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DETERMINING THE STRUCTURAL FEATURES OF THE CHROMIUM AND COPPER ALLOY MATERIAL OBTAINED BY ELECTRON BEAM WELDING

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This study considers a welded joint between copper and chromium. The task addressed is to enable the formation of a copper and chromium joint based on the selection of the alloy material's optimal structure.

Based on scanning electron microscopy, micro-X-ray spectral analysis, and microhardness measurement, the properties of the welded joint material in a copper and chromium joint were investigated. The joint was obtained by electron beam welding by preheating one of the metals while removing additional heat supply from the other. It was established that a moving electron beam leads to the formation of different types of microstructure in the alloy material with significant concentration heterogeneity: quasi-dendritic; linearly elongated; scaly; cellular; quasi-spherical.

Welding with a stationary, linearly deployed along the joint, electron beam with preheating of one of the metals and providing additional heat removal from the other enables the formation of a concentrically uniform weld with a quasi-spherical microstructure of copper-chromium eutectic.

The directional nature of the copper-based grains, which are elongated in the direction across the welded joint, which corresponds to the direction of additional heat removal from one of the welded metals, was revealed. The material obtained by a stationary, linearly deployed along the joint, electron beam under the mode $U_{acc} = 60$ kV, $I_{eb} = 40$ mA, $P = 5 \cdot 10^{-3}$ Pa for a duration of 7 seconds with preheating of chromium to 900°C and providing additional heat removal from copper was determined as the alloy material of the welded joint between copper and chromium with an optimal structure.

The results could be used while making copper-chromium joints by fusion welding in a vacuum with regulation of the speed of movement and focusing of the source of thermal energy supply

Keywords: weld, electron beam welding, microstructure, eutectic, phase formations, temperature gradient

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1. Introduction

Devising the technology for joining copper and chromium is predetermined by the expediency of industrial application of a bimetal with high electrical conductivity of copper and a whole chain of useful properties of chromium – corrosion resistance, high melting point, thermal and heat resistance. The combination of these properties is necessary when making articles that involve applying voltage or removing heat from chromium structural elements. To obtain a high-quality welded joint, it is necessary to understand the processes occurring in the contact zone of these metals.

Two types of processes are used for joining: welding in a solid or liquid state. In electron beam welding, melting occurs during the formation of a weld, which, as a rule, causes the formation of a complex metallographic structure and a multiphase composition of the material in such a zone. In the absence of macro defects in the material of the welded joint, it is the structure of such a material and its phase composition that determine the mechanical properties of the resulting joint, which imposes appropriate requirements for the study and analysis of such parameters.

Electron beam welding is one of the most precise types of welding as it takes place in a vacuum, which reduces the influence of the gas environment. The ability to adjust the parameters of the electron beam makes it possible to change the energy supply to the contact zone of the welded metals quite accurately. In addition, the use of the electron beam makes it possible to perform preliminary or final heat treatment of welded materials.

Thus, investigating the application of electron beam welding of copper and chromium is a promising task for solving the current task of finding ways to achieve the optimal microstructure of the weld between copper and chromium under fusion welding conditions.

2. Literature review and problem statement

For welding metals with a significant difference in melting temperatures, solid-state joining by diffusion welding, described in [1], explosion welding, described in [2], or vacuum impact welding, described in [3], are often used. However, these types of welding involve plastic deformation of the article, which limits their application. Typically, explosion welding is used to join plates of a large area. Vacuum impact welding does not involve joining large-sized elements, and this method does not weld end parts but elements for the manufacture of a workpiece. Diffusion welding is more versatile, but its feature is the almost mandatory formation of a weld that corresponds to the equilibrium phase diagram. This can be both a positive and a negative factor affecting the strength of the joint.

It is shown in [1] that for diffusion welding of chromium and copper it is advisable to use perforated copper gaskets and ensure their plastic deformation in the process of diffusion annealing. The authors did not study the processes of welding copper and chromium with fusion, which limits production both by long duration and by the design features of the article to be deformed.

In [4], the efficiency of electron beam welding of copper-chromium-zirconium alloy was shown. In particular, the conclusion drawn is the decisive influence of the beam force and the accelerating voltage on the width and depth of the penetration region. For this type of alloy, the authors of [4] recommended using not a high welding speed, which reduces the depth of penetration of the welded materials. At the same time, the work does not consider either the properties of the alloy material or the processes of welding copper and chromium, which limits the practical use of the results.

Copper and chromium differ significantly in physicochemical and mechanical properties. The melting point of copper is much lower than that of chromium, and the thermal conductivity and heat capacity are much higher. Chromium is intensively oxidized by oxygen, forming a strong oxide film. All this complicates the tasks of welding them. For their high-quality connection, a weld with a variable composition of both elements must be formed. At the same time, the Cu-Cr phase diagram indicates [5] the absence of the formation of intermetallics and the minimum mutual solubility of these elements in the solid state in this binary system. During the cooling of the Cu-Cr melt, eutectic decomposition into minimally mutually saturated copper and chromium occurs. The solubility of chromium in copper is limited from 0.05% at 300°C to 0.8% at 1070°C.

In [6], the microstructure and phase distribution features of Cu-Cr alloys with a chromium content of 25 and 50 wt. % were investigated after treatment with a high-current pulsed electron beam. Before electron beam treatment, the microstructure of the Cu-Cr alloy with a chromium content of 25 wt. % is characterized by chromium dendrites in the copper matrix. The Cu-Cr alloy with a chromium content of 50 wt. % is characterized by a microstructure consisting of globular chromium particles distributed in the copper matrix. As a result of the influence of the electron beam, the formation of microcracks in chromium grains is observed. After electron beam treatment, the microstructure of the Cu-Cr alloy with a chromium content of 25 wt. % is characterized by the absence of a dendritic structure and the presence of chromium spheroids with a size of 0.1 to 2 μm. For the Cu-Cr alloy with a chromium content of 50 wt. % after treatment with electron beam pulses, the formation of a chromium film on the surface of the alloy is characteristic. The boundaries between chromium particles and the copper matrix become blurred. It is also noted in [6] that the formation of small chromium spheroids in the copper matrix is observed. However, no recommendations are given regarding the optimal mechanical properties between copper and chromium alloys, which limits the use of the results when studying copper and chromium welding.

