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INVESTIGATION OF STRUCTURE, MECHANICAL AND THERMOPHYSICAL PROPERTIES OF ELECTRON BEAM MODIFIED WELDS ON COPPER PARTS OF LANCES

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The study of real operating conditions of the lance for oxygen blasting shows that in its head part, located near reaction zones of the converter, high thermal stresses arise caused by nonuniform heating of different parts of the unit. The nozzles of the head are intensively cooled by water and oxygen, and the tip of the lance, on the contrary, is heated by thermal radiation of a liquid metal pool. Namely, thermal stresses along with mechanical loads (reaction of return effect from oxygen jets flowing from the nozzles) cause a premature destruction of the welds joining the lance nozzles with its tip. The need in developing electron beam welding of components of copper lances is predetermined by disadvantages of using traditional method of their welding — argon-arc method, which does not provide satisfactory properties of welded joints and their stability during operation of a product. The use of electron beam welding in the manufacture of lance heads for oxygen blasting allows increasing their service characteristics by alloying welding pool with the elements, having a deoxidizing effect on a liquid copper. At the same time, in order to increase the service life of lance heads, it is necessary to reduce the level of thermal stresses in them. The latter becomes possible if in terms of thermal conductivity the weld metal is as close as possible to the base metal. The paper presents the results of mechanical tests of electron beam welded joints produced on M1 copper using different alloying inserts. On the basis of studies of microstructure and character of fractures of the modified electron beam welds, the influence of alloying inserts on their operational properties was established. Together with the specialists from the ISM of the NASU, a procedure for conducting investigations on thermal conductivity of welded joints was developed and measurements of thermal conductivity coefficients for the joints produced on M1 copper by AAW and EBW methods using alloying inserts was performed. Computer simulation of the temperature field arising in the areas of welded joints in the conditions of operation of copper lances was also performed. 12 Ref., 1 Table, 8 Figures.

Keywords: electron beam welding, weld modification using alloying inserts, metallographic and factographic examinations, thermal conductivity, coefficient, porosity

Operating conditions of converter lances for oxygen blasting are much more rigid than those of blast furnace lances. A typical design of an oxygen blast lance body consisting of an outer head (*1*), an inner shell (*2*) and a central (*3*) and five side (*4*) nozzles is shown in Figure 1.

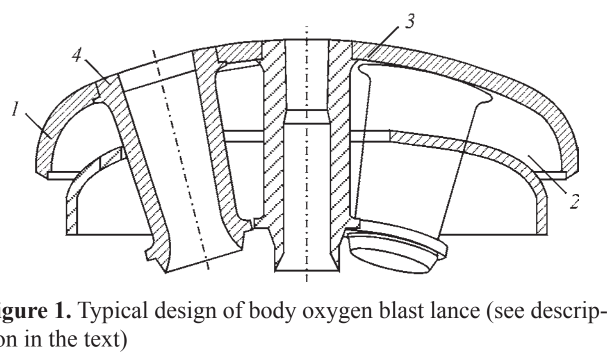

Figure 1. Typical design of body oxygen blast lance (see description in the text)

The nozzles of the head are intensively cooled by water and oxygen, and the tip of the lance, on the contrary, is heated by a thermal radiation of a liquid metal pool. Even its inner surface, which is well washed by water, can be heated up to 170 °C in the process of converter melting. The outer surface, facing the mirror of metal, is heated to a temperature of 400–500 °C and higher. Electron beam welding has a prospect of improving the operating characteristics of welded joints on copper [1–6]. However, such a weld defect as porosity does not allow realizing the advantages of this welding method quite effectively, because under the conditions of rigid temperature stresses and mechanical loads, under which the lance

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head operates, the pores in the weld cause its premature fracture. In EBW of copper an intensive removal of gases proceeds, which do not have a time to be evolved from the metal of the welding pool, forming pores or concentrating in microcontinuities, which creates a high pressure and leads to crack initiation [1–8]. Among the possible causes of porosity in EBW of oxygen-free copper, the authors of [9, 10] mention evaporation of elements with a high vapor elasticity. Such a well-known metallurgical method of reducing porosity as refining remelting is not always effective in the case of welding, because it can cause excessive deformations and inner stresses in welded structures. Another metallurgical method to avoid the porosity consists in alloying welding pool with the elements that improve the solubility of gases in a liquid metal or bind them into stable compounds. In EBW of copper it is rational to carry out alloying of a welding pool by aluminium and titanium as they differ by a low vapour elasticity as compared to copper and have a deoxidizing effect on a liquid copper in the process of welding.

