain open. This is due to objective limitations associated with the high cooling gradient characteristic of SLM technology.

These difficulties can be overcome by using methods that significantly affect the process of metal structure formation. In [6], the application of such an approach to improve the performance properties of products made of titanium alloy TA15, manufactured by laser direct metal deposition (Directed Energy Deposition, DED). To modify the structure and strengthen the material, the method of layer-by-layer ultrasonic impact treatment (UIT) was used. Applying a combination of DED and UIT technologies made it possible to achieve the ultimate strength of the samples at the level of 1031.3 MPa. The use of UIT during the deposition process contributed to local recrystallization and intensification of phase transformations, which ensured a significant refinement of the grain structure. Such microstructural evolution caused an increase in the strength characteristics of the material and increased its resistance to fatigue loads. This method demonstrates the greatest efficiency on open surfaces and edges, which is due to its technological features. But questions remain open regarding the use of the UIT method for processing hard-to-reach areas, internal cavities, and areas with complex geometry.

An option for overcoming related difficulties is to use additive electron beam technology (Electron Beam Melting, EBM). This is the approach used in [7]. It is shown that the use of EBM provides for obtaining for titanium alloys TA15 a set of mechanical properties that exceed similar indicators of deformed metal. In particular, it was established that the tensile strength reaches 1139 MPa, which is 27% higher compared to the deformed material; the relative elongation is 16.5%, which is 77% higher. At the same time, questions remain open regarding the assessment of the durability of products under cyclic loading conditions.

A similar approach was implemented in [8], in which it was found that for samples of titanium alloys TA15 manufactured by the EBM method, the limited endurance limit at $2{\cdot}10^6$ cycles is 508 MPa, which exceeds the corresponding values for conventionally processed materials by 11%. The high level of mechanical characteristics is due to the features of the EBM technological process, which enables the formation of a fine-grained, homogeneous, defect-free two-phase structure with needle-shaped crystals of the α'-phase up to 1.8 μm in size. An additional factor is maintaining the temperature of the powder layer during printing at a level of more than 870 K, which contributes to the stability of the microstructure and the reduction of residual stresses.

But the issues related to the use of EBM technology for the production of gas turbine engine components from VT6 titanium alloy powders remain unresolved. The problem of ensuring density, chemical and structural uniformity, stability of the phase composition and mechanical properties in products made of VT6 alloy must be solved.

Work [9] results the results of the development and analysis of models of gas turbine engine blades made of titanium alloys using additive electron beam technology, which makes it possible to predict their properties at the design stage.

Our review of the literature demonstrates that, despite significant progress in the development of additive technologies for the manufacture of aircraft engine components, a number of unresolved problems remain. In particular, when using VT6 titanium alloys, the issues of ensuring density and structural uniformity of products, stability of the phase composition and mechanical properties are insufficiently studied. The limitations of selective laser melting technology are a decrease in mechanical characteristics due to high cooling gradients. Combined processing methods (DED+UIT) demonstrate the potential for increasing strength but have limitations in use for complex geometries and internal cavities. EBM technology combined with methods of computer modeling of additive processes shows a significant improvement in the strength, ductility, and fatigue life of titanium alloys. However, there is no systematic data on its application specifically for the VT6 alloy in the manufacture of gas turbine engine parts. The problem of comprehensively ensuring high density, uniformity of structure and stability of operational properties of VT6 components manufactured using additive electron beam technology remains unresolved.

The facts above confirm the feasibility of conducting a study on the use of additive electron beam technology for the manufacture of aircraft engine components from VT6 titanium alloys. This will allow us to assess the effectiveness of the specified technology for improving the mechanical characteristics and reliability of products.

3. The aim and objectives of the study

The aim of our work is to determine the properties of gas turbine engine components manufactured by using additive electron beam technology and assess their compliance with operational requirements. This will enable the additive manufacturing of products with a dense structure and improved mechanical characteristics.

To achieve this aim, the following objectives were accomplished:

– to investigate the microstructure of the experimental products;

– to determine the chemical and phase composition of the samples, the uniformity of the distribution of elements in the metal structure;

– to investigate the microhardness and porosity of the products.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is products manufactured by using additive electron beam technology (EBM) from titanium alloy powder VT6 (Ti-6Al-4V).

The hypothesis of the study assumes that the use of additive electron beam technology makes it possible to obtain articles of complex geometry with improved metal properties from titanium alloys VT6.

Before the start of the study, a number of assumptions were adopted. It was believed that the main influence on the properties of articles made of titanium alloys VT6, manufactured by the EBM method, is determined by the microstructural features that are formed during the printing process. It was assumed that the properties of the articles depend primarily on the technological printing modes, and the correct selection of these modes in combination with computer modeling methods makes it possible to improve the structural state, reduce the level of porosity and residual stresses in the articles.

In the process of conducting the study, certain simplifications were also accepted. The chemical composition of the VT6 powder was considered stable, without taking into account possible deviations from the rated values. Microstructural analysis was limited to the study of characteristic zones without continuous mapping of the product volume.

4. 2. Materials and equipment

To print the articles, titanium alloy powder VT6 (Ti-6Al-4V) produced by TOV "Multiflex" (Ukraine), manufactured by the method of rotary plasma spraying of a bar billet [10], was used.

The chemical composition (Table 1) and technological characteristics [10] of titanium alloy powder VT6 meet the requirements of TU U 24.4-31914753-001:2018 "Spherical titanium alloy powders for additive growth processes" [11].

The powder particles have a regular spherical shape with a granule diameter of 40 μm to 160 μm (Fig. 1), which enables high bulk density and uniform melting during the electron beam additive process.