In [7], a supersaturated solid solution of the Cu-5 wt. % Cr alloy with a chromium solubility of 0.94 wt. % was obtained by combining mechanical alloying and spark plasma sintering. The results of the study showed that the alloy demonstrated a hardness of 106.27 HV at 500°C, which is 23.14% higher than that of the conventional sample. In addition, an increase in the yield strength at elevated temperatures (300–700°C) from 320 MPa to 337 MPa was observed, which is due to the strengthening effect of residual chromium precipitates. The authors of the study believe that the high thermal stability is mainly explained by two types of residual chromium precipitates in the matrix. The larger ones act as obstacles that inhibit the movement of copper grain boundaries at elevated temperatures, and the smaller ones dispersed in the Cu matrix fix dislocations.

Thus, welding between copper and chromium has so far been usually performed by techniques that do not involve melting of metals. Elements of the Cu-Cr-Zr alloy were joined by melting, and electron beam welding was successfully applied in [4]. The microstructure of Cu-Cr alloys with a chromium content of 25 and 50 wt. % was studied in [6] both in the initial state and after treatment with a high-current pulsed electron beam. The structural features of alloys with different chromium contents and the characteristic effect of a powerful source of electron energy supply to the surface of the alloys were established. All available research results border on the problem of electron beam welding between copper and chromium, but do not solve it. Welding of these two metals by melting should lead to the formation of a weld with a variable composition and microstructure, depending on the welding cycle used.

Thus, the issues related to the possibility of welding copper and chromium by fusion, in particular by electron beam welding, remained unresolved. A likely reason is the difficulties in forming a weld from a liquid bath consisting of two metals that have minimal mutual solubility. Given the tendency to form a supersaturated solid solution of chromium in copper under conditions of electric spark influence [7], as a result of electron beam welding, one can expect the formation of thermodynamically unstable structural-phase formations in the weld. To thermally stabilize the properties of such a material, it is necessary to either select heat treatment modes for each variant of the obtained alloy material, or to obtain it structurally homogeneous with two types of residual chromium precipitates in the matrix [7]. It is this structure of the alloy material of a welded joint between copper and chromium that can be considered optimal. An option for overcoming the difficulties is to select optimal conditions for crystallization of the material in the weld zone.

All this allows us to state that it is a relevant task to perform studies aimed at establishing a dependence of the microstructure of the alloy material on the conditions of electron beam welding. This is the way to define the characteristics of the welding cycle, which could enable the formation of a welded joint with an optimized weld microstructure.

3. The aim and objectives of the study

The purpose of our study is to enable the formation of a copper-chromium compound based on the creation of conditions for the optimal structure of the alloy material. This will make it possible to recommend a welding mode to obtain a high-quality welded joint with a structurally homogeneous weld with two types of residual chromium deposits in the matrix.

To achieve this aim, the following objectives were accomplished:

– to determine the effect of heating each of the welded metals on the structure of the alloy material obtained by a moving electron beam;

– to determine the effect of heating the welded metals on the structure of the alloy material obtained by a stationary defocused electron beam;

4. The study materials and methods

The object of our study is a welded joint between copper and chromium. The principal hypothesis of the study assumes that in order to obtain a fine-grained and maximally homogeneous microstructure of the weld, it is necessary to perform welding with different options for moving the electron beam with changes in its sweep. In addition, it is necessary to heat one of the welded metals by creating conditions for heat removal from the metal that was not previously heated.

It was assumed that the cooling conditions of the welded material could be determined without fixing the temperature field in the heat removal zone.

To consider the structural features of the weld, a simplification was adopted regarding the homogeneity of the material structure along the depth of the weld.

The materials studied in the experiments were chromium of the X99 grade, the composition of which corresponds to the parameters given in Table 1, and copper of the M1 grade, the composition of which corresponds to the parameters given in Table 2.

Table 1

Composition of X99 chromium grade according to ISO 10387:1994 [8] (wt. %)

Cr	Si	Al	Fe	C	S	Sb	P	Cu	As	Zn
≥ 99.0	≤ 0.2	≤ 0.5	≤ 0.5	≤ 0.03	≤ 0.02	≤ 0.002	≤ 0.02	≤ 0.02	≤ 0.01	≤ 0.01

Table 2

Composition of M1 copper grade according to DSTU GOST 859:2003 [9] (wt. %)

Cu	Bi	Fe	Ni	Zn	Sn	Sb	Ag	Pb	S	O
≥ 99.90	≤ 0.001	≤ 0.005	≤ 0.002	≤ 0.004	≤ 0.002	≤ 0.002	≤ 0.002	≤ 0.005	≤ 0.004	≤ 0.050

Copper and chromium samples were machined into plates measuring 20 × 30 × 4 mm. The flat surfaces to be welded 20 × 4 mm were ground to a roughness of Rz ~10 μm and butt-welded without a gap.

Electron Beam Welding (EBW) was performed in the welding chamber of the UEL-144 installation (UEL-144, Pilot Paton Plant, Ukraine).

The connection was performed by welding the joint in a free position. Electron beam welding with a focused beam was performed with through-penetration according to the mode: $U_{acc} = 60$ kV, $I_{eb} = 40$ mA, $v_{eb} = 10$ mm·s^{-1}, $P = 5\cdot10^{-3}$ Pa. In this case, the beam sweep (cross-section) during welding was elliptical 3 × 4 mm, and the scanning frequency was 170 Hz (mode 1). The electron beam moved along the joint of the welded samples. Welding was performed in one pass. After welding, the welded samples were cooled to room temperature in a vacuum in the welding chamber. The welding mode with a stationary linearly deployed electron beam along the joint (defocused electron beam) provided for the formation of a calmer weld pool and was implemented under the mode $U_{acc} = 60$ kV, $I_{eb} = 40$ mA, $P = 5\cdot10^{-3}$ Pa for 7 seconds (mode 2).

The welded samples were heated by scanning the welded joint zone with an electron beam according to the parameters of electron beam welding. The heating temperature of copper was 600°C, the heating temperature of chromium was ~900°C. The heating temperature of the metals was controlled by the results of measurements with a chromel-alumel thermocouple inserted into the heating area. The heating area was the junction zone of the weld and the corresponding metal or directly the weld zone without displacement towards one of the metals. The heating temperature of the alloy material was determined by the indicators of a thermocouple inserted into the copper at a distance of 3 mm from the weld. The heating time was 300 seconds. Heating was performed before welding. To estimate the contribution of diffusion to the width of the weld, the formula of the linear dimension $\boldsymbol{X}$, which characterizes the area of diffusion influence [10], was used:

$$\boldsymbol{X} = \boldsymbol{R}\cdot\left(\boldsymbol{D}\boldsymbol{t_l}\right)^{-1/2}, \qquad (1)$$

where $\boldsymbol{C}$ is the concentration of the diffusing element, at. %; t is the duration, time, s; $\boldsymbol{D}$ is the diffusion coefficient, cm^2·s^{-1}; $\boldsymbol{x}$ is the coordinate, mm. $\boldsymbol{X}$ is the width of the welded joint (diffusion zone), mm; $\boldsymbol{t_l}$ is the diffusion duration. The value of the coefficient $\boldsymbol{R}$ depends on changes in the concentration $\Delta\boldsymbol{C}/\boldsymbol{C}$ and is in the range from 2 to $2\cdot6^{-1/2}$.

