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FEATURES OF SMELTING OF HEAT-RESISTANT TITANIUM ALLOY OF THE Ti–Nb–Al–Mo–Zr ALLOYING SYSTEM BY ELECTRON BEAM MELTING WITH A COLD HEARTH

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ABSTRACT

In order to develop the technique and technology of smelting ingots of heat-resistant alloys based on titanium with the content of the Ti_2AlNb ortho-phase, experimental works were carried out to produce the experimental Ti–39Nb–16Al–2.6Mo–1.4Zr alloy. The results of studies of the ingot produced by double electron beam remelting are presented. The developed technology and experimental melting of the 110 mm diameter Ti–39Nb–16Al–2.6Mo–1.4Zr ingot by the electron beam melting method with a cold hearth showed the prospects of using the EBM method for producing ingots of heat-resistant alloys based on titanium with the content of the Ti_2AlNb ortho-phase.

KEYWORDS: electron beam melting, cold hearth, ingot, refractory elements, chemical composition, titanium aluminide, ortho-phase

INTRODUCTION

Creation of intermetallic alloys of the Ti–Al–Nb system and technologies for their production are a perspective direction, which is being developed in the world in the field of new metal materials with a high level of heat resistance, high-temperature strength and thermal stability [1–3]. Ortho-alloys may well replace heat-resistant steels and nickel alloys used in the rotor and stator of a high-pressure compressor, but despite the advantages of these alloys, none of ortho-alloys are still used abroad. Obviously, this is associated with the fact that such alloys have proved to be quite difficult in metallurgical production. The need in using more expensive and refractory elements (niobium, molybdenum, etc.) for alloying, providing high homogeneity of ingot composition, the use of equipment with a protective atmosphere, strict testing of macro- and microstructure in semi-finished products are the main reasons for slowing down the industrial implementation of this grade of alloys. Nevertheless, there are real prerequisites and technical capabilities to overcome many of these difficulties.

The most interesting are ortho-alloys within the Ti–(22–25)A1–(25–30)Nb alloying range (at.%), which contain precipitations of the Ti_2AlNb ortho-phase. It should be noted that although an increase in the aluminium content above 25 at.% improves the heat resistance of the material, it leads to a drop in toughness [4, 5]. In addition to aluminium and niobium, ortho-alloys may contain additional alloying elements. Thus, macroalloying with an element such as Mo leads to an expansion of the β-phase existence area, which acts as a plastic matrix and delayering of diffusion processes in the volume and at the interfacial boundaries of the material, increasing its melting point and facilitating softening at operating temperatures. Zirconium, acting as a neutral hardener in relation to titanium and intermetallic titanium alloys, provides solid-solution hardening of the main phases and increases creep resistance.

One of the methods of producing intermetallic ingots is smelting technology based on independent heating sources. It should be considered that heat-resistant titanium-based alloys contain such alloying elements as Nb, Zr, Mo, which, like titanium, have high chemical activity towards gases at elevated temperatures, which necessitates melting of these materials in a protective atmosphere or under vacuum [6]. Among the modern methods of special electrometallurgy, electron beam melting is the most efficient method of vacuum metallurgy [7, 8].

As shown in [6], when smelting ortho-alloys with a high content of refractory alloying elements (niobium, molybdenum, tungsten) by electron beam melting, it is significantly more difficult to ensure a uniform chemical composition in the ingot volume. It is especially difficult to provide a uniform content of elements with high vapour elasticity, such as aluminium and chromium. Therefore, in [9], a mathematical model of the processes of evaporation of alloying

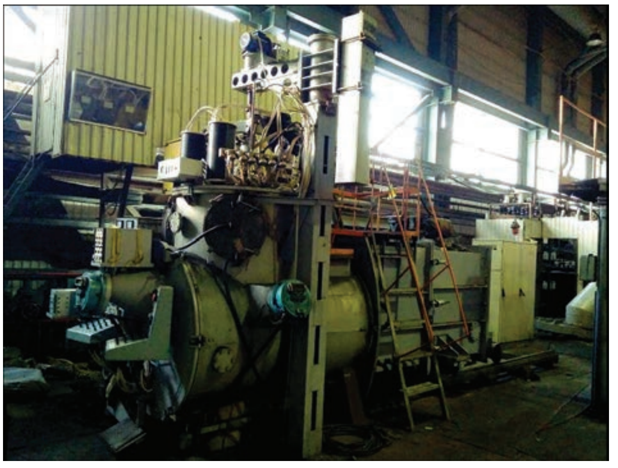

Figure 1. Laboratory electron beam UE-208M installation

elements from titanium alloys during electron beam melting with a cold hearth was developed and, using the example of the process of producing the titanium aluminide Ti–29Al–12Nb–3Cr–3Zr alloy ingot, the dependencies of the concentration of alloying elements in the ingot on the technological parameters of melting and the content of alloying elements in the initial charge were established.

