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# DETERMINING THE TECHNOLOGICAL PARAMETERS OF ELECTRON-BEAM WELDING OF HIGH-STRENGTH TITANIUM ALLOYS

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***It is usually quite difficult to carry out deep penetration of thick-walled products from titanium alloys using conventional welding technologies. In this study, it was proposed to use electron beam welding under high vacuum conditions for the realization of 40 mm thick melting of VT23, VT3-1 alloys.***

***This paper considers the possibility of obtaining high-quality welded joints from high-strength titanium alloys having (α+β) two-phase structures. For the implementation of research works, samples were made from selected materials, samples were welded according to the specified modes, metallographic analysis was performed, and the level of mechanical properties was determined. The research results were verified under laboratory conditions.***

***The technological features of the processes of electron-beam welding of products with a thickness of 40 mm were considered; the parameters affecting the weldability of titanium alloys and their structure were determined. The welded samples were checked by X-ray non-destructive testing, the microstructure of the welds was studied, and the physical and mechanical properties of the welded joints were checked. It was established that a feature of titanium alloys VT3-1, VT23 is the need for heat treatment after welding under the base metal regimes to improve the characteristics of the welded joint. The resulting strength limit of the alloys after heat treatment reached values of 1250 MPa and more, while the impact toughness was at the level of 48–50 J·cm$^{-2}$.***

***Modeling the welding process has made it possible to ensure the reproducibility of the characteristics of the welded joint at a level close to that of the base metal, to increase the quality indicators of welded joints, and to reduce the time required to test the technology. The studies of simulator samples showed compliance of the quality of welded joints with the predefined parameters***

***Keywords: high-strength titanium alloys, electron beam welding, technological parameters, macrostructure***

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## 1. Introduction

The evolution of the rocket and space industry requires constant improvement of the quality of responsible products (reduction of production costs and increase of the service life), which are obtained by applying various technologies, methods, and types of welding. Special attention is paid to the welding of critically important products, high-load power units of aircraft and rocket engines, elements of turbopumping units, and parts of power plants.

The quality of the seam is determined by a set of technological and energy parameters of the fusion welding process. Stability of the operational parameters of the welded joint is provided for by maintaining at the required level of energy parameters of the welding process under unchanged technological conditions, geometric dimensions, structural properties, strength, and other indicators. However, the possibility of forming a unique "dagger" shape penetration with minimal dimensions of the weld pool conflicts with the achievement of stable operational parameters of the welded joint. Violation of specified welding modes most often leads to the appearance of defects in seams, even on well-welded materials. They are found in any fusion welding technique: under-welding, undercuts, sagging of the weld seam, as well as increased metal spattering [1, 2].

The technology of manufacturing thick-walled units from titanium alloys has a number of significant technical and economic disadvantages that enhance with increasing dimensions. One of the ways to improve technical and economic indicators can be the use of welding. Dividing the structure of nodes into several parts with subsequent welding makes it possible to significantly reduce the dimensions and cross-section of the workpieces, increase the stability of their properties, and reduce allowances.

The main task that must be solved when designing the technology of welding thick-walled structures from high-strength titanium alloys is to ensure the stability of product quality. When designing welded structures for a responsible purpose, quality indicators are usually specified on the drawings in the form of direct instructions or technical requirements: absence of defects, level of mechanical properties, shape and dimensions of the seam. Therefore, quality indicators are the principal data when designing welding technology. One of the main stages in the development of the technological process, which depends on the stability of the quality of welded structures, is the design of the parameters for the welding mode and the dimensions of the weld. Usually, the welding modes defined in the reference literature require experimental work-out, which requires significant costs for material and technical means. After determining the welding modes and preliminary testing on simulator samples, the compliance of the quality indicators with the specified characteristics is checked. In the case of non-compliance, welding modes, filler materials, and other welding approaches are refined. The increase in costs for quality assurance during testing of the welding technology of new products is associated with a low level of experimental testing of processes.