To cool chromium and copper after welding, a copper clamp weighing 100 g was connected to the corresponding plates, the distance from which to the welded joint was 15 mm.

Chemical etching of the studied samples to reveal the microstructure was carried out in two stages: first in a 4% solution of nitric acid (HNO_3) and subsequent electrolytic etching in a chromic anhydride reagent.

The samples were studied using a JSM-840 scanning electron microscope (JEOL, Japan) with a Link-860/500 microanalysis system (Link Analytical, England). The studies were performed un the secondary (SE) and backscattered electron (BE) modes. Secondary electrons are generated by thin near-surface layers (1–5 nm), so they are sensitive to the surface state; this type of radiation provides information about the surface relief. For backscattered electrons that were reflected from the sample surface due to elastic scattering (depth 1–5 μm), the signal intensity is directly related to the average atomic number of elements in the studied area. This allows direct determination of areas of different composition. The electron probe current was 10^{-10}–10^{-8} A. This allowed us to study the nature of changes in the shape and size of individual fragments and elements of the surface structure.

For detailed determination of the composition of elements in the test sample, the energy dispersive analysis (EDS) technique was used, which allows microanalysis of dispersed particles and phases.

The main advantage of the microanalysis method is its high locality due to its use in conjunction with an electron microscope. The minimum size of the analyzed area depends on the composition of the material and is about 1 μm.

The main advantage of the energy dispersive spectrometer is the high speed of spectrum accumulation, the ability to conduct quantitative analysis in 1 minute and the rapid receipt of element distribution cards over the sample area.

The main disadvantage of the method is the low detection limit of most elements – no better than 0.1–0.5% by weight. The problem of local analysis of elements with low concentrations is solved by installing a second spectrometer with wavelength dispersion.

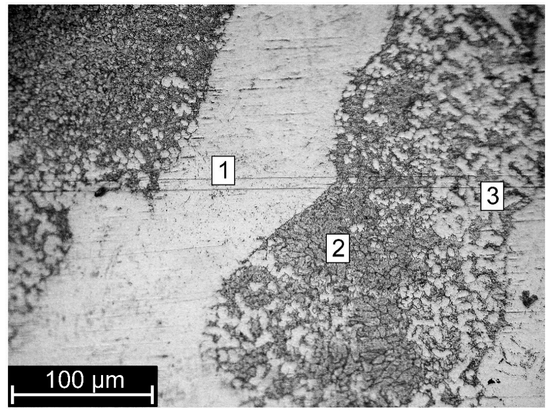
A TESCAN VEGA 3 scanning electron microscope with an energy dispersive X-ray analyzer was also used. Acceleration voltage range: 0–30 kV. Available detectors: SE, BSE, EDS. Resolution: 3–3.5 nm under SE mode. Maximum sample size: 50 × 50 × 50 mm.

5. Results of investigating the influence of electron beam motion and heating on the structure of the alloy material

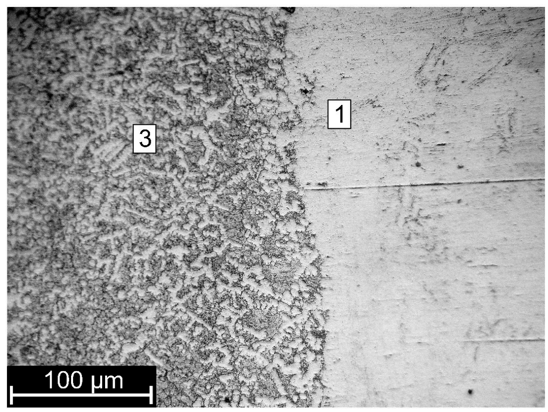
5. 1. The influence of heating on the structure of the alloy material obtained by a moving electron beam

As a result of electron beam welding under mode 1 without heating, copper-chromium welded joints with a weld were obtained, the microstructure of the material of which in different areas is shown in Fig. 1. The resulting weld is characterized by significant macroscopic heterogeneity. Along the line along the weld, both areas with the maximum chromium content (region 1) and with the maximum copper concentration (region 2) are observed. In the region of the alloy material where chromium and copper were mixed by the influence of the electron beam, the chromium-containing phase has a predominantly dendritic nature of the distribution of phase formations (region 3 – Fig. 1, *a–c*). At the same time, in the areas with the maximum concentration of chromium, its grains of the chromium phase have a globular character (area 1 – Fig. 1, *a, c*). The results of the micro-X-ray spectral analysis of the ratio of the concentration of chromium and copper of the characteristic structural elements of the weld are given in Table 3.

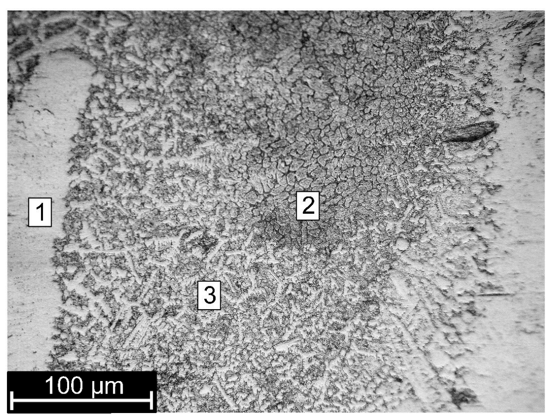
The areas of the alloy material in the area of contact of the weld with chromium have a microstructure with chromium grains of different sizes. Such grains with copper impurities (from 5 to 100 microns) border on clusters of copper-chromium eutectic distributed along the boundaries of such large grains (Fig. 2, *a*).



a



b



c

Fig. 1. Microstructure of the welded joint material of the copper-chromium compound obtained by a focused electron beam without heating in the areas: *a* — upper part of the welded joint; *b* — middle part of the welded joint; *c* — lower part of the welded joint; 1 — copper region; 2 — copper-chromium eutectic region; 3 — chromium region

The copper-chromium mixture material has a structure typical of eutectics in the form of elongated eutectic components (Fig. 2, *b*), or a scaly-type structure (Fig. 2, *c*) with small areas of submicron quasi-spherical inclusions of the chromium-based phase.

