Investigation of Effect of Electron Beam Surface Treatment of Titanium Alloy Ingots on Structure and Properties of Melted Metal

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Abstract. Based on accumulated experience of application of concentrated power sources for elimination of defects of ingot surface layer it is shown that remelting of surface layer of treated ingot provokes evaporation of alloying elements with high vapor pressure form a liquid pool, i.e. change of composition of treated layer in relation to ingot base. This can indicate the possible change of metal structure since it is determined by content of alloying elements.

Ingots of wrought titanium alloys VT3-1, VT-6, VT20, VT22 of 400 and 600 mm diameter and up to 2 m length made by EBM were melted by electron beam for investigation of effect of electron beam treatment of a surface layer on composition, structure and properties of metal of the treated layer. The investigations of mass concentration of alloying elements, penetration depth, macro and microstructure of melted metal layer of treated ingots were carried out.

The results of carried works showed that electron beam treatment allows efficient elimination of defects of the surface layer of titanium alloy ingots to 12 mm depth, content of alloying elements corresponds to grade composition, reduction is observed in content of alloying elements, in which vapor pressure is higher than in the alloy base, and respectively rise of content of alloying elements with vapor pressure is lower than in the alloy base. There is insignificant increase of content of interstitial impurities, i.e. oxygen and nitrogen, which do not have obvious effect on mechanical properties of treated metal. It is determined that macrostructure of metal in the treated layer of titanium alloy ingots is characterized with absence of pores and discontinuities, crystals close to equiaxial, the melted layer is formed by finer crystals in comparison with the rest part of the ingot, elongated in solidification direction, i.e. to ingot center. Solidification rates of more than 50 mm/min in the melted layer of titanium alloy ingots provoke two times refining of α-colonies and α-lamellas of ingot grains in comparison with the ingot base.

1. Introduction
Titanium is one of the most important of modern structural materials and in current industrial production the semi-finished products of titanium alloys take an important place [1, 2]. Titanium alloys having high indices of mechanical properties, high corrosion and high-temperature resistance are perspective structural materials, which have found application in aircraft, space [3, 4], marine engineering [5], power machine building, oil-and-gas and chemical branches [5-7].

Titanium is alloyed with aluminum, vanadium, chromium, molybdenum and some other elements in order to get set mechanical properties. Addition of alloying elements in predetermined combinations and amounts allows varying the properties titanium alloys in the wide limits [8-9]. Sufficiently wide interval of complex of mechanical properties based on titanium permits selecting the alloys, which in the best way satisfy the technical requirements for this specific application. Comparatively small density in combination with sufficiently high strength characteristics provides higher specific strength in a wide temperature range to titanium alloys in comparison with aluminum alloys, steels and high-temperature nickel alloys [8]. This circumstance has a decisive role, determining preference of application of titanium alloys, and reduction of prime cost of titanium alloy ingots as initial part for manufacture of semi-finished products simultaneously with rise of their quality is a relevant problem.

Today vacuum arc and electron beam melting as well as plasma-arc remelting are sufficiently effectively used in production of titanium alloys. Electron beam melting (EBM) is the most efficient method of vacuum
metallurgy for manufacture of alloys including refractory and high-reactive, with ultra-low content of gases, volatile additives and non-metallic inclusions [10, 11]. However, a series of reasons caused by metallurgical and technological peculiarities in process of ingot melting can provoke on their surface the defects in form of corrugations, cracks and longitudinal band due to metal pouring (see Figure 1). It is virtually impossible to eliminate such type of defects at current level of production, and this in turn complicates further hot treatment of ingots and billets resulting in hot cracking.

The required quality of ingots and billets surface using the traditional technology is reached by means of removal of surface layer by machining. It is necessary to note that mechanical treatment provokes local metal heating in the place of contact with a cutter and, naturally, chips oxidation. High requirements to cleanness of initial charge materials imposes a series of limitations of secondary used chips for ingot manufacture, that in turn leads to irretrievable losses of metal up to 20-35% depending on ingot size [12, 13].

Treatment of surfaces of ingots and billets with concentrated power sources from point of view of material saving and reduction of technological operations is an effective solution for this problem. Up to the moment there is a huge experience of application of concentrated power sources, namely electron beam and plasma arc for elimination of defects of ingot surface layer [14-16]. The peculiarity of methods of treatment of ingot surface based on application of concentrated power sources is the fact that remelting of surface layer of the treated ingot takes place in vacuum or gas-shielded medium that results in evaporation of alloying elements with high pressure vapor from a liquid pool, i.e. change of composition of the treated layer in relation to ingot base. This can indicate possible change of metal structure since it is determined by content of alloying elements.