One promising type of welding is the use of an electron beam, which provides a very high energy density, which is a significant advantage when welding thick parts. Nevertheless, in the welding process, unique root defects are observed when welding with full penetration of thick-walled structures. Because of this, determining the causes and devising methods for preventing the formation of defects and ensuring the stability of the quality of welded joints are of scientific interest. Most researchers from the USA and China conducted studies on welding titanium alloys up to 20 mm thick. During the development of new components of aviation and rocket-space technology, there was a need to weld parts of considerable thickness, and their properties should be higher than before.

Therefore, the urgent task is to determine the parameters of the welding mode, which will ensure the reproducibility of the characteristics of the welded joint according to the specified parameters. Solving this problem could improve the quality of responsible products and the stability of welded joints of thick-walled structures for the needs of the aerospace industry.

## 2. Literature review and problem statement

Paper [3] described promising techniques of welding high-strength titanium alloys with (*a*+ ) two-phase structures. Based on the analysis of available research, it was concluded that almost all welding techniques are used for welding titanium alloys. However, laser welding is indicated as one of the most promising techniques for the aerospace industry; it should be noted that the studies were conducted for parts with a thickness of up to 16 mm. The main advantage of this welding technique is the use of low vacuum (100 Pa), which allows welding titanium alloys. This is due to the scattering of the laser beam in the air under atmospheric conditions.

An overview of the results of research into processes associated with electron beam welding with a high concentration of electron beam power, with the aim of using them for the repair of gas turbine engines, is given in work [4]. Heat treatment of the samples was carried out using a vacuum oven and heating to a temperature of 700 °C. The applied procedure was chosen from the practice of industrial repair of aircraft engines. Disadvantages of this procedure include the considerable time it takes to move the workpieces from the electron beam installation to the vacuum furnace with large dimensions. The use of new approaches could make it possible to reduce the time of processing products.

In order to avoid pores in the weld, the authors of [5, 6] suggest using a sharp beam focus to form a narrower weld. This procedure can be used only for parts with a thickness of 20 mm since an increase in thickness would lead to the formation of defects in the root of the seam. In order to melt thick-walled products and prevent the formation of defects, in some works [7] it is proposed to apply edge processing for parts with a thickness of 30 mm or more. The defects in the root of the seam that are formed are the result of the displacement of the electron beam from the joint. To prevent such incomplete penetration, it is necessary to carefully adjust the beam to the joint. The revealed undercuts on the side of the weld are characteristic of the welding mode with a refocused beam. On real structures, where there is an allowance, undercuts can be eliminated by machining.

Increasing the welding speed with a significant thickness of parts will also lead to significant vaporization and spattering of the metal in the welding zone. Works [8, 9] show that the mechanical properties of the weld metal are heterogeneous at different depths. This affects the quality of the welded joints and is explained by the non-uniform cooling rate of the welded joints.

The microstructure and geometric characteristics of the welds have a decisive influence on the mechanical properties that are related to the welding process. Works [10, 11] proposed an approach to solving problems related to structural and phase transformations occurring in titanium alloys during welding, and their relationship with welding speed. The main problem is that titanium has a high chemical activity, due to which the molten weld metal interacts with the oxygen, nitrogen, and hydrogen of the air. Interaction with gases leads to an increase in strength and a sharp decrease in plasticity and impact strength of welded joints. However, this is not the only disadvantage of welds made of high-strength titanium alloys. At high temperatures (300–500 °C), titanium has a tendency to increase the grain and change the microstructure, which also leads to an increase in the fragility of the weld. But at the same time, the cited works provide results where the welding speed does not affect the change in microstructure and mechanical properties.

In [12–15], the effect of filler material on the properties of a weld made by the electron beam welding method was studied. An analysis of the microstructure and microhardness of the weld metal and the thermally affected zone was carried out. It has been established that during welding by traditional techniques, there are difficulties in protecting the weld pool from interaction with the atmosphere, and heat treatment, in turn, can lead to a decrease in some physical and mechanical parameters. To improve the mechanical properties, the authors suggest using low beam energy and filler material. When studying the microstructural characteristics of welded joints, a sharp transition from the equiaxed microstructure of rolled and annealed plates to structures with noticeable needles, found both in the weld metal and in the heat-affected zone, was revealed. The microstructure of the heat-affected zone in the welds was the same, even if they were made with different filler materials. This fact is related to the use of a procedure with a very similar cooling rate.