The concentration heterogeneity of the distribution between copper and chromium at the macro level is observed in all areas of the weld, which is obtained as a result of electron beam welding under mode 1 without heating.

Table 3

Results of micro-X-ray spectral analysis of the ratio of chromium and copper concentrations in the structural elements of the weld, which was obtained under the following mode: U_{acc}=60 kV, I_{eb}=40 mA, v_{eb}=10 mm·s^{-1}, P=5·10^{-3} Pa without heating

Concentration, at. %	Region 1	Region 2	Region 3
Cr	0.23–3.82	43.55–72.55	97.62–99.96
Cu	96.18–99.77	27.45–56.65	0.04–2.38

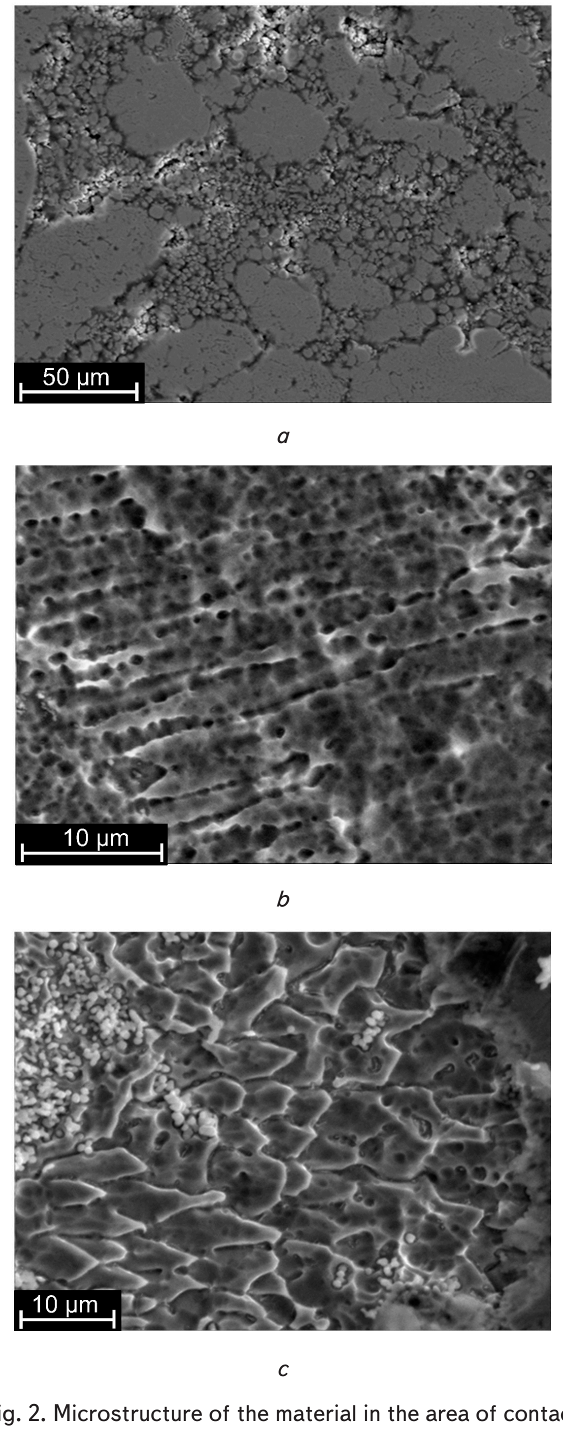


Fig. 2. Microstructure of the material in the area of contact of the weld with chromium: *a* — coarse-grained nature of the chromium-containing phase; *b* — linearly elongated type of copper-chromium eutectic; *c* — scaly type of copper-chromium eutectic

In the case of heating copper with heat removal from chromium, certain changes are observed in the microstructure of the alloy material. The dendritic nature of the chromium phase structure is not observed. Crystal grains, both based on copper with chromium impurities and chromium with copper impurities, have a wide range of sizes from 3–5 µm to 80–100 µm. Areas with significant macroscopic heterogeneity of copper distribution are formed both on the copper side and on the chromium side. Areas that have a homogeneous nature (Fig. 3, 4) are characterized by a small content of another element, which, however, exceeds the solubility level (Tables 4, 5) of both copper and chromium, respectively, in the phase diagram [5]. It should be noted that large areas of chromium with small copper impurities are observed at a distance of up to 800 µm from the chromium sample (Fig. 3). At a similar distance from the copper sample, regions with a copper content of 86–67% are observed (Fig. 4).

In the regions of copper-chromium eutectic, the material has a predominantly linearly elongated type of microstructure with areas of submicron quasi-spherical inclusions of the chromium-based phase, the number of which increases in areas with a higher chromium concentration.

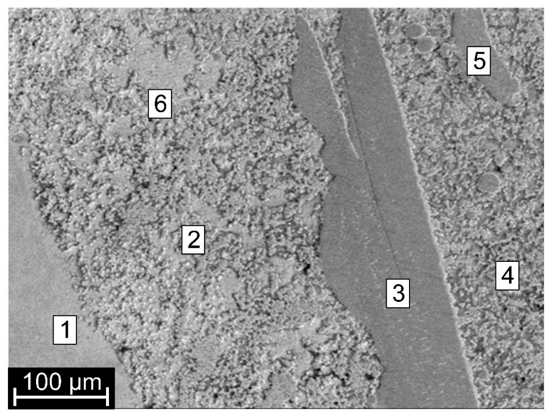


Fig. 3. Microstructure of the welded joint material of copper with chromium (from the copper side), obtained by a focused electron beam with heating of copper: 1 — copper region; 2 — copper-chromium eutectic region; 3 — chromium region; 4 — copper-chromium eutectic region; 5 — chromium region; 6 — copper region

