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INFLUENCE OF TECHNOLOGICAL AND METALLURGICAL FACTORS ON COPPER WELDED JOINT FORMATION IN ELECTRON BEAM WELDING

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The influence of technological and metallurgical factors on welded joint formation in electron beam welding of M1 copper grade with the thickness δ = 18 mm by a vertical electron beam in the flat position in a one pass was studied. The system of a computer control of the process of electron beam welding in the UL-209M installation allows performing cleaning of the adjacent butt zone from the remnants of contaminants and oxides using a low-power electron beam focused on the metal surface in a single technological cycle. The use of high-speed local electron beam scanning in a circle allowed a significant reduction in the temperature in the central part of the welding pool and, thus, eliminated burnouts and splash of weld metal. It was established that the optimal welding speed at an accelerating voltage U_{acc} = = 60 kV is in the range v_w = 6–8 mm/s. Metallurgical treatment of welding pool with the help of inserts of aluminium and titanium foil eliminates the susceptibility to pores formation in the weld metal. 16 Ref., 1 Table, 5 Figures.

Keywords: electron beam welding, electron beam, computer control, circular scanning, penetration depth, input energy, welding speed, facial bead width, porosity

In electron beam welding (EBW), copper has a number of difficulties, which are mainly predetermined by its high thermal conductivity, high fluidity, intense evaporation in vacuum during heating above the melting point, as well as significant activity of the metal in interaction with oxygen and hydrogen in the molten state. A high thermal conductivity leads to increased cooling rates of the weld metal and the weld zone and to a short time of when the welding pool remains in the liquid state, which leads to a deterioration of the weld formation and the need in additional investigations to reduce weld porosity.

An increased fluidity of copper does not allow performing one-sided butt welding with a full penetration of edges in the flat and vertical positions. For satisfactory weld formation, on the reverse side backings are applied which densely adjoin to metal being welded, or are limited by a lock joint at non-through penetration.

The use of electron beams with normal (Gaussian) power density distribution in welding copper leads to overheating of the metal in the near-axial zone, its intensive evaporation and, as a consequence, spattering and unsatisfactory weld formation [1]. Thus, in electron beam welding of copper with a thickness δ > > 4 mm electron optical systems are used that provide uniformity of current across the cross-section of the beam, or systems in which the maximum current density is displaced outside the near-axial zone [2, 3].

The content of impurities in EBW copper has a great influence on the quality of welded joints [4]. The most harmful impurity that reduces the mechanical, technological and anticorrosion properties of copper is oxygen, the content of which should be limited and minimized by deoxidation [5].

In connection with the abovementioned, a set of studies was conducted on EBW M1 copper with a thickness of δ = 18 mm in order to determine the optimal energy, time and geometric parameters of the electron beam, as well as the influence of the preparation of the welded edges, and metallurgical methods for the formation and quality of welded joints.

Research procedure. EBW of plane specimens of M1 copper with the thickness δ = 18 mm of the size 200×80×18 mm was performed in the flat position by means of a vertical electron beam in the UL-209M installation with a computer control of all parameters and systems (vacuum, movement and rotation of electron beam gun (EBG), welding current, welding speed, focusing and deflection of electron beam, local scanning), created at the PWI [6]. The UL-209M installation is equipped an power complex based on ELA-60/60 and EBG, which moves inside the vacuum chamber along the linear coordinates *X*, *Y*, *Z* and also rotates around the *Y*–*Y* axis at an angle of 0–90°. At an accelerating voltage U_{acc} = 60 kV, EBG with a tungsten metal cathode with 3 mm diameter provides

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Chemical composition of copper, wt.%

Grade of copper	Content of impurities, not more than											
	Bi	Sb	As	Fe	Ni	Pb	Sn	S	Zn	P	Ag	Composition of copper
M1*	0.0003	–	0.0007	0.004	0.0001	0.0013	0.0001	–	0.0017	–	0.0055	99.98
M* — chemical composition of copper was determined by emission spectral method.												

the current range of the electron beam I_b = 0–500 mA, as well as realization of technological scanning of the beam in the EBW process. The accuracy of EBG positioning on the coordinates not worse than 0.1 mm is provided. The alignment of the electron beam with the butt is provided by the RASTR system with an accuracy of not less than 0.1 mm [7].

