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ELECTRON BEAM SURFACE MELTING OF INGOTS OF HIGH-TEMPERATURE TITANIUM ALLOY VT9

O.M. Pikulin, S.V. Akhonin, V.O. Berezos, A.Yu. Severyn, O.G. Yerokhin

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

Proceeding from the results of the performed package of research work, it was established that the chemical composition of metal in the surface-melted layer of high-temperature titanium alloy VT9 corresponds to standard requirements; and a lowering of aluminium content, an alloying element with vapour pressure higher, and an increase in the content of molybdenum and zirconium, alloying elements with vapour pressure lower than that of titanium, is observed. Investigations of the surface-melted layer showed that the penetration depth of the surface layer in ingots of high-temperature titanium alloy VT9 of 600 mm diameter reaches 8 mm, the ingot surface is high-quality mirror-like with characteristic vacuum etching, even microrelief without cracks, tears or lacks-of-fusion, its roughness is within the range of 3–4 class at a waviness of 0.2–0.6 mm. The surface-melted layer of the ingot has a finer structure, compared to base metal, and it consists of areas with isolated α-plates of 1.0–2.5 μm thickness, where the α-plates are gathered into colonies of 10–50 μm width, and the gaps between them are taken up by dispersed particles of 1–2 μm size, which can be the products of metastable phase decomposition.

KEYWORDS: high-temperature titanium alloy, ingot, surface defect, electron beam surface melting, chemical composition, structure

INTRODUCTION

In recent decades, an increased attention has been paid to the creation of alloys based on refractory and chemically active metals. Aerospace and aircraft engineering requires light and strength materials that will be able to supplement high-temperature nickel-, cobalt- and iron-based alloys traditionally used in these areas. The use of titanium-based high-temperature alloys is one of the ways to solve this problem. The world trends in the development of high-temperature titanium alloy ingots and making semi-finished products of them for manufacture of parts are mostly general for leading aircraft enterprises and namely the technology of manufacturing them is a decisive factor in providing stability and the required level of operational properties [1–4].

Figure 1. Ingot of high-temperature titanium alloy VT9 with a diameter of 600 mm, produced by EBM method

ANALYSIS OF LITERATURE DATA AND PROBLEM STATEMENT

Reducing the cost of ingots of high-temperature titanium alloys as an output link for manufacturing semi-finished products simultaneously with the improvement of their quality is a relevant task, since the determining factor in making the decision on their use instead of conventional structural materials is a price-quality ratio [5, 6].

One of the progressive trends in metallurgical production of high-temperature titanium alloys is electron beam melting, which allows not only cleaning these materials from gas and volatile metal impurities, but also significantly simplifying the process of metallurgical treatment and provides manufacturing products with qualitatively new mechanical properties. Electron beam melting also provides the possibility of producing high-temperature titanium alloy ingots by remelting the primary charge in the form of spongy titanium and master alloy [5, 6]. However, for a number of reasons caused by metallurgical and technological features, in the process of electron beam remelting, on the surface of produced ingots, defects in the form of corrugations, cracks, tears and longitudinal strip of metal filling may occur (Figure 1) [7].

It is almost impossible to avoid the formation of this type of defects in EBM, which, in turn, complicates the further heat treatment of ingots and billets, leads to the propagation of hot cracks. The necessary quality of the surface of ingots and billets is achieved by removing the surface layer during mechanical treatment. The mechanical properties of titanium-based alloys show that the efficiency of the blade stripping on existing machine-tools is 3–6 times lower than during stripping of alloyed structural steels, and the heat conductivity of titanium-based alloys during blade stripping causes local overheating at the place of contact with the cutter and, as a consequence, to oxidization of chips. High requirements to cleanliness of the source charge materials impose a number of restrictions on reused chips for ingots, which leads to irreversible metal losses [8, 9].