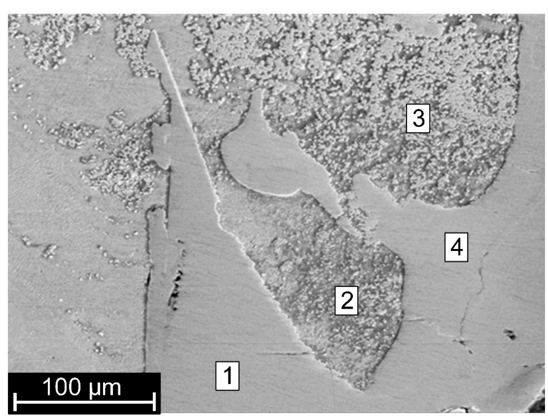


Fig. 4. Microstructure of the material of the welded joint of copper with chromium (from the chromium side), obtained by a focused electron beam with heating of copper: 1 — chromium region; 2 — copper-chromium eutectic region; 3 — copper-chromium eutectic region; 4 — chromium region

Table 4

Results of micro-X-ray spectral analysis of the ratio of chromium and copper concentrations in the structural elements of the weld (Fig. 3), which was obtained under the following mode: U_{acc} = 60 kV, I_{eb} = 40 mA, v_{eb} = 10 mm·s^{-1}, P = 5·10^{-3} Pa with heating of copper

Concentration, at. %	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
Cr	0.13	13.32	96.22	27.72	91.36	2.22
Cu	99.87	86.68	3.78	72.23	8.64	97.78

Table 5

Results of micro-X-ray spectral analysis of the ratio of chromium and copper concentrations in the structural elements of the weld (Fig. 4), which was obtained under the following mode: U_{acc} =60 kV, I_{eb} =40 mA, v_{eb} = 10 mm·s^{-1}, P = 5·10^{-3} Pa with heating of copper

Concentration, at. %	Region 1	Region 2	Region 3	Region 4
Cr	99.61	12.23	13.92	99.70
Cu	0.39	87.77	86.08	0.30

The concentration heterogeneity of the distribution between copper and chromium is observed in all macro-areas of the weld obtained as a result of electron beam welding under mode 1 with heating of copper and heat removal from chromium.

In the case of heating of chromium with heat removal from copper, the nature of the distribution between copper and chromium in the alloy material changes. Fig. 5 shows a typical structure of the alloy material.

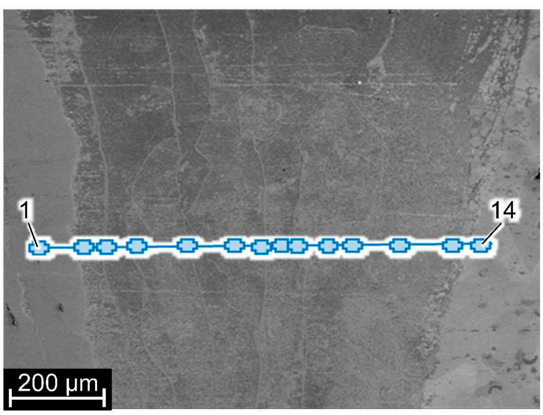
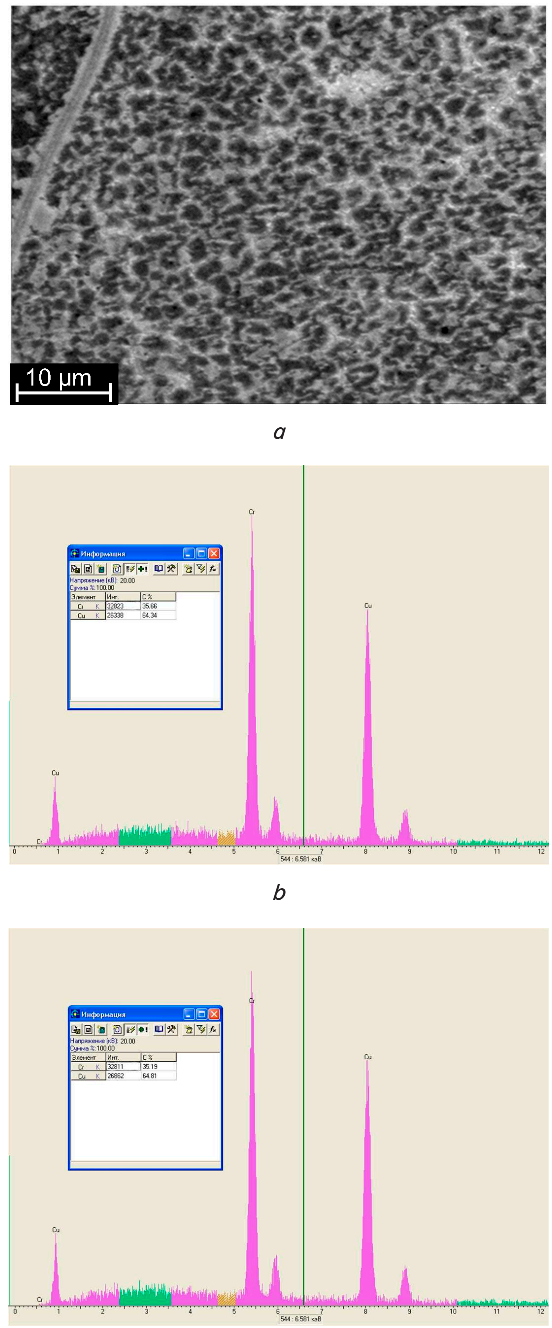


Fig. 5. Material structure of a welded joint of copper (right) and chromium (left), obtained by focused electron beam heating of chromium (micro-X-ray spectral analysis points 1–14 from left to right)

The results from determining the ratio between copper and chromium concentrations in different areas of the weld are given in Table 6.

To assess the possibility of forming a weld in a quasi-equilibrium liquid medium due to diffusion processes only, it is advisable to use formula (1). It should be taken into account that liquids are characterized by the diffusion coefficient $\boldsymbol{D}$ ~10^{-5} cm^2·s^{-1}, and the duration of the liquid bath (intensive diffusion period) $\boldsymbol{t_l}$ ~5–20 s). Such a diffusion zone does not exceed 200 µm in size and usually has a characteristic Gaussian concentration distribution. The width of the resulting weld is many times greater than the width of the diffusion zone and does not have characteristic exponential declines, which allows us to exclude diffusion processes from the factors that determine the width of the weld. Studies of the copper-chromium component of the material of the resulting weld have shown that this material is characterized by a cellular structure (Fig. 6, *a*), which also includes thin (3–5 µm wide) long layers, which are similar in microstructure to the material of the cell walls. The composition of the materials of the light layers and cell walls (Fig. 6, *a*) is characterized by the results of micro-X-ray spectral analysis (Fig. 6, *b*, *c*).



c

Fig. 6. Results of analyzing the copper-chromium component of the alloy material in the joint obtained by a focused electron beam with chromium heating: *a* – microstructure of the material; *b* – elemental composition of the light layer material; *c* – elemental composition of the cell wall material