At modern stage of development of production an important conditions of its improvement is development of high-performance methods and means for modeling and control of produced parts. Large attention is given to application of modern methods of mathematical and computer modeling, which have become a powerful tool for investigation and understanding of the processes taking place in a liquid metal pool [17-19]. At the present time the models were developed for prediction of depth of the melted layer and its composition.

Taking into account mentioned above the researches on investigation of metal quality of the treated layer of titanium alloy ingots using concentrated power sources are of large interest. The positive results of such works allow reducing the metal loss in form of off-standard wastes (chips) and precious alloying elements.

2. **Aim of the work**

Aim of the present work lies in investigation of effect of electron beam treatment of the surface layer of titanium alloys VT3-1, VT6, VT20, VT22 ingots on metal quality of treated layer, i.e. its composition, structure and properties.

3. **Materials and procedure of investigation**

The ingots of wrought titanium alloys VT3-1, VT6, VT20 and VT22 of 400 and 600 mm diameter and up to 2 m length produced by EBM (see Figure 2) were melted for investigation of effect of electron beam treatment of the surface layer on composition, structure and properties of metal of the treated layer. These alloys have sufficiently high content of base alloying element for titanium alloys, namely Al, which in turn has high vapor pressure that results in its evaporation from the treated metal. There are also different classes of phase
composition, i.e. VT3-1, VT-6 α+β, VT22 - α+β, on composition close to critical, VT20 – pseudo-α that allows deeper investigation of effect of change of the treated metal composition on its structure.

Figure 2. Ingot of VT6 titanium alloy before EBT

EBT (electron beam treatment) process of the ingots was carried out using a technological scheme, at which electron beam is fixed and ingot is rotated around its axis (see Figure 3).

Figure 3. Scheme of electron beam treatment of titanium alloy ingot: 1 – electron beam gun; 2 – ingot; 3 – ingot rotating mechanism rolls

The surface of produced ingots was subjected to electron beam treatment in UE-185 unit with linear melting rate 54 mm/min and specific power of heating 6-7 W/mm² (see Figure 4).

Figure 4. Process of ingot melting

Investigation of penetration depth and structure of metal of the melted layer of titanium alloy ingots were carried out on transverse templates cut out of the treated ingots and for investigation of change of metal composition of the melted layer before and after treatment the probes were taken in form of chips and cut-off samples from the treated layer on ingot length.
Content of chemical elements was determined by atomic absorption method on GOST 19863.1-91 on Saturn-1 device. Content of oxygen and nitrogen was determined using a method of melting of analyzed trial sample in vacuum in a graphite crucible, heating of which was carried out by passing of current of 900-1000 A power, on devices of RO-316, TN-114, RH-3 type of LECO Company (USA).

Metallographic examinations of the samples were performed on optical microscope Neophot-32. The value of grain was determined using a procedure described in “VIAM Instruction No. 1054-76”. Microstructure of the samples was examined after detection in the standard chemical agents of HF:HNO₃:H₂O=(1:1:3). The dimensions of structure elements were determined on a procedure developed for titanium alloys [20]. For this the analyzed structures were compared with the reference ones for evaluation of value of α-colonies and for determination of thickness of α-lamellas at corresponding magnification.

The microhardness tests were carried out by indentation method on GOST 9450-76.

4. Investigation results

The experimental evaluation of penetration depth of the surface layer of ingots was performed on transverse templates and made 9-12 mm (see Figure 5). A side surface of ingots after treatment with electron beam acquires a flat microrelief, has smooth mirror-like appearance without obvious defects appearing in process of melting in the surface layer (see Figure 6). Roughness of the surface lied in the Rz20 - Rz80 range at waviness of surface equal to 0.2 – 0.6 mm.