Thus, the works are promising, which study the possibility of non-waste removal of surface defects of the ingots. Positive results of such works allow reducing metal losses in the form of non-conditional wastes (chips) and valuable alloying elements. At the same time, the most promising is the way of application of new technological processes that allow excluding some technological redistributions from the production chain, and at the expense of it improving the quality of the ingot surface, improving the output of suitable material and significantly reducing the cost of products.

At the PWI of the NASU, an extensive experience has been gained in the use of electron beam for treatment of a surface layer of ingots of round and rectangular sections, a number of studies have been conducted using mathematical modeling of the processes of heat and mass transfer in the ingot treated by electron beam [10]. On the basis of these studies, the technology of electron beam surface melting and specialized equipment for its implementation have been developed [10].

The conducted investigations were aimed at studying the effectiveness of the use of the technology of electron beam surface melting of the surface layer of ingots of high-temperature titanium alloy VT9 and the influence of technological parameters of electron beam surface melting on the chemical composition, penetration depth of the surface layer and the structure of the ingot metal.

To achieve the set aim, the following tasks were solved:

● to study the chemical composition and structure of the base metal and the surface-melted layer of ingots;

● to determine the penetration depth of the surface layer of ingots.

MATERIALS AND RESEARCH METHODS

The first widely used serial high-temperature titanium alloy was titanium (α+β)-alloy VT3-1, developed in 1957. The alloy was used for GTE parts, operating for a long time at temperatures of up to 450 °C. In 1958, titanium alloys VT8 and VT9 were developed for long-term operation at 500 °C [11].

The alloy VT9 is a two-phase (α+β)-alloy. A high content of aluminium and silicon alloying provide higher heat-resistant properties compared to alloy VT6. Titanium alloy VT9 is a wrought alloy and refers to materials with a high heat and corrosion resistance. The alloy VT9 is strengthened by heat treatment — hardening and aging. The optimal combination of mechanical properties is provided by double annealing. It can be used to produce GTE parts — discs, blades and other compressor parts [12, 13].

The metal of the high-temperature titanium alloy VT9 was produced by the technology of electron beam melting with cold hearth developed at the PWI. The surface of the produced ingots was subjected to electron beam treatment in the specialized electron beam installation UE-185 (Figure 2) for surface melting of the ingots according to the modes obtained on the results of mathematical modeling of processes of heat and mass trnasfer in the ingots of titanium alloys in electron beam surface melting [10].

Surface melting of ingots of high-temperature titanium alloy VT9 with a diameter of 600 mm was carried out according to the scheme, where the electron beam is fixed and the ingot rotates around its axis (Figure 3). In this case, the linear rate of surface melting was 54 mm/min, and the specific heating power was 7.25 W/mm^2.

To investigate the impact of technological parameters of electron beam surface melting on the chemical composition and penetration depth of the treated layer, the samples were selected in the form of chips and cut-off samples before and after surface melting (Figure 4).

For accurate analysis of the content of alloying elements in the ingots of the produced alloys, the method of optical emission spectrometry with an inductively-coupled plasma (ICP-OES) in the ICP-spectrome-

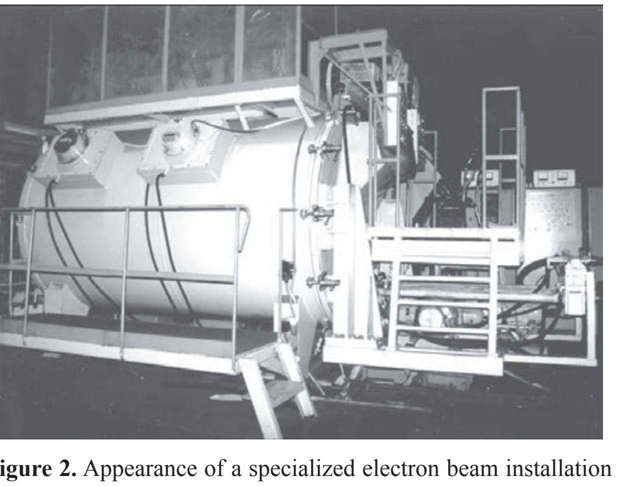

Figure 2. Appearance of a specialized electron beam installation for surface-melting of ingots