The working distance from the end face of EBG to the surface of welded specimens was 200 mm, the residual pressure in the welding chamber reached $1\cdot10^{-2}$ Pa. Immediately before welding, the specimens were degreased with aviation gasoline (GOST 1012–72) or white spirit (GOST 3134–52), and then the ends and adjacent areas of 10 mm width were scraped by hand. The electron beam was focused on the surface of butt welded specimens, and the value of the welding current was set in such a way that at the optimal input energy, through penetration in a one pass with a guaranteed formation of the facial bead of the weld and point punctures on the back side of the weld was provided.

Mechanical tensile tests of round (type II) specimens of welded joints and base metal were performed in a rupture machine of type TsDM-10R (Germany) according to GOST 6996–66. In the manufacture of round specimens for tension, the middle part of the weld was chosen according to the penetration depth. Plane specimens with a V-shaped notch (type XI) for impact toughness determination were also manufactured.

The structure of welded joints was examined in the optical microscope of Neophot-32 type at a magnification of ×20–500. The nature of decrease in the strength of the base metal in HAZ was determined by measuring the hardness on the cross-sections in a microhardness tester of M-400 type of COMPASS Company at a load of 1N (application time is 10 s) at three levels of penetration depth (top, middle, bottom).

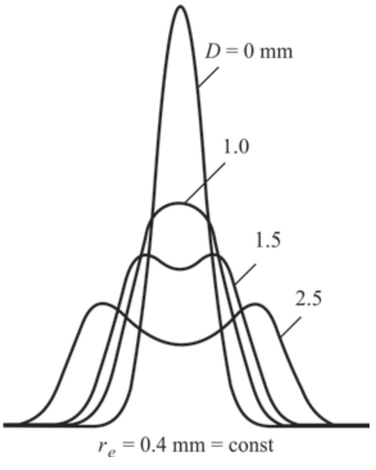

Figure 1. Distribution of electron beam power density while measuring the diameter of a circular scanning *D* and a constant effective beam radius r_e

The chemical composition of M1 copper, given in Table, was determined by the method of emission spectral analysis in the ICAP6500 DUO installation («Thermo Electron Corporation», UK). Gas analysis performed in the RO-316 installation (LECO, USA) and the RH-402 installation (LECO, USA) showed that the content of oxygen and hydrogen in the investigated M1 copper is lower than the values admissible by GOST and amounts to O_2 = 0.0028 wt.%, H = = 0.0012 wt.%, respectively.

Evaluation of the results of EBW of M1 copper with a thickness δ = 18 mm was performed according to the following criteria: process stability, reproducibility of results, formation of a set penetration geometry, density and strength of welded joint, minimum porosity and absence of cracks.

Results of technological investigations. Deprivation of a high-temperature axial part of the heating spot at EBW of M1 copper was achieved by a high-velocity electron beam scanning in a circle, when the distribution of the resulting heat flux represents a rectangular pulse with a plane top and sloping edges or curves with two maximums [8, 9]. In this case, the power of electron beam is distributed along the scanning trajectory almost uniformly at frequencies f_{scan} > 1000 Hz [8]. As is shown in Figure 1, by changing the diameter of electron beam rotation, it is possible to significantly reduce the temperature in the central part of the welding pool and, thus, to eliminate burnouts and splashes of weld metal.

However, due to thermophysical properties of copper, which lead to high cooling rates of weld metal, it was found that at electron beam current I_b > 150 mA, welding speed $v_w \geq 5$ mm/s and a circular scanning diameter *D* > 1.5 mm, it becomes impossible to form a weld without craters and spattering of weld metal (Figure 2). Experimental penetrations on copper to a depth h_p = 18 mm and at *D* = 1.5 mm showed that the position of electron beam focus relative to the surface of the specimen within ± 5 % does not lead to elimination of the mentioned defects. Further investigations on the selecting conditions of EBW of M1 copper was carried out with a diameter of circular scanning *D* = 1.5 mm.