![Figure 5](image1.png)

**Figure 5.** Penetration depth of surface layer: a - VT3-1, b - VT6, c - VT22

![Figure 6](image2.png)

**Figure 6.** Appearance of side surface of ingot of VT20 titanium alloy melted with electron beam
The results of investigation of mass concentration of the alloying elements in the melted metal layer of ingots showed that their content corresponds to grade composition, decrease of content of aluminum and chromium, in which vapor pressure is higher than in the alloy base, and rise of content of vanadium, molybdenum and niobium with vapor pressure lower than in the alloy base (see Table 1) are respectively observed. It is also determined that there is insignificant rise of content of detrimental impurities, namely oxygen and nitrogen, at that values of their mass concentration are within the limits of standards’ requirements.

| Alloy  | Sampling place | Al  | V   | Zr  | Cr  | Mo | O  | N   |
|--------|----------------|-----|-----|-----|-----|----|----|-----|
| VT6    | GOST 19807-91  | 5.3–6.8 | 3.5–5.3 | ≤ 0.3 | -  | -  | -  | ≤ 0.20 | ≤ 0.05 |
|        | Initial        | 6.21 | 3.77 | -   | -   | -  | -  | 0.050 | 0.026 |
|        | After EBT      | 5.98 | 3.89 | -   | -   | -  | -  | 0.075 | 0.030 |
| VT3-1  | GOST 19807-91  | 5.5–7.0 | -   | ≤ 0.5 | 0.8–2.0 | 2.0–3.0 | ≤ 0.15 | ≤ 0.05 |
|        | Initial        | 6.21 | -   | -   | 1.26 | 2.64 | 0.014 | 0.013 |
|        | After EBT      | 5.64 | -   | -   | 1.13 | 2.60 | 0.032 | 0.021 |
| VT20   | GOST 19807-91  | 5.5–7.0 | 0.8–2.3 | 1.4–2.5 | -  | 0.5–1.8 | ≤ 0.15 | ≤ 0.05 |
|        | Initial        | 6.9  | 2.05 | 1.81 | -   | 1.57 | 0.066 | 0.011 |
|        | After EBT      | 6.48 | 2.14 | 1.78 | -   | 1.63 | 0.078 | 0.019 |
| VT22   | GOST 19807-91  | 4.4–5.7 | 4.0–5.5 | ≤ 0.3 | 0.5–1.5 | 4.0–5.5 | ≤ 0.18 | ≤ 0.05 |
|        | Initial        | 5.24 | 4.73 | -   | 1.45 | 4.04 | 0.050 | 0.010 |
|        | After EBT      | 5.05 | 4.95 | -   | 1.14 | 4.26 | 0.059 | 0.012 |

Metallographic analysis of metal of the melted ingots was carried out for detection of structural changes taking place in metal as a result of thermal effect of electron beam on a side surface and ingot base.

Metallographic examinations were carried out on the samples taken from the transverse templates, which were cut of the ingot. Metal macrostructure is characterized with absence of pores and discontinuities, crystals close to equiaxial, the melted layer is formed by more dense crystals in comparison with the rest part of the ingot, elongated in solidification direction, i.e. to the ingot center. Grain size determined on ten-point scale of macrostructures of VIAM Instruction No. 1054-76, corresponds to size Nos. 6-7 in the melted layer and size Nos. 8-9 in the heat affected zone and base metal.

Analysis of microstructure of VT6 alloy ingots, melted with electron beam, showed that the microstructure of base sample, cut of the ingot, is characterized with initial grains of β-phase, fringed on the boundaries with fine α - “fringe”. The internal volume of the grains consists of the packages of α-lamellas divided with β-phase interlayers. Electron beam melting of the side surface of ingot surface resulted in re-solidification of alloy structure of the ingot melted layer to 12 mm depth. Microstructure of the melted layer is typical for cast metal and has finer structure in comparison with the ingot base that in turn stipulates higher solidification rates of melted layer (see Figure 7).
The sample cut of the ingot of pseudo α-alloy VT20 consists of equiaxial polyedric primary β-grains with lamellar α-phase inside the grain, accumulated in the colonies. Value of the α-colonies in different grains of ingot base metal is somewhat different, since their average size varies from 200 to 300 μm, the average thickness of lamellas of α-phase at that makes around 5 μm. The metal of treated surface layer consists of the colonies of α-phase lamellas, the average size of which varies in 100 – 200 μm limits at α-lamellae thickness 5 μm. i.e. after melting there is refining of the α-colonies at stable thickness of α-phase lamellas. The α-fringe (see Figure 8) is often observed on the boundaries of grains of ingot metal and surface layer.