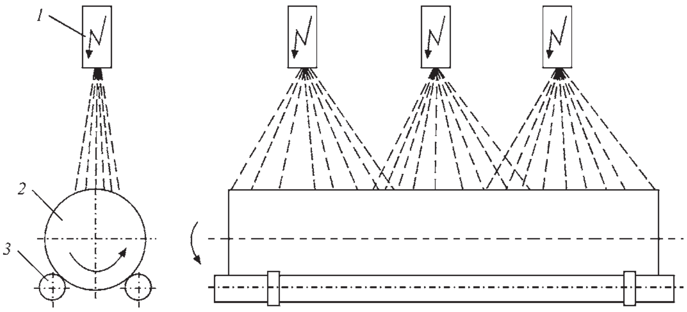

Figure 3. Surface melting scheme: *1* — electron beam gun; *2* — ingot; *3* — rolls

Table 1. Mass concentration of alloying elements in the metal of surface-melted layer of ingots of high-temperature titanium alloy VT9, wt.%

Place of sampling	Al	Mo	Fe	Zr	Si	O	N
Base	6.64	3.63	0.21	1.64	0.32	0.11	0.012
Surface-melted layer	6.13	3.68	0.20	1.69	–”–	0.13	0.016
OST1 90013–81	5.8–7.0	2.8–3.8	≤0.25	1.0–2.0	0.20–0.35	<0.15	<0.05

ter ICAP 6500 DUO of Thermo Electron Corporation production was used. To determine the content of oxygen and nitrogen, the samples of cylindrical shape with diameter and length of 3 mm were made. The content was determined in the devices RO-316 and TN-114 of LECO Company (USA).

The macrostructure of ingots was studied on the transverse templates, cut out from the middle of the ingots. The structure was revealed by etching the templates in a 15 % solution of fluoride acid with the addition of a 3 % solution of nitric acid at room temperature.

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

The structure of the samples was examined in the light microscope Neophot-32 at different magnifications. The photos of microstructures were obtained by means of a digital camera C-3000 of OLYMPUS Company.

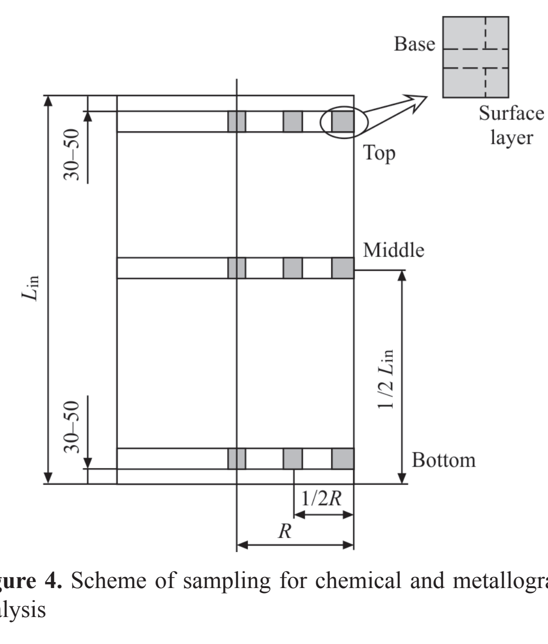

Figure 4. Scheme of sampling for chemical and metallographic analysis

RESEARCH RESULTS AND DISCUSSION

In order to check the efficiency of the use of electron beam surface melting of the surface layer of high-temperature titanium alloy at the production facilities of SE "SPC "Titan" of the PWI", comprehensive research work were carried out in melting of the batch of ingots with a diameter of 600 mm and a length of up to 2 m and surface melting of their side surface by electron beam (Figures 1, 5).

The side surface of the ingots, melted with an electron beam, had an even microrelief, it was mirror-like with a characteristic vacuum etching, without cracks, tears and lacks-of-fusion, its surface roughness was within 3–4 classes at a waviness of 0.2–0.6 mm (Figure 5).