The aim of the work consisted in evaluation of strength and thermophysical properties of modified electron beam welded joints of copper lances.

Procedure of investigations. In order to reduce pore formation in welds, EBW of copper specimens with a thickness of 18 mm was performed using alloying inserts in the form of a thin (0.05 and 0.1 mm) foil. Welding of the specimens was performed in the EBW installation of type UL-209m, equipped with the ELA-60 power unit (60/60 kW). The structural-phase characteristics were studied using a set of experimental methods of modern metals science, including optical metallography (microscopes «Versamet-2» and «Neophot-32»), analytical scanning microscopy (SEM-515 of PHILIPS Company). The hardness of the phase components was measured in a microhardness tester M-400 of LECO Company, the load was 1 N.

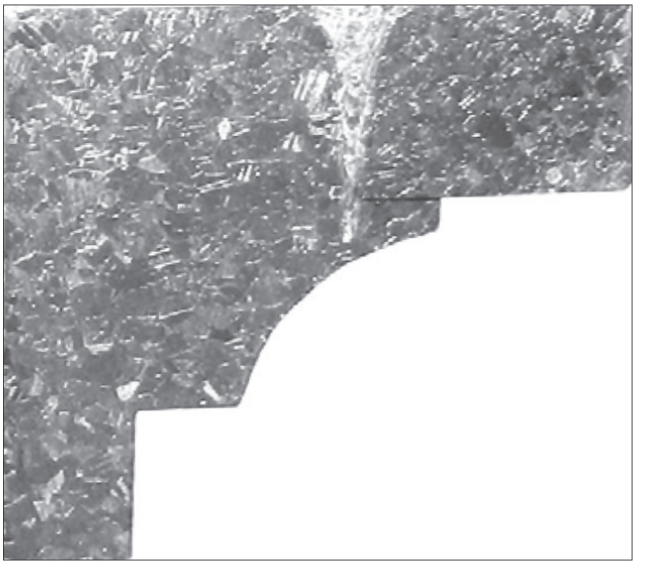

Figure 2. Welded joint with a thickness δ = 18 mm of lance and oxygen blasting. EBW conditions: U_p = 60 kV; I_b = 197 mA; v_w = = 7.5 mm/s; + ΔI_f = 5 mA, A_{circ} = 0.8 mm; L_{op} = 200 mm

Mechanical properties of welded joints such as a value of ultimate strength, proof strength and relative elongation of welded joints were determined at a room temperature on round specimens according to GOST 6996–66 type II, impact toughness was determined on the specimens with a Charpy-type notch. The structures of the arc weld and the modified electron beam welds were compared. In addition to metallographic examinations of the effect of alloying inserts on the microstructure of welded joints, their fractographic analysis was carried out. The examinations were ended in comparative measurements of a thermal conductivity coefficient of arc and modified electron beam welds. The measurement of thermal conductivity of welded joints was carried out with the participation of specialists and in the laboratory equipment of the ISM of the NASU.

Discussion of results. In the design of the welded unit, a «locking» joint is used, which allows preserving the advantage of electron beam welding and the possibility of removing root defects of the weld

