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INVESTIGATIONS OF THE QUALITY OF WROUGHT SEMI-FINISHED PRODUCTS FROM VT9 TITANIUM ALLOY PRODUCED BY ELECTRON BEAM MELTING

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ABSTRACT

Complex works were performed to study the quality of wrought semi-finished products, manufactured from an ingot of VT9 titanium alloy. Electron beam remelting technology was used to produce ingots of 600 mm diameter and 1.5 m length, from which semi-finished products were manufactured in the form of hot-pressed rods of 315 mm diameter. Results of investigations of structural and mechanical properties of semi-finished products in the form of hot-pressed rods are given. It is shown that the metal of the produced ingots and wrought semi-finished products after the respective heat treatment meets the requirements of the standards.

KEYWORDS: electron beam melting; high-strength titanium alloy; ingot; chemical composition; structure; deformation; mechanical properties

INTRODUCTION

High-strength VT9 titanium alloy of Ti–Al–Mo–Zr–Si alloying system was developed in the middle of the previous century, and it became widely accepted in batch production of parts of gas turbine engines (GTE), which operate for a long time at up to 450 °C temperature [1]. VT9 alloy is a two-phase (α+β)-alloy. High aluminium content and silicon alloying ensure its higher high-temperature properties, compared to the most widely accepted VT6 titanium alloy. VT6 titanium alloy is deformable, and it belongs to materials with a high heat and corrosion resistance. VT9 alloy is strengthened by heat treatment, namely hardening and aging. An optimum combination of mechanical properties is ensured by double annealing. It is used to make discs, blades and other GTE compressor parts [2, 3].

High requirements are made of service properties of critical parts, which are constantly increased and become more stringent. This largely applies also to the quality of initial materials [4]. Therefore, for extensive application of titanium alloys in different structures it is necessary to not only create new titanium-based materials with higher service properties, but also to improve manufacture of semi-finished products from these alloys further on. Note that any imperfections of chemical or structural homogeneity in titanium alloys lead to lowering of product strength and fatigue life. Producing titanium alloys involves difficulties, which are due to high sensitivity of titanium to interstitial impurities, particularly, oxygen, nitrogen, hydrogen, carbon, as well as interaction with many chemical elements, resulting in formation of solid solutions or chemical compounds. More over, one of the main structural imperfections of titanium alloys is presence of refractory nonmetallic inclusions. High activity of titanium leads to running of physicochemical processes of interaction with gases even in the solid state. Therefore, nonmetallic inclusions, in particular nitrides and oxides, can form both during ingot production, and at different stages of technological processing into finished products. Nonmetallic inclusions can be introduced into the finished product from charge materials during melting, as well as formed at thermodeformational treatment of metal. Titanium actively interacts not only with gases, but also with other elements, including alloying components of the alloys, so that local enrichment of individual volumes of the ingots by alloying elements can lead to formation of intermetallic inclusions, for instance, Ti_3Al, TiAl, $TiCr_2$, and oth. [5].

At present, not all the processes of manufacturing titanium alloy ingots allow producing sound metal,

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Figure 1. Ingot of VT9 alloy produced by EBM process

and violation of the technological process of producing titanium alloys results in appearance of defects in the ingots, which lower the metal quality. Electron beam melting (EBM) is the most effective process of vacuum metallurgy to produce alloys, also from refractory and reactive metals, with superlow content of gas, volatile impurities and nonmetallic inclusions. EBM allows controlling the melting rate in a wide range, owing to an independent heating source, that, in its turn, enables controlling the duration of metal staying in the liquid state. EBM is a technology that allows practically completely ensuring removal of high-melting inclusions of high- and low density. Thus, EBM allows improving the quality of titanium alloy ingots [6].

