UDC 669.187.526:51.001.57
DOI: 10.15587/1729-4061.2022.265014

DETERMINING THE STRUCTURE AND PROPERTIES OF HEAT-RESISTANT TITANIUM ALLOYS VT3-1 AND VT9 OBTAINED BY ELECTRON-BEAM MELTING

Serhii Akhonin
Doctor of Technical Sciences, Professor,
Deputy Director for Scientific Work,
Academician of the National Academy of Sciences of Ukraine*
Oleksandr Pikulin
PhD*
Volodymyr Berezos
Corresponding author
Doctor of Technical Sciences*
E-mail: titan.paton@gmail.com
Andrii Severyn
PhD*
Oleksiy Erokhin
Postgraduate Student*
Vitalii Kryzhanovskyi
Postgraduate Student
LLC Scientific and production association HVYLYA
Naberezhna Peremohy str., 44/1, Dnipro, Ukraine, 49094
*Department of Metallurgy and Welding of Titanium Alloys
E. O. Paton Electric Welding Institute
of the National Academy of Sciences of Ukraine
Kazymyra Malevycha str., 11, Kyiv, Ukraine, 03150

This paper reports a comprehensive study that investigated the quality of heat-resistant titanium alloys VT3-1 and VT9 obtained by the method of electron beam melting (EBM). It is shown that EBM makes it possible to produce high-quality metal of ingots of heat-resistant titanium alloys VT9 and VT3-1.

Semi-finished articles were made in the form of bars from ingots obtained by the EBM method. It was established that in the macrostructure of the deformed metal there are no cracks, delamination, cavities, metal and non-metallic inclusions. The macrostructure of the metal of the bars corresponds to 4 points for the alloy VT3-1 and 4–5 points for the alloy VT9 on the 10-point scale of microstructures of instruction 1054-76. It was shown that the metal microstructure of forged bars of VT9 alloy consists of primary β grains with a continuous or intermittent α-rim along the grain boundaries 3–4 µs thick. The structure of the metal in the volume of grain – lamellar type with partially globularized plates of the α phase, plates of α-phase of close orientation form α colonies measuring 10–40 µs. The thickness of the α plates is 1–5 µs, between the plates or globules of the α phase there is a layer of β phase with a thickness of 1–2 µs. The microstructure of the deformed metal of titanium alloy VT3-1 consists of primary β grains, the volume of which contains colonies of lamellar α phases measuring 10–100 µs. The thickness of α plates is 1.5–3 µs, the layer of β phase in the intervals between α-plates is mainly 0.3–0.5 µs. The microstructure of semi-finished articles in the form of deformed bars of alloys VT9 and VT3-1 corresponds to type 4–6 according to the 9-type scale of the microstructure of instruction 1054-76. Studies of the mechanical properties of the obtained semi-finished articles have shown that they meet all the requirements of regulatory standards that are put forward by industry to the quality of the metal of heat-resistant titanium alloys

Keywords: electron beam melting, intermediate capacity, heat-resistant titanium alloy, structure, mechanical properties

Received date 08.07.2022
Accepted date 10.09.2022
Published date 12.10.2022

How to Cite: *Akhonin, S., Pikulin, O., Berezos, V., Severyn, A., Erokhin, O., Kryzhanovskyi, V. (2022). Determining the structure and properties of heat-resistant titanium alloys VT3-1 and VT9 obtained by electron-beam melting. Eastern-European Journal of Enterprise Technologies, 5 (12 (119)), 6–12. doi: https://doi.org/10.15587/1729-4061.2022.265014*

1. Introduction

Currently, there is a great need to obtain and use materials for aviation and power engineering. Aerospace and aviation technology needs light and durable materials that can complement the heat-resistant alloys traditionally used in these areas, based on nickel, cobalt, and iron. Heat-resistant alloys based on titanium are one of the ways to solve this task. A conventional technological method to produce titanium alloy ingots is vacuum-arc remelting (VAR) of consumable electrodes. The quality of the materials used for parts of responsible use is subject to high requirements, which are constantly being improved and become more stringent. Using exclusively the VAR method for the production of titanium alloy ingots does not always make it possible to obtain high-quality metal, and in the case of violation of the technological process for the production of titanium alloys, defects are found in the ingots that reduce the quality of the metal. Therefore, in order to widely use heat-resistant titanium alloys in various structures, it is necessary to improve the technology for obtaining ingots and producing semi-finished articles from them. The results of such studies are needed by practice because it seems promising to use the method of electron beam remelting to obtain high-quality titanium alloys.

2. Literature review and problem statement

Global trends in the development of technology for obtaining ingots of heat-resistant titanium alloys and the production of semi-finished articles from them for the manufacture of parts are practically common for leading aviation enterprises. The production of titanium alloys is associated with difficulties caused by the high sensitivity of titanium to impurities. Titanium interacts with many chemical elements, in particular oxygen, nitrogen, hydrogen, carbon, resulting in the formation of solid solutions or chemical compounds [1]. It is shown in works [2, 3] that one of the main structural imperfections of titanium alloys is the presence of non-metallic inclusions. And work [4] assumes that the uneven distribution of alloying elements over the volume of grain in titanium alloys leads to the destruction of articles. EBM technology avoids these shortcomings but the possibilities for obtaining complex alloyed heat-resistant alloys by this method have not been sufficiently studied.