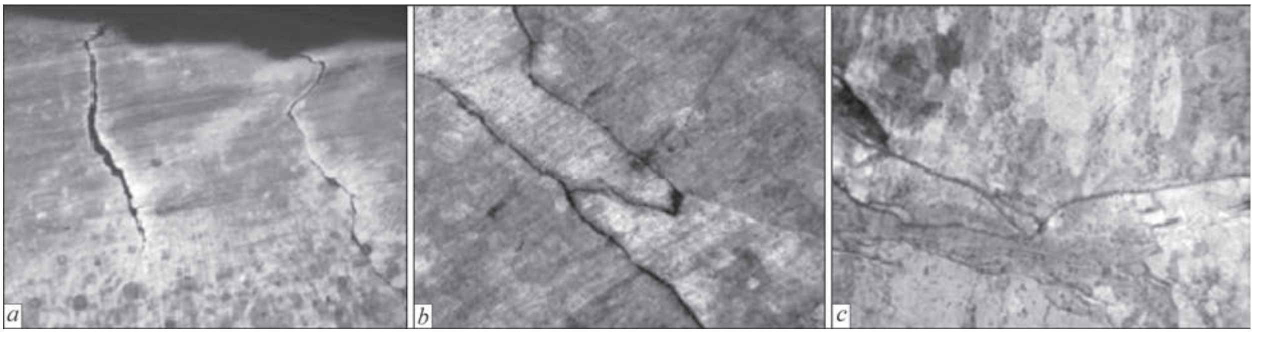

Figure 3. Microstructure of welded joints produced by AAW with additive MNZhKT 5-1 (*a*, *b*) and by EBW (*c*): *a* — crack propagation from the surface deep into the weld (×50); *b* — cracks in the central part of the weld (×200); *c* — thickening of grain boundaries in the root part of the weld, probably eutectics Cu + C_2O (×400)

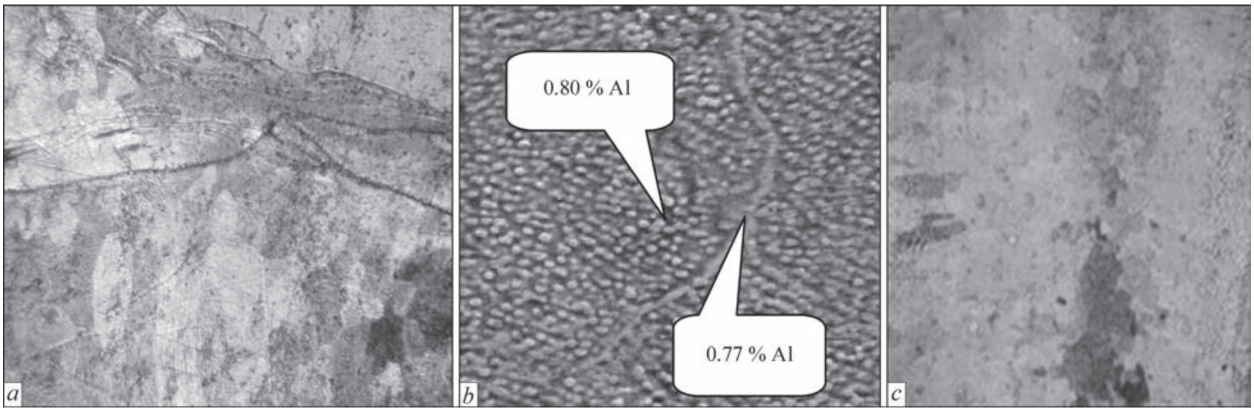

Figure 4. Microstructure of welded joint produced by EBW on M1 copper with AD-0 insert: *a* — weld root (×400); *b* — middle part of the weld (×2020); *c* — VT1-0, upper part of the weld (×100)

from the area of acting service loads. Previous studies (Kravchuk L.A. and Rusynik M.O., PWI) showed that using rigid modes of EBW, it is possibile to optimize the shape and quality of the weld. The obtained shape of the non-through weld is shown in Figure 2.

Electron beam welds and their HAZ differ favorably from arc welds in sizes and width and a smaller number of defects (Figure 3).

The grains in the metal of the argon-arc weld are large (mostly 500–700 μm, grains of 250 μm in size are more rare). At the same time, the structure of the electron beam weld consists of rounded grains that are by an order of value smaller and larger in the upper part of the weld (~ 70 μm), which are refined to ~ 48 μm at the weld root. The grain size in the near-weld zone and the base metal does not differ (on average 200–220 μm). The introduction of titanium and aluminium into the weld promotes producing of a fine-grained primary structure with a minimum width of intercrystalline boundaries. It is known that aluminium belongs to the elements, which are soluble in copper, its impurities in small concentrations can not be detected under a microscope, as far as they are included in a solid solution. With introduction of up to 1 % of aluminium (AD-0) to the weld, its structure almost does not change, but at the same time the hardness of the weld metal, which reaches *HV*–1030–1050 MPa increases. The heat-affected-zone does not have an expressed structure and represents large grains of irregular shape with a twin structure. As a result of metallographic examinations of the structure of welded joints produced on M1 copper alloy using alloying inserts from AD-0 alloy together with the positive effect of introduction of aluminium into the weld (significant reduction in the number and sizes of pores), microcracks were detected, located along the grain boundaries. This is most probably associated with the appearance of weak compounds with a low ductility, in this case eutectics or mixtures of $\alpha(Cu) + Cu_2O$ at the grain boundaries (Figure 4, *a*).