Most of the titanium alloys contain a large number of alloying elements that makes their production by electron beam melting somewhat more complicated. At melting ingots of high-strength titanium alloys by EBM there arises the problem of ensuring the specified chemical composition of the ingot, as melting in vacuum promotes selective evaporation of alloying elements with high vapour pressure [7]. In this case, such elements include aluminium, whereas concentration of elements in the ingot with vapour pressure lower than that of titanium, in this case Mo, Zr and Si, may even become somewhat higher. Calculations of the predicted chemical composition of the ingots were conducted proceeding from fundamental investigations of the processes of alloy component evaporation from the melt in vacuum earlier performed at PWI [6], and their results were used for correction of the billet charge components. The alloying component with a high vapour pressure, namely, aluminium, was added to the charge to compensate for evaporation losses. The charge billet for producing the ingots was formed in a nonconsumable box. Electron beam unit UE5810 was used to conduct the melting operations [6].

Work on producing an ingot of VT9 titanium alloy was performed and an ingot of a round cross-section of 600 mm diameter and 1500 mm length was manufactured (Figure 1). Ingots were produced by cold-hearth EBM technology with portioned feed of liquid metal into a water-cooled crucible.

The side surface of the produced ingots after cooling in vacuum to a temperature below 300 °C is clean without any concentration of impurity elements on the surface in the form of an oxidized or alphized layer. The depth of surface defects of “corrugation” type was 2–3 mm, defects in the form of ruptures, cracks or lacks-of-fusion were absent.

In order to assess the quality of metal of the produced ingots, chemical composition was studied in samples, cut out along the ingot length from the upper, middle or lower part. Results of analysis of the produced ingot metal composition showed that alloying element distribution along the ingot length is uniform, and their content corresponds to grade composition (Table 1).

Ultrasonic testing method was used to study the presence or absence of internal defects in titanium ingots in the form of nonmetallic inclusions, as well as pores. Investigations were performed by pulse-echo method with ultrasonic flaw detector UD4-76 at contact testing variant. When testing the ingots, multiple small-amplitude reflections were observed, that is typical for cast metal and is the result of signal reflection from grain boundaries (dendrites). No shrinkage cavities, porosity or isolated reflections which could be interpreted as large nonmetallic inclusions, were found in the ingot.

In order to determine the influence of electron beam melting technology on the quality of semi-finished products from high-strength titanium alloy hot-pressed rods of 300 mm diameter were manufactured from an earlier produced VT9 alloy ingot of 600 mm dia (see Figure 1).

Forging was performed by the technological procedure, which consisted of three stages.

First stage is heating of 600 mm ingot to 1180 °C temperature; billet soaking for 8 hours; forging on flat heads to form a 450×450 mm square.

Table 1. Distribution of alloying elements along the length of VT9 titanium alloy ingot, wt.%

Alloy grade	Ingot part	Al	Mo	Fe	Zr	Si	O	N
VT9	Upper	6.06	3.63	0.21	1.69	0.32	0.11	0.012
	Middle	6.13	3.68	0.14	1.64	Same		
	Lower	6.64	3.21	0.22	1.67	0.31		
OST1 90013–81 for VT-9 alloy		5.8–7.0	2.8–3.8	≤0.25	1.0–2.0	0.20–0.35	<0.15	<0.05

Second stage is heating of 450×450 mm blank to a temperature of 1100 °C; forging into a round rod of 360 mm diameter and its cutting into three parts.

Third stage is heating the billet of 360 mm diameter to 1100 °C temperature; billet forging through a square into a finished size of 315 mm diameter; and straightening.

The temperature of the end of forging was not lower than 850 °C. Three deformed rods were produced, and a 15 mm thick template was cut from each of them for further studies.

In order to study the quality of the produced semi-finished products from VT9 titanium alloy, comprehensive investigations were performed, which included the following operations: producing templates from wrought semi-finished products; heat-treatment of the templates; preparation of template surface; chemical etching of the templates; control of metal macrostructure; cutting up into samples; determination of polymorphous transformation temperature (T_{pt}), 20° C mechanical properties, long-term strength level at 500 °C; and microstructure control.