Our review of the literature tackling the development of technologies for welding thick-walled products allowed us to identify some specific features characteristic of these industrial technologies. So, for welding high-strength titanium alloys, it is not always possible to apply standard methods for determining the parameters of the welding mode. To overcome this problem, a detailed consideration of the processes of obtaining integral welded joints of large-sized parts is necessary. Most of the studies were conducted without the use of computer simulation and product design methods, which greatly complicated the determination of welding modes and increased the costs of working out the modes. Therefore, it is necessary to consider the possibility of improving the existing technologies of electron beam welding and to devise new approaches to welding processes that could ensure the mechanical characteristics of welded joints at the level of the base metal. Research data can become the basis for industrial use.

## 3. The aim and objectives of the study

The purpose of this work is to ensure the required level of mechanical properties of welded structures made of high-strength titanium alloys with a thickness of 40 mm, based on the results of theoretical modeling and experimental substantiation of the weld formation processes. The improved technology will make it possible to weld large-sized thick-walled structures made of high-strength titanium alloys with a thickness of more than 40 mm in one pass using filler material to improve physical and mechanical characteristics.

In order to achieve the specified goal, the following tasks were set and solved in this paper:

– to determine the EBW regimes of body parts made of titanium alloys;

– to devise and implement recommendations for the technological processes of obtaining body parts from high-strength titanium alloys used in rocket and space technology and aircraft construction.

## 4. The study materials and methods

The object of our research is welded joints made of high-strength titanium alloys VT23, VT3-1. The samples were made in the form of rings by mechanical processing.

Samples were welded according to specified welding modes; metallographic analysis was performed, and the level of mechanical properties was determined at normal and elevated temperatures. An analysis of the fracture surface of the samples after mechanical tests was carried out and the reliability of the experimental results was assessed. The research results were verified under laboratory conditions.

For the numerical analysis, the thermophysical characteristics of pure titanium under normal conditions were taken without considering their temperature dependence.

Experimental verification was carried out on samples from the VT23 alloy under the condition that each cross-section of the heat-affected zone can be considered as a material after exposure to different tempering and annealing temperatures. The samples were heated to temperatures of 1300, 1000, 900, 800, 700 °C in an electron beam unit, imitating the thermal effect of the welding process, and then some of these samples were reheated to temperatures of 900, 800, 700, 600, 500 °C, as for electron beam annealing. Next, some samples were subjected to heat hardening under the mode used for the base metal.

Modes of electron beam welding: accelerating voltage, $U$=27 kV; welding current, $I$=410 mA; welding speed, $V$=3·10$^{-3}$ m·s$^{-1}$.

Testing of welding modes was carried out on technological rings made of VT23, VT3-1 alloys with a diameter of 400 mm, a thickness of 40 m, and a width of 40 mm, on a U530M installation with a U250A energy source (E. O. Paton IEZ of the National Academy of Sciences of Ukraine).

EBW of the samples was carried out under two welding modes:

– with normal beam focusing (focus on the surface of parts to be welded);

– with refocusing of the beam (focus over the surface of the welded parts).

The main task of predicting the quality of the weld is to estimate the probability of one of the indicators of the formation of the weld (for example, the width of the weld) exceeding the permissible value for this connection. For these and many other purposes, related to the reduction of labor intensity of technological preparation of production and improvement of the technology of various types of welding, computer software products and software packages MATLAB, ANSYS, Abaqus, and Comsol are widely used.

Modeling of the EBW process of titanium alloy samples (Fig. 1) was carried out using ANSYS and Abaqus software suites.

All welding processes are characterized by linear energy consumed per unit length of the weld. Linear energy (J) is calculated by the formula:

$$E=\frac{I\cdot U}{V}, \tag{1}$$

where $U$ – welding voltage (V);

$I$ – welding current (A);

$V$ – welding speed (m·s$^{-1}$).