In most cases, at a limited mutual solubility of copper and aluminium, it is extremely difficult to avoid the formation of stable intermetallic phases, which have high hardness and brittleness. To determine the chemical composition of these compounds, the method of scanning electron microscopy was used. During the quantitative analysis of the chemical composition of the welded joint metal, an increased (up to 2.5 %) aluminium content was detected. From the works of V.Ya. Agarkov and other authors [5, 6], it is known that a further increase in the aluminium content reduces the strength of the weld metal. Technological measures were taken to reduce the mass fraction of aluminium in the welded joint by reducing thickness of the alloying insert from 0.1 to 0.05 mm. Repeated analysis of the chemical composition of the thickened grain boundaries showed the aluminium content at the level of 0.56–0.77 % (Figure 4, *b*). Microcracks located along the grain boundaries were also not detected.

It is obvious that by changing the mass fraction of aluminium in the cast zone of the weld, it is possible to control the parameters of the primary structure and, as a consequence, the final microstructure of the weld metal. The use of VT1-0 titanium alloy inserts in EBW of copper also significantly affected the structure and hardness of the produced welds. The structure of the weld consists of a light matrix and a large number of dispersed precipitations (Figure 4, *c*). A number of precipitations in the center of the weld is greater than near the fusion line. The matrix represents a solid solution based on copper, and dispersed precipitations are obviously presented by copper titanites. On the specimens with VT1-0 titanium insert, the carried out chemical analysis (scanning electron microscopy) showed that the elemental composition in the depth of the weld does not change, as well as during aluminium alloying. The weld metal contains 0.89–1.23 % of Ti (the rest is copper).

An increase in microhardness in the weld root as compared to its middle part is observed. On all the