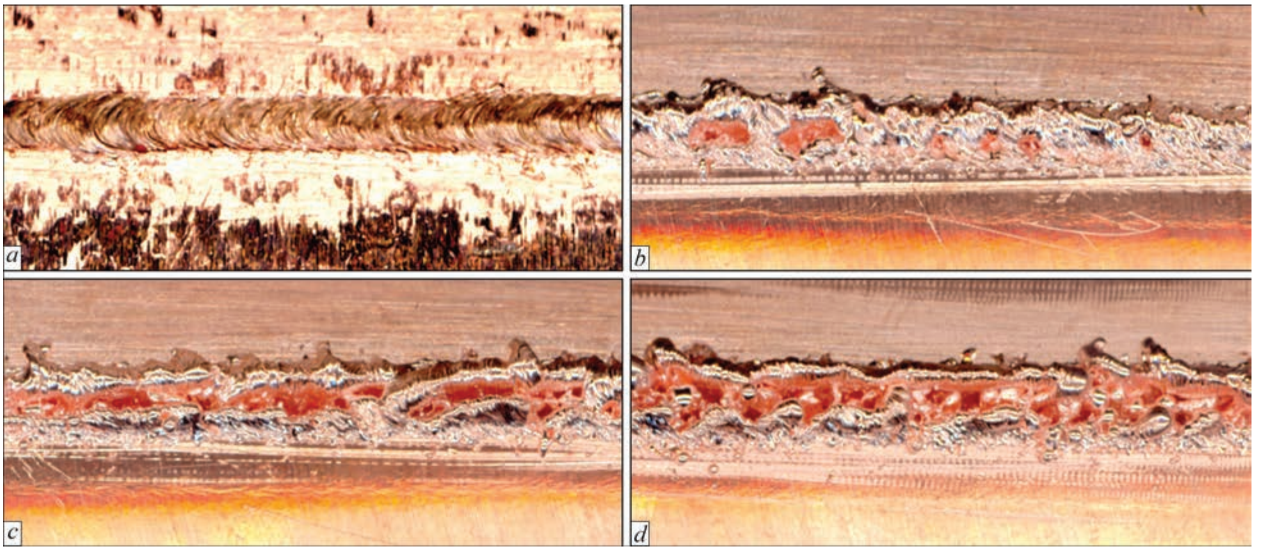

Figure 2. Formation of facial bead in the EBW weld of M1 copper with a thickness δ = 18 mm and different diameters of circular scanning: *a* — D = 1.5; *b* — 2.0; *c* — 2.5; *d* — 3.0 mm. EBW conditions: U_{acc} = 60 kV, I_b = 190 mA; v_w = 7.5 mm/s; ΔI_f = 0 mA; l_w = = 200 mm (×2)

The choice of the optimal value of welding speed is determined, on the one hand, by the condition of the minimum intensity of fluid dynamic excitations in the welding pool [10], on the other hand, by the condition of the minimum weld width for reduction of deformations, increase in crack resistance and minimizing the porosity of welded joint. Welding speed significantly affects the penetratability of electron beam and the amount of input energy of welding. In [11, 12] it was shown that in EBW of M1 copper of 12.5 mm with an accelerating voltage U_{acc} = 28 kV, the optimal range of welding speeds is 6–8 mm/s, and at increased welding speeds the instability of penetration depth and the value of lack of fusion at the weld root increases. To specify the effect of welding speed on the amount of input energy, we conducted investigations to determine the nature of the dependence $q/v = f(v_w)$ in the range of welding speed v_w = 5–10 mm/s at an accelerating voltage U_{acc} = 60 kV. As is shown in Figure 3, the value of the input energy in the studied range of welding speed varies significantly: at first it decreases quite sharply in the dependence q/v, and starting from the welding speed v_w = 7.5 mm/s, the decrease slows down. Similarly, the dependence $B_1 = f(v_w)$ varies and at a welding speed v_w = 7.5 mm/s the width of the facial bead of the weld is $B_1 \approx 2.5$ mm/s. Taking into account the data of the work on the porosity of the weld metal [11] and on the basis of the dependences obtained by us, the further investigations were performed at a welding speed v_w = 7.5 mm/s.

The main defect of the weld metal in EBW of copper is porosity. To prevent pores, at first it is necessary to remove oxides, adsorbed moisture and grease films from the surface of welded edges. In a single process cycle of EBW in the UL-209M installation, the adjacent joint area can be additionally cleaned from contaminants and oxides with the help of an electron beam focused on the metal surface with a power that does not lead to melting of the joint edges. In the conditions U_{acc} = 60 kV, I_b ~ 10 mA, v_w = 7.5 mm/s, $D \approx 10$ mm the pass was produced along the entire length of the joint before producing the main welding pass [6].