For many welding techniques, there is a relationship between the linear energy and the dimensions of the penetration region. For EBW, it was experimentally established that the linear energy $E$ is not a determining parameter during the quantitative assessment of the seam dimensions. With a constant linear energy, it is possible to obtain a penetration depth in various ranges from 1 to 20 mm, which is due to the formation of a "dagger" penetration during EBW not only by the amount of input energy but also by its density.

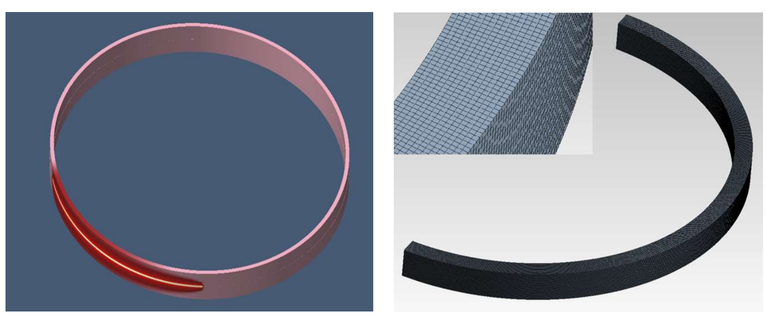
The power of the electron beam $q$ (W) at a given beam diameter $d$ (m), required to obtain a seam with a width of $B_e$ (m) and a depth of $H$ (m) at a welding speed of $V$ (m·s$^{-1}$), is determined by the formula:

$$q=\frac{\pi\cdot H\cdot S\cdot B_e^2\cdot V}{4\cdot d\cdot \eta}, \tag{2}$$

where η is the ratio of the energy localized in the contact zone to the energy introduced into the part;

$S$ is the heat content in the part material (J).

For EBW, η=0.2...0.48 is accepted.



*a* *b*

Fig. 1. Estimated finite-element model: *a* – distribution of weld temperature fields; *b* – construction of a mesh of finite elements

The following methods were used in the study of welded joints made of high-strength alloys:

– metallographic method. The obtained samples were cut along the axis into segments. On the side of the cross-section, the micro sections were prepared for metallographic studies. A 10-point scale of macrostructures for titanium alloys was used as standards. To study the macrostructure of the joints, successive grinding of the surface of the samples was carried out. To identify the structure of the base metal and welded joints, chemical etching was used, which makes it possible to clearly identify the structural components of the titanium alloy and trace the kinetics of the formation of the welded joint. Analysis of the microstructure of the base metal and welded joints was carried out both by visual inspection of the micro sections and by using a MIM-8 microscope (USSR) at a magnification from ×500 to ×1500;

– microhardness measurement methods. In the process of research, the microhardness of the base material was also determined in various areas of the welds. Microhardness was measured on a PMT-3 device (USSR) according to DSTU ISO 6507–1:2007. To compare the values of the hardness of the base metal, welds, and the heat-affected zone directly on the indicated device, the obtained microhardness values of HV were converted into HRC. To measure the microhardness of the base metal and the thermally affected zone, transverse micro sections were made that were subjected to mechanical polishing. The magnification of the microscope was from 500 to 1500 times. At least 10 prints of a four-sided diamond pyramid (the angle between the faces is 136°) were placed on each sample;

– mechanical tensile and impact strength tests were performed on samples manufactured according to DSTU EN ISO 4136:2014 on the INSTRON-8862 machine (Great Britain);

– radiographic analysis was performed according to DSTU B A.1.1–8–94. The characteristics of the phases and their composition in the studied samples were investigated using X-ray structural analysis on a DRON-3 diffractometer (USSR). X-ray structural analysis involved determining the dimensions of the unit cell of α- and β-phase crystals by analyzing the geometry of the location of the diffraction maxima.