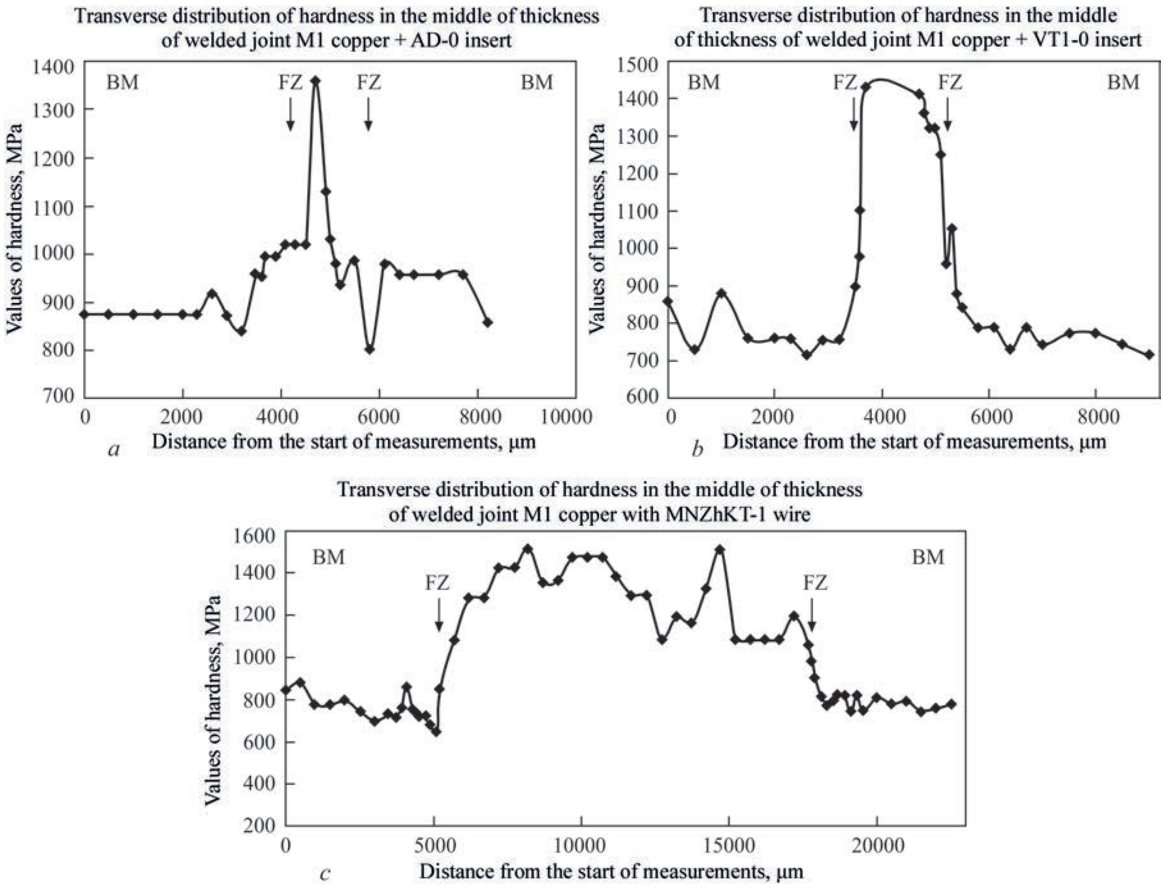

Figure 5. Comparative indices of sizes and level of microhardness: *a*, *b* — electron beam welds; *c* — argon-arc weld

specimens welded using alloying inserts, the hardness of the weld metal increases. The width of the softening areas has no noticeable propagation. It should be noted that the difference in hardness in the characteristic zones for both arc and electron beam welds is proportional. The same cannot be said about their width (Figure 5).

The tests of Mi-12 specimens on static tension at a temperature of +20 °C confirmed that the presence of alloying inserts with AD-0 and VT1-0 in the butt does not deteriorate the level of structural strength, which is typical of joints produced on M1 copper using EBW. The values of tensile and yield strengths of the welded joints and the base metal differ slightly from each other. The higher values of tearing strength of the welded joint modified by titanium can be explained by the degree of refinement and homogeneity of the grain in the cast zone, as well as the absence of defects. The tests of the metal of the welded joints on impact toughness also did not reveal significant deteriorations in the mechanical properties of the weld and HAZ metal as compared to the base metal (Figure 6).

Fractographic analysis was performed using a scanning electron microscope (SEM). In the area of defects located on the fusion boundary, the nature of the fracture is mixed with the degrees of chipping and tears along the grain boundaries and with a combination of micropores («pit» relief) and ridges of a nar-

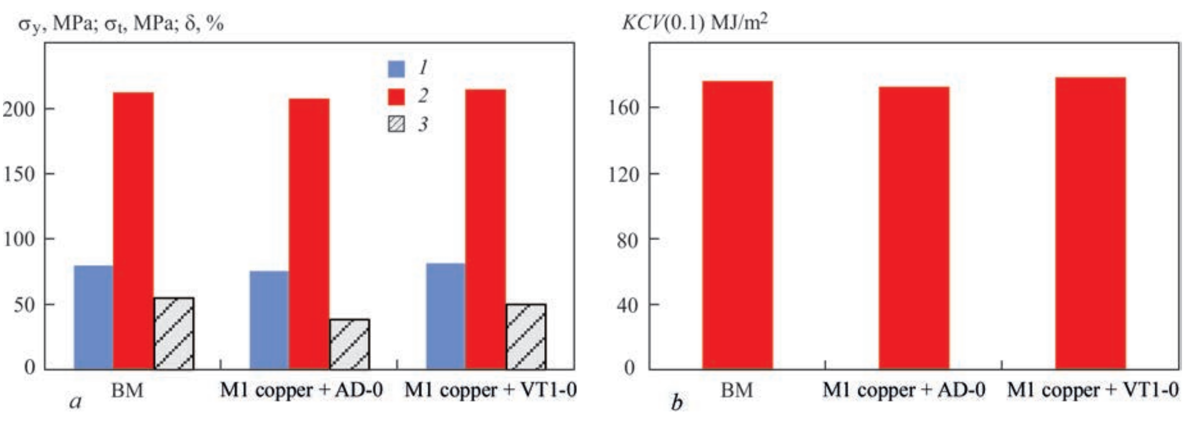

Figure 6. Testing of welded joints and base metal: *a* — static tension (Mi-12): *1* — σ_y, *2* — σ_t, *3* — δ; *b* — impact bending (Mi-50)

