Influence of the welding parameters on the weld metal mechanical heterogeneity of EP517 (Fe12Cr2NiMoWVNb) steel and 36NKhTYu (Fe36Ni12Cr3TiAl) alloy dissimilar welded joints

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Abstract. The article presents the results of assessing the effect of the welding speed and the displacement of the electron beam relative to the joint on the mechanical heterogeneity of the weld metal of dissimilar welded joints of EP517 (Fe12Cr2NiMoWVNb) steel and 36NKhTYu (Fe36Ni12Cr3TiAl) alloy. Aging curves are plotted for the weld metal of welded joints made at electron beam welding (EBW) speeds of 30 m/h and 120 m/h, as well as for the weld metal of the welded joint made at a speed of 30 m/h with various electron beam displacements. An assessment of the change in the mechanical heterogeneity of the weld metal was carried out by the change in the standard deviation of the hardness values, and metallographic studies were also carried out. It was found that a decrease in the EBW speed leads to a decrease in the standard deviation of the results of measuring the hardness of the weld metal after aging from 45 to 14 HV5 or from 18% to 6%. It was also found that an increase in the displacement of the electron beam to alloy 36NKhTYu (Fe36Ni12Cr3TiAl) to 60% leads to an increase in the hardness of the weld metal from 225 to 305 HV5 (by 35%).

1. Introduction

Reduced mechanical properties of dissimilar welded joints are an urgent problem of modern mechanical engineering due to the difficulty of achieving their homogeneity associated with a strong difference in the chemical composition and physical properties of the metals being welded. Most researchers consider the mechanical heterogeneity of a dissimilar welded joint in terms of properties in its various zones, such as heat-affected zones (HAZ), weld metal and diffusion layers, while assuming that the structure and chemical composition of the weld metal are relatively homogeneous [1-5]. In welded joints of dissimilar materials, the weld metal can often have an inhomogeneous chemical composition due to the short residence time in the liquid state, which leads to uneven mixing of the alloys being welded [6]. This can lead to an increase in internal stresses due to different coefficients of linear expansion and phase transformations, as well as to the segregation of harmful impurities. Uneven distribution of internal stresses in the weld metal can affect the mechanical properties of the welded joint and the appearance of defects during welding or operation [7-10]. This problem is especially relevant when the weld metal has a lower strength compared to the alloys being welded.
In structures with soft weld metals, an increase in the strength of welded joints is possible due to a decrease in the weld width \[4, 12\] to \[15\], however, uneven internal stresses can significantly limit this possibility. For example, in \[14, 16, 17\], the possibility of increasing the strength of dissimilar welded joints of EP517 steel with 36NKhTYu alloy (Table 1) by reducing the weld width and optimizing the heat treatment modes is shown, however, when selecting the electron beam welding (EBW) modes, the problem of high mechanical heterogeneity of the weld metal was not taken into account. At the same time, the significant influence of the EBW speed on the process of mutual dissolution of the materials to be welded is obvious.

### Table 1. Chemical composition of materials

| Metal grade | Element, % (wt.) |
|-------------|------------------|
|             | C    | Si   | Mn  | Cr   | Mo   | Ni   | V    | P    | S    | W    | N    | Nb   | Ti   | Al   |
| EP517       | 0,13-0,18 | ≤0,5 | ≤0,5 | 11,0-12,5 | 1,35-1,65 | 1,7-2,1 | 0,18-0,3 | ≤0,03 | ≤0,015 | 0,65-1,0 | 0,02-0,2 | - | - |
| 36NKhTYu    | <0,05 | 0,3-0,7 | 0,8-1,2 | 11,5-13 | - | 35-37 | - | ≤0,02 | ≤0,02 | - | - | 2,7-3,2 | 0,9-1,2 |

Increasing the hardness of the weld metal of dissimilar welded joints is possible due to a change in the chemical composition of the weld metal, for example, due to the displacement of the beam relative to the joint \[18, 19\]. In the literature, insufficient attention has been paid to the influence of the displacement of the electron beam relative to the joint on the distribution of mechanical properties in dissimilar welded joints of EP517 steel with alloy 36NKhTYu, although it is obvious that with an increase in the displacement beam to alloy 36NKhTYu, the concentration of elements that form strengthening phases during aging increases. Thus, the purpose of this work is to study the possibility of reducing the mechanical heterogeneity of welded joints of EP517 steel and 36NKhTYu alloy by changing the displacement of the electron beam relative to the joint and welding speed.

### 2. Research methodology

Flat samples welded by EBW at speeds of 30 and 120 m/h were used to determine the effect of the welding speed on the mechanical heterogeneity of the weld metal. The thickness of the plates was about 11 mm, welding was carried out "at the joint" without using an additive material. The EBW was carried out on the AELTK-344-12 unit with the welding parameters shown in Table 2. The choice was of parameters was carried out taking into account the desire to obtain a joint with guaranteed through penetration and parallelism of walls.

