Effect of Electron-Beam Welding Speed on Weld Metal Mechanical Properties of 5V Titanium Alloy

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Abstract. The results of metallographic studies of 5V titanium alloy welds obtained with the range of electron-beam welding speeds from 20 to 120 m/h are presented. It was established that at all welding speeds some identical microstructure of a weld metal is formed, which can differ only in sizes and shapes of the primary crystals. The results of Vickers hardness, ultimate tensile stress and yield stress estimation by sample-free indentation methods are shown. The weld metal hardness distribution in the transverse direction is homogeneous while from the top to the root an increase in hardness values at all welding speed modes is occurred. It was also revealed that both the hardness and strength of the weld metal grow with the rising welding speed, herewith the increase in these properties in the top of the weld is more significant than in the root. According to the analysis of the interrelation between structure and mechanical properties it was concluded that the main reason of mechanical properties fluctuations is a change in the weld metal chemical composition as a result of the volatile components evaporation during welding.

1. Introduction
A 5V titanium alloy is applied in welded units of steam-turbine plants due to a successful combination of operational and heat resistance properties [1, 2]. The number of researches [3–8] has been devoted to solve technological challenges as well as improving performance and quality of titanium alloy weld joints. Based on these studies, it is necessary to use high-quality blanks and develop welding technologies taking into account design features to achieve homogeneous defect-free weld joints.

According to the tensile tests results of titanium alloys weld joints [8], a part of them obtained by electron beam welding (EBW) always break down in the parent metal while specimens made by argon arc welding (AAW) are broken along weld joints or heat treatment zones (HAZ). The values of ultimate tensile stress (UTS) in such cases are not lower than the minimum ones for the parent metal. In addition, the use of EBW for making weld joints of large thickness causes minimum welding deformations because of a small weld width. Vacuum as a protective atmosphere also allows to attain high quality of weld metals. Under these conditions, the EBW can be considered as the most preferable method for 5V titanium alloy welding.

Typically, the welding modes parameters selection is carried out primarily on the basis of technological requirements and minimizing the probability of defect occurrence [4–6, 9–11]. For example, the welding speed has a significant effect on hot cracks formation [12, 13], on weld shape formation (for the full penetration welding) [6, 10, 11, 14], on the probability of specific structures formation in welds [15] and pores occurrence [16]. On the other hand, the welding speed has an
impact on the welding thermal cycle, so it determines the structure and chemical composition of the weld. In particular, a welding speed growth leads to a change in the crystallization conditions and a decrease in both the crystals size and the loss of alloys volatile components [14, 17, 18].

At the same time, for some alloys it is possible to get structures without any initial defects using a wide range of welding speeds. Choosing the welding speed it is more rational to be based on providing the best mechanical properties for the metal under study. In [19–21], the results of researches concerning welding conditions parameters effect on welded joints mechanical properties are presented. However, in the scientific and technical literature there is a lack of information regarding the effect of EBW speed on the mechanical properties of the 5V titanium alloy weld metal. For instance, in [22] the data relating to the hardness distribution in weld joints of 5V alloy are given. Also in [14] the results of investigation of 5V titanium alloy welds obtained at welding speeds of 20 m/h, 60 m/h and 120 m/h are performed. It was established that the mechanical properties of the weld metal increase with the welding speed rising. However, a number of experiments were insufficient to determine this conclusion reliably. In addition, it is important to understand the reasons for such phenomenon and to establish the interrelation between mechanical properties and structure parameters.

Thus, the main aim of this study is to establish a quantitative dependence of the weld metal mechanical properties on the EBW speed taking into account the microstructure parameters of a 5V titanium alloy.

2. Research methods

The studies were performed on 5V titanium alloy welded joints obtained by EBW without full penetration. Welding modes are presented in Table 1. The thickness of the welded plates was 32 mm. The chemical composition and mechanical properties according to the quality certificates are shown in tables 2 and 3.