## 5. Results of studying the mechanisms of formation of the weld seam of high-strength titanium alloys

### 5. 1. Determination of electron beam welding modes of titanium alloy body parts

According to the results of the obtained values of impact toughness of different states of the thermally affected zone, it was established that after EBW near the fusion line of the weld with the base metal, the impact toughness is the lowest and is 31 J·cm$^{-2}$. In the more distant zones from the fusion line, which were heated to lower temperatures, the average value of the impact toughness corresponds to the values for the main heat-strengthened material of 48–50 J·cm$^{-2}$ (Table 1).

As a result of the analysis of experimental data, it was found that the dimensions of the zone of thermal influence obtained as a result of calculations do not exceed the dimensions obtained during the analysis of the macrostructure of welded joints of live samples, according to which the zone of thermal influence is 1÷1.5 mm (Fig. 2). The distribution of temperature fields shown in Fig. 2, *a* allows us to predict the cooling rate and heating zones from the electron beam. On parts of a complex shape, the zone of thermal influence is clearly visible.

Table 1

Mechanical properties of welded joints made of high-strength titanium alloys

| Type of welding | Tensile strength $\sigma_t$, MPa | Impact strength, J·cm$^{-2}$ |
|---|---|---|
| EBW with filler material | 1250 | 48–50 |
| EBW without filler material | 1220 | 25–35 |

Based on the results of welding process modeling, it was determined that the fusion line of the weld with the base metal is at a distance of 0.4 mm from the axis of the weld and is a deviation of 11.5 % from the experimental data. This may be due to the fact that the efficiency factor of EBW is not taken into account. It was found that the annealing of welded joints made of the VT23 alloy at a temperature of 850 °C for 1.5 hours increases the impact strength of the welds to the level of the base metal.

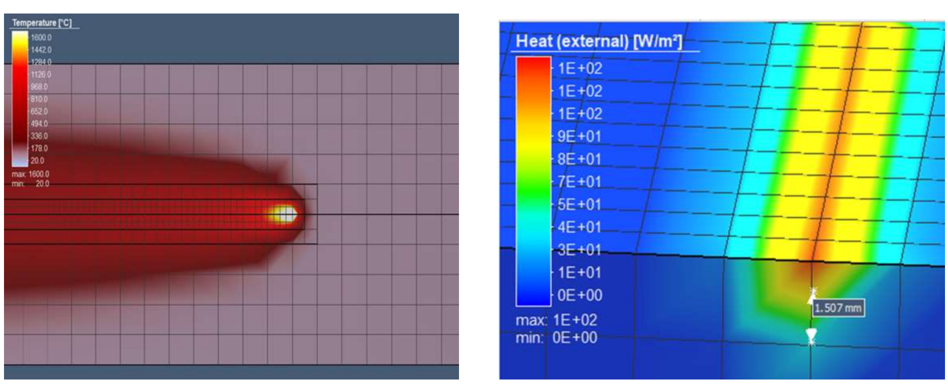
As a result of modeling welding processes, the technological modes of welding large-sized parts made of VT23 alloy with a thickness of 40 mm were determined. Modeling of welding processes has made it possible to determine the distribution of temperature fields of the weld seam and establish that they correspond with minor deviations within 10–15 % to the value obtained during experimental testing.

Based on the results of modeling and experimental testing of welding modes, it can be assumed that the obtained welding modes are quite correct and meet engineering calculations. This is confirmed by the produced high-quality welds with physical and mechanical characteristics at the level of the base metal. The determined EBW modes of welded joints made of the VT23 alloy are given in Table 2.

Table 2

Modes of electron beam welding of joints made of VT23 alloy with a thickness of 40 mm

| Regime | Accelerating voltage *U*, kV | Beam current *I*, mA | Focus current *I*, mA | Welding speed *V*, m/g |
|---|---|---|---|---|
| 1 | 27 | 400 | 70 | 20 |
| 2 | 27 | 379 | 70 | 18 |




*a* *b*

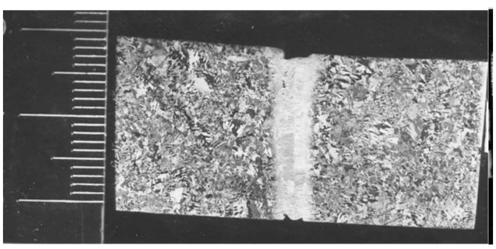
Fig. 2. Distribution of temperature fields: *a* — during electron beam welding of VT23 alloy samples; *b* — zone of thermal influence in the cross section

It was established that the defined technological parameters of EBW can be successfully used to calculate the characteristics of welds when welding products that have a thickness of more than 40 mm and are quite difficult to process by traditional methods of argon arc welding. The use of conventional welding techniques is possible only if the edges are slotted and the filler wire is used.