Table 1

Chemical composition of VT6 powder according to TU U 24.4-31914753-001:2018 [11]

Composition of alloying elements, wt. % particles				Impurity composition, wt. % particles			
Al	V	Fe	Ti	O	C	N	H
5.5–6.75	3.5–4.5	≤ 0.3	Balance	≤ 0.2	≤ 0.08	≤ 0.05	≤ 0.015

The test samples were printed on experimental equipment (Fig. 2) designed at the E. O. Paton Electric Welding Institute.

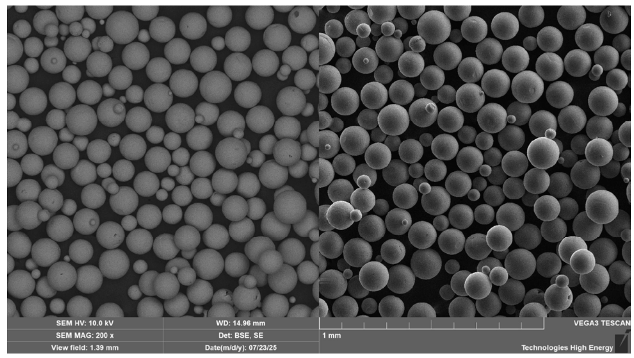


Fig. 1. Morphology of VT6 titanium alloy powder particles

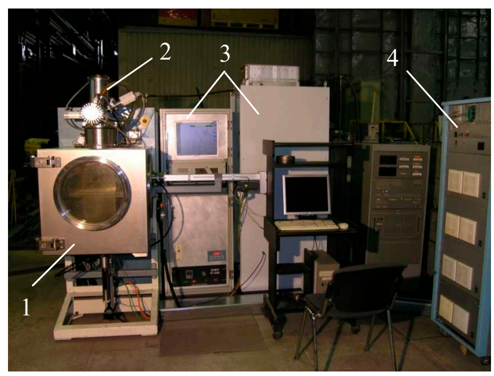


Fig. 2. Additive electron beam equipment: 1 — vacuum chamber; 2 — electron beam gun; 3 — control cabinets; 4 — high-voltage source

During installation operation, the powder material in vacuum chamber 1 (Fig. 2) melts under the action of a focused electron beam. High-voltage source 4 with a voltage of 60 kV provides electron acceleration while the control system handles the beam trajectory and powder feed parameters. This principle of operation makes it possible to obtain articles with high density and a homogeneous microstructure.

During printing, the working pressure in the vacuum chamber 1 was 10^{-2} Pa. Preheating of the powder layer to a temperature of 680°C was carried out by a raster beam with a power of 1900 W, which enabled uniform heating of the material and reduction of thermal gradients during melting.

After the printing process was completed, the articles were cooled in vacuum to a temperature of 300°C. Further temperature reduction was carried out in the equipment chamber in a helium environment at a pressure of 10^2 Pa. After cooling, the finished assembly was removed from the equipment and cleaned of powder residues.

A full description of the additive electron-beam technology and the principles of operation of the equipment is given in [1, 12]. Detailed parameters for the printing modes of articles made of titanium alloys Ti-6Al-4V (VT6) are defined in [13, 14].

4. 3. Research methods

4. 3. 1. Investigating the microstructure of samples

Our study of the microstructure was carried out by conventional metallographic methods. Cross sections of the test sample were made on an electric discharge machine, after which the surfaces were ground with sandpaper and polished with a diamond suspension. To detect microstructural elements, the samples were etched with an aqueous solution containing 6% HNO_2 and 2% HF.

The microstructure was studied using an optical microscope Carl Zeiss Jena and a scanning electron microscope TESCAN VEGA 3 SBH EP.

The optical microscope Carl Zeiss was used to observe the microstructure after etching. The morphology of grains, pores, and other microdefects was studied in reflected light.

The scanning electron microscope TESCAN VEGA 3 SBH EP was used for detailed analysis of the phase composition and surface topography. It operates under SE (secondary electron) modes for surface topography analysis and BSE (backscattered electron) for phase contrast. It has high resolution at accelerating voltages up to 30 kV. The analysis was performed under secondary electron (SE) and backscattered electron (BSE) modes at various magnifications using an accelerating voltage of 20 kV for high resolution and phase contrast.

4. 3. 2. Determining the chemical and phase composition of the samples, as well as the distribution of elements in the metal structure

We determine the chemical and phase composition of the test samples in order to establish the presence of basic and alloying elements, as well as identify the phase composition of the material. This analysis makes it possible to assess the uniformity of the distribution of elements in the metal structure, to detect secondary phases or inclusions, and to draw conclusions about the compliance of the properties of the samples with the requirements for titanium alloys [15].

The chemical composition of the samples was determined by X-ray fluorescence analysis (XRF) using a Bruker Quantax 610M spectrometer. The analysis was carried out in the range of atomic numbers from magnesium (Mg, $Z = 12$) to uranium (U, $Z = 92$), which enable reliable determination of the elemental composition of both the basic components and alloying impurities.

The distribution of chemical elements in the structure of the samples was studied using a Bruker Quantax 610M energy-dispersive X-ray spectrometer mounted on a TESCAN VEGA 3 SBH EP scanning electron microscope. The system makes it possible to map elements in the range from boron (B, $Z = 5$) to uranium (U, $Z = 92$), which provides high accuracy in determining the elemental composition of the phases.

Qualitative and quantitative phase analysis was performed by X-ray diffraction (XRD) using an Inel EQUINOX-1000 diffractometer in sliding geometry. The X-ray source was a copper anode (Cu Kα, $\lambda = 0.15418$ nm). To increase sensitivity to surface phases, the study was carried out at an angle of incidence of 5° to the sample surface. The diffractograms were recorded in the range $2\theta = 10–110°$ using a radial position-sensitive detector, which provides high spatial resolution. The accelerating voltage was 30 kV; the current was 15 mA. Data processing and phase identification were carried out using the Match! software; the experimental diffractograms were compared with the data from reference bases.