### Table 2. EBW parameters

| Welding speed, m/h | Accelerating voltage, kV | Beam current, mA | Focusing lens current, mA | Working distance, mm |
|-------------------|--------------------------|------------------|--------------------------|---------------------|
| 30                | 60                       | 70               | 832                      | 208                 |
| 120               |                          | 140              | 858                      | 150                 |

The displacement of the electron beam relative to the joint was performed at the EBW speed of 30 m/h to assess its effect on the mechanical properties. The beam displacement relative to the joint during welding was varied from 0 at the beginning of the weld to 0,1 mm at the end of the weld.

The heat treatment by aging was carried out at a heating temperature of 650 °C and a holding time of 1 hour to 32 hours in a Nabertherm muffle furnace with controller P330. After each exposure, the samples were air-cooled and the surface was ground on sandpaper with P320 grain. The weld boundary detection surface was then etched electrochemically in 10% oxalic acid aqueous solution. Measurements of hardness were taken on the Wolpert Wilson Instruments 432SVD hardness gage by the Vikkers method with loading 5 kgf and endurance under loading of 10 seconds for aging plotting, and with loading of 1 kgf and endurance under loading of 5 seconds – for creation of distribution of
hardness. At least 10 measurements were made at each joint to construct aging curves. The content of chemical elements determination in weld metal was carried out using an atomic emission spectrometer with laser excitation LAES Matrix.

Research micro and macrostructures of weld metals were carried out on a microscope of Zeiss Observer Z1m. Preparation of microslips for the structure study was carried out according to the conventional method. The cut fragments of the welded samples were pressed into the compound on a hot press machine. Then the samples were ground and polished using diamond paste and polishing suspensions. Electrochemical etching was also carried out in a 10% aqueous solution of oxalic acid.

3. Results and discussion

Figure 1 shows aging curves for weld metal obtained at different EBW speeds.

![Aging curves of weld metal](image)

Figure 1. Aging curves of the weld metal of welded joints made at speeds of 30 m/h and 120 m/h

As can be seen from the figure, the welding speed does not significantly affect the average hardness of the weld metal both before and after the aging heat treatment. At the same time, the standard deviation comparison shows significant differences both after welding and after aging (Table 3). For qualitative evaluation of mechanical heterogeneity, table 3 shows the change in standard deviation (STD) of measured hardness values with an increase in holding time.

| Aging time, h | Welding speed, m/h | 30 | 120 |
|---------------|-------------------|----|-----|
|               |                   | HV [HV_{min}, HV_{max}] | STD | HV [HV_{min}, HV_{max}] | STD |
| 0             |                   | 178.4 [175.4, 181.3]   | 2.73 | 174.3 [161.8, 222.1]   | 16.45 |
| 1             |                   | 200.6 [187.0, 212.4]   | 9.07 | 223.2 [177.4, 300.7]   | 41.91 |
| 24            |                   | 258.5 [237.0, 291.8]   | 21.84 | -               | -         |
| 32            |                   | 263.0 [243.7, 279.9]   | 13.70 | 253.2 [188.7, 319.9]   | 45.39 |

The largest standard deviation of 45 HV5 (~ 18% of the average hardness) is the weld metal made at a welding speed of 120 m/h after aging for 32 hours, while at an EBW speed of 30 m/h, the standard deviation is 14 HV5 (~ 6%). Obviously, the decrease in the welding speed results in a decrease in the mechanical heterogeneity of the weld metal, which may be due to the longer residence time of the weld bath in the liquid state and the better mutual dissolution of the heterogeneous alloys. Figures 2 and 3 show photographs of the microstructure of welded joints obtained at speeds of 30 m/h and 120 m/h.
Figure 2. Panoramas of welded joints made at a welding speed: (a) 30 m/h; (b) 120 m/h, 50x

Figure 3. Microstructure of welded joints made with welding speed: (a, c) 30 m/h; (b, d) 120 m/h at the apex (a, b) and central part (c, d), 100x
Figure 3(b) shows untouched areas with a martensitic structure, which may indicate the preferential participation of steel EP517 in the formation of these areas during the formation of the weld. The same areas are observed in Figure 3(d).

Figure 4 shows the weld metal aging curves of welded joints obtained at a speed of 30 m/h with various electron beam displacement relative to the joint, and Table 4 shows the average hardness and standard deviation.