The results of studies of mass concentration of alloying elements in the metal of the surface-melted layer of ingots of the high-temperature titanium

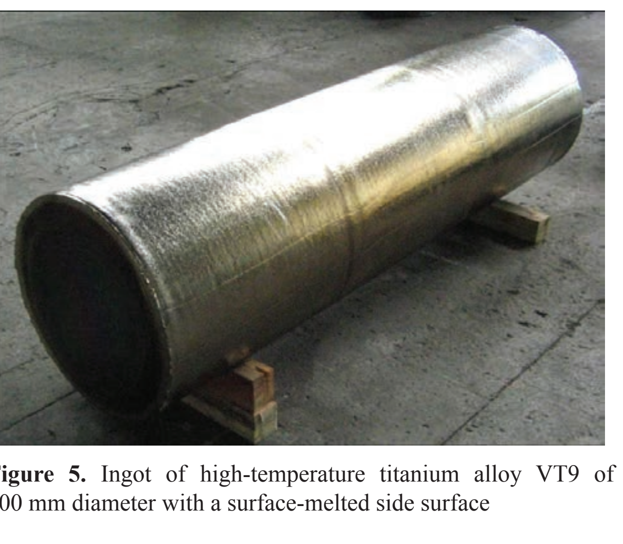

Figure 5. Ingot of high-temperature titanium alloy VT9 of 600 mm diameter with a surface-melted side surface

alloy VT9 showed that their content corresponds to the grade composition, a decrease in the content of aluminium is observed, alloying element with vapor elasticity higher than in the base of the alloy, and an increase in the content of molybdenum, zirconium, alloying elements with vapor elasticity lower than in the base of the alloy (Table 1).

The experimental evaluation of penetration depth of the surface layer of ingots according to the above-mentioned modes was performed on the transverse templates and it amounted up to 8 mm (Figure 6). In this case, the side surface of the ingots had an even microrelief, it was mirror-like with characteristic vacuum etching, without cracks, tears, and lacks-of-fusion (Figure 5).

Metallographic analysis of the metal of the surface-melted ingot of the titanium alloy VT9 was carried out in order to detect structural changes that took place in the metal as a result of thermal impact of the electron beam on the side surface and the base of the ingot. The macrosections of the ingot of the alloy VT9 of 600 mm diameter with the layer surface-melted by electron beams on the surface had no cavities and discontinuities. The macrostructure was characterized by the crystals close to equiaxial, the surface-melted layer was formed by smaller crystals compared to the base of the ingot, elongated towards the crystallization, i.e. to the center of the ingot.

Near the surface of the ingot, the grains of 0.8–1.2 mm size, which were observed to a depth of about 8 mm from the surface, were formed, further in the ingot, the grains were much coarser (Figure 7).

Microstructure of the metal of the surface-melted layer at a larger magnification is shown in Figure 8. The heat-affected-zone from the action of electron beam in melting of the surface is probably narrow and may represent a part of the grain that is not structurally different from the rest of the metal of the ingot. The size of the grain, which is determined on the 10-point scale of macrostructures of the Instruction No. 1054–76 VIAM, corresponds to the grain size Nos 6–7 in the surface-melted layer and the grain size Nos 8–9 in the area of the base metal.

Figure 6. Macrostructure of metal of ingot of high-temperature titanium alloy VT9 of 600 mm diameter with a surface-melted side surface

Examination of the sample microstructure has shown that the surface-melted layer consists of areas with single α-plates, the gaps between which are taken up by dispersed particles. In the metal of the surface-melted layer, there are also areas of the structure, where α-plates are gathered in colonies of different sizes, and dispersed particles are in the gaps between the parallel plates (Figure 8). The areas with single α-plates predominate near the surface of the ingot and deeper in the surface-melted layer, a number of α-colonies is increased. The width of α-colonies in the surface-melted layer is 10–50 μm, and the thickness of α-plates is 1.0–2.5 μm. In the rapidly cooled metal of the surface-melted layer, metastable β-phases and martensite phases can be present. Dispersed particles can be the products of metastable phase decomposition. The size of dispersed particles is 1–2 μm.