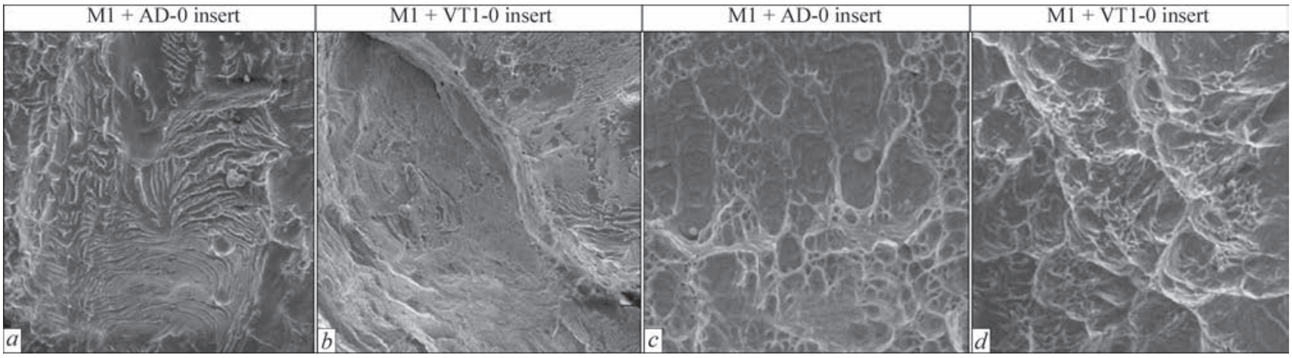

Figure 7. Microfractography of fracture fragments in different zones of welded joint, SEM; *a* — zone of main propagation of Mi-50 cracks (×300); *b* — center of Mi-12 specimen (×300); *c* — zone of main propagation of Mi-50 cracks (×2020); *d* — zone of main propagation of Mi-50 cracks (×500)

row tear (Figure 7, *a*, *b*). The fracture surface has a tough nature of fracture with a length of 100–150 μm with pits of different sizes (1–15 μm). Inside the pits, the particles can be seen, on which the pores arised (Figure 7, *c*). On the specimens alloyed with aluminium, detailed studies showed that in the fracture of the specimens there are areas fractured by the mechanism, which has a lower energy intensity of the fracture as compared to a tough one. Namely, the latter is the cause for some decrease in the ultimate strength of the weld metal as compared to the ultimate strength of the base metal. The action of titanium has a more balanced effect on the structure of the weld metal during its modification, promotes the formation of a more homogeneous fine-crystalline structure and transfers the fracture area at a static loading of the specimens into the base metal. The type of fractures of impact specimens alloyed with titanium is characterized by a tough intragranular fracture in the area of the main crack propagation (Figure 7, *d*). Reduction in the grain sizes limits the microcrack by effective barriers — by the boundaries of grains and crystallites. As a result, the initiated microcrack remains within the subcritical dimensions or under the effect of external forces it changes its direction during the further propagation. Thus, the results of the work show the possibility of using fractographic analysis of all the zones of the welded joint as one of the tools of a complex analysis of their quality and strength.

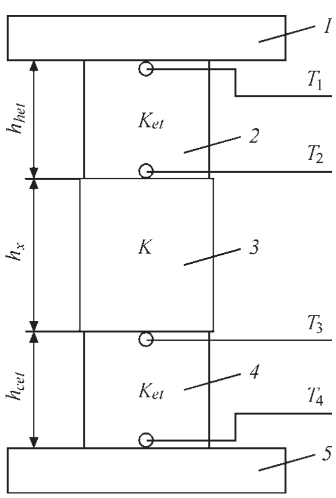

Figure 8. Scheme of measuring thermal conductivity with two reference specimens (see description *1–5* in the text)

An increase in strength and a decrease in the degree of softening of the welds and welded joints can be explained by refinement of the weld structure during welding using inserts of titanium and aluminium. The type of fracture in the near-weld zone and over the base metal is almost identical, which indicates a smooth transition from the zone of overheating to the base metal through a poorly expressed heat-affected-zone.

The study of real operating conditions of the lance for oxygen blasting shows that in its head part, located near the reaction zones of the converter with a temperature of 2700–2900 °C, large thermal stresses arise, caused by a nonuniform heating of different parts of the unit. The nozzles of the head are intensively cooled by water and oxygen, and the tip of the lance, on the contrary, is heated by thermal radiation of a liquid metal pool. Namely, thermal stresses along with mechanical loads (reaction of return effect from oxygen jets flowing from the nozzles) cause fracture of the welds joining the nozzles with the tip. Therefore, to increase the service life of the lance heads, it is necessary to minimize the temperature gradient between the nozzles and the tip. The latter is possible if in terms of thermal conductivity, the weld metal is close to the base metal.

Together with the experts of the ISM of the NASU a procedure of studying thermal conductivity was developed, which applied to the zones of welded joints produced on M1 copper using the AAW and EBW methods with alloying inserts and the design of a cylindrical specimen for measurements was developed.

