DOI: https://doi.org/10.37434/tpwj2024.03.05

PRODUCING ADVANCED ALLOYS BASED ON TITANIUM ALUMINIDES FOR MODERN AIRCRAFT ENGINE MANUFACTURING

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ABSTRACT

Works have been performed on optimization of the technological scheme of producing ingots for consumable electrodes with a stable chemical composition and properties. The paper presents the results of studying an ingot of 195 mm diameter from a titanium aluminide-based alloy of Ti–28Al–7Nb–2Mo system, made by double electron beam remelting. Further ingot remelting in the arc furnace was performed, which allowed producing a homogeneous and defect-free ingot of an optimal composition of Ti–28Al–7Nb–2Mo–0.3 (Y, Re, B). The influence of modifying on the structure and properties was studied. It was determined that addition of surfactants promotes refining of the structural components and improvement of the alloy mechanical properties.

KEYWORDS: electron beam melting, vacuum-arc melting, ingot, titanium aluminide, modifying, structure, mechanical properties

INTRODUCTION

The development of modern aircraft engine manufacturing requires the use of new materials with enhanced properties and functional characteristics, which are ensured by the stability of chemical composition and structure and depend on the manufacturing technology [1]. Technological aspects, including optimization of technological parameters, repeatability of the obtained results and shaping are interrelated. The impact of technology on the properties of aircraft materials requires process regulation, for example, the use of vacuum-arc remelting in the production of titanium alloys [2, 3].

Titanium aluminide-based alloys, whose properties depend on the parameters of technological processes, are among the advanced materials for the aircraft industry. These alloys are an important class of structural materials with a unique set of physical and mechanical properties. Intermetallic alloys based on titanium aluminides are characterised by low density, high heat strength, heat resistance, and thermal stability. They have a high potential for replacing nickel-based alloys designed for operation at temperatures of up to 850 °C [4].

Heat-strength titanium aluminide-based alloys are characterised by a multicomponent chemical composition. The individual alloying elements of these alloys differ significantly in thermal and physical properties and density. Therefore, it is necessary to provide a uniform distribution of alloy components at the nominal level throughout the whole ingot volume, as macrosegregations may cause arising of different microstructures and, consequently, high anisotropy of mechanical properties.

The industrial development of titanium aluminide-based alloys involves the production of high-quality semi-finished ingots with a uniform distribution of elements and a homogeneous structure with stable physical, mechanical and operational characteristics.

Mechanical properties largely depend on the ultimate shaping technology for which the optimal chemical composition was developed.

When developing the alloy composition, it is necessary to focus on the peculiarities of the technological process of manufacturing stator and rotor engine parts, such as turbine blades. Motor Sich enterprise uses consumable electrodes of its own production for the smelting vacuum-arc furnace to produce titanium alloy shaped castings [5–7].

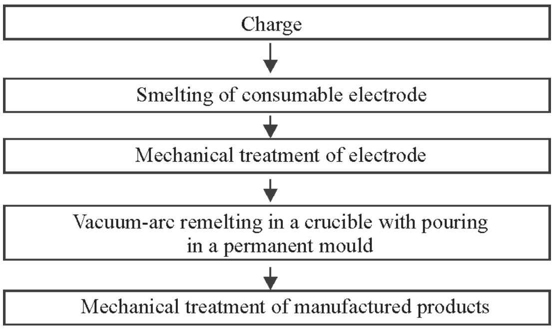


Figure 1. Scheme of the technological process for manufacturing titanium aluminide products

To introduce new titanium aliminide-based alloys for advanced engines, it is necessary to develop the entire technological process, taking into account the ultimate shaped casting technology and ensuring the chemical composition and mechanical properties of the alloy.

Taking into account the serial technological process of casting from the consumable electrode with a diameter of more than 200 mm, the aim of the work is to produce industrial ingots for consumable electrodes from titanium aluminide with stable chemical composition and properties.

RESEARCH PROCEDURE, EQUIPMENT AND MATERIALS

The object of the research was the technological processes of casting, which included the operations of producing a consumable electrode, remelting of the electrode in a crucible and pouring of metal from a crucible in a permanent mould (Figure 1). As a product, a turbine blade of the last stage made of a nickel-based VZhL12E-VI alloy was chosen. Taking into account earlier research works [8, 9], to ensure service properties, the following composition of the alloy based on titanium aluminide Ti–28Al–7Nb–2Mo–0.3 (Y, Re, B) was substantiated.