![Figure 8. Microstructure of VT20 alloy ingot: a – base, b - melted layer](image)

Microstructure of the samples of α+β-alloy of martensite type VT3-1 is presented on Figure 9. Grains of metal of VT3-1 alloy ingot consist of the colonies of lamellar α-phase of preferable size around 300 μm, thickness of α-lamellae makes 5-7.5 μm. β-phase is located between α-lamellae. The α-fringe is observed on the boundaries of some β-grains. There is refining of size of the α-colonies as well as α-lamellae in the treated surface layer after melting. The average size of the α-colonies varies in 100 -200 μm limits and average thickness of α-lamellae makes 5 μm.

![Figure 9. Microstructure of VT3-1 alloy ingot: a – base, b - melted layer](image)

Microstructure of metal of VT22 alloy ingot is presented on Figure 10. In the ingot of VT22 alloy the α-colonies of around 100 μm size, α-lamella thickness makes 2 -3 μm, are located in the β-grain volume. The boundaries of grains are often decorated with the α-fringe, along the boundaries there is precipitation of parallel α-lamellae almost normal to boundary line. β - phase is located in the gaps between the α-phase lamellas, besides, metal structure of VT22 alloy ingot contains locally fixed light areas of β-phase without lamellar α-precipitations or α-phase is at the stage of pre-precipitation. The metal structure of the surface layer after
melting is also consists of equiaxial β-grains, however, their size in the spots is less than in the ingot depth. Size of α-colonies and thickness of α-phase lamellas in the surface layers after melting make 50 µm. The boundaries of β-grains in the surface layer also have α-fringe, there are areas of undecayed β-phase.

Figure 10. Microstructure of VT22 alloy ingot: a – base, b - melted layer

Carried analysis of the microstructure sample of the melted layer and ingots base showed that solidification rates of more than 50 mm/min provoke in the melted layer of titanium alloy ingots two times refining of the α-colonies and α-lamellas of ingot grains in comparison with ingot base.

Therefore, electron beam melting of the surface of titanium alloy ingot allows eliminating the defects of the surface layers of titanium alloy ingots up to 12 mm depth providing at that typical for the cast metal structure, finer in comparison with the alloy base.

Examination of distribution of microhardness in the zones of transverse template (see Figure 11) was carried out for evaluation of effect of electron beam treatment on mechanical properties of metal of VT3-1 ingot melted layer. Obtained results show that in the melted layer it is insignificantly lower than in the base metal.

Figure 11. Distribution of microhardness on depth of deposited layer for VT3-1 titanium alloy ingot

From our point of view this is explained by decrease of aluminum content at EBT, which stabilizes and strengths the α-phase in the alloy as well as increase of content of molybdenum, which results in rise of amount of more lamellar β-phase in the alloy. This results also demonstrate that rise of amount of detrimental impurities (oxygen and nitrogen) determined in experimental way does not have negative effect on the
properties of metal of the melted layer. Decrease of microhardness of the melted layer at pressure treatment reduces the tendency to cracking. Thus, electron beam treatment allows effective elimination of the defects of surface layer of titanium alloy ingots at up to 12 mm depth without application of mechanical treatment and get at that high quality of metal of the surface layer with uniform defect-free structure typical for cast metal of finer structure relatively to ingot base.

5. Conclusions
The results of investigation of mass concentration of alloying elements in the metal of melted layer of titanium alloy ingots show that their content corresponds to grade composition, decrease of content of alloying elements, in which vapor pressure is higher than in the alloy base, and, respectively, rise of alloying elements with vapor pressure lower than in the alloy base are observed, insignificant rise of content of detrimental impurities, i.e. oxygen and nitrogen, but at that values of their mass concentration are in the limits of standards requirements.

It was determined based on the results of metallographic examinations that macrostructure of metal in the treated layer of titanium alloy ingots is characterized with absence of pores and discontinuities, crystals close to equiaxial, melted layer is formed by finer crystals in comparison with the rest part of the ingot, elongated in the solidification direction, i.e. to the ingot center.

It is found that at solidification rate more than 50 mm/min there is two times refining of the α-colonies and α-lamellas of ingot grains in the melted layer of titanium alloy ingots in comparison with the ingot base.

The results of investigation of distribution of microhardness on zones of the transverse template show that change of content of alloying elements and insignificant rise of oxygen and nitrogen in the melted layer does not have considerable effect on mechanical properties of the treated metal.

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