The high activity of titanium leads to the flow of physicochemical processes of interaction with gases, even in the solid state. Therefore, non-metallic inclusions, in particular nitrides and oxides, can be formed both in the process of smelting ingots and at various stages of technological redistribution into finished articles. Non-metallic inclusions in the finished product can be made from charge materials during the smelting process, as well as formed during the heat treatment of the finished product. Titanium actively interacts not only with gases but also with other elements, including alloying components of alloys. Thus, in [4], it is noted that this can lead to the formation of intermetallic inclusions, for example, Ti_3Al, TiAl, TiCr and others, due to local enrichment of individual volumes of ingots with alloying elements. Therefore, in order to avoid these problems, it is necessary to involve innovative technologies for obtaining ingots of heat-resistant titanium alloys.

One of the promising areas of metallurgical production of heat-resistant titanium alloys is electron beam melting. It makes it possible not only to deeply clean these materials from gas and volatile metal impurities but also greatly simplifies the process of metallurgical redistribution and ensures the production of articles with qualitatively new mechanical properties. In [5], it is shown that EBM also provides the possibility of obtaining ingots of titanium alloys by melting the primary charge of both spongy titanium and ligature. However, the issue of obtaining heat-resistant titanium alloys by the EBM method remains unresolved.

It is shown in [6, 7] that the strength of heat-resistant titanium alloys is determined not only by the degree of doping but also by the parameters of pressure treatment, subsequent heat, or thermomechanical treatment. Papers [8, 9] report the results that show that increasing the strength of the alloy, as a rule, leads to a decrease in its ductility. This is a significant drawback of the material in the manufacture of structures from it that work on vibration, repeated statics, bending, shock loads. Therefore, it is expedient to carry out work on the choice of such technological modes that will make it possible to achieve an optimal combination of the mechanical properties of heat-resistant titanium alloys obtained by EBM.

Studies [10, 11] note that more attention should be paid to improving (α+β)-titanium alloys, optimizing the parameters of deformation of ingots in the manufacture of semi-finished articles from them and strengthening heat treatment modes because the structure and mechanical properties of forgings, like other semi-finished articles made of titanium alloys, depend on the deformation parameters and can vary within fairly large limits. At the same time, a feature of semi-finished products obtained by the forging method is more significant heterogeneity and instability of the structure and mechanical properties, which is explained by a wide range of deformation parameters within each forging. Therefore, stable provision of the required quality of forged semi-finished articles, as a rule, is a more challenging task than ensuring the required quality of semi-finished articles manufactured by other methods of plastic deformation.

The low thermal conductivity of titanium and its alloys negatively affects the hot deformation process directly. Due to the thermal effect of deformation with large degrees of forging, significant overheating of the metal is observed in areas of intense deformation, deterioration of its structure and properties. To prevent the formation of zones with an unfavorable structure is possible only with a careful selection of the scheme, degree, speed, and initial temperature of metal deformation. In [12], it is shown that the temperature regimes of subsequent forging operations, especially the final ones, depend on the requirements that are imposed on the structure and mechanical properties of the forgings, and on the structure of the original blanks and the level of deformation. Therefore, the primary forging of ingots or blanks must be carried out at temperatures of single-phase β state. Such high-temperature forging not only greatly facilitates the deformation process but also contributes to a more complete and uniform processing of the cast structure, ensuring the production of a fine-grained macrostructure.

Consequently, it is expedient to conduct experiments on the production of heat-resistant titanium alloys by the EBM method and to study their quality.

3. The aim and objectives of the study

The aim of this study is to determine the structure and mechanical properties of semi-finished articles made of heat-resistant titanium alloys VT3-1 and VT9, which will make it possible to show the prospect of using EBM to obtain high-quality metal ingots.

To achieve the set aim, the following tasks have been solved:

– to carry out experimental smelting to obtain ingots of heat-resistant titanium alloys VT3-1 and VT9 and to investigate their chemical composition and structure;

– to carry out work on the manufacture of semi-finished articles in the form of bars from ingots of heat-resistant titanium alloys VT3-1 and VT9;

– to investigate the macro- and microstructure of the deformed metal of the bars of titanium alloys VT3-1 and VT9, obtained from ingots of electron beam melting;

– to determine the mechanical properties of the bars of heat-resistant titanium alloys VT3-1 and VT9 of electron beam melting.

4. The study materials and methods

The first widely used serial heat-resistant titanium alloy was titanium (α+β)-alloy VT3-1, developed in 1957. The alloy was used for GTE parts that operate for a long time at temperatures up to 450 °C. Alloy VT3-1 is a deformed heat-resistant titanium alloy of the Ti–Al–Mo–Cr–Fe–Si system and belongs to the two-phase α+β alloys of martensitic class [7, 9, 10]. The temperature of α+β↔β transition is 970±20 °C. The macro and microstructure of semi-finished articles made of VT3-1 alloy depends on the conditions of deformation and subsequent heat treatment. After the final deformation in the (α+β) region, the grain size may be different depending on the manufacturing conditions of a workpiece: from the smallest (invisible) fiber to the grain of 6 or more points [8, 9]. The optimal set of properties that ensure reliable performance corresponds to the macrostructure of 4–8 points and the microstructure of types 5–8 [10].