The metal microstructure of the ingot base is shown in Figure 9, from which it is seen that in the

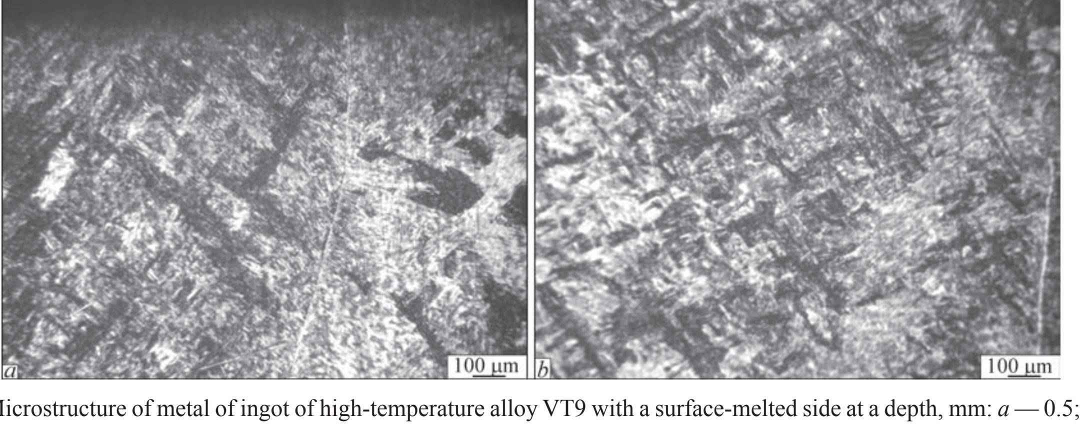

Figure 7. Microstructure of metal of ingot of high-temperature alloy VT9 with a surface-melted side at a depth, mm: *a* — 0.5; *b* — 12.0

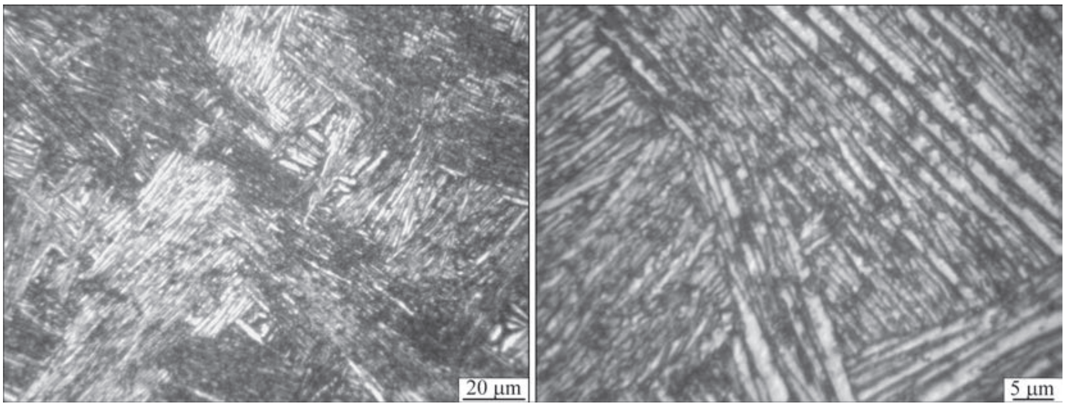

Figure 8. Microstructure of metal of surface-melted ingot at different magnification