Table 6

Results of micro-X-ray spectral analysis of the ratio of chromium and copper concentrations in different areas of the weld (Fig. 5), which was obtained under the following mode: U_{acc} = 60 kV, I_{eb} = 40 mA, v_{eb} = 10 mm·s^{-1}, P = 5·10^{-3} Pa with heating of copper

Region	Concentration, at. %	
	Cr	Cu
1	83.64	14.36
2	18.31	81.69
3	71.44	29.56
4	3.36	96.64
5	83.29	16.71
6	4.57	95.43
7	65.74	34.26
8	3.36	96.64
9	42.24	57.76
10	3.13	96.87
11	3.28	96.72
12	3.17	96.83
13	2.49	97.51
14	0.00	100.00

The core of such a cell is a copper matrix with dissolved chromium in a small concentration (up to 2.4% Cr), and the cell walls consist of a eutectic mixture of chromium and copper phases (Fig. 7).

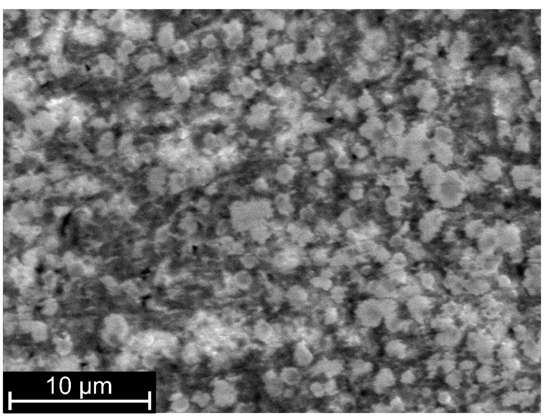


Fig. 7. Microstructure of the chromium-copper eutectic phase in a compound obtained by focused electron beam heating of chromium

The total ratio of chromium and copper concentrations in a separate area of the material is determined both by the ratio of the amount of light (copper-chromium eutectic) phase and dark (copper) phase, and by the ratio of the amount of chromium and copper in the light eutectic phase. Chromium inclusions in the composition of the eutectic have the appearance of quasi-spherical formations up to 4 μm in size. The shape of the formations is mainly non-equilibrium, with uneven edges.

The zone of concentration heterogeneity of the distribution between copper and chromium is observed in the areas of the copper-chromium interface of the weld, which was obtained as a result of electron beam welding under mode 1 with chromium heating and heat removal from copper.

5. 2. Effect of heating on the structure of the alloy material obtained by a defocused electron beam

As a result of electron beam welding with a stationary, linearly deployed along the joint, electron beam under mode 2 with heating of chromium and heat removal from copper, a welded joint of copper with chromium was obtained. The microstructure of the alloy material in different areas is shown in Fig. 8.

The resulting weld has a predominantly homogeneous structure with clearly defined boundaries with copper (Fig. 8, *a*) and chromium (Fig. 8, *c*).

The alloy material is characterized by two main structural components: a copper base with characteristic grains that are elongated with a predominant orientation transverse to the plane of the welded joint (Fig. 8, *b*), and quasi-spherical inclusions of the chromium phase with a size of 0.2 to 12 μm (Fig. 9, *a*). At the boundaries of copper grains, precipitates of the chromium phase with a size smaller than 0.5 μm are observed (Fig. 8, *b*).

The elemental composition of both phases is characterized by the results of micro-X-ray spectral analysis (Fig. 9, *b, c*). It should be noted that the average composition of the alloy material changes slightly from 3.99% chromium at the copper boundary to 4.98% chromium at the chromium boundary.

A feature of the chromium phase inclusions is the presence of two different types of inclusions. They are clearly determined under the condition of enlarging the image in Fig. 9, *a* by 10 times. In the first type of inclusions, the surface is quite smooth and close to spherical approximations (Fig. 10, *a*). Even with a complex shape of the inclusion, its components have smooth surfaces, parts of which can be approximated by spherical surfaces. The second type of inclusions is similar to a flower with petals growing from a single center (Fig. 10, *b*).

At the same time, the determined elemental composition of such formations (Fig. 9, *c*) gives grounds to consider them eutectic.

When approaching the copper region, a decrease in the concentration of chromium-containing inclusions in the copper base is observed.

When comparing the weld boundaries with the base materials, it should be noted that the boundary between the weld and copper is less well defined than the boundary between the weld and chromium (Fig. 11). The decrease in chromium concentration as it approaches copper occurs due to the decrease in the concentration of chromium-containing inclusions in the copper base.

This is particularly reflected in the microhardness (Fig. 12), which was measured in the copper matrix (points 1 and 2), in the weld (points 3–10) and in the chromium matrix (points 11 and 12). The microhardness was measured along the axis perpendicular to the plane of the welded joint with a step of 200 μm.

Changes in the microhardness of the welded joint material (Fig. 12) show the gradual strengthening of the welded joint material during the transition from copper to the weld. It is worth noting the sufficient stability of the microhardness over the main part of the weld obtained as a result of electron beam welding with a defocused electron beam under mode 2 with chromium heating and heat removal from copper. For the weld with copper and chromium, obtained under mode 2 with chromium heating and heat removal from copper, the minimization of the concentration heterogeneity of the distribution of copper and chromium is characteristic. When performing the weld under the same mode with copper heating and heat removal from chromium, welded joints without detected defects were obtained. The alloy material of these joints has a predominantly homogeneous structure with clearly defined boundaries with copper and chromium.