After that, in 1958, titanium alloys VT8 and VT9 were developed, designed for long-term operation at 500 °C. VT9 alloy is a two-phase (α+β)-alloy. The high content of aluminum and silicon alloying provide higher heat-resistant properties compared to the VT6 alloy. Titanium alloy VT9 is a deformable alloy and belongs to materials with high heat resistance and resistance to corrosion manifestations. Alloy VT9 is strengthened by heat treatment – quenching and aging. The optimal combination of mechanical properties is provided by double annealing. Parts can be made from it – GTE discs, blades, and other parts of the compressor [10–12].

The metal of heat-resistant titanium alloys VT3-1 and VT9 was obtained according to the technology developed at EEZ named after Paton, NAS of Ukraine, the technology of electron beam melting with intermediate capacity. Experimental melting was carried out on the electron beam installation UE5810, equipped with 7 cathode ray guns “Paton 300” (Ukraine) with a capacity of 300 kW each. The installation UE5810 (Ukraine) makes it possible to smelt ingots of titanium alloys with diameters from 400 to 1100 mm in length up to 4000 mm. The smelting process was carried out in a vacuum of 0.1–0.01 Pa, which created the most favorable conditions for the removal of hydrogen from the metal and made it impossible to contaminate titanium with nitrogen and oxygen. The use of intermediate tank ensured the removal of refractory inclusions of high and low density [5].

For an accurate analysis of the content of alloying elements in the ingots of the resulting alloys, the method of inductively coupled plasma/optical emission spectrometry (ICP-OES) was used on the ICP-spectrometer ICAP 6500 DUO manufactured by Thermo Electron Corporation (USA). To determine the content of oxygen, nitrogen and hydrogen, samples of a cylindrical shape with a diameter of 3 mm and a length of 3 mm were made. The content was determined on devices RO-316, TN-114 of LECO (USA).

To study the presence or absence of internal defects in the form of non-metallic inclusions in titanium ingots, as well as pores and leaks, the method of ultrasonic flaw detection was used. The studies were carried out using the ultrasonic flaw detector UD4-76 (Ukraine) by the echo-pulse method with the contact control option. The operating frequency of the analysis was 1.25 MHz, which provided the maximum signal-to-noise ratio.

The deformation processing of the obtained ingots of heat-resistant titanium alloys was carried out on a horizontal forging machine produced by NKMZ with a nominal force of 1200 tons (Ukraine) and a reversible rolling double-rolled mill 500/350 of Skoda (Czech Republic).

The macrostructure of the ingots was studied on transverse templets cut from the middle of the ingots. The structure was detected by etching the templets in a 15 % solution of fluoric acid with the addition of a 3 % solution of nitric acid at room temperature.

To identify the microstructure of the samples, etching was carried out in a special reagent, which consists of a mixture of hydrofluoric and nitric acids in the ratio: 1 part hydrofluoric (HF) and 3 parts nitric (HNO_3).

The sample structure was examined on the light microscope “Neophot-32” (Germany) at various magnifications. Photos of microstructures were obtained using the S-3000 digital camera from OLYMPUS (Japan).

Mechanical strength tests were carried out on standard samples with a diameter of 5 mm with five times the calculated length using machines for static load. Samples for mechanical testing were cut along the diameter of the ingot in cross-section. Tests for impact toughness were carried out on pendulum copra using samples with a U-shaped incision. Hardness control was carried out on Brinell’s press.

5. Results of studying the quality of semi-finished articles from heat-resistant titanium alloys VT3-1 and VT9 obtained by the method of electron beam melting

5. 1. Production of ingots of heat-resistant titanium alloys VT3-1 and VT9 by electron beam melting

In order to study the quality of the metal of heat-resistant titanium alloys, experimental melting was carried out to obtain ingots of titanium alloys VT3-1 with a diameter of 400 mm and VT9 with a diameter of 600 mm on the electron beam installation UE5810. Ingots were obtained using electron beam melting technology with an intermediate capacity and portion supply of liquid metal to a water-cooled pass-through crystallizer (Fig. 1). When determining the technological parameters of melts, the modes of heating the surface of liquid titanium in the crystallizer were used, which ensure a homogeneous fine-grained structure of the ingot and high quality of its side surface [5].

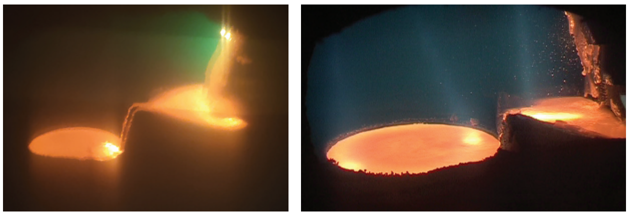

a *b*

Fig. 1. The process of electron beam melting of ingots of heat-resistant titanium alloys: *a* – alloy VT3-1; crystallizer diameter, 400 mm; *b* – alloy VT9; crystallizer diameter, 600 mm

The composition of the initial charge was determined by the results of calculations according to the mathematical model of evaporation processes from the melt in vacuum under electron beam melting conditions [13]. This model establishes the dependence of the concentration of aluminum and other alloying elements of the alloy in the ingot on the melting rate, the concentration of alloying elements in the output charge and the melt temperature. This makes it possible to predict the chemical composition of the ingots of titanium alloys.