Heat treatment of the manufactured forgings and templates cut out of them was performed by the following mode:

● heating up to 950 °C temperature, soaking for 60 min, cooling in air;

● heating up to 550 °C temperature, soaking for 360 min, cooling in air.

After machining and etching of the template surfaces, their macrostructure was studied, and it was established that the macrostructure of the manufactured rod metal does not have any cracks, delaminations, voids, ant no metal or nonmetal inclusions were found.

For further studies samples were cut out of three templates by electric-spark cutting by a scheme given below (Figure 2) for determination of mechanical characteristics and temperature of polymorphous transformation of VT9 titanium alloy.

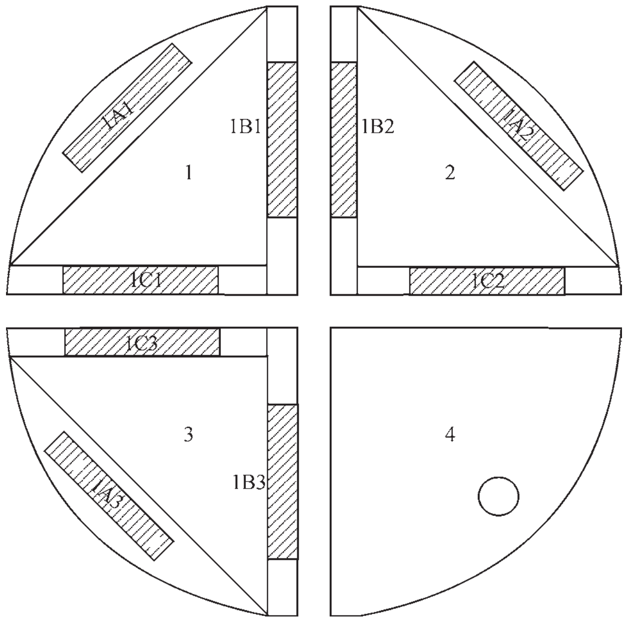

Figure 2. Scheme of cutting up a template into samples for further mechanical testing

The experimentally determined polymorphous transformation temperature (T_{pt}) for these samples of VT9 titanium alloy was 950 °C.

Mechanical properties were determined at temperatures of 20 and 500 °C after conducting the above-described heat treatment. Testing for compliance to standard requirements included tensile, impact toughness, hardness and long-term strength testing (Tables 2, 3).

These data lead to the conclusion that the majority of mechanical properties of semi-finished products from VT9 alloy, produced by EBM process, comply with standard requirements, but the ductility properties turned out to be lower than the standard ones. This may be related to the fact that the deformation temperature was in the region of β-phase existence and a completely platelike structure with a rather large size of the plates formed in the metal. It is known that the values of material ductility very strongly depend on the type of the structure and crystallite dimensions. Lowering of reduction in area with a platelike struc-

Table 2. Mechanical properties of samples of wrought semi-finished product from VT9 titanium alloy

Template number	Sample number	σ_t, MPa	δ, %	ψ, %	*KCU*, J/cm^2	Hardness, *HB*
1	1C1	1129	3.2	9.0	23	341
	1C2	1116	4.8	17.0	25	
	1C3	1120	4.0	12.0	20	
2	2C1	1142	4.8	14.5	23	331
	2C2	1139	Same	12.6	28	
	2C3	1127	3.2	11.8	Same	
3	3C1	1089	4.0	13.4	35	321
	3C2	1078	Same	18.5	Same	
	3C3	1101	6.0	20.6	30	
OST1.90107–73		932–1177	>6	>14	>29	269–363

Table 3. Long-term strength of samples of wrought semi-finished products from VT9 titanium alloy at 500 °C temperature