### Table 1. The EBW modes.

| Accelerating voltage | Welding speed | Beam current | Penetration depth | Mean width |
|----------------------|---------------|--------------|-------------------|------------|
| $U$, kV              | $v$, m/h      | $I$, mA      | $H$, mm           | $B$, mm    |
| 60                   | 20            | 100          | 29.4              | 2.68       |
|                      | 40            | 135          | 26.8              | 2.16       |
|                      | 60            | 170          | 28.1              | 1.79       |
|                      | 90            | 215          | 26.4              | 1.63       |
|                      | 120           | 250          | 27.7              | 1.43       |

### Table 2. The chemical composition of 5V titanium alloy.

| Elements | Ti | Al | V | Mo | Zr | Cr | Si | Fe | Mn | O | N | C | Others |
|----------|----|----|---|----|----|----|----|----|----|---|---|---|---------|
| Base     | 4.8| 1.45| 1.05| 0.08| 0.05| 0.04| 0.1| 0.05| 0.06| 0.01| 0.07| 0.14 |        |

### Table 3. The mechanical properties of 5V titanium alloy.

| Ultimate tensile stress $R_U$, MPa | Yield stress $R_{0.2}$ MPa | Total elongation $\delta$, % | Total cross section reduction $\psi$, % | Impact strength $KCU$, kJ/m$^2$ |
|------------------------------------|-----------------------------|------------------------------|------------------------------------------|-------------------------------|
| 880                                | 860                         | 9                            | 22                                       | 540                           |

Four microsections were made from each weld joint. The first microsection was used to study the microstructure, the second one to define the microhardness and the other two to determine the UTS and yield stress (YS) using the indentation method.
These microsections were prepared according to the generally accepted methodology: stepwise grinding on abrasive silicon carbide paper with a grain size from P180 to P1000, then polishing using a diamond suspension with particle sizes of 9 μm and 1 μm and final polishing using a colloidal suspension with the size of oxides silicon of 0.06 microns on synthetic velvet. The first microsection was etched during 5–10 seconds in a reagent of the composition: hydrofluoric acid - 5 ml, nitric acid - 5 ml, water - 90 ml to reveal the microstructure.

The microstructure was investigated by an Observer Z1m Carl Zeiss optical microscope. Grain sizes were determined at a magnification of x100 in accordance with Russian State Standard GOST 5639 using the method of grains counting.

The weld metal hardness was defined by the Vickers method on an Instron Tukon 2500 hardness tester under the load of 5 kg (49.05 N). For each weld joint microsection the indents were made with a constant step, in 3 lines over the entire height of the weld. The scheme of measuring hardness using the second microsection is represented in figure 1.

The UTS \( R_u \) and YS \( R_{0.2} \) were determined by the equations:

\[
R_{0.2} = k_{0.2} \cdot HB_{0.2} \tag{1}
\]

\[
R_u = k_u \cdot HB_{\text{max}} \tag{2}
\]

where \( k_U, k_{0.2} \) - correlation coefficients, \( HB_{\text{max}}, HB_{0.2} \) - ultimate hardness and hardness at yield stress, MPa.

![Figure 1. The weld joint hardness measurements scheme.](image)

The procedure of determining the specific characteristics of hardness \( (HB_{\text{max}}, HB_{0.2}) \) is regulated by Russian State Standards GOST 22761 and GOST 22762. However, the correlation coefficients presented in these Standards are given only for carbon and low alloy steels. Therefore, in this study the predefined experimental coefficients for 5V alloy \( k_U = 0.323 \) and \( k_{0.2} = 0.427 \) were applied.

3. Results

The weld metal microstructure at all welding modes is martensite (\( \alpha' \)-phase). The boundaries of the primary crystals are thin and clear (figure 2). The weld metal has a specific columnar structure with crystals growing from fused grains of the base metal to the weld joint centre in the direction opposite to the heat sink. Moreover, the grains in the central part are almost equiaxed since the heat removed through the weld pool rear wall and these crystals grew in the direction of welding. With an increase in the welding speed, such crystals became longer while a number of equiaxed crystals decreased due to the formation of elongated weld pool and prevailing heat dissipation through the side walls.

It is worth noting that the size of the primary crystals in the weld top is significantly larger than in the rest part of the weld. Such phenomenon can be explained by a lower cooling rate and a greater weld width which is quite typical for weld joints made by EBW. According to figure 2, the primary grains size corresponds to No. 3 according to GOST 5639 scale in all cases. The main difference
consists in the form of crystals. At low speeds the grains are equiaxed (figure 2a), while at high speeds the crystals are elongated (figure 2c). In the weld top the size of the primary grains differs considerably.

![Image](figure2.png)

**Figure 2.** The microstructure of the central part of weld metal obtained at the welding speed of 20 m/h (a), 60 m/h (b) and 120 m/h (c), x200.

The grain number gradually decreases from 3 to 0 with a welding speed increasing that can be explained by considerably different crystallization conditions. Figure 3 shows the dependence of the mean grain size in the central part of the weld and in the weld top on the welding speed.