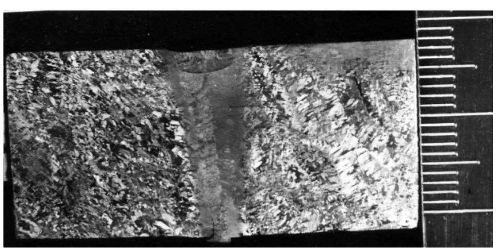
The study of the resulting welded joints (Fig. 3) revealed significant disadvantages of using the welding mode with normal beam focusing without slit processing of the edges. The seam, made with normal focusing, is wedge-shaped (Fig. 3, *b*), a slight narrowing is observed at the root of the seam, and an even gap up to 3 mm high is formed at the top of the seam.

When welding under a refocused mode, the weld metal is formed at the level of the base metal, in some places uneven undercuts with a depth of up to 0.5 mm are observed at the root of the seam (Fig. 3, *a*).

Welded seams made regardless of the welding option with normal beam focusing or refocused electron beam, after welding have a coarse-grained structure with liquation heterogeneity, which is manifested in uneven etching of the seam. Inside the grains, there is a relief of the α' phase of the martensitic type with separate allocations of the α phase at the grain boundaries. Welds after heat hardening have a similar structure (Fig. 4).



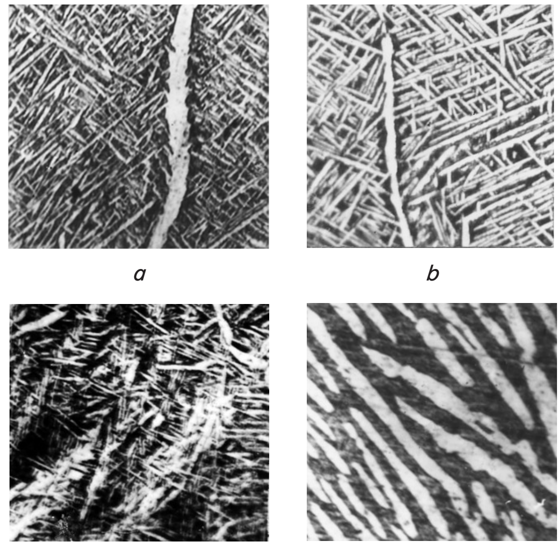
*a*



*b*

Fig. 3. Macro sections of welded joints: *a* — electron beam welding with refocusing of the beam; *b* — electron beam welding with normal beam focusing

As a result of the analysis of our research, it can be concluded that the welding mode with a refocused beam makes it possible to obtain welded joints with physical and mechanical characteristics at the level of the base metal. This technique makes it possible to obtain a rectangular seam, which ensures the melting of the walls along the entire depth and guarantees the exclusion of incomplete penetration at the root of the seam. A significant advantage is also the fact that the welding current within ±10 mA does not disrupt the stability of the seam formation, which is confirmed by experimental testing on simulator samples.



*a* *b*

*c* *d*

Fig. 4. Mode of heat treatment of hardening and aging ×500: *a* — seam without filler material; *b* — seam with filler material; *c* — zone of thermal influence; *d* — base metal

**5. 2. Recommendations for technological processes of electron beam welding of high-strength alloys VT23, VT3-1**

There are two known techniques of alloying welds during EBW of thick-walled structures made of high-strength titanium alloys, which are used in practice to increase the strength limit to an average of 1100–1200 MPa. In the first technique of welding, sheet alloyed titanium inserts are inserted into the butt of the welded edges; in the second, the welded edges are pre-welded with a highly alloyed filler material of the SP-15 type (GOST 27265-87) followed by EBW treatment. These techniques of welding thick-walled structures are not satisfactory because they require an increase in contact surfaces, which in turn leads to the formation of defects in the form of pores, additional equipment costs, and increased labor intensity.