Figure 4. Aging curves of the weld metal for various sections of the welded joint made at a speed of 30 m/h

Table 4. Average values of hardness and their standard deviations of the weld metal of welded joints obtained at a speed of 30 m/h with various electron beam displacement relative to the joint

| Aging time, h | Beginning of the weld | Middle of the weld | End of the weld |
|---------------|------------------------|--------------------|-----------------|
|               | HV5, kgf/mm²           | STD                | HV5, kgf/mm²    | STD                | HV5, kgf/mm²    | STD                |
| 0             | 176.0                  | 6.27               | 178.4           | 2.73               | 170.8           | 4.25               |
| 1             | 225.5                  | 9.44               | 200.6           | 9.07               | -                | -                  |
| 24            | 315.7                  | 14.55              | 258.5           | 21.84              | 231.2           | 6.56               |
| 32            | 314.0                  | 9.73               | 263.0           | 13.70              | 230.7           | 8.98               |

The displacement of the electron beam in welding towards the 36NKhTYu naturally leads to an increase in hardness, which is associated with an increase in the content of elements such as Al and Ti, which form reinforcing phases in the seam during aging (Table 5). It should be noted that the change in the electron beam displacement does not significantly affect the mechanical inhomogeneity of the weld metal. Figure 7 shows the microstructure of the weld metal for two samples of welded joints with different displacement of the electron beam, from which it can be seen that the displacement of the electron beam during welding towards the alloy 36NKhTYu leads to an increase in the number of reinforcing phases (dark areas in the figure).

Table 5. The content of chemical elements in the weld metal for beginning and end of the welded joint

| Section of the welded joint | Cr, % (wt.) | Ni, % (wt.) | Ti, % (wt.) | Al, % (wt.) |
|-----------------------------|-------------|-------------|-------------|-------------|
| Beginning                   | 12.46       | 22.43       | 1.96        | 0.74        |
| End                         | 12.51       | 19.28       | 1.48        | 0.52        |
Figure 5. Macrostructure of the weld metal of a welded joint made at a welding speed of 30 m/h for the beginning (a) and the end (b) of the welded joint.

Figure 6 shows the hardness distribution in the weld joint for two different electron beam displacement before and after heat treatment by aging. There is a sharp increase in hardness in the HAZ from the EP517 side after welding, which is associated with martensitic transformation as a result of rapid cooling. The hardness distribution before heat treatment is similar for both welds. However, after aging at the electron beam displacement to the alloy 36NKhTYu about 60% (displacement of the electron beam relative to the joint by 0.1 mm in the direction of the alloy 36NKhTYu), the hardness of the weld metal is not lower than the hardness of the steel EP517, while at an equal displacement of electron beam there is a clear decrease in the hardness of the weld metal relative to the hardness of the welded metals. It is worth noting that after aging, the hardness of the HAZ from the 36NKhTYu side increases to the hardness of the base metal, while the one hundred side of the steel EP517 hardness also decreases to the level of the base metal as a result of the decay of the quenching structures.
Figure 6. Distribution of Vickers hardness HV1 over the cross-sections of welded joints with different electron beam displacement after welding and after heat treatment at the beginning (a) and end (b)

Thus, obtaining an equal-strength welded joint of 36NKhTYu alloy with EP517 steel is possible due to an increase in the electron beam displacement to 36NKhTYu alloy. However, in this case, technological problems may arise associated with the appearance of lack of penetration at the root, especially when welding large thicknesses. Therefore, when welding large thicknesses, it is more rational to use the effect of contact hardening to obtain welded joints of equal strength, and when welding small thicknesses, it is more rational to regulate the chemical composition by displacing the electron beam relative to the joint.

4. Conclusions
A decrease in the EBW speed when welding dissimilar materials leads to a decrease in the chemical, structural and mechanical heterogeneity of the weld metal. A decrease in the welding speed from 120 m/h to 30 m/h at EBW of alloy 36NKhTYu with EP517 steel leads to a decrease in the standard deviation of the results of measuring the hardness of the weld metal after aging from 45 to 14 HV5 or from 18% to 6%.

The displacement of the electron beam relative to the joint towards the 36NKhTYu alloy by 0.1 mm leads to an increase in the hardness of the weld metal from 225 to 305 HV5 due to an increase in the proportion of titanium and aluminium, which form intermetallic hardening phases. In this case, the displacement of electron beam relative to the joint to alloy 36NKhTYu was about 60%.

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References
[1] Goncharov A L, Marchenkov A Yu, Terentyev E V, Zhmurko I E, Sliva A P 2019 Study of structural non-homogeneity impact on mechanical properties of dissimilar weld joints of carbon steel 20 and corrosion-resistant austenitic 12Kh18N10T steel IOP Conference Series:
Materials Science and Engineering 681(1) 012016
This reference has two entries but the second one is not numbered (it uses the ‘Reference (no number)’ style.