Earlier studies have shown that the specified chemical composition of titanium intermetallic alloys can be achieved only by performing at least a double electron beam remelting. In addition, to facilitate adding of alloying elements into the alloy composition, various master alloys were used, which are quite scarce and expensive. Therefore, it is of particular interest to develop a technology that allows using pure components to produce materials of this grade.

RESEARCH PROCEDURE

In order to practice the technique and technology of smelting ingots of titanium-based high-temperature alloys containing the Ti_2AlNb ortho-phase, experimental works were carried out to produce an experimental Ti–39Nb–16Al–2.6Mo–1.4Zr alloy (wt.%).

For experimental studies, a multipurpose laboratory electron beam UE-208M installation [10] was used (Figure 1).

The technological sequence of ingot smelting consisted of the following stages: calculation of the quantity of components of the initial charge, taking into account evaporation losses; preparation of equipment and technological fixture for melting; formation of consumable billets; melting process; sampling for chemical and gas analysis of a smelted ingot.

Before conducting the experimental ingot melts, the equipment was prepared by cleaning the melting chamber, the electron beam gun plate, the cold hearth and the mold, and the bottom-plate from condensation, dust and metal residues from previous melts.

Figure 2. Charge billet for the production of ortho-titanium aluminide Ti–39Nb–16Al–2.6Mo–1.4Zr alloy

Experimental melts were carried out in a 110 mm diameter mold. The works on producing a heat-resistant titanium Ti–39Nb–16Al–2.6Mo–1.4Zr alloy ingot were carried out in two stages. When smelting titanium-based alloys by electron beam melting, the main problem of alloying elements distribution arises namely with elements that have high vapour elasticity [11, 12]. Therefore, in order to ensure a more uniform distribution of aluminium in the final ingot, at the first stage, an intermediate billet of a commercial titanium aluminide was smelted without adding refractory alloying elements. The charge billet was prepared, which included briquettes of TG-120 titanium sponge and a commercially pure aluminium (Figure 2).

At the second stage, alloying elements in the form of electrolytic niobium, commercially pure molybdenum and refined zirconium iodide were added to the produced ingot of a commercial titanium aluminide.

After loading the charge, the installation was vacuumed to the level of a residual pressure in the melting chamber of 10^{-2} Pa. Then the billet was melted into a cold hearth until it was filled and the liquid metal was periodically poured into a copper water-cooled mold.

Figure 3. Melting process of an ingot with a diameter of 110 mm made of ortho-titanium aluminide Ti–39Nb–16Al–2.6Mo–1.4Zr alloy

Figure 4. Ingot with a diameter of 110 mm made of ortho-titanium aluminide Ti–39Nb–16Al–2.6Mo–1.4Zr alloy

The first pouring portions were used to form a seed for the future ingot. Then, the achieved technological mode was used to smelt the ingot of the required height (Figure 3).

During the experimental melts, the following technological parameters were monitored: melting rate, electron beam current and accelerating voltage. The numerical values of the accelerating voltage and beam current were measured and adjusted using the devices intended for this purpose. The melting rate was controlled by the rate of feeding the consumable billet into the melting zone.

Technological parameters of melting an ingot with a diameter of 110 mm made of ortho-titanium aluminide Ti–39Nb–16Al–2.6Mo–1.4Zr alloy

Total EB heating power, kW 130
Power in the mold, kW 30
Melting rate, kg/h 30

After melting, the ingot was kept in a vacuum chamber until it cooled completely. An ingot with a diameter of 110 mm and a weight of approximately 40 kg was produced (Figure 4).