After smelting for cooling to a temperature below 300 °C, the ingots were left in the vacuum chamber of the UE5810 installation at a residual pressure of not more than 10 Pa for 6–8 hours. As a result, the side surface of the ingots smelted by the method of electron beam melting had a metallic color; an increased concentration of impurity elements on the surface in the form of an oxidized or alfed layer was not observed. The depth of surface defects of the “corrugation” type on the surface of the ingots was 2–3 mm.

In order to remove surface defects, the side surface of the obtained ingots was treated in vacuum using electron beam melting technology [14, 15]. After melting, the surface of the ingots of titanium alloys VT3-1 and VT9 has a smooth mirror appearance, without visible cracks, breaks, and other surface defects that may occur during electron beam melting (Fig. 2).

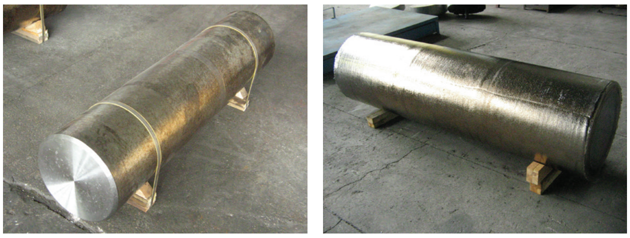

a *b*

Fig. 2. Ingots of heat-resistant titanium alloys of electron beam melting: *a* – alloy VT3-1, ∅400 mm; *b* – alloy VT9, ∅600 mm

To assess the homogeneity of the distribution of alloying elements along the length of the obtained ingots, the chemical composition of the samples taken at a distance of 50 mm from the upper and lower ends of the ingot, as well as from its middle was determined (Table 1). Samples for determining the concentration of gas impurities in titanium alloys VT3-1 and VT9 were selected only from the main part of the ingots.

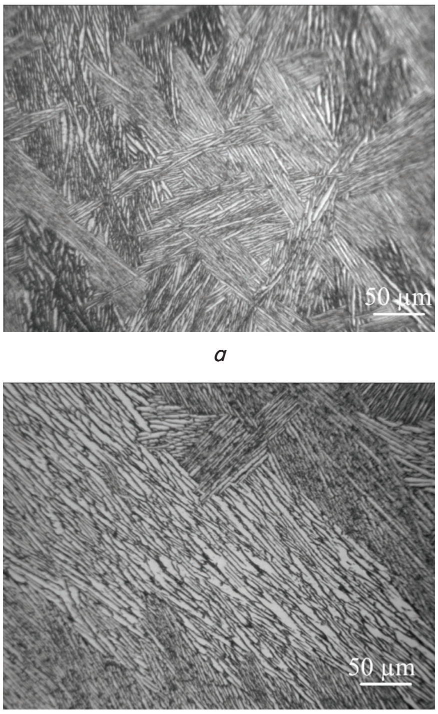
The study of the macrostructure of the metal of the ingots showed that it is dense, homogeneous, with the absence of zones that are etched differently, along the cross-section of the ingot. There is no significant difference in the structure of the central ingot zone and the peripheral zone. Defects in the form of pores, shells, cracks, and non-metallic inclusions were not detected. Segregation of alloying elements characteristic of vacuum-arc remelting ingots was not detected. The crystal structure of the metal is the same along the entire length of the ingots and is characterized by crystals, close in shape to equivocal. There are no sections of the columnar structure.

The most important criterion for the quality of ingots of titanium alloys is the absence of non-metallic inclusions in the metal, especially in the form of refractory nitrogen-containing titanium particles or titanium nitrides [16]. When remelting titanium using electron beam melting technology with an intermediate capacity, thermal and physical-chemical conditions are created to ensure the removal of the above inclusions.

In the ultrasound examination of the ingots, multiple reflections of small amplitude were observed. This is typical of cast metal and is the result of signal reflection from the grain boundaries. The analysis found no signals that could be interpreted as large non-metallic inclusions, pores, and shrinkage caverns.

The microstructure of the metal ingot α+β-alloy VT3-1 belongs to the structure of the martensitic type (Fig. 3, *a*). The grains of cast metal of titanium alloy VT3-1 consist of colonies of the lamellar α phase mainly about 300 μs in size, the thickness of the α plates is 5–7.5 μs. The β-phase is located in the spaces between the α-plates. An α-phase rim is observed along the boundaries of some primary β-grains.