4. 2. 3. Investigating the microhardness and porosity of articles

The microhardness of samples was determined by the Vickers method using a PMT-3 microhardness tester at a load of 0.1 kg with a holding time of 10 s.

The porosity of the material was calculated from (1) [16]

$$P = \left(1 - \frac{\rho v}{\rho t}\right) \times 100\%, \qquad (1)$$

where P is porosity, %;

ρ_v is the determined sample density, g/cm^3;

ρ_t is the actual material density, g/cm^3.

The density of the articles was determined according to a standard procedure based on Archimedes' principle. The samples were pre-weighed in air, then immersed in a liquid with a known density (distilled water) for re-weighing. Based on the difference in weight, the volume and density of the material were calculated, which makes it possible to assess the level of porosity and structural uniformity.

AXIS HIDRO density determination instrument set was used for the research. The device includes high-resolution electronic scales, a suspension system for sample immersion, and a heat-resistant container for liquid. It allows automated density calculation with an accuracy of ±0.001 g/cm^3.

4. 2. 4. Printing of experimental articles from titanium alloy VT6

A computer model of the product assembly (Fig. 3) was constructed in the Materialise Magics software [17]. In the Simufact Additive environment [18], a layer-by-layer analysis of the assembly and modeling of the additive process were carried out, which allowed us to take into account the deformations of the formation that occur during printing. Based on the modeling results, an optimized assembly model was built, which enables the minimization of geometric deformations and increases the accuracy of the final product [19].

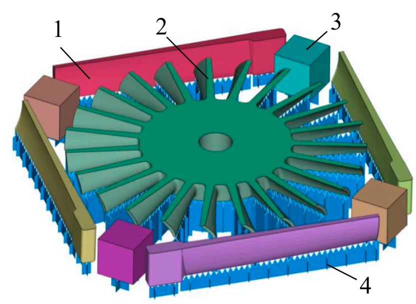


Fig. 3. Computer model of article assembly: 1 – blade; 2 – turbine wheel; 3 – reference samples; 4 – technological supports

The experimental articles were manufactured by sequential layer-by-layer deposition according to the computer model (Fig. 3). After the printing and cooling process was completed, the finished assembly (Fig. 4) was removed from the equipment and the parts were cleaned of powder residues, enabling the preparation of the samples for further testing.

The following articles were printed from VT6 titanium alloy powder (Fig. 5):

– turbine wheel (Fig. 5, *a*) – 1 pc.;

– gas turbine engine blade (Fig. 5, *b*) – 4 pcs.;
– control sample (Fig. 5, *c*) – 4 pcs.

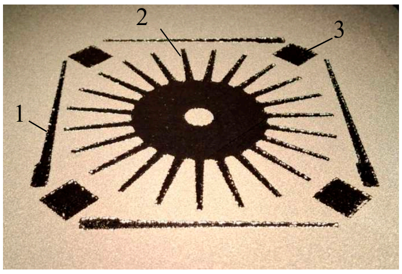
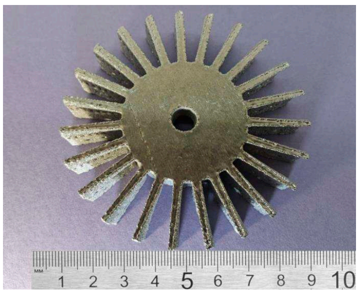
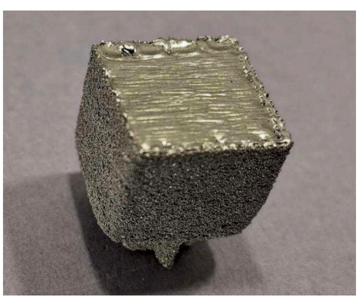


Fig. 4. Experimental articles: 1 – gas turbine engine blade; 2 – turbine wheel; 3 – reference sample



a

b



c

Fig. 5. Printed articles: *a* – turbine wheel; *b* – gas turbine engine blade; *c* – reference sample

The following technological parameters were used for printing:
– beam speed – 500 mm/s;
– power – 400 W;
– trajectory offset step – 0.2 mm;
– powder layer thickness – 100 μm.

The electron beam energy density was 40 J/mm^3.

The scanning strategy was chosen as bidirectional, with the scanning direction rotated by 90° for each layer to enable uniform heating and minimize internal stresses.

To increase the accuracy of the product geometry and reduce the roughness of the side surfaces, two external contours were used, which contributed to the improvement of the quality characteristics of the surface and enabled dimensional stability during the molding process [20].

The surface condition of the samples was assessed visually. It was found that the articles are characterized by a smooth, defect-free surface, which is confirmed by the data in Fig. 4, 5. Such results indicate a high level of quality of shape formation and the efficiency of the applied technological printing modes.

5. Results of determining the properties of gas turbine engine components manufactured using additive electron beam technology

5. 1. Investigating the microstructure of articles

A sample of a gas turbine engine blade was used to analyze the metal structure (Fig. 5, *b*). A cross-section of the sample was made; its surface was prepared for testing by grinding and polishing.

Our research focused on determining the features in structure formation, including the presence of defects (pores, cracks, non-alloying), the type of microstructure and grain size, which makes it possible to assess the quality of the additive process and its effect on the mechanical properties of the article.

Analysis of the gas turbine blade section revealed the presence of a dense cast metal structure (Fig. 6). The surface of the sample is smooth, without signs of macro defects (shells, cracks, non-alloying). At the same time, single dark inclusions (point formations) were recorded, which are artifacts associated with the preparation of the section. In some areas, signs of boundaries between individual layers of deposition were detected. A surface layer about 1 mm thick was formed in the upper part of the sample.