To smelt ingots from the charge, well-optimized technologies [10–12] for manufacturing aircraft materials by electron beam melting (EBM) of charge in the UE-208M unit were used [13] (Figure 2).

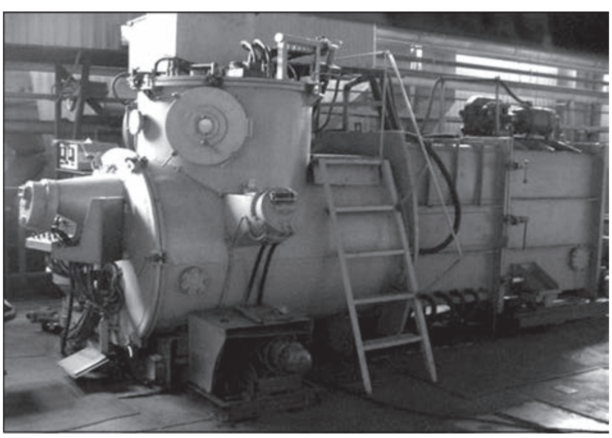


Figure 2. Appearance of electron beam unit UE-208M

For the studies, the ingot of the basic composition Ti–28Al–7Nb–2Mo was melted using the EBR method, which made it possible to correct the chemical composition and additional charging.

Stability of the chemical composition of the base alloy was achieved by double remelting. During the first remelting, refractory alloying elements such as niobium and molybdenum were introduced into the alloy. During the second remelting, aluminium was added to the ingot to account for evaporation losses. This allowed minimising aluminium losses and ensured that refractory alloying elements were dissolved and unifromly distributed over the length and cross-section of the ingot.

Ingot smelting was carried out in accordance with the capacities and configuration of ingot surface heating in the mould built in accordance with the calculated mathematical models [14].

The melting parameters of an ingot with a diameter of 195 mm from titanium aluminide Ti–28Al–7Nb–2Mo are as follows:

total power of EB heating, kW 60
power in the mould, kW 18
melting rate, kg/h 60

After loading the charge (Figure 3, *a*), the unit was pumped down to a residual pressure of 10^{-2} Pa in the gun chamber and 10^{-1} Pa in the melting chamber. Then the billet was melted in a cold hearth until it was filled and the liquid metal was periodically poured in a copper water-cooled mould (Figure 3, *b*). The first portions of the discharge were used to form the dummy bar for the future ingot to a height equal to the inner diameter of the mould, at which, according to mathematical calculations, the melting transfers to a quasi-stationary mode. The ingot of the required height was smelted at the achieved technological mode.

The composition of the charge for smelting basic and modified ingots: aluminium of A5 grade according to GOST 11069–2001, titanium billet (remelting of initial charge of titanium sponge of grade TG-100) according to DSTU 3-25-22–94; niobium (rods); master alloy (93 % Ti–7 % Mo); master alloy Al–Re, Al–Y, aluminoboron. The master alloys were produced by melting pieces of sponge titanium and aluminium with the corresponding elements Y, Re and B in the form of powders in a vacuum in a copper mould using a nonconsumable tungsten electrode. In such a way, master alloys with the content of modifying elements of 5, 10 and 15 % each, for example, Ti–5 % Y, A1–5 % Y, Ti–10 % Re, etc. were produced to ensure

Figure 3. Charge billet (*a*) and electron beam melting process (*b*) of titanium aluminide ingot Ti–28Al–7Nb–2Mo

the required concentration of elements in the composition of the experimental alloy.

To produce an ingot of a specified composition with modifiers Y, Re, B, to determine the transition coefficients of alloying elements and to model the processes occurring in electron beam melting, the alloy of the base composition was remelted in an arc furnace with a nonconsumable electrode with a controlled atmosphere (Figure 4) [15, 16].