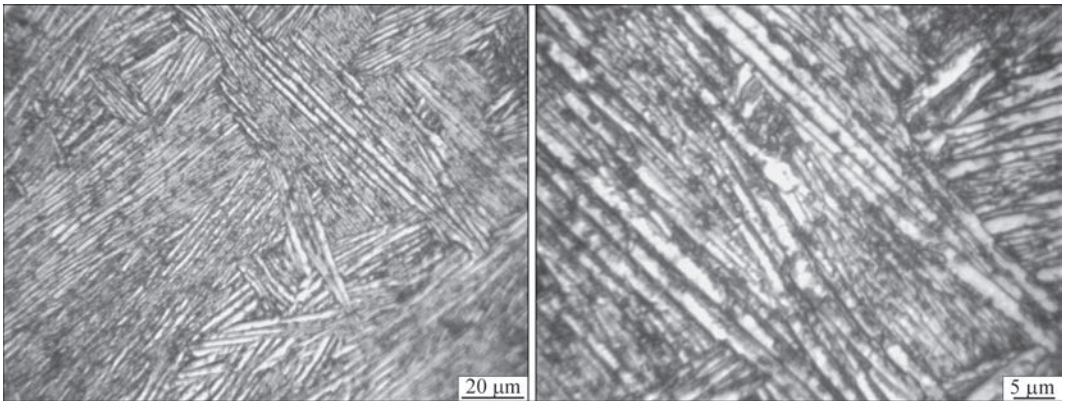

Figure 9. Microstructure of metal base of ingot at different magnification

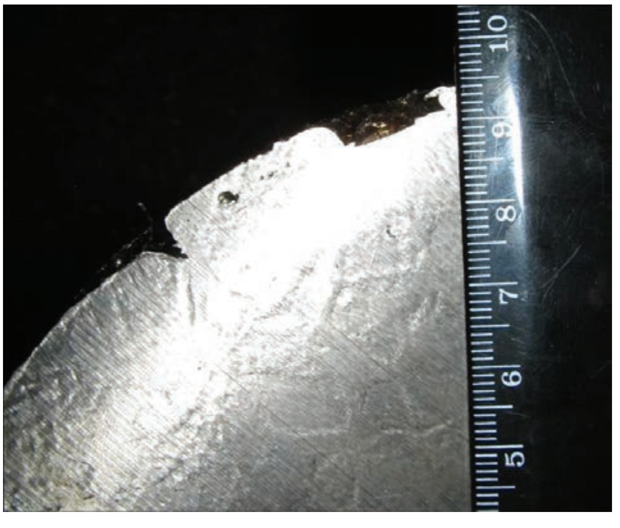

Figure 10. Defective layer of ingot surface

metal a coarse-grained structure predominates, the formation of which was facilitated by a slow cooling of the large volume of metal. The boundaries of primary β-grains are decorated with α-fringe, which in places is continuous and sometimes is intermittent, its width is up to 7 μm. The intragranular structure consists mainly of α-colonies of 10–60 μm. In the gaps between the colonies the areas with a dispersed structure are observed, the sizes of dispersed particles are up to 1–2 μm. Such small particles are also present between α-plates in the colony. In our opinion, this can be explained by the fact that during a slow cooling of the large-sized ingot, a redistribution of alloying elements occurs between the phase components, resulting in the decomposition of metastable martensite phases and β-metastable phase with the precipitation of dispersed particles of stable α- and β-phases. The thickness of the plates in colonies is 1–3 μm.

Thus, the results of the analysis of the microstructure of the surface-melted layer and the base of the ingot of the high-temperature titanium alloy VT9 indicate that the treatment of the ingot surface by electron beams on the abovementioned modes leads to the refinement of α-colonies and α-plates of grains in the surface-melted layer compared to the ingot base.

According to standard technology, defects formed on the surface of ingots of titanium alloys during their melting are eliminated by removing the surface layer using mechanical methods. The thickness of the defective layer, removed from the ingot surface, reaches up to 9 mm (Figure 10), the losses in the chips are up to 100–140 kg for an ingot with a diameter of 600 mm, which amounts up to 4.0–5.5 % of the total ingot mass.

Therefore, the technology of electron beam melting of the ingot surface layer of a high-temperature titanium alloy VT9 allows producing a high-quality metal in the surface-melted layer with a high efficiency, which meets the requirements of the standard and at the same time maintaining up to 5.5 % of the ingot total mass of a high cost metal.