The microstructure of the cast metal of titanium alloy VT9 has a two-phase structure and consists of α- and β-phases (Fig. 3, *b*). Primary β-grains have an α-phase rim, the thickness of which is 5–10 μs. In the volume of grain, the plates of the α phase form colonies, the width of which is 50–300 μs, the thickness of the α plates is 1.5–6 μs. In the intervals between the α-plates there is a β phase with a thickness of 0.3–1.5 μm.



a

b

Fig. 3. Microstructure of cast metal of heat-resistant titanium alloys: *a* – alloy VT3-1; *b* – alloy VT9

Table 1

The content of alloying elements and gas impurities in the ingots of heat-resistant titanium alloys VT3-1 and VT9 obtained by the method of electron beam melting

Alloy type	Alloy part	Content, wt%								
		A1	Mo	Si	Fe	Zr	Cr	O	N	H
VT9	Upper	6.08	3.51	0.28	0.17	1.64	≤0.1	0.10	0.01	0,002
	Middle	5.98	3.52	0.27	0.17	1.62	≤0.1			
	Lower	6.10	3.55	0.27	0.18	1.66	≤0.1			
OCT1 90013-81		5.8–7.0	2.8–3.8	0.20–0.35	≤0.25	1.0–2.0	≤0.1	<0.15	<0.05	<0.015
VT3-1	Upper	6.66	2.05	0.25	0.43	0.006	1.16	0.08	0.005	0.002
	Middle	6.92	2.30	0.28	0.47	0.008	1.28			
	Lower	6.44	2.43	0.23	0.52	0.007	1.30			
GOST 19807-91		5.5–7.0	2.0–3.0	0.15–0.40	0.2–0.7	≤0.1	0.8–2.0	<0.15	<0.05	<0.015

5. 2. Manufacturing semi-finished articles from ingots of heat-resistant titanium alloys VT3-1 and VT9

In order to study the quality of the metal of ingots of heat-resistant titanium alloys obtained by the EBM method, work was carried out on the manufacture of deformed bars of 45 mm from the ingot ∅400 of the alloy VT3-1 and ∅300 mm from the ingot ∅600 mm of the alloy VT9 (Fig. 4).

The thermodeformation treatment of VT3-1 alloy ingots was carried out on a reversible rolling double-roll rolling mill, by gradually running the ingot onto the ∅45 mm bar. Rolling was carried out in several passes with intermediate heating of workpiece during the deformation process. The heating temperature of workpiece in the electrical resistance furnace was 1050 °C.

Previous studies have shown that the temperature of the polymorphic transformation (CCI) for VT3-1 alloy samples was T=985 °C.


a *b*

Fig. 4. Semi-finished articles in the form of rolled and forged rods made of heat-resistant titanium alloys: *a* – ∅45 mm from VT3-1 alloy; *b* – ∅300 mm from alloy VT9

To relieve residual stresses, heat treatment of the resulting bars was performed according to the following modes. Heating to 950 °C; exposure in the furnace for 60 minutes; moving to a furnace with a temperature of 550 °C; exposure in the furnace for 135 minutes; air cooling.

Thermodeformation treatment of VT9 alloy ingots was carried out on a horizontal forging machine with a nominal force of 1200 tons by forging in three stages.

At the first stage, the ∅600 mm ingot was heated in a furnace to a temperature of 1180 °C and kept for 8 hours. Forging was carried out on flat molds in a square of 450x450 mm.

At the second stage, the resulting square billet was heated to a temperature of 1100 °C, forged into a round bar ∅360 mm, and cut into three parts.

At the third stage, the resulting bar was heated to a temperature of 1100 °C and forged through a square to the finished size of ∅300 mm. Next, we carried out the straightening.

The temperature of the end of forging at each stage was not lower than 850 °C.

Previous studies have shown that the temperature of the polymorphic transformation (CCI) for VT9 alloy samples was 950 °C.

To relieve residual stresses, heat treatment of the resulting bars was performed. The heat treatment mode included heating to 950 °C; exposure in the furnace for 60 minutes; air cooling; heating in the furnace to a temperature of 550 °C; exposure in the furnace for 360 minutes; air cooling.

5. 3. Investigation of the structure of semi-finished articles from heat-resistant titanium alloys VT9 and VT3-1

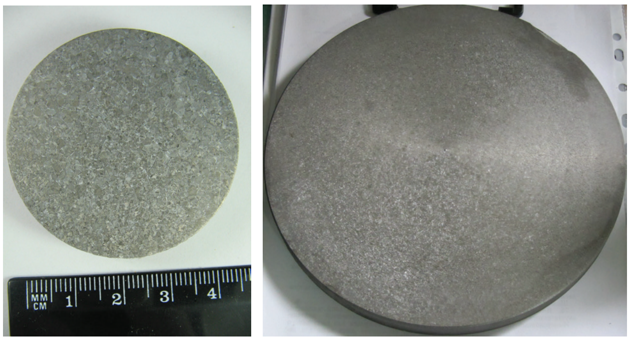
The study of the microstructure, as well as the study of porosity, was carried out on transverse and longitudinal micro sections, which were cut from the metal of the resulting semi-finished articles in the form of bars. The etching of micro sections occurred in the reagent; hydrofluoric acid is an obligatory component of the reagent.