To determine the chemical composition of the base alloy, samples in the form of a chip were taken from the melted ingot. Samples for analysis were taken from the head, middle and bottom parts of the ingot along its length. The content of alloying elements was determined by the method of inductively coupled plasma of optical emission spectrometry (ICP-OES) using an ICP spectrometer ICAP 6500 DUO. To determine the content of oxygen, nitrogen, and hydrogen, the ELTRA gas analyser was applied with the use of cylindrical samples of 3 mm in diameter and length. The essence of determining gas mixtures consisted in burning the mentioned samples and determining the volume of gaseous chemical elements that have been released.

The chemical composition of the alloy was analysed on the samples taken along the entire length of the ingot using a spectral reference-free method in an Expert 3L energy dispersive X-ray fluorescence analyser.

The etching of the samples for metallographic examinations was performed in the Titan etchant with the composition $HF:HNO_3:H_2O = 1:2:6$.

The macrostructure of the template was evaluated by the naked eye over the ingot thickness. The microstructure of the ingot material was examined with the use of the AxioObserver 5 optical microscope at magnifications from 25 to 200.

Tensile mechanical properties were determined in accordance with DSTU ISO 6892-1:2019. The samples for testing were cut out transversely to the ingot axis.

During the statistical processing of the experimental data, the dispersion and standard deviation were determined.

RESEARCH RESULTS AND DISCUSSION

As a result of the research, an ingot Ti–28Al–7Nb–2Mo with a diameter of 195 mm and a mass of 106 kg was produced (Figure 5, *a*). The ingot had no external coarse defects (tears and cold laps), the surface was satisfactory with small corrugations.

To eliminate cast defects in the form of corrugations, the ingot surface was subjected to turning to a depth of 5 mm (Figure 5, *b*).

Figure 4. Arc furnace with nonconsumable electrode

Figure 5. Appearance of the base composition ingot before (*a*) and after mechanical treatment (*b*)

Table 1. Chemical composition of the ingot with a diameter of 195 mm, wt.%

Alloy	Sample, sampling location	Ti	Al	Nb	Mo	O	N	H
Ti–28Al–7Nb–2Mo (without modifiers)	1 (top)	Base	26.6	7.6	2.0	0.13	<0.01	<0.005
	2		27.4	7.5	–»–			
	3		27.2	–»–	2.1			
	4		31.0	7.2	1.9			
	5 (bottom)		30.5	7.3	2.2			

From the produced ingot without modifiers, the samples for ICP analysis were taken according to the scheme shown in Figure 6. The data of chemical analysis are presented in Table 1.

The deviation in the aluminium content in the head and bottom parts is explained by nonstationary melting modes at the beginning and end of melting during the dummy bar formation and removal of the shrinkage cavity, respectively. The levelling of the content by alloying elements and the achievement of the required chemical composition were further planned with the use of an arc furnace.

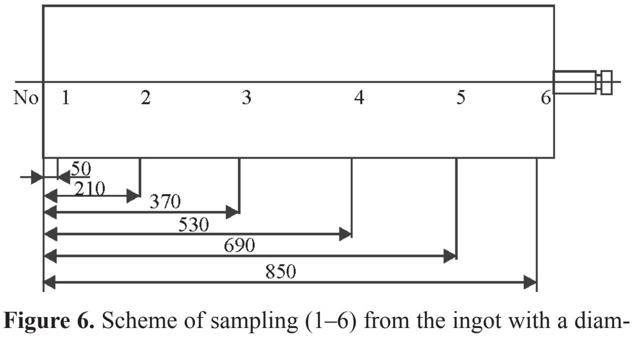


Figure 6. Scheme of sampling (1–6) from the ingot with a diameter of 195 mm

To provide the optimal chemical composition, parts were cut off from an ingot of 195 mm diameter, which were additionally charged with modifiers and remelted with the use of a small-scale furnace shown in Figure 4. The vacuum-arc remelting of the electrode was performed in a graphite MPG-7 crucible, and the metal was poured in a permanent mould (Figure 7).

The chemical composition of the alloy was analysed on the samples taken along the entire length of the ingot from the upper, middle and lower parts (Table 2).

Due to the fact that when smelting titanium alloys in a graphite crucible, the carbon content does not exceed the admissible limits of 0.10–0.15 %, the carbon content for experimental melting was not studied.

Figure 7. Appearance of graphite crucible (*a*) and permanent mould (*b*) for vacuum-arc remelting

The results of studying chemical composition of the metal showed a uniform distribution of alloying elements along the length of the melted ingots.