CONCLUSIONS

1. It was established that the chemical composition of the metal in the surface-melted layer of high-temperature titanium alloy VT9 meets the requirements of the standard, a decrease in aluminium content, alloying element with vapour elasticity higher and an increase in the content of molybdenum, zirconium, alloying elements with vapour elasticity lower than in titanium is observed.

2. It is shown that the penetration depth of the surface layer of ingots of a high-temperature titanium alloy VT9 with a diameter of 600 mm, produced by the technology of electron beam surface-melting reaches up to 8 mm, and the ingot surface is high-quality, mirror-like with characteristic vacuum etching, even microrelief without cracks, tears and lacks-of-fusion, its roughness is within 3–4 class at a waviness of 0.2–0.6 mm.

3. It is shown that the surface-melted layer of the ingot has a smaller structure compared to the base metal and consists of areas with single α-plates of 1.0–2.5 μm thickness, where α-plates are gathered in colonies with a width of 10–50 μm, the gaps between which occupied by dispersed particles with the sizes of 1–2 μm that can be the products of metastable phase decomposition.

REFERENCES

1. Niinomi, M. (2011) Recent trends in titanium research and development in Japan. In: *Proc. of 12th World Conf. on Titanium*, **1**, 30–37.
2. Bania, P. (1993) Beta titanium alloys and their role in the titanium industry. *Beta Titanium Alloys in the 90's*. TMS Publ., Warrendale, PA, 3–14.
3. Cui, C., Hu, B.M., Zhao, L., Liu, S. (2011) Titanium alloy production technology, market prospects and industry development. *Mater. Des*., **32**, 1684–1691. DOI: http://doi/org/10.1016/j.matdes.2010.09.011?
4. Babenko, E.P., Dolzhenkova, E.V. (2014) Investigation of the causes of destruction of a large-sized product made of VT23 alloy. *Metallurgical and Mining Industry*, **3**, 82–85.
5. Khoreev, A.I. (2007) Theory and practice of development of titanium alloys for promising structures. *Tekhnologiya Mashinostroeniya,* **12**, 5–13 [in Russian].
6. Antonyuk, S.L., Moyar, A.G., Kalinyuk A.N. et al. (2003) Titanium alloys for aircraft industry of Ukraine. *Advances in Electrometallurgy*, **1**, 9–13.
7. Pikulin, A.N. (2016) Electron beam fusion of complexly-alloyed titanium alloys. Sovrem. Elektrometall., **3**, 26–30 [in Russian].
8. Koryagin, S.I., Pimenov, I.V., Khudyakov, V.K. (2000) *Methods of treatment of materials: Manual.* Kaliningrad, Kaliningr. University [in Russian].
9. Krivoukhov, V.A., Chubarov, A.D. (1990 *Cutting of titanium alloys*. Moscow, Mashinostroenie [in Russian].
10. Paton, B.E., Trigub, N.P., Akhonin, S.V., Zhuk, G.V. (2006) *Electron beam melting of titanium.* Kyiv, Naukova Dumka [in Russian].
11. Pavlova, T.V., Kashapov, O.S., Nochovnaya, N.A. (2012) *Titanium alloys for gas turbine engines. All materials.* Encyclopaedic Handbook [in Russian].
12. Khoreev, A.I., Khoreev, M.A. (2005) Titanium alloys, their application and prospects of development. *Materialovedenie*, **7**, 25–34 [in Russian].
13. Aleksandrov, V.K., Anoshkin, N.F., Bochvar, G.A. et al. (1979) *Semi-finished products from titanium alloys. Moscow, Metallurgiya* [in Russian].

ORCID

O.M. Pikulin: 0000-0001-6327-3848,
S.V. Akhonin: 0000-0002-7746-2946,
V.O. Berezos: 0000-0002-5026-7366,
A.Yu. Severyn: 0000-0003-4768-2363,
O.G. Yerokhin: 0000-0003-2105-5783

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

S.V. Akhonin
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: akhonin.sv@gmail.com

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