It is proposed to provide for the following when designing and manufacturing welded structures:

– EBW of thick-walled structures should be performed with filler wire for narrow-gap edge processing;

– to catch the assembled elements of the welded structure with a sharply focused beam inside the slot processing;

– to perform EBW in one pass; to feed filler wire during EBW along the upper edges of slot processing;

– for a structure with a thickness of more than 30 mm, it is advisable (to stabilize the process due to changing the filler material feed rate) to perform edge processing to a depth of 10 mm with a width of 1.5–2 mm, and to conduct electron beam welding with the supply of two or more filler wires.

After performing the main weld, annealing with an electron beam should be conducted (repeating the main weld with a narrower seam). The width of the annealing seam should be 1–1.5 mm less than the main seam. Such a decrease in the width of the seam can be provided by a sharp focus of the beam or a decrease in the welding speed.

## 6. Discussion of results of studying the welding processes of high-strength titanium alloys

The studies reported in the current work show the possibility of improving the quality of welded joints from two-phase titanium alloys VT23, VT3-1. At the same time, technological modes of welding were determined by calculation methods, which make it possible to predict the energy characteristics during the manufacture and repair of responsible thick-walled products. The use of computer simulation of welding processes reduced the time for working out welding modes (Fig. 2).

It was determined that the level of mechanical properties of welded joints, obtained by EBW with filler material, on average exceed the mechanical properties of those without filler material by 10 % (Table 2).

Our research results showed that with an increase in the diameter of the heating beam, the loss of alloying elements increases sharply due to the increase in the area of evaporation. As a result of the experiments, it was established that with an increase in the welding speed, the loss of alloying components decreases.

The reason for the appearance of defects in the root of the seam during welding with normal focusing is an incorrectly selected ratio of current and welding speed (Fig. 3, *b*). The disadvantage of this mode is that as a result of the narrowing of the weld in its lower part, incomplete penetration may form, hidden from visual detection and during X-ray control, due to the sticking of the edges. The reason for these cases of incomplete penetration is the displacement of the beam from the joint during the welding process or its inaccurate setting.

The cause of undercuts during refocused mode welding is a fairly high concentration of beam power at the exit from the metal, which causes intense spattering. At the top of the seam, undercutting and local undercuts are observed, which are easily eliminated by an additional pass (Fig. 3, *a*). Failure to weld at the root of the seam is a consequence of the displacement of the electron beam from the joint. In order to prevent under-welding at the root of the seam, careful adjustment of the beam on the joint and its control is necessary. Detected undercuts on the side of the incomplete penetration are characteristic of the welding mode with a refocused beam. Defects formed at the root of the seam were eliminated by mechanical processing. This mode is the most promising, especially when welding with edge processing and the use of additives, since the seam has a rectangular shape. The width of the weld at the top and the width of the penetration are almost the same, which ensures the melting of the walls along the entire depth and guarantees the exclusion of non-welds at the root of the seam.

A significant advantage of welding with a refocused beam is that a change in the welding current does not disturb the stability of the seam formation. At the same time, the characteristics of the electron beam can vary in wide ranges, which makes it possible to adjust the process of heating and cooling the product. Performing heat treatment directly in the electron-beam installation could reduce the time of production of large-sized products from high-strength titanium alloys obtained by the EBW method, eliminating breaks between welding and heat treatment, transportation and vacuuming time.

In the course of experimental work, it was established that the properties of titanium alloys depend on the content of alloying impurities, while the weld metal differs in its parameters from the base metal. A change in grain size can be observed (Fig. 4). The strength limit decreases, and the ductility of the welded joint increases. The resistance of the weld metal to aggressive environments also changes. It is also stated that evaporation is the cause of significant changes in the shape and size of the melting zone. Evaporation of impurities affects the shape of the melt not only due to the change in pressure. A significant change in concentration leads to a change in material properties.