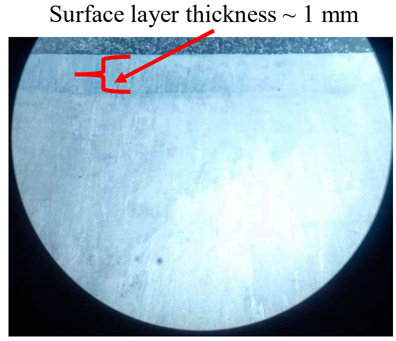
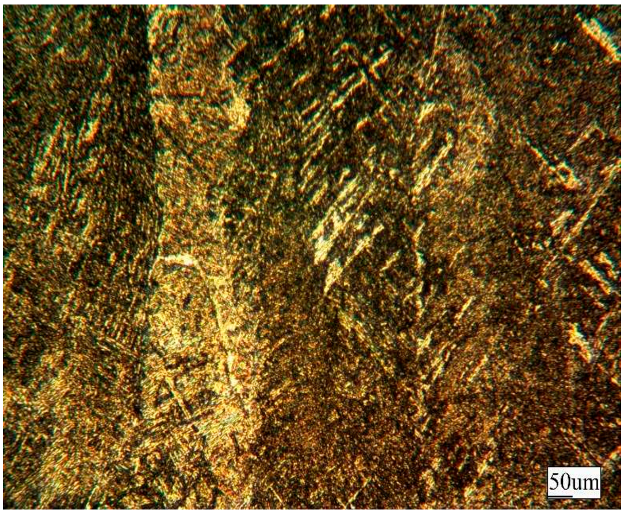


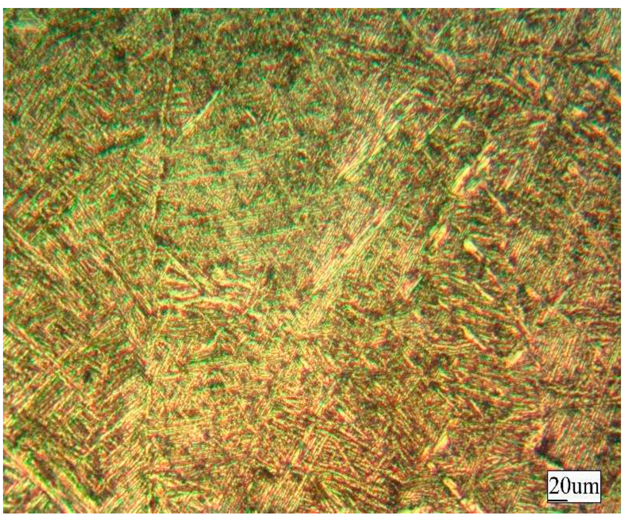
Fig. 6. Gas turbine engine blade section cut

In general, the metal structure is homogeneous at the macro level, which confirms the high quality of the deposition process. The formation of the surface layer is due to intensive cooling of the product surface in a protective gas environment (He). This feature of the thermal cycle can affect local changes in the microstructure and properties of the surface layers, in particular their hardness and resistance to fatigue loads.

The microstructure of the metal at a magnification of 50 μm (Fig. 7, *a*) is characterized by a finely dispersed and uniform structure throughout the cross-section of the section. It is represented by crystallites elongated in the direction of heat removal. Inside the β-grains, lamellar colonies of the α'-phase with a small interlamellar distance are clearly visible, which indicates increased values of hardness and strength with moderate plasticity.



a



b

Fig. 7. Microstructures of a gas turbine engine blade at a scale: *a* — 50 μm; *b* — 20 μm

Upon closer examination of the microstructure (scale 20 μm, Fig. 7, *b*), it was found that the α'-phase has an acicular morphology. Inside the β-grains, the α-plates intersect at characteristic angles (60–90°), which is typical for the martensitic decomposition of the β-phase due to cooling.

Thus, the structure of the deposited metal in the crystallite body is mainly formed in the form of an acicular α'-phase (supersaturated solid solution of alloying elements in α-titanium) with a small amount of residual β-phase. The grain boundaries are clear and do not contain non-metallic inclusions. A lamellar (plate-like) morphology is observed, characteristic of the two-phase state ($\alpha + \beta$) of titanium alloys, which occurs after cooling from the β-region.

In the SEM image of the microstructure of GTD blade at a magnification corresponding to a scale of 20 μm (Fig. 8), a pronounced phase contrast is observed. The average thickness of the acicular crystals of the α-phase is ~0.5–1.5 μm, and their length reaches 10–15 μm. The obtained parameters correlate well with the characteristic values for the VT6 alloy after cooling from the β-region.

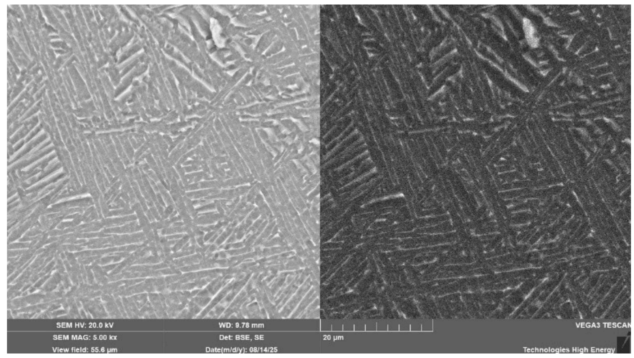


Fig. 8. SEM image of the microstructure of a gas turbine engine blade

Between the α-phase needles, β-phase layers are visible, which appear as darker areas in the contrast image. This morphology corresponds to a lamellar structure formed as a result of relatively slow cooling after heating above the β-transus temperature.

5. 2. Determining the chemical and phase composition, as well as uniformity of element distribution in the metal structure

The chemical composition of the samples was investigated by X-ray fluorescence analysis (XRF) using a Bruker Quantax 610M spectrometer.

The results showed that the content of the main alloying elements and the concentration of impurities in the samples meet the requirements for the titanium alloy VT6 (Ti-6Al-4V) (Table 2).