Template number	Sample number	σ, MPa	τ, h	Note
1	1A1	60	132	No fracture
	1A2		Same	Same
	1A3		96	With fracture
2	2A1	Same	126	No fracture
	2A2		137	Same
	2A3		113	»
3	3A1	»	96	With fracture
	3A2		126	No fracture
	3A3		137	Same
OST1.90107–73		»	≥100	–

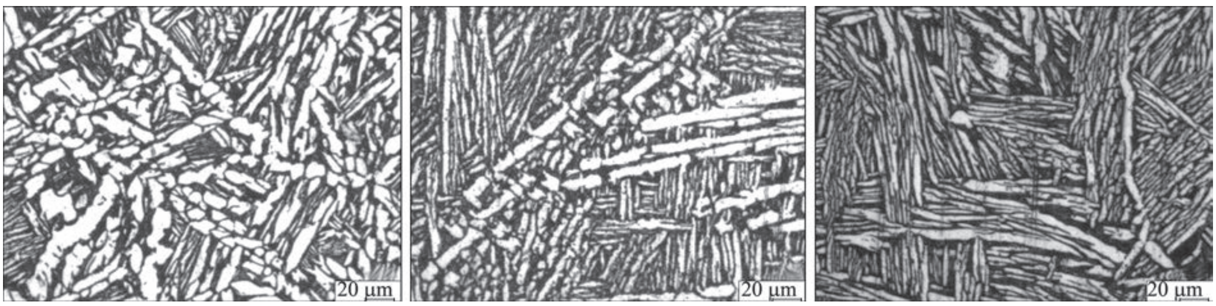

Figure 3. Microstructure of 315 mm dia rods, produced by deformation processing of 600 mm dia ingot from VT9 titanium alloy: *a* — 1; *b* — 2; *c* — 3

Table 4. Mechanical properties of samples of wrought semi-finished product from VT9 titanium alloy after additional heat treatment

Template number	Sample number	σ_t, MPa	δ, %	ψ, %	*KCU*, J/cm^2	Hardness, *HB*
1	1	1068	11	29	29	321
	2	1092	10	14	30	311
2	1	1092	7	16	29	321
	2	1067	10	42	30	Same
3	1	1078	11	29	33	»
	2	1118	14	32	32	»
OST1.90107–73		932–1177	>6	>14	>29	269–363

ture, compared to the globular one, can reach 70–80 wt.%, and relative elongation can be reduced by 40–50 % [8, 9]. Annealing temperature also was quite low — at the lower limit of polymorphous transformation.

Most of the samples of VT9 titanium alloy have passed long-term strength testing at 500 °C temperature and σ = 60 MPa without fracture; average testing time was 122 h.

Analysis of microstructure of the manufactured semi-finished products from VT9 titanium alloy in the form of hot-formed rods of 315 mm diameter showed that the microstructure of all the samples corresponds to type 4a–6a of the 9-type microstructure scale in Instruction No.1054-76 (Figure 3) [10].

Additional heat treatment of VT9 titanium alloy samples was conducted to improve the ductility characteristics. First heating temperature was increased to 980 °C, and the furnace soaking time of samples was extended up to 120 min. Conducted mechanical testing of the samples after additional heat treatment (Table 4) showed the complete compliance of mechanical characteristics of VT9 titanium alloy semi-finished products, manufactured by EBM, with standard requirements.

CONCLUSIONS

1. It is shown that ingots of VT9 titanium alloy, produced by the technology of cold-hearth electron beam melting, are characterized by high homogeneity both by their chemical composition, and by structure, and absence of defects in the form of pores or nonmetallic inclusions.

2. A technological procedure of thermodeformational treatment of 600 mm dia ingots from VT9 titanium alloy is proposed, which ensures producing 315 mm dia rods of a homogeneous structure.

3. Modes of heat treatment of 315 mm dia rods from VT9 titanium alloy were determined, which ensure complete correspondence of semi-finished

product mechanical characteristics to standard requirements.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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