Longitudinal and transverse templets were cut from the obtained forged bars ∅45 mm from heat-resistant titanium alloy VT3-1 and ∅300 mm alloy VT9 to determine the macrostructure. In the macrostructure of the metal of the resulting bars there are no cracks, delamination, cavities, areas of liquation origin, metal and non-metallic inclusions visible to the naked eye (Fig. 5). The background of the macrostructure is brilliant. The macrostructure of the metal of the bars corresponds to 4 points for the alloy VT3-1 and 4–5 points for the alloy VT9 on a 10-point scale of instruction 1054-76 [17], which fully meets the requirements of the standards.

In addition, to assess the quality of the metal obtained by the method of electron beam melting, according to standard methods [18], a study of the microstructures of the obtained semi-finished articles of heat-resistant titanium alloys VT3-1 and VT9 was carried out.

The studies have shown that the microstructure of samples of deformed metal alloy VT3-1 corresponds to type 5–6 of the 9-type scale of microstructures OST1 90197-89 [17]. The microstructure of the metal of the rod ∅45mm titanium alloy VT3-1 consists of primary β grains, the volume of which contains colonies of plate α phases measuring 10–100 µs. The thickness of α-plates is 1.5– 3 µs, the layer of the β phase in the intervals between the α plates is less than 1 µm (mainly 0.3–0.5 µs) (Fig. 6, *a*).

The microstructure of samples of deformed rods ∅300 mm of the alloy VT9 corresponds to type 4–6 of the 9-type scale of microstructures OST1 90197-89 [17]. The metal of the rod consists of β grains with a continuous or intermittent α-rim along the grain boundaries, the thickness of which is 3–4 µs. The structure of the wrought-iron rod in the volume of grain is of a lamellar type with partially globularized plates of the α phase (Fig. 6, *b*). Between the plates or globules of the α phase there is a layer of β phase with a thickness of 1–2 µs. Plates of the α-phase of close orientation form α-colonies measuring 10–40 µs. The thickness of α-plates is 1–5 µs.



a *b*

Fig. 5. Macrostructure of forged bars of heat-resistant titanium alloys: *a* – alloy VT3-1, ∅45 mm; *b* – alloy VT9, ∅300 mm

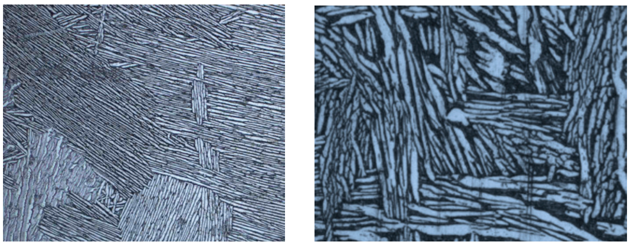

a *b*

Fig. 6. Microstructure of deformed metal bars of heat-resistant titanium alloys: *a* – alloy VT3-1; *b* – alloy VT9

5. 4. Mechanical properties of bars of heat-resistant titanium alloys VT3-1 and VT9

The mechanical characteristics of semi-finished articles in the form of ∅45mm bars made of VT3-1 alloy and ∅300 mm rods made of VT9 alloy were determined at a temperature of 20 °C. In order to check the compliance of the mechanical properties of semi-finished articles with the requirements of the standards, samples for stretching, impact strength, and hardness were tested (Tables 2, 3).

As can be seen from the results obtained, all values of the mechanical properties of the studied samples do not go beyond the requirements of industrial standards, which indicates the high quality of the metal.

Table 2

Mechanical properties of samples of deformed semi-finished titanium alloy VT3-1

Sample No.	$\mathbf{s}_t$, MPa	**d**, %	**y**,%	KCU, J/cm^2	Hardness, HB
1	1,100	16	31	32	331
2	1,126	18	31	31	316
3	1,088	20	34	30	321
OST1.90173-75	980–1,225	>10	>30	>29	269–363

Table 3

Mechanical properties of samples of deformed semi-finished product of heat-resistant titanium alloy VT9

Sample No.	$\mathbf{s}_t$, MPa	**d**, %	**y**,%	KCU, J/cm^2	Hardness, HB
1	1,140	8	24	29	331
2	1,089	12	30	31	320
3	1,081	11	30	32	328
4	1,070	13	28	30	323
OCT1.90107-73	932–1,177	>6	>14	>29	269–363

6. Discussion of results of studying the quality of the obtained semi-finished articles from titanium alloys VT3-1 and VT9

When smelting heat-resistant titanium alloys, complex physicochemical processes of interaction between charge materials and alloying components, a protective atmosphere and conditions for heating and cooling of the metal take place [5, 13]. Therefore, the choice of technology for smelting heat-resistant titanium alloys and determining technological modes of the melting process are decisive factors in obtaining a high-quality metal. The use of high vacuum in combination with a concentrated independent heating source gives EBM technology significant advantages over other conventional methods of obtaining ingots of heat-resistant titanium alloys. And the presence of an intermediate tank generally brings the quality of the resulting metal to a qualitatively new level unattainable for other smelting methods.