X-ray spectral microanalysis confirmed (Fig. 9) that the alloying elements in the structure of the experimental sample are distributed evenly. The Al/Ti/V distribution map (Fig. 9, *b*) shows uniformity of pixel intensity without local zones of increased or decreased contrast, which indicates the absence of macro segregation of aluminum and vanadium and the homogeneity of the titanium matrix (Fig. 9, *a*).

A detailed analysis of the element distribution maps revealed the uniformity of the Al concentration (Fig. 9, *c*) and V (Fig. 9, *e*), which determine the ratio of α- and β-phases. This distribution pattern is a prerequisite for the formation of a correct phase state without manifestations of local "enrichments" due to vanadium, which confirms the high quality of the additive electron-beam process.

Table 2

Results of chemical composition determination (XRF), wt. % (Ti — basis)

Title	Chemical element						
	Mg	Al	Si	V	Fe	Ni	Zr
Experimental sample	–	5.644	0.062	4.091	0.104	0.046	0.0076
VT6 alloy [21]	≤ 0.30	5.3–6.8	≤ 0.1	3.5–5.3	≤ 0.6	≤ 0.08	≤ 0.30

The results of X-ray phase studies are shown in Fig. 10. The diffractogram reflects the intensity of X-ray scattering depending on the angle 2θ within 10–110°. The blue line corresponds to the experimental XRD profile, the red vertical lines indicate the α-Ti peaks according to the data from reference bases.

X-ray phase analysis revealed that the sample matrix is represented by the dominant hexagonal α-phase of titanium, while the β-phase in the body-centered cubic structure is present as weak peaks, indicating its small volume fraction. The use of the Rietveld refinement method in the Match! software allowed us to estimate the volume fractions of the phases: α-Ti – 92 ± 3%, β-Ti – 8 ± 3%. Secondary phases (oxides, intermetallics) were not detected within the sensitivity of the method, which indicates the absence of intensive oxidation during printing.

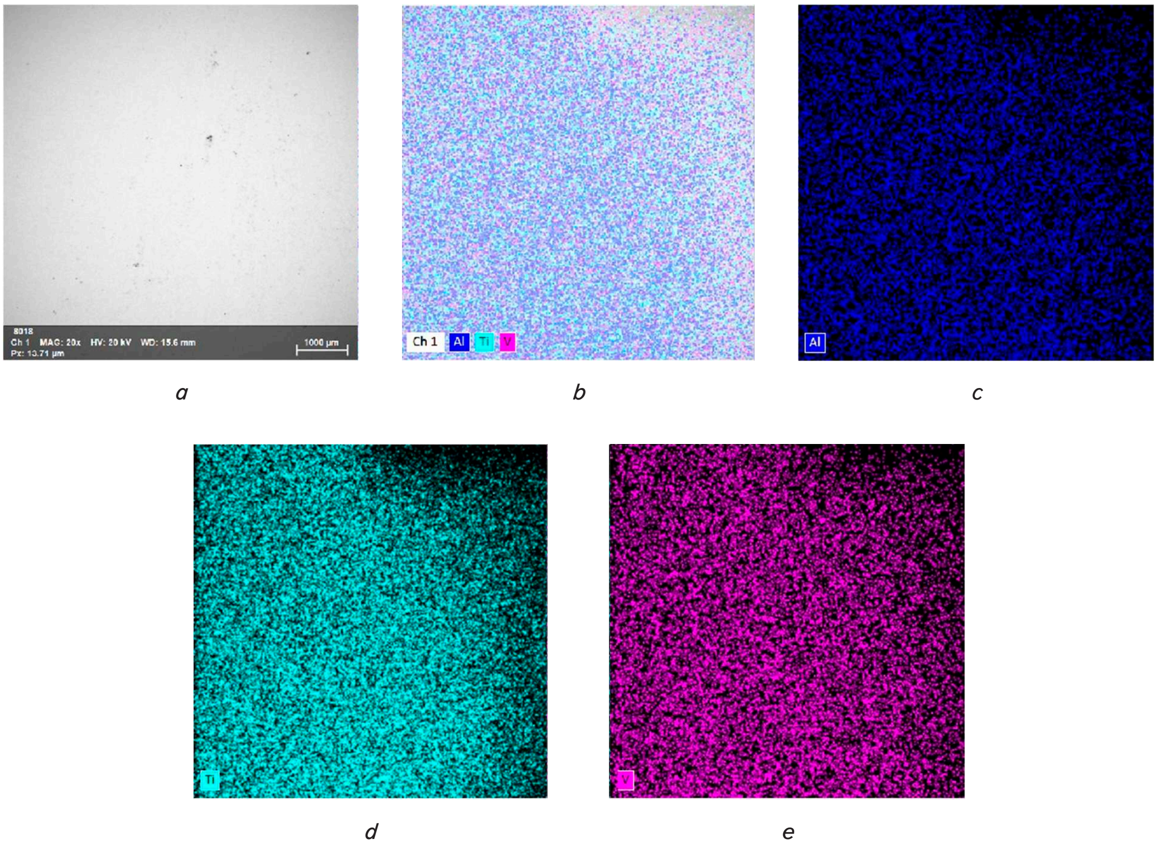


Fig. 9. Distribution of elements in the structure of the VT6 alloy: *a* — microsection; distribution maps of chemical elements: *b* — Al/Ti/V; *c* — Al; *d* — Ti; *e* — V