When measuring the thermal conductivity of metals, a relative (comparative) method was used, which is based on the fact that the same amount of heat pass-

Values of thermal conductivity coefficients of weld metal

Method of welding	K_x, W/(m·K)
Body material of M1 lance	420.53
AAW using MNZhKT5-1 filler wire	181.78
EBW using alloying insert of AD-0 aluminium alloy with a thickness of 0.05 mm	366.60
EBW using alloying insert of VTI-0 titanium alloy with a thickness of 0.05 mm	197.98
Notes. Body material of M1 lance; $h_{specimen}$ — 10 mm; $d_{specimen}$ — $10^{\pm 0.1}$ mm.	

es through the specimen with already known thermal conductivity (reference), located in series with the studied specimen. Heat flux is calculated by the temperature gradient on the reference specimen [11]. As a rule, in the laboratory specialized equipment the scheme with two reference specimens, given in Figure 8, is used.

Between the specimen (*3*), the thermal conductivity of which should be determined and the heat source (*1*), the reference specimen with a known thermal conductivity (*2*) is placed. On the other side of the measured specimen, the second reference specimen (*4*) is placed, which is in contact with the refrigerator (*5*). The measurement error will be smaller, the better the contact between the contacting surfaces. The temperatures are measured using four thermocouples connected to the reference specimen and the measured specimens.

To minimize the contact resistance on all the surfaces of the references and the specimen a special thermal interface (metal alloy based on gallium) is deposited, which at a room temperature is in the state of a viscous fluid (paste), which moistens the contact surfaces. The computer monitoring system in real time records the indices of four thermocouples. The first thermocouple is located in a thin groove on the upper surface of the hot reference directly under the heater. The second thermocouple is located in a thin groove on the lower surface of the hot reference. The arithmetic mean of the readings of the first and second thermocouples is the temperature of the hot reference. The third and the fourth thermocouples are fixed in the grooves on the upper and lower surfaces of the cold reference, respectively. As in the previous case, the arithmetic mean of their readings is the temperature of the cold reference. The average value of readings of the second and the third thermocouples determines the temperature of the measured specimen. When determining the thermal conductivity of the test specimen, the heater temperature does not exceed 30 °C. The formula for the thermal conductivity coefficient K_x of the specimen with the height h_x and cross-sectional area S_x takes into account the presence of both references and the readings of four thermocouples:

$$K_x = \frac{K_{et} S_{et} h_x}{2S_x (T_2 - T_3)} \left(\frac{T_1 - T_2}{h_{het}} - \frac{T_3 - T_4}{h_{cet}} \right),$$

where h_{het} and h_{cet} is the height of hot and cold references, respectively; S_{et} is their cross-sectional area; K_{et} is the the thermal conductivity coefficient of the reference material.

The measurement takes place after the measuring system starts operating in the stationary mode, the value of the thermal conductivity coefficient of the specimen is averaged over four experiments. During the trial tests of the installation and the procedure on the reference specimens with a known thermal conductivity coefficient, the relative measurement error did not exceed 5 %.

The results of measurements of the thermal conductivity coefficient of M1 copper specimens with different types of welded joints according to the abovementioned formula are shown in Table.

The obtained measurement results were used during computer simulation of the temperature field, that arises in the area of the welded joint in the conditions of operation of copper lances. The results of calculations of the temperature difference in the center line of the weld and on the periphery of the calculation area showed a significant advantage of the joints produced by EBW with alloying of AD-0 aluminium in terms of maximum reduction of the temperature gradient between the nozzles and the tip of a real lance.

Conclusions

1. Results of carried out metallographic examinations showed the prospects for the use of alloying inserts in the manufacture of parts of copper components of lances using EBW.

2. Mechanical tests and factographic analysis of welded joints confirmed that the presence of AD-0 and VT1-0 inserts in the butt does not deteriorate the level of structural strength typical of electron beam joints produced on M1 copper.

3. In the root part of the produced welds, the chemical inhomogeneity inherent in EBW with a non-through penetration is noted. To remove probable root defects of a weld from the zone of acting operation-

al loads in the structure of copper lances, the use of «lock» joint is justified.

4. Along with the positive effect from the introduction of VTI-0 (significant reduction in the level of porosity at high mechanical values), it is unacceptable to recommend it as an alloying element in EBW of lance components because of a low thermal conductivity of the weld metal, commensurable with the argon arc weld (filler wire MNZhKT5-1).

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