The results of the study of heat-resistant titanium alloys VT3-1 and VT9 obtained using EBM technology showed that there are no defects in the volume of ingots. There were no insubstantialities, non-metallic inclusions with a size of more than 1 mm, as well as dense clusters of smaller inclusions. The structure of the resulting EBM metal is dense, crystalline heterogeneity and zonal liquation are absent. Segregation of alloying elements characteristic of VAR ingots [19] was not detected. The distribution of alloying elements along the length of the ingots is uniform, and their content corresponds to the grade composition of the corresponding alloys (Table 1). This is ensured through the use of an intermediate container in which the chemical composition is averaged and inclusions of high at low density are removed.

It was determined that the content of gas impurities in the ingots obtained by the method of electron beam melting is significantly less than the maximum limit values. The presence of a vacuum medium in the smelting zone and the action of a concentrated heating source contribute to ensuring the hydrogen content in the alloys 7.5 times lower than required by the standards (Table 1).

In contrast to [19], the crystal structure of the metal of the ingots is the same throughout the cross-section and is characterized by crystals that are close in shape to equidistant. Sections of the columnar structure are absent in all cases. This is achieved by conducting the process under modes that provide a minimum depth of the liquid bath on the surface of the ingot in the crystallizer.

The investigated microstructure of the examined bars is typical of heat-resistant titanium alloys VT3-1 and VT9 (Fig. 6). The smaller structure of the alloy VT3-1 in comparison with the structure of the alloy VT9 is explained by a greater general degree of deformation of the metal. Thus, in the manufacture of ∅45 mm bars, the degree of deformation was more than 98 %, against 75 % in the manufacture of ∅300 mm bars.

Studies of the mechanical properties of samples cut from semi-finished articles in the form of ∅45 mm rods from heat-resistant titanium alloy VT3-1 obtained by cathode ray melting showed some variation in properties (Table 2). The reason for this may be the structural heterogeneity of the metal samples. To obtain the best combination of strength characteristics, more complex heat treatment modes are recommended for the resulting semi-finished articles.

Analysis of the mechanical characteristics of ∅300 mm bars from VT9 alloy led to the conclusion that the mechanical properties of semi-finished articles made of VT9 alloy obtained by the EBM method fully comply with the requirements of the standards (Table 3).

A rather large margin of ductility of the studied metal of both alloys attracts attention: the elongation of samples is one and a half to two times higher than the minimum requirements of the standards (Tables 2, 3) while the strength limit is in the middle of the permitted range of values. This is a characteristic feature for the metal of electron beam melting [5]. This is facilitated by the low content of gases, impurity elements and inclusions, which is not always possible to achieve by other smelting methods, in particular VAR [19].

Studies have shown that electron beam melting is an effective method of obtaining high-quality ingots of titanium alloys VT3-1 and VT9, and the properties of semi-finished articles made from these ingots fully meet the industry requirements for heat-resistant titanium alloys. Thus, EBM production of heat-resistant titanium alloy ingots is a competitive technology for other conventional methods of manufacturing these materials.

The use of the developed technology of EBM smelting ingots of heat-resistant titanium alloys VT3-1 and VT9 may be promising for obtaining other brands of heat-resistant titanium alloys and requires additional research.

The limitation of the study is that all systems of doping of heat-resistant titanium alloys, which can be obtained by the EBM method, are not covered. In the future, it is necessary to carry out experimental smelting to obtain ingots of heat-resistant titanium alloys containing niobium and tin in their doping system.

7. Conclusions

1. Our studies showed that electron beam melting makes it possible to obtain ingots of heat-resistant titanium alloys VT3-1 and VT9, which are characterized by chemical ho-

mogeneity and the absence of defects of cast origin or in the form of refractory non-metallic inclusions.

2. The modes of deformation and heat treatment of semi-finished articles in the form of bars made from heat-resistant titanium alloys VT3-1 and VT9, obtained by the EBM method, have been determined. Deformation treatment of cast metal alloy VT3-1 obtained by the EBM method should be started at a temperature of 1050 °C, alloy VT9 – 1180 °C. To relieve residual stresses, it is necessary to perform heat treatment of the deformed metal according to the following modes – heating up to 950 °C; aging in the furnace for 60 minutes; cooling in air; heating up to 550 °C; aging in the furnace; cooling in the air.

3. It was found that the microstructure of the deformed metal of titanium alloy VT3-1 consists of primary β grains, the volume of which contains colonies of lamellar α phase with a size of 10–100 μs. The thickness of α plates is 1.5–3 μs, the layer of the β phase in the intervals between the α-plates is mainly 0.3–0.5 μs. It was shown that the microstructure of the metal of forged bars of the VT9 alloy consists of primary β grains with a continuous or intermittent α-rim along the grain boundaries with a thickness of 3–4 μs. The structure of the metal in the volume of grain is of a lamellar type with partially globularized plates of the α phase, the plates of the α-phase of close orientation form α-colonies measuring 10–40 μs. The thickness of α-plates is 1– 5 μs, between the plates or globules of the α phase there is a layer of β-phase with a thickness of 1–2 μs.