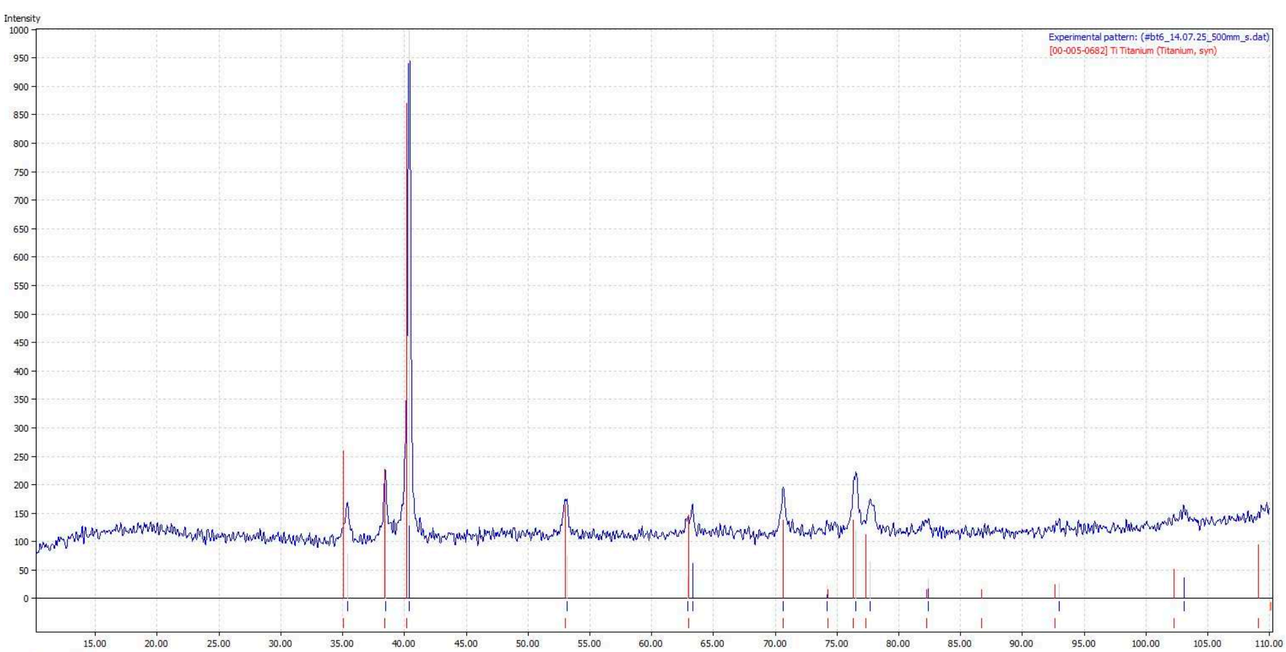


Fig. 10. Results of X-ray phase studies

5. 3. Investigating the microhardness and porosity of articles

The microhardness of the samples was determined by the Vickers (*HV*) method. The hardness distribution along the cross-section of the section, from the surface of the sample to its base (vertically), is shown in Fig. 11. Analysis of the obtained data makes it possible to assess the uniformity of mechanical properties throughout the volume of the part and the influence of technological printing modes on local changes in hardness.

The distribution of the microhardness of the sample along the height demonstrates non-uniformity with gradients from $HV_{100(min)}$ = 3.29 GPa to $HV_{100(max)}$ = 4.13 GPa. The average value of the microhardness is $HV_{100(ave)}$ = 3.71 GPa with a deviation $HV_{100(dev)}$ = ± 0.42 GPa, which is consistent with the literature data for the titanium alloy Ti-6Al-4V [14, 20].

The density of the samples was determined by hydrostatic weighing. The study was conducted on a cubic sample with an edge size of 10 mm (Fig. 12, *a*), obtained by milling the surfaces of the reference sample (Fig. 5, *c*). The use of such a sample makes it possible to ensure the accuracy of measurements and minimize the influence of surface irregularities on the research results.

The porosity of the material was determined from (1). The results of the studies are given in Table 4.

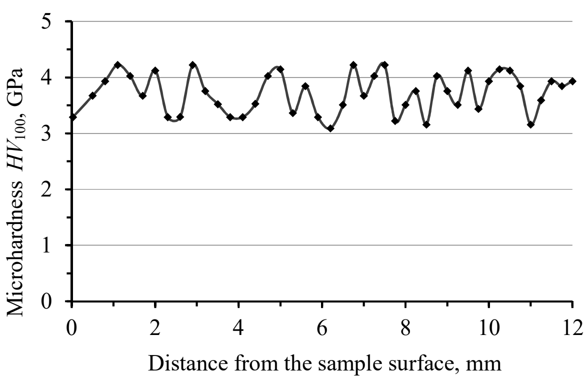
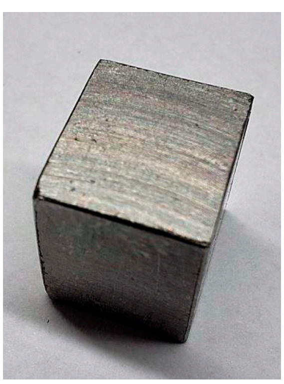


Fig. 11. Microhardness variations (HV_{100}) in the cross-section of the section cut



a

b

Fig. 12. Density determination: *a* – test sample; *b* – measurement result

The compliance of the measured density with the tabulated value (within the metrological error) indicates the absence of open and closed pores in the product. The hydrostatic weighing method confirmed the full density of the sample, which is an indicator of the high quality of the EBM process. Microstructural analysis confirmed that the material has no cavities, cracks, or signs of segregation, which ensures its homogeneity and high density.

Table 4

Results of density and porosity measurements of the test sample

Measured density, ρ_v, g/cm^3	The actual density of VT6 [21], ρ_t, g/cm^3	Porosity, *P*, %
4.46	4.456	0

6. Results of investigating the properties of gas turbine engine components: discussion

The results of our study demonstrate a clear correlation between the stage of preliminary simulation, process parameters, and the final structural and mechanical characteristics of the articles.

The use of Materialise Magics programs for constructing product assemblies and Simufact Additive for layer-by-layer analysis and modeling of additive processes made it possible to predict heat concentration zones, potential deformations, and residual stresses even before the start of printing. That made it possible to optimize the technological parameters, printing strategy, and geometry of technological supports in such a way as to ensure a uniform thermal regime and stability of shaping. As a result, no geometric defects were found in the finished articles, and the density of the material (Table 4) reached the tabular value for the VT6 titanium alloy (4.46 g/cm^3), which indicates the absence of both open and closed pores.