During testing of the welding modes, it was established that the maximum penetration depth is achieved when the focal beam plane is located in the middle of the penetration depth. Some deviations of the focal plane can be explained by the difficulty of accurately determining the position of the focus under the conditions of electron beam welding, in particular, it is technically very difficult to estimate the degree of ion focusing of the beam of the steam-gas channel.

Analysis of the structure of welded joints reveals that there are no dependences associated with changes in the properties of welds and their structure. The structure of seams made by EBW with filler material ensures high mechanical properties: strength limit, 1250 MPa; impact toughness, 48–50 $J \cdot cm^{-2}$.

The structure of welds made by EBW and heat-treated under different regimes has a significant difference in mechanical properties. It is possible that the effect of a change in properties is related to a change in the phase composition of the metal, which depends on the degree of alloying.

Increasing the welding speed makes it possible to obtain high-quality welded joints with reinforcement at the top of the seam (Fig. 3). This is due to the fact that a high cooling rate is provided, thereby preventing the flow of metal from the side of the root of the weld. At the same time, an increase in the welding speed is achieved by increasing the power of the electron beam. This leads to the fact that the metal of the seam and the heat-affected zone is heated to higher temperatures, which does not always have a positive effect on the structure and mechanical properties of the welded joint (Fig. 4).

It was established that the welding process is complicated by the problem of changing deformations during the welding process from the beginning of the beam introduction to the moment of closing the seam. In order to solve this problem, in the technological process, it is necessary to carry out the clamping of the parts, and then their full welding.

As a result of research, it was established that computer simulation of welding processes makes it possible to determine technological regimes that ensure the stability of the quality of welded joints. Modeling of the EBW process is used to reduce the number of defects on already existing parts and shortens the time for developing the technology for new parts and nodes of responsible purpose. The only limitation is the time-consuming calculations of welding processes, especially for thick-walled structures. Calculations require significant computing resources (dozens of hours on a computer with a Xeon E5-2690 processor).

In the future, it is necessary to consider the processes occurring in the steam-gas channel and to investigate the possibility of controlling electron-beam welding processes. This analysis will make it possible to modernize existing equipment and improve the quality of welds. One of the main conditions for the successful development of EBW technology is the reliable and stable operation of the equipment.

## 7. Conclusions

1. Technological modes of welding were defined, in which the seam is formed without concavity at the top and reduces the formation of defects in the root of the seam, which is due to the possibility of predicting the required geometric parameters and energy characteristics.

The quality of samples obtained according to the specified parameters of electron beam welding meets the requirements for responsible products made of high-strength titanium alloys. The improvement of welding technology and the use of computer simulation methods made it possible to reduce the time for experimental work-out and reduce material costs. Welding of titanium alloys VT23, VT3-1 with a thickness of 40 mm was successfully implemented using electron beam welding, the optimal balance of strength and impact toughness was achieved by heat treatment of welded joints. During tear tests of welded samples, the fracture occurs, as a rule, either along the seam or along the base metal away from the thermally affected zone. It can be assumed that the zone of thermal influence due to its small size does not significantly affect the operational characteristics of welded joints.

2. Based on our results of welding of simulator samples, technological recommendations were devised for the production of large-sized body parts from high-strength titanium alloys with a thickness of 40 mm. Heat treatment for thick-walled products made of high-strength titanium alloys is most expedient to be carried out with an electron beam with a certain configuration of temperature fields, which will ensure the necessary structure, phase and chemical composition of the welded joint. Increasing the impact strength of welded joints to the level of the base metal is possible thanks to the joint use of filler materials and heat treatment. The execution of crevice processing of the edges is a necessary condition for obtaining a high-quality welded joint of a large thickness. The use of our recommendations could make it possible to improve the quality of welded structures from the VT23, VT3-1 alloy and to obtain the strength limit of the weld up to 1250 MPa.

## Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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## Data availability

The data will be provided upon reasonable request.

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