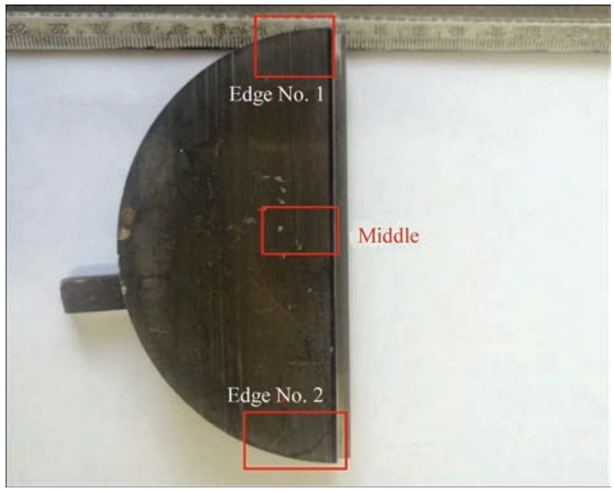

Figure 5. Scheme of sampling for microstructure examination

The head part with the shrinkage shell was cut off from the ingot and samples were taken for chemical analysis. The samples were taken at three points in the form of chips by drilling. In this case, at first, the upper layer of the ingot was removed to a depth of at least 5 mm, and then chips were sampled for analysis to a depth of 10 mm from the surface of the ingot.

To accurately analyse the content of alloying elements in the produced ingot, inductively coupled plasma/optical emission spectrometry (ICP-OES) was used in the ICAP 6500 DUO ICP-spectrometer. The studies showed that after a double electron beam remelting, the distribution of alloying elements was satisfactory and did not exceed the technical specifications (Table 1). The oxygen content was 0.04 wt.%, which corresponded to the data of the certificate of oxygen content in the TG-120 titanium sponge.

To study the microstructure of the material in the cast state by the method of optical metallography, samples were taken from the produced ingot according to the scheme shown in Figure 5.

The general appearance of the microstructure at magnifications ×50, 500 and 1000 is shown in Figure 6. The analysis of the images (Figure 6, *a*–*c*, ×50) shows that the structure is formed by equilibrium grains of the β-phase body-centered cubic lattice with dispersed precipitations in the grain body. Comparison of Figure 6, *b* with Figure 6, *a*, *c* shows that the grain size in the middle zone is coarser than in the peripheral zones of the ingot. This is explained by the

Table 1. Chemical composition of an ingot with a diameter of 110 mm made of ortho-titanium aluminide Ti–39Nb–16Al–2.6Mo–1.4Zr alloy produced by EBM, wt.%

Ingot part	Nb	Al	Mo	Zr	Ti	O
Top	39.2	16.4	2.62	1.37	Base	0.04
Middle	39.2	15.3	2.76	1.36		
Bottom	39.7	14.9	2.63	1.35		