The absence of porosity is important for ensuring high mechanical characteristics of printed articles. Full density of the material contributes to the maximum tensile strength, increased fatigue life and stability of plastic properties, which is especially important for components of aircraft engines where the combination of strength and reliability is an important factor in operational efficiency.

Unlike most additive technologies, where residual porosity, geometric distortions, and the need for additional compaction (e.g., HIP processing) are often observed, our result – obtaining articles with zero porosity, stable geometry, and full compliance with the tabular density – makes it possible to ensure maximum structural density, repeatability of mechanical properties, and suitability for serial production of critical structures.

This becomes possible owing to preliminary modeling of the process, which makes it possible to adapt EBM parameters to the specific geometry of the product, avoid local overheating, and enable a controlled thermal regime at all stages of molding.

The results of the microhardness studies HV_{100} demonstrate a gradient along the height of the sample (Fig. 11), which is a consequence of local differences in thermal effects during the electron beam deposition process. Such a hardness distribution is essential for ensuring the operational reliability of gas turbine engine parts. High values of microhardness in the surface layers provide increased resistance to contact wear and abrasive effects of working media, which is especially important for turbine blades and disks. At the same time, the presence of a more plastic volumetric zone with moderate hardness contributes to maintaining strength and prevents the development of brittle fractures under the action of cyclic loads. The detected controlled gradient of mechanical properties along the height of the sample reflects the specificity of thermal processes characteristic of EBM where the formation of layers is accompanied by repeated heating and cooling cycles. This is not a defect in the material but, on the contrary, creates conditions for optimizing the ratio of strength and durability in articles with complex geometry. Overall, our results confirm that the high microhardness of the test specimens is a consequence of the formation of a dense fine-grained structure, which provides improved mechanical characteristics of parts and meets the requirements for gas turbine engine materials.

Unlike conventional additive manufacturing methods, in which mechanical properties are often homogeneous but not adapted to the functional load, our result – the formation of a controlled microhardness gradient with increased values in the surface layers and moderate plasticity in the volume – makes it possible to combine wear resistance, impact toughness, and resistance to brittle fracture within one product.

This is made possible by the specificity of additive electron beam technology, in particular repeated thermal cycles, stable thermal regime, as well as a fine-grained structure formed as a result of directional cooling and an optimized scanning strategy.

The materials science approach to solving the problems of various metallic materials is that the required level of mechanical properties is provided by a certain chemical composition and its microstructure. To assess the microstructure, a dispersed equiaxed microstructure was chosen as the standard, which is characteristic of titanium alloys with high strength characteristics and resistance to fatigue fractures, which is regulated for highly loaded aviation parts [2–4].

Compliance of the chemical composition with the regulatory values (Table 2) is important since it is the balance of α- and β-stabilizers that determines the nature of phase transformations, the formation of the microstructure and, accordingly, the level of mechanical properties of the alloy. This balance provides the predicted behavior of the material under operational loads, which is of particular importance for aviation components.

For parts made of titanium alloys VT6, fabricated by using EBM technology, the expected microstructure is characterized by a fine-grained $\alpha+\beta$-structure. Such morphology provides high material density, increased tensile strength, fatigue resistance and stability of plastic properties, which is important for gas turbine engine components [9].

It is known that the reduction in the thickness of the acicular crystals of the α-phase and their uniform distribution contribute to an increase in the strength and hardness of the material due to a larger number of interphase boundaries that impede the movement of dislocations [8, 9]. At the same time, the significant length of the needles and the presence of β-layers ensure the preservation of sufficient plasticity and resistance to low-cycle fatigue, which is important for aircraft engine parts [22].

Microstructural analysis of the printed material revealed that the structure (Fig. 7) is characterized by a nanocrystalline, fine-grained α phase of titanium with a low level of micro deformations, where the α-phase has an elongated morphology with a thickness of acicular crystals of ~0.5–1.5 μm (Fig. 8). The high proportion of the α phase and the insignificant content of the β phase correspond to the $\alpha+\beta$ structure with the $\beta\rightarrow\alpha$ transformation during cooling. The arrangement of the phases indicates cooling from the β-region at a medium rate, which is a characteristic feature and advantage of additive electron beam technology. Such a structure is formed due to a stable thermal gradient and the absence of local overheating, which was achieved through preliminary process modeling and optimization of printing parameters.

Unlike conventional methods for processing titanium alloys, in which the microstructure is formed as a result of heat treatment and often has a heterogeneous morphology with coarse α-needles and residual stresses, our result – the formation of a nanocrystalline, fine-grained $\alpha+\beta$-structure with a uniform phase distribution and controlled morphology – allows for high strength, fatigue resistance, and stability of plastic properties without additional thermal operations.

This is made possible by combining preliminary simulation that predict thermal fields and residual stresses with optimized EBM parameters that ensure stable cooling, control over phase transformations, and formation of the desired microstructure during the fabrication process.

X-ray phase analysis (Fig. 10) confirmed the α-dominant phase state with a hexagonal close-packed lattice with a negligible β-phase content within the sensitivity of the method. This is a direct consequence of the controlled cooling from the β-region provided by optimized EBM parameters with stabilization of the assembly temperature during the printing process at 680°C. The deviation from the reference peak intensities indicates the presence of a crystallographic texture formed as a result of the directional growth of columnar β-grains. Such a texture, in combination with the lamellar α-phase, determines the anisotropy of mechanical properties, which can be used as a technological advantage for parts with directional loads.