Transverse templates were cut out from the ingots and macrosections were made to control the structure. It was found, that in the ingots, a homogeneous and dense structure was formed. No defects in the form of pores, cavities or cracks visible to the naked eye were detected.

The macrostructure of the ingot without modifiers is characterised by grains close to equilibrium. The grain size corresponds to 8-9 numbers of the 10-number scale of titanium alloys' macrostructures (Figure 8, *a*).

The macrostructure of the ingot with modifiers contains smaller grains corresponding to 2–3 numbers of the macrostructure scale (Figure 8, *b*).

No difference in the grain size number in the central part of the ingot and on the periphery was found.

During a metallographic examination of the produced ingots, a significant effect of modifiers on the morphology of the alloy structure was revealed. Thus, the microstructure of the alloy without modifiers was characterised by a coarse-grained structure, in the middle of which there are colonies of light and dark coloured plates of 100–350 μm in size, disoriented within one grain (Figure 9, *a*). The combined effect of the three modifiers in the amount of 0.1 % each led to the formation of a fine-grained duplex (α_2+γ)-structure with the sizes of plate colonies of not more than 30 μm (Figure 9, *b*).

The main mechanical properties of the Ti–28Al–7Nb–2Mo (Y, Re, B) alloy are as follows: σ_t, MPa – 800–870; δ, % — 0.8–1.3.

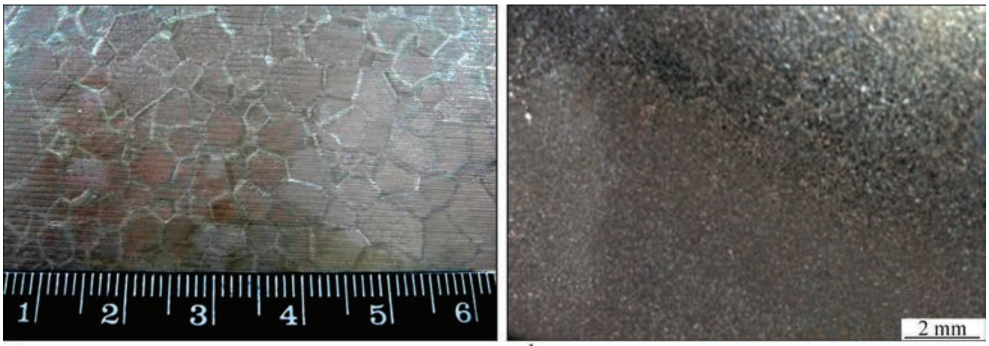
As is known, cast titanium aluminide-based alloys have almost zero ductility, which makes it very difficult to conduct standard tensile tests, but the analysis of literature data showed that the tensile strength of cast alloys of a similar composition is at a level of 500 MPa [17], while with the combined introduction of modifiers, an increase in strength of up to 800 MPa is achieved, i.e. almost 2 times compared to the initial one.

Based on the results of the carried out research, a scheme was developed that corresponds to the industrial technology and includes the manufacture of a consumable electrode by double remelting, its additional charging with modifiers to provide the optimal chemical composition in an arc furnace with a controlled atmosphere and subsequent pouring of metal in a permanent mould.

For this scheme, optimal melting modes have been calculated and proven, that ensure the absence of anisotropy of properties both when introducing refractory elements in the ingot of the basic composition, as well as when producing a consumable electrode of a modified composition during smelting in a permanent mould.

Table 2. Chemical composition of the ingot with modifiers, wt.%

Alloy	Sampling location	Ti	Al	Nb	Mo	Modifiers		
						Y	Re	B
Ti–28Al–7Nb–2Mo–0.3 (Y, Re, B)	Top	Base	28.3	7.5	2.0	0.13	0.09	0.10
	Middle		28.7	7.6	1.8	0.09	0.12	–»–
	Bottom		29.4	7.5	2.1	0.08	0.08	0.12



a *b*

Figure 8. Macrostructure of ingots after etching: *a* — without modifiers; *b* — with modifiers