4. The mechanical properties of semi-finished articles made from the ingots obtained by the method of electron beam melting of heat-resistant titanium alloys VT3-1 and VT9 meet all the requirements of current standards. In terms of ductility, they exceed by one and a half to two times the minimum requirements put forward by the industry to the quality of the metal of heat-resistant titanium alloys.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

References

1. Narushima, T., Sugizaki, Y. (2020). Recent activities of titanium research and development in Japan. MATEC Web of Conferences, 321, 01004. doi: https://doi.org/10.1051/matecconf/202032101004
2. Williams, J. C., Boyer, R. R. (2020). Opportunities and Issues in the Application of Titanium Alloys for Aerospace Components. Metals, 10 (6), 705. doi: https://doi.org/10.3390/met10060705
3. Mizukami, H., Kitaura, T., Shirai, Y. (2020). Dissolution Behavior of a Titanium Nitride Sponge in Titanium Alloy Melt. MATEC Web of Conferences, 321, 10005. doi: https://doi.org/10.1051/matecconf/202032110005
4. Babenko, E. P., Dolzhenkova, E. V. (2014). Issledovanie prichin razrusheniya krupnogabaritnogo izdeliya iz splava VT23. Metallurgicheskaya i gornorudnaya promyshlennost', 3, 82–85. Available at: http://nbuv.gov.ua/UJRN/MGRP_2014_3_27
5. Paton, B. E., Trigub, N. P., Zhuk, G. V. (2008). Crystallization of titanium ingots in the course of electron-beam melting. Materials Science, 44 (3), 328–335. doi: https://doi.org/10.1007/s11003-008-9090-2
6. Mantione, J., Garcia-Avila, M., Arnold, M., Bryan, D., Foltz, J. (2020). Properties of Novel High Temperature Titanium Alloys for Aerospace Applications. MATEC Web of Conferences, 321, 04006. doi: https://doi.org/10.1051/matecconf/202032104006
7. Khorev, A. I. (2014). Fundamental'nye i prikladnye raboty po konstruktsionnym titanovym splavam i perspektivnye napravleniya ikh razvitiya. Tekhnologiya mashinostroeniya, 11, 5–10.
8. Lei, X., Dong, L., Zhang, Z., Liu, Y., Hao, Y., Yang, R., Zhang, L.-C. (2017). Microstructure, Texture Evolution and Mechanical Properties of VT3-1 Titanium Alloy Processed by Multi-Pass Drawing and Subsequent Isothermal Annealing. Metals, 7 (4), 131. doi: https://doi.org/10.3390/met7040131
9. Pavlova, T. V., Kashapov, O. S., Nochovnaya, N. A. (2012). Titanovye splavy dlya gazoturbinnykh dvigateley. Vse materialy. Entsiklopedicheskiy spravochnik, 5, 8–14.
10. Il'in, A. A., Kolachev, B. A., Pol'kin, I. S. (2009). Titanovye splavy. Sostav, struktura, svoystva. Moscow: VILS-MATI, 520.
11. Simonov, Y. V., Ushakov, I. V. (2020). Mechanical properties of surface structures of titanium alloy VT9 after repeated local processing with nanosecond laser pulses. Bulletin of the Moscow State Regional University (Physics and Mathematics), 2, 19–35. doi: https://doi.org/10.18384/2310-7251-2020-2-19-35
12. Singh, B. K., Singh, P. N., Singh, V., Ramachandra, C. (1999). Stabilisation Treatment of Titanium Alloy VT9. Defence Science Journal, 49 (2), 169–176. doi: https://doi.org/10.14429/dsj.49.3826
13. Akhonin, S. V., Severin, A. Yu., Beresos, V. O., Pikulin, O. M., Erokhin, O. G. (2022). Mathematical modeling of evaporation processes at ebm of alloys based. Sovremennaâ Èlektrometallurgiâ, 2, 10–16. doi: https://doi.org/10.37434/sem2022.02.02
14. Akhonin, S. V., Pikulin, O. M. (2019). Investigation of Effect of Electron Beam Surface Treatment of Titanium Alloy Ingots on Structure and Properties of Melted Metal. IOP Conference Series: Materials Science and Engineering, 582 (1), 012047. doi: https://doi.org/10.1088/1757-899x/582/1/012047
15. Akhonin, S. V., Pikulin, A. N., Klochai, V. V., Ryabtsev, A. D. (2019). Electron-Beam Surface Treatment of Titanium Alloy Ingots. Part 1. Metallurgist, 63 (1-2), 183–191. doi: https://doi.org/10.1007/s11015-019-00808-9
16. Paton, B. E., Akhonin, S. V., Prilutsky, V. P. (2012). Development of welding technologies in titanium component manufacturing. Ti 2011 - Proceedings of the 12th World Conference on Titanium, 2, 1585–1591.
17. Borisova, E. A., Bochvar, G. A., Brun, M. Ya. et. al. (1980). Titanovye splavy. Metallografiya titanovykh splavov. Moscow: «Metalurgiya», 464.
18. Boer, R. R. (1985). Titanium and Titanium Alloys. Metallography and Microstructures. ASM, Metals Park, OH, 458–475.
19. Shved, F. I. (2009). Slitok vakuumnogo dugovogo pereplava. Chelyabinsk: OOO «Izadetl'stvo Tat'yany Lur'e», 428.