Evaluation of chemical homogeneity by element distribution maps (Al, Ti, V) (Fig. 9) confirmed the absence of macro segregation in the sample volume. Al/Ti/V maps demonstrate dense, uniform fields without local enrichment or leaching zones, which indicates composition stability. Such homogeneity guarantees stability of mechanical characteristics throughout the cross-section of the part, which is especially important under the action of complex operational loads inherent in GTE components.

The observed homogeneity of the samples is a direct result of the optimization of EBM parameters in the Simufact Additive environment. Due to the controlled heat input, preheating of the layers, and changing the scanning direction by 90°, it was possible to align the thermal fields, avoid segregation, and enable the stable formation of the $\alpha+\beta$-structure, which determines the predicted mechanical properties.

The results of the elemental analysis confirm that the applied EBM technology in combination with simulation makes it possible not only to control the microstructure but also ensure chemical stability, which is a key factor for the durability and reliability of critical structures. The absence of porosity, stable $\alpha+\beta$-structure with controlled texture and high accuracy of the geometry indicate that the key problem area identified in chapter 2 has been completely resolved. The proposed approach allowed us to simultaneously achieve high density, structural uniformity, and predicted mechanical properties without additional compaction operations, which favorably distinguishes it from many known analogs, where hot isostatic pressing or additional heat treatments are often required [23].

Unlike most known additive technologies, in which additional hot isostatic pressing (HIP) or heat treatment is often used to achieve the required density and structural uniformity, our result – obtaining a dense, chemically stable material with a controlled texture and predicted mechanical properties – makes it possible to eliminate post-processing, reduce the production cycle, and ensure the functional suitability of articles for operation under complex loading conditions.

This is made possible by integrating simulation with optimized printing parameters, which ensure stable thermal conditions, control of phase transformations, uniform distribution of elements, and formation of a textured $\alpha+\beta$-structure already during the product construction process.

The efficiency and reliability of gas turbine engines are determined by the combination of properties of structural materials: high strength, fatigue durability, lack of porosity, stable microstructure, and controlled phase composition [2–5, 9].

The results of a comprehensive study of samples of titanium alloy VT6 (Ti-6Al-4V) manufactured using EBM technology confirm their compliance with the basic requirements for gas turbine engine materials.

The average microhardness value HV_{100} = 3.71 GPa with fluctuations of ± 0.42 GPa is consistent with the literature data for two-phase Ti-6Al-4V [14, 20]. High hardness in combination with a fine-grained structure provides an increased tensile strength, wear resistance, and resistance to low-cycle fatigue, which is important for turbine blades and disks [2–5].

The measured density of the samples ($\rho_v \approx 4.46$ g/cm^3) practically coincides with the theoretical one for the VT6 alloy ($\rho_t = 4.456$ g/cm^3) [21]. The calculated porosity is $P = 0\%$, which indicates the absence of open and closed pores. This guarantees maximum strength, stability of plastic properties, and high reliability under cyclic loads [2–5].

X-ray phase analysis confirmed the presence of α+β structure: α-Ti – 92%, β-Ti – 8%, without secondary phases. The microstructure is characterized by a finely dispersed α'-phase with an interlamellar β-phase, which meets the requirements for heat-resistant and highly loaded components of gas turbine engines made of VT6 alloy [13, 22, 23]. The absence of macro segregation of alloying elements confirms the uniformity of mechanical properties throughout the product volume [24].

Moderate cooling in the EBM process contributes to the formation of a nanocrystalline fine-grained α'-structure with minimal micro deformations [25]. This ensures the stability of mechanical characteristics during high-temperature operation, which is a necessary condition for the operation of turbine blades [2, 4].

The results of our studies show that the samples printed from VT6 alloy fully meet the basic requirements for materials for gas turbine engine components. High density, no porosity, optimal microhardness, and controlled phase composition guarantee the required strength, fatigue life, and stability of properties under real operating conditions.

Our solutions completely bridge the gap identified in chapter 2, related to providing density, chemical and structural homogeneity, stability of phase composition, as well as predicted mechanical properties in articles made of VT6 alloy manufactured by the EBM method.

Thus, the integration of a simulation stage with subsequent printing using EBM technology, optimization of process parameters, and the use of domestic VT6 powder ensured the production of gas turbine engine components with zero porosity, stable microstructure, and controlled texture. The finished articles are characterized by high geometric accuracy and fully meet the basic requirements for gas turbine engine components. This not only confirms the effectiveness of the proposed approach but also opens up opportunities for its scaling in serial production of critical parts with predicted operational characteristics.

Our research results have certain limitations. The material properties are anisotropic in nature; they are effective only under directional loading. Optimization of printing parameters was carried out for a specific VT6 powder, changing the supplier or fraction requires re-validation.

The disadvantages of the study are the lack of long-term tests (fatigue, corrosion, creep), as well as the locality of the optimized printing parameters, which require re-validation when changing the product configuration or powder composition. This provides a basis for further research.

Future studies should involve researching the durability of articles under cyclic loading. It is necessary to determine the long-term performance characteristics under actual conditions of GTE operation.

7. Conclusions

1. The GTE components made by additive electron-beam method from titanium alloy VT6 have a stable fine-grained α'-phase morphology with lamellar interlamellar β-layers, which indicates a controlled mechanism of phase transformations during the cooling process. The absence of pores and cracks reveals a high density and homogeneity of the structure, which meets the requirements for aviation materials.

2. The samples of the VT6 alloy produced by the EBM method are characterized by phase purity and chemical uniformity. The uniform distribution of Al and V in the metal structure ensures stability of properties throughout the volume, and the dominance of the α-phase with textured morphology contributes to high microhardness. Our results confirm the effectiveness of specified technology for critical structures.

3. The test specimens are characterized by high microhardness ($HV_{100} \approx 3.71$ GPa) with a pronounced height gradient, which provides a combination of wear resistance and mechanical strength. The established zero porosity and the correspondence of the density to the tabular value indicate the structural density and stability of mechanical properties necessary for reliable operation of gas turbine engine components.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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