[2] Lanin A A, Ilin S A, Prokhorova T V, Reva V V 2017 Prediction of strength reduction factor for welded joints of dissimilar steels 15Kh1M1F and Kh10CROMVB9-1 (R91) at high-temperature operation Proceedings of the IX Eurasian Scientific and Practical Conference Prochnost' neodnorodnykh struktur - PROST 2018 p. 36

[3] Khanzhin C G, Lanin A A, Prokhorova T V Long-term strength of dissimilar welded joints of steels 15Kh1M1F and Kh10CROMVB9-1 (R91) at high-temperature operation Proceedings of the IX Eurasian Scientific and Practical Conference Prochnost' neodnorodnykh struktur - PROST 2018 p. 36

[4] Trykov Yu P, Gurevich L M, Shmorgun V G, Bogdanov A I, Kiselev O S 2020 About the implementation of equal strength of annular welds (soft interlacks) of dissimilar pipes and vessels Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta 4(64) 35-38

[5] Khanzhin C G, Lanin A A, Prokhorova T V Long-term strength of dissimilar welded joints of steels 15Kh1M1F and Kh10CROMVB9-1 (R91) at high-temperature operation Proceedings of the IX Eurasian Scientific and Practical Conference Prochnost' neodnorodnykh struktur - PROST 2018 p. 36

[6] Olshanskaya T V 2014 Peculiarities of crystalization of welded seams from dissimilar materials in electron-beam welding on the example of high-chromium steel with bronze Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Mashinostroyeniye, materialovedeniye 16(3) 43-53

[7] Krektuleva R A, Cherepanov O I, Cherepanov R O 2014 Effects of concentration of residual stresses and localization of deformations in welded joints of dissimilar steels Izvestiya vysshikh uchebnykh zavedeniy. Fizika 55(7-2) 100-103

[8] Nikulina A A, Skeeba V Yu, Kornienko E E, Mironov E N 2011 Simulation of structure formation during welding of heterogeneous steels Obrabotka metallyov (tehnologiya, oborudovaniye, instrumenty) 4(53) 54-61

[9] Kyzniatsova V V 2014 Finite-element modeling of welded X-shaped joint Science & Technique 5 74-81

[10] Lukyanov V F, Assaulenko S S 2015 Simulation of multicentric destruction with regard for inhomogeneous distribution of rated voltage Advanced Engineering Research 15 4(83) 31-36

[11] Efimov M V, Kidalov N A, Gabelchenko N I, Aliev D O, Semenova L S 2021 Investigation of the mutual influence of welding technology and heat treatment of welded joints made of dissimilar grades of steel Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta 7(254) 83-87

[12] Lanin A A, Il'in S A, Prokhorova T V 2008 Investigation of the dissimilar thick-walled pipe butt welded joints for using in the steam turbines inlet-system Tyazhelye mashinostroyeniye 6 21-25

[13] Kuzeev I R, Poyarkova E V, Naumkin E A 2011 Interrelation of mechanical behaviour of heterogeneous welded joints with morphology of their fatigue breaks Neftegazovoye delo 9(2) 80-86

[14] Terentyev E V, Marchenkov A Yu, Goncharov A L, Sliva A P 2018 Improving the structural strength of dissimilar welded joints of 36NKhTYu alloy and EP517 steel by optimizing the geometric parameters of the weld Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Mashinostroyeniye, materialovedeniye 20(3) 63-72

[15] Ilin A V, Karpov I G, Kashchenko D A, Sobolev A A 2020 Evaluation of the effect using possibility of contact strengthening in welded joints of high-strength low-alloy steels Svarochnoye proizvodstvo 12 3-11

[16] Terentyev E V, Marchenkov A Yu, Goncharov A L, Sliva A P 2019 Application of Local Strengthening for Increasing the Strength of the Welded Joint of EP517 Steel and 36NKhTYu Alloy Russian Metallurgy (Metally) 2019(10) 1061–1066
[17] Terentyev E V, Marchenkov A Yu, Goncharov A L, Sliva A P, Borodavkina K T 2020 Heat treatment mode optimization of dissimilar weld joints of EP517 steel to 36NKhTYu alloy IOP Conference Series: Materials Science and Engineering 759 (1) 012024

[18] Malikov A G, Orishich A M, Vitoshkin I E, Karpov E V, Ancharov A I 2020 Laser welding of dissimilar materials based on VT20 titanium and V-1461 aluminum alloys Journal of Applied Mechanics and Technical Physics 61(2) 307-317

[19] Dragunov V K, Goncharov A L, Portnov M A 2017 Effect of the electron beam welding conditions on the structure and mechanical properties of welded joints in an austenitic steel with bronzes in the manufacture of power engineering structures Welding International 31(7) 554-560