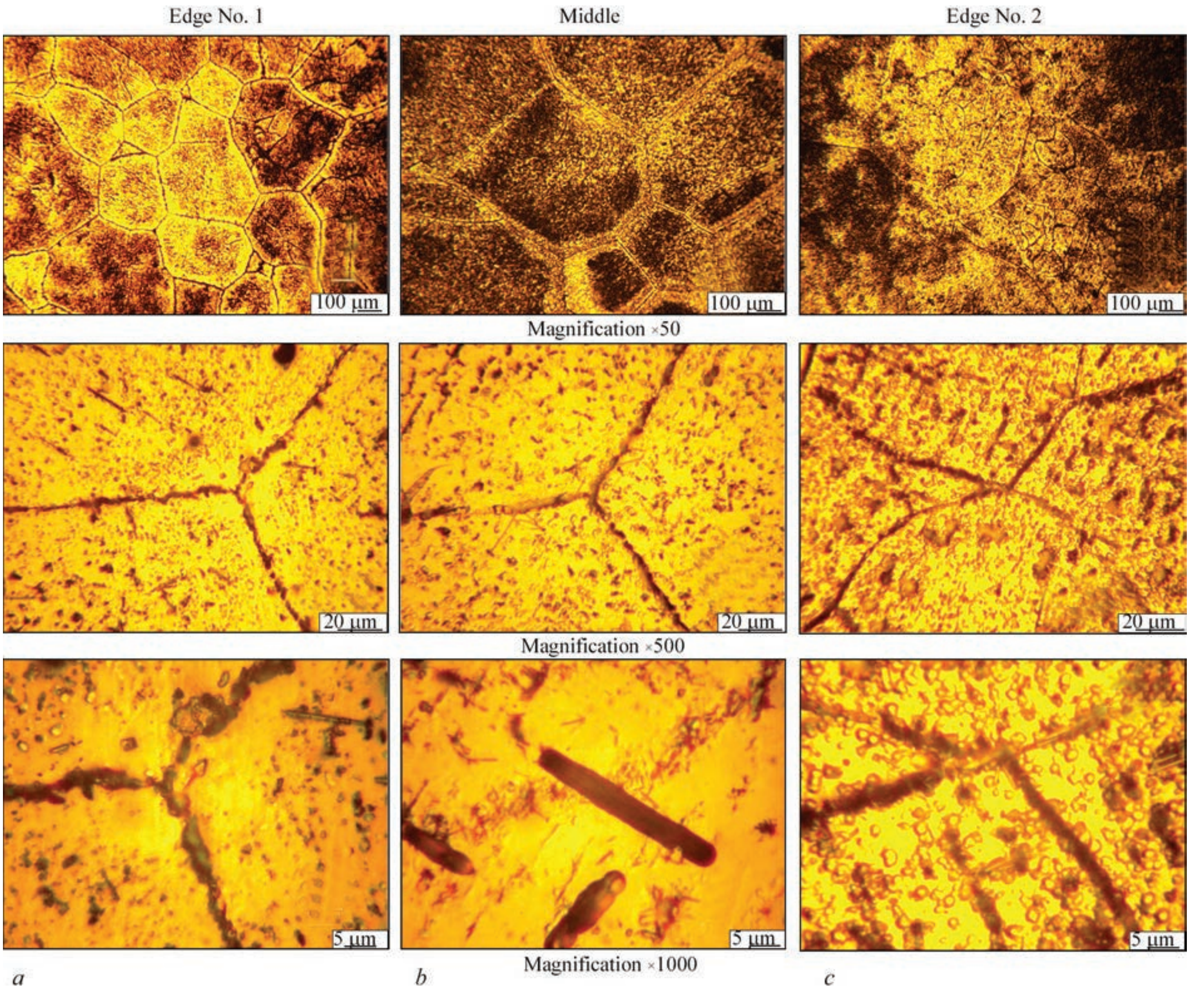

Figure 6. General appearance of the cast metal microstructure: *a* — sampling place corresponds to the edge 1 zone; *b* — middle; *c* — edge 2

difference in the cooling rate of the periphery and centre of the ingot.

In order to study the morphology of the phases precipitated in the grain body, the microstructure of the material was examined at magnifications of ×500 and ×1000 (Figure 6). The analysis of the microstructures shows that the bulk of the precipitations are dispersed particles of approximately equilibrium shape, which are localised in the grain body. The grain boundaries are free of precipitations (Figure 6, *a*–*c*, ×500). At the same time, in the middle zone, separate lamellar precipitations of 20–30 μm length are observed (Figure 6, *b*, ×1000). Based on the particles morphology, it can be assumed that dispersed particles are α_2-phase (Ti_3Al), and lamellar ones are θ-phase crystals (orthogonal Ti_2AlNb phase).

Thus, the developed technology and experimental melts of the Ti–39Nb–16Al–2.6Mo–1.4Zr ingot with a diameter of 110 mm by the electron beam melting method with a cold hearth showed the prospects of using the EBM method to produce ingots of heat-resistant alloys based on titanium with the content of the Ti_2AlNb ortho-phase.

CONCLUSIONS

1. The Ti–39Nb–16Al–2.6Mo–1.4Zr alloying system containing intermetallic Ti_2A1 and Ti_2AlNb phases was selected for experimental melts.

2. A new method of adding alloying elements into the alloy was developed and an experimental melting of a 110 mm diameter ingot was carried out.

3. It was shown that electron beam melting allows producing ingots of titanium-based alloys with a high content of aluminium and niobium and a sufficiently uniform distribution of alloying elements.

4. An examination of the microstructure of the cast metal showed that the structure is formed by equilibrium β-phase grains with dispersed inclusions in the grain body. Based on the particles morphology, it can be assumed that dispersed precipitations are α_2-phase, and lamellar precipitations are θ-phase crystals (orthogonal Ti_2AlNb phase).

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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