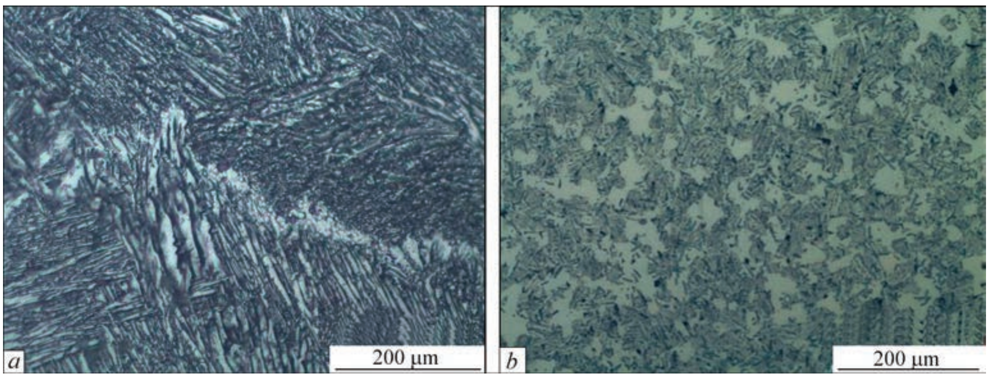


Figure 9. Microstructure of ingots after etching: *a* — without modifiers; *b* — with modifiers, ×200

It was established that in the end product, due to the uniform distribution of alloying and modifying elements and the absence of a gradient of elements' concentrations, the structure was significantly refined from 8–9 to 2–3 numbers of the macrostructure grain, which is an important parameter for ensuring the quality of casting products.

The grain refinement of the cast structure was achieved by introducing modifiers Y, Re, and B, which contribute to a reduction in grain size, lead to a change in phase morphology, refine grain boundaries from impurities, delay the development of diffusion processes at the boundary interface and inhibit the processes of growth of structural components. This, in turn, made it possible to improve the mechanical characteristics of the material, including strength and ductility.

The tensile strength of the experimental alloy was 800–870 MPa, the relative elongation was 0.8–1.3 % at the tensile strength of the serial VZhL12E-VI alloy at a level of ≥ 830 MPa.

Thus, it is shown that the technological process with the established modes makes it possible to manufacture serial products of the experimental alloy from titanium aluminide instead of a serial nickel-based alloy. The reduction in weight of one blade, taking into account the density of experimental and serial alloys, amounts to 34 % and is a significant advantage of the experimental alloy for rotor parts operating at high temperatures.

CONCLUSIONS

1. Technological scheme for smelting titanium aluminide ingots of the Ti–28Al–7Nb–2Mo system by the EBR method with the use of certain technological modes is proposed. The use of double remelting provided a uniform distribution of refractory elements and elements with a high vapour pressure along the ingot length and cross-section.

2. Further remelting of titanium aluminide ingot in an arc furnace with a controlled atmosphere was carried out, the transition coefficients of alloying elements were determined, and a homogeneous and defect-free ingot of the composition Ti–28Al–7Nb–2Mo (Y, Re, B) was produced.

3. In the end product, the structure of the cast metal was significantly refined — from 8–9 to 2–3 numbers of macrostructure grains. The grain refinement of the cast structure was caused by the introduction of surface-active elements in the alloy, namely Y, Re, B. The microstructure of the alloy without modifiers was characterised by a coarse-grained structure, in the middle of which there were collonies of plates of 100–350 μm in size, disoriented within the same grain. The combined effect of three modifiers in the amount of 0.1 % each resulted in obtaining a fine-

grained duplex structure with the size of the plate colonies not exceeding 30 μm.

4. The tensile strength of the alloy of the optimal composition was 800–870 MPa, which is 1.7 times higher than the properties of the alloy of the base composition, and corresponded to the tensile strength of the serial VZhL12E-VI alloy.

5. The calculated reduction in weight of the blade when using the experimental alloy instead of a serial one amounts to 34 %, which is a significant advantage of the experimental alloy for rotor parts operating at high temperatures, rotation speeds and dynamic loads.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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SUGGESTED CITATION

O.V. Ovchinnikov, S.V. Akhonin, V.O. Berezos, A.Yu. Severin, O.B. Galenkova, V.G. Shevchenko (2024) Producing advanced alloys based on titanium aluminides for modern aircraft engine manufacturing. *The Paton Welding J*., **3**, 33–39.

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Received: 22.12.2023
Received in revised form: 14.02.2024
Accepted: 03.04.2024