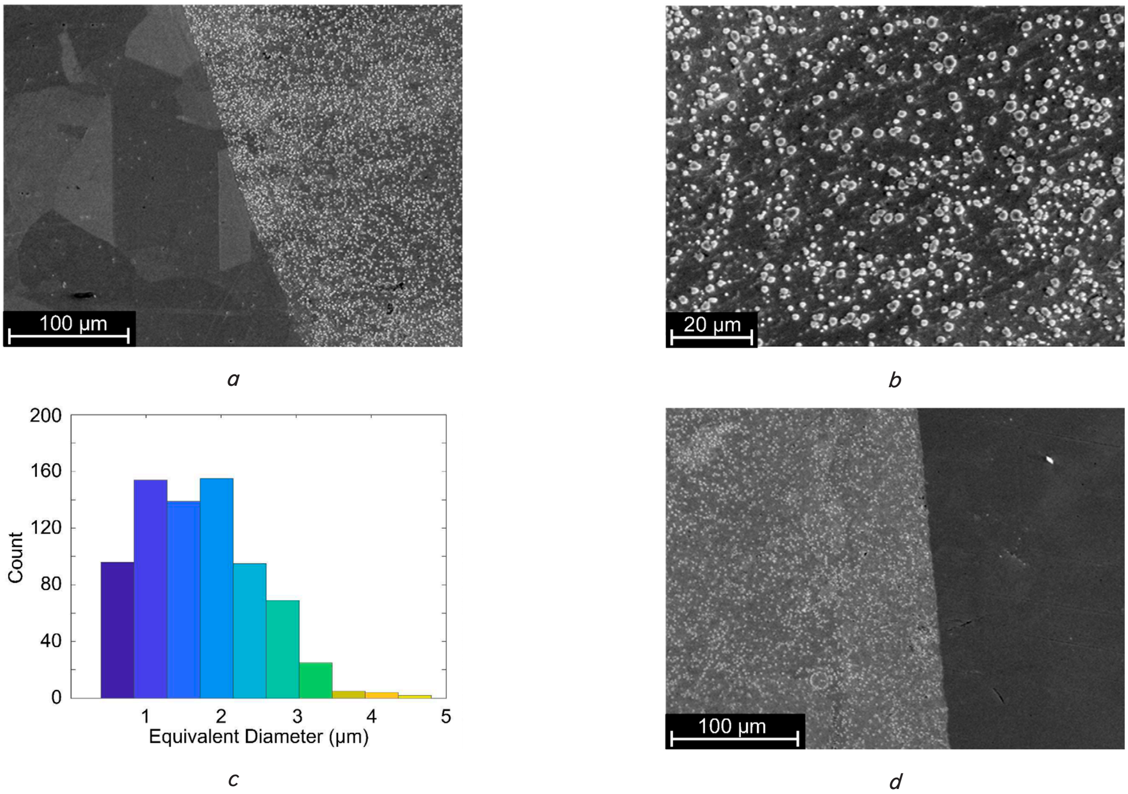


Fig. 8. Microstructure of the alloy material of the copper-chromium joint, which was obtained by a defocused electron beam with chromium heating: *a* – area of the copper (left) and weld (right) interface; *b* – weld area; *c* – size distribution of quasi-spherical inclusions of the chromium-based phase (image b); *d* – area of the weld (left) and chromium (right) interface

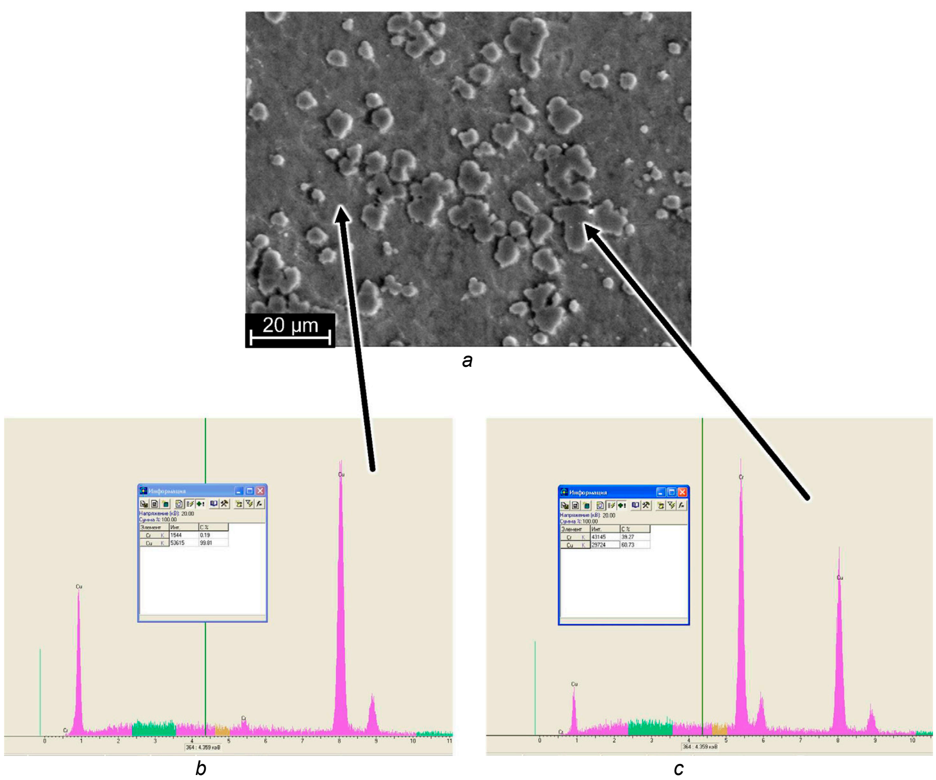
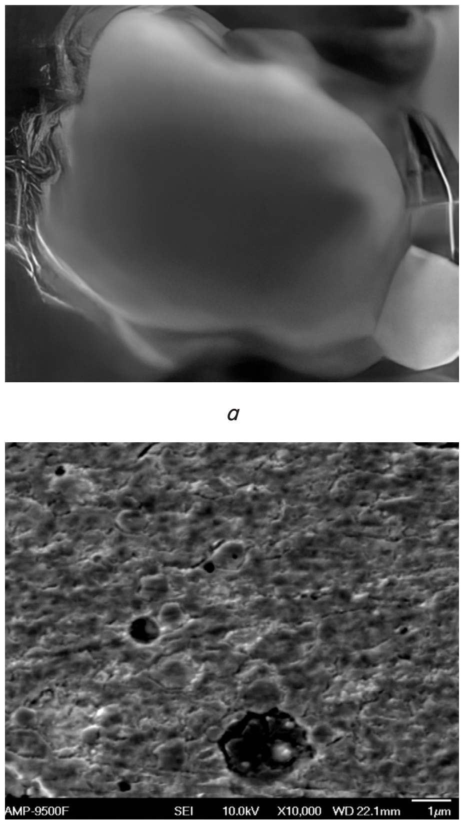


Fig. 9. Main structural components of the alloy material: *a* – distribution of copper and chromium phases in the weld area; *b* – micro-X-ray spectral characteristics of the copper phase; *c* – micro-X-ray spectral characteristics of the chromium phase



a

b

Fig. 10. General view of phase formations with an increased chromium content in the copper base material of the welded joint of a copper-chromium compound obtained by a defocused electron beam with chromium heating (×10,000):
a — quasi-spherical type; *b* — petal type