Metallurgical treatment of the welding pool to eliminate the susceptibility to pore formation in the weld metal and near the fusion line, as well as crystallization cracks in EBW of M1 copper was carried out by inserting foil of aluminium (AD0 alloy, 0.04 mm thickness) and titanium (VT1-00 alloy, 0.05 mm thickness) into the butt, acting as active deoxidizers and nitride-forming elements [13, 14]. By changing the width and thickness of the foil, the problem of dosed supply of these elements to the welding pool was solved. As is shown by experimental welding, the process of EBW of copper using alloying inserts of aluminium and titanium is characterized by a high hydrodynamic stability of welding pool and absence of

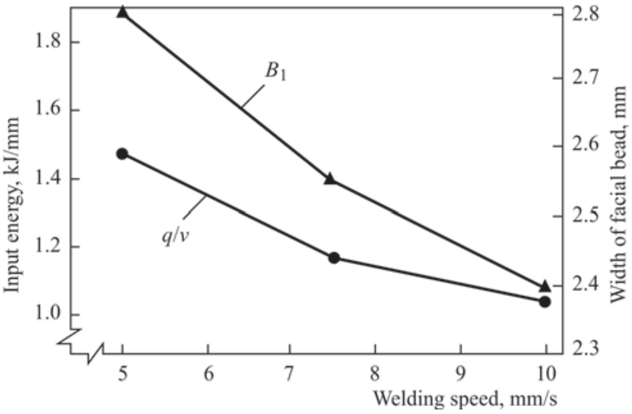

Figure 3. Dependence of the amount of input energy q/v and width of the facial bead in the weld B_1 on the speed of EBW of M1 copper with a thickness δ = 18 mm. EBW conditions: U_{acc} = = 60 kV; ΔI_f = 0 mA; l_w = 200 mm; D = 1.5 mm

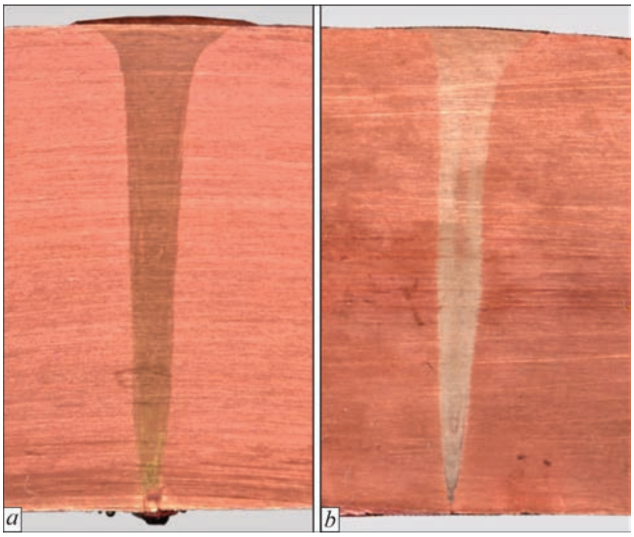

Figure 4. Formation of the weld cross-section with alloying inserts at EBW in the flat position by means of a vertical electron beam of M1 copper (×5): *a* — aluminium foil of AD0 grade with a thickness $\delta = 0.04$ mm; *b* — titanium foil of VT1-00 grade with a thickness $\delta = 0.05$ mm. EBW conditions: $U_{acc} = 60$ kV; $I_b = 197$ mA; $v_w = 7.5$ mm/s; $\Delta I_f = 5$ mA; $l_w = 200$ mm; $D = 1.5$ mm

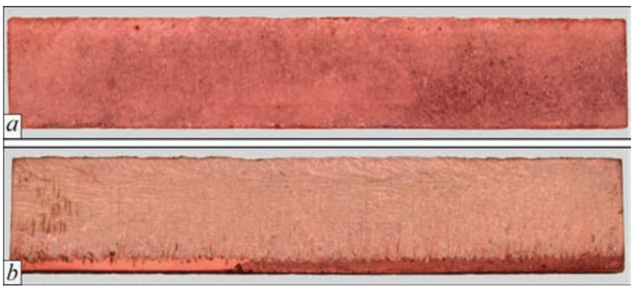

Figure 5. Formation of weld metal in the longitudinal section along the axis of M1 copper with 100 mm length during EBW in the flat position along the butt (×1.5): *a* — without an insert; *b* — with an insert with VT1-00 thickness $\delta = 0.05$ mm. EBW conditions: $U_{acc} = 60$ kV, $I_b = 197$ mA; $v_w = 7.5$ mm/s; $\Delta I_f = 5$ mA; $l_w = 200$ mm; $D = 1.5$ mm

liquid metal spattering, which provides a satisfactory facial bead formation in the weld and the stability of penetration depth along the weld length (Figure 4).