![Image](figure3.png)

**Figure 3.** The dependence of the mean grain size \(d_m\) on the EBW speed.

Figure 4 shows the relation between the mechanical properties of the weld metal (hardness, UTS and YS) and welding speed. The UTS was determined in the top and central part of the weld, YS was defined only in the central part of the weld. The mean hardness was established by making 70-75 indents in each weld joint, while for the UTS and YS it was required to conduct 3...5 indents.

UTS in the weld top rises by 10% with an increase of the EBW speed from 20 m/h to 120 m/h whereas in the central part of the weld a growth does not exceed 5%. It should also be noted that with an increase in the EBW speed from 20 m/h to 120 m/h the gap between the UTS values in the weld top and weld central part decreases gradually from 7% to 2%. The difference between the weld metal YS and UTS values is quite small which is typical for the 5V titanium alloy and remains constant for all welding speeds.
Figure 4. The impact of EBW speed on the weld metal mechanical properties.

Hardness test results show that the hardness of the weld metal in the transverse direction is constant. Namely, the hardness values in adjacent columns (figure 1) differ by less than 1% in all specimens. Moreover, there is a clear decrease in hardness in the weld top compared with the rest part of the weld. In figure 5 the distribution of hardness along the weld depth is presented.

Figure 5. The distribution of hardness along the weld depth obtained for different welding speeds.

The distribution of hardness along the weld height shows that hardness in the root is almost identical at all modes and fluctuates from 340 to 350 HV5 the hardness begins to decline smoothly closer to the weld top at welding speeds of 40–120 m/h. At the EBW speed of 20 m/h a rapid hardness fall to 310 HV5 at a depth of 11–14 mm occurs. At the same time, it should be taken into account that the primary boundaries of such large crystals are unlikely to make a great contribution to the martensitic structure.

4. Discussion of the results
The analysis of mechanical properties and weld structure results does not allow to establish a constant patterns. Two main factors – structure and chemical composition – influence on weld metal mechanical properties. The structure of the weld metal is equal for all welding modes, only a slight difference in the sizes and shapes of the primary crystals is observed. The largest difference in the
primary crystals sizes is noticed in the weld top. Therefore, the mechanical properties in the weld top differ from the rest part of the weld significantly.

In order to set the effect of grain-boundary hardening on the weld metal hardness, the relation between hardness and the number of primary grains under the indent was made. Even in the central and root parts of the weld joints the size of the primary grains is large and commensurate with the indents which were carried out by Vickers hardness tests under the load of 5 kg (49.05 N). The study of the area around the indents showed that the indenter interacted with 1–9 primary crystals or on average with 2–4 ones. In this case, the processing of the results represented that the hardness does not depend on the number of grains under the indent. Thus, the difference in the size of the primary grains cannot be the main reason of weld metal mechanical properties variation.

It should be viewed that during EBW the chemical composition of the weld metal could change due to the evaporation of volatile components.

The aluminium contained in the 5V titanium alloy has the highest saturation vapor pressure among the other components at the melting temperature of titanium. Thus, substantial evaporation of aluminium can affect the weld metal mechanical properties adversely. Moreover, the longer the metal is in a liquid state, the more significant the chemical composition changes. It is obvious that the metal stays in the liquid state longer at lower welding speeds. According to this, aluminium content becomes less and hence the strength properties decrease too. The experimental results fully confirm this assumption.

5. Conclusion
The weld metal microstructure is identical at all welding speeds, some differences were observed only in the sizes and shapes of the primary crystals. The largest difference in the primary crystals sizes was noticed in the top of the weld, while the mean grain size was almost the same in the weld central part and in the root.

With an increase in the EBW speed from 20 m/h to 120 m/h, the UTS rose from 880 MPa to 960 MPa in the weld top and from 940 MPa to 980 MPa in the central part. The YS grew from 900 MPa to 940 MPa.

The hardness of weld joints varied in height significantly. The lower the welding speed, the higher the difference in mechanical properties. Thus, at a speed of 20 m/h the hardness from the root to the top of the weld declined from 340 to 310 HV5 and at 120 m/h from 350 to 340 HV5.

Apparently, the main reason for weld metal poor mechanical properties at low welding speeds was the intense evaporation of aluminium and a decrease in its concentration in the weld metal. Finally, to obtain high and uniform mechanical properties over the entire height of the weld, it is preferable to use rather high welding speeds.

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**Acknowledgements**
This study conducted by Moscow Power Engineering Institute was financially supported by the Ministry of Science and Higher Education of the Russian Federation (project No. FSWF-2020-0023).