When the composition in the weld metal of aluminium or titanium is in the range of 0.1 wt.% and higher, the porosity can be reduced to a minimum value (lower than 10 mm^2 on the length of the weld being 100 mm), and the welds along the entire length will have a dense macrostructure (Figure 5).

It should be noted that microalloying of the weld, which occurs at this time, on the one hand, allows improving the mechanical properties of welded joints, and on the other hand, it leads to a decrease in thermal [15] and electrical conductivity [16].

Conclusions

1. The use of circular electron beam scanning with a diameter of up to $D = 1.5$ mm in EBW of M1 copper with the thickness $\delta = 18$ mm at an accelerating voltage $U_{acc} = 60$ kV provides the formation of a weld without craters and metal spattering in the near-axial zone.

2. It was established that at EBW of M1 copper with a thickness $\delta = 18$ mm, the optimal welding speed is in the range $v_w = 6$–8 mm/s.

3. Metallurgical treatment of welding pool with inserts of aluminium and titanium foil in EBW of M1 copper with a thickness $\delta = 18$ mm eliminates the susceptibility to pores formation in the weld metal.

1. Kajdalov, A.A., Nazarenko, O.K. (1973) Some problems of theory of electron beam welding. Elektron. *Obrab. Materialov*, **3**, 9–13 [in Russian].
2. Shilov, G.A., Akopyants, K.S., Kasatkin, O.G. (1983) Influence of frequency and diameter of electron beam circular scan on metal penetration in EBW. *Avtomatich. Svarka*, **8**, 25–28 [in Russian].
3. Ryzhkov, F.N., Bashkatov, A.V., Zakomoldin, A.F. et al. (1973) Welding of bronze Br.Kh0.8 and steel EI811 with oscillating electron beam. *Ibid*., **5**, 56–58 [in Russian].
4. Johnson, L.D. (1970) Some observation on the electron-beam welding of copper. *Weld. J.*, 49(**2**), 55–60.
5. Anoshin, V.A., Ilyushenko, V.M., Bondarenko, A.N. et al. (2014) Integrated evaluation of effect of main impurities on weldability of copper. *The Paton Welding J.*, **11**, 24–27.
6. Paton, B.E., Nazarenko, O.K., Nesterenkov, V.M. et al. (2004) Computer control of electron beam welding with multi-coordinate displacements of the gun and workpiece. *Ibid*., **5**, 2–5.
7. Nesterenkov, V.M., Kravchuk, L.A., Arkhangelsky, Yu.A. et al. (2015) Electron beam welding of medium-pressure chamber of gas turbine engine. *Ibid*., **12**, 29–33.
8. Nazarenko, O.K., Kajdalov, A.A., Kovbasenko, S.N. et al. (1987) Electron beam welding. Kiev, Naukova Dumka [in Russian].
9. Skryabinskyi, V.V., Nesterenkov, V.M., Rusynyk, M.O. (2020) Electron beam welding with programming of beam power density distribution. *The Paton Welding J.*, **1**, 49–53. DOI: https://doi.org/10.37434/as2020.01.07
10. Nesterenkov, V.M. (2003) Special features of capillary waves in the vapour-gas channel in electron beam welding of thick metal. *Ibid*., **4**, 7–12.
11. Agarkov, V.Ya. (1980) Electron beam welding of copper (Review). *Avtomatich. Svarka*, **11**, 42–43 [in Russian].
12. Nazarenko, O.K., Agarkov, V.Ya., Ikonnikov, V.I. (1986) Influence of method of edge preparation on weld pore formation in electron beam welding. *Ibid*., **2**, 21–25 [in Russian].
13. Goncharov, A.N., Krivosheya, V.E. (1980) *Effect of alloy additives on weldability of copper. In: Current problems of welding of nonferrous metals*. Kiev, Naukova Dumka, 221–225 [in Russian].
14. Ilyushenko, V.M., Anoshin, V.A., Bondarenko, A.N. et al. (1980) Investigation of influence of additives and a number of alloying elements on crack formation in welding of copper. *Ibid*., 217–221 [in Russian].
15. Kolachev, Ya.L., Livanov, V.A., Elagin, V.I. (1981) *Metals science and heat treatment of nonferrous metals and alloys*. Moscow, Metallurgiya [in Russian].
16. Si, L., Zhou, L., Zhu, X. et al. (2016) Microstructure and property of Cu–2.7Ti–0.15Mg–0.1Ce–0.1Zr alloy treated with a combined aging process. *Mater. Sci. Eng.: A650*, 345–353.

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