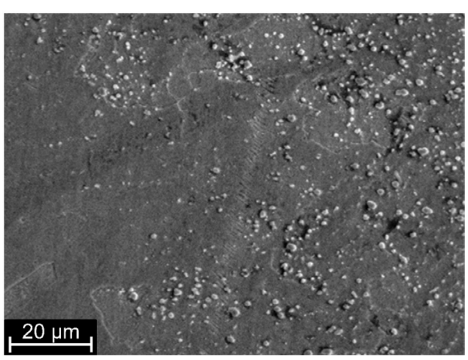


Fig. 11. Microstructure of the copper-weld transition region

A feature of the material of the resulting weld in comparison with heating from the chromium side and cooling of copper is the distribution of chromium-containing inclusions. In this variant of the weld, chromium-containing inclusions are located mainly at the boundaries of copper (with chromium impurities) grains (Fig. 13, *a*). In this case, the elongated directionality of copper grains and the orientation across the weld are even more pronounced (Fig. 13, *b*) than in the variant with chromium heating.

Analysis of the appearance of chromium-based inclusions revealed the predominant smoothness of their surfaces and a shape that is close to spherical approximations (Fig. 14).

For a weld with copper and chromium, obtained under mode 2 with heating of copper and heat removal from chromium, the concentration uniformity of the distribution between copper and chromium across the width of the weld is characteristic. At the same time, this material is characterized by the localization of chromium-containing inclusions at the boundaries of copper grains.

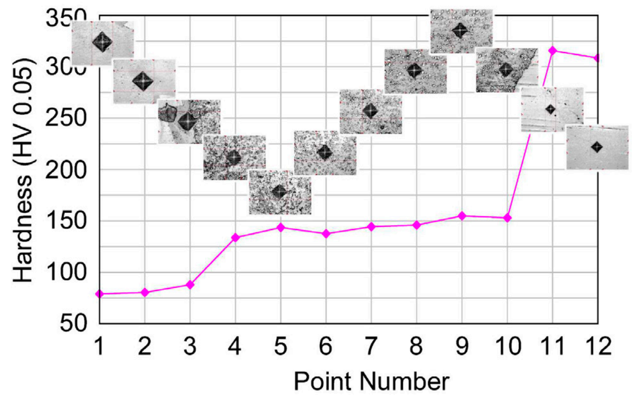
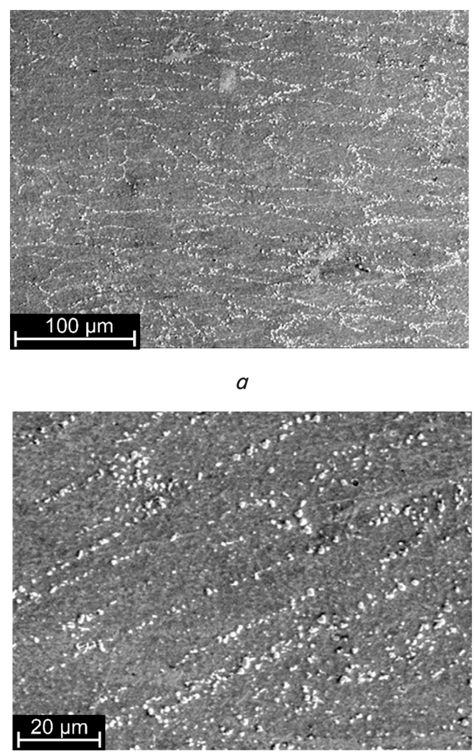


Fig. 12. Microhardness of the material of the welded joint between copper and chromium: 1, 2 — copper; 3–10 — welded joint Cu-Cr; 11, 12 — chromium



a

b

Fig. 13. Microstructure of the welded joint material of copper with chromium obtained by defocused electron beam with heating of copper: *a* — distribution of chromium-containing inclusions along the boundaries of copper grains;
b — elongated nature of copper grains

Thus, it was established that changes in the conditions of melt formation and crystallization in the zone of the welded joint between copper and chromium under the action of an electron beam significantly change the structure of the material of the weld between copper and chromium.

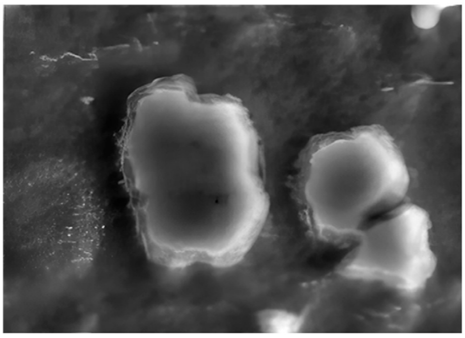


Fig. 14. General view of phase formations with an increased chromium content in the copper-based material of the weld of a copper-chromium joint, which was obtained by a defocused electron beam with heating of the copper (×10000)

6. Results of investigating the structural features of the alloy material at different welding cycles: discussion

Our experimental studies showed that as a result of electron beam welding of copper and chromium under modes 1 and 2 both with heating of copper or chromium and without heating, a weld is formed in which there are no macro defects. As a result of establishing the structural features of the alloy material depending on the characteristics of the welding cycle, it was determined that the main structural components of the alloy material are as follows:

– copper with a chromium content exceeding its solubility under equilibrium conditions;

– chromium with a copper content exceeding its solubility under equilibrium conditions;

– copper-chromium eutectic, which has a different structure and composition.

The formation of copper and chromium grains with an excess of the solubility of the second element may be associated either with the formation of a significantly supersaturated solid solution under thermodynamically non-equilibrium conditions. It is also possible to connect with the formation of copper-chromium eutectic cells in such grains, which are small in size and cannot be distinguished by the means of metallography used. In previous studies [7], it was shown that non-equilibrium conditions of a combination of mechanical alloying and spark plasma sintering make it possible to obtain a supersaturated solid solution of chromium in copper up to 0.94% chromium, which is significantly less than those given in Tables 4–6. Considering that under all conditions of the experiments performed on welding copper and chromium, the crystallization of the weld pool occurred slowly enough (to establish thermodynamic equilibrium), therefore, the presence of small-sized eutectic phases is more likely.

Analysis of the copper-chromium eutectic in the alloy material revealed that the following characteristic types of microstructures are observed:

– quasi-dendritic (Fig. 1);

– linearly elongated (Fig. 2, *b*);

– scaly (Fig. 2, *c*);

– cellular (Fig. 6, *a*);

– quasi-spherical (Fig. 7–9, *a*, 13).

The type of microstructure of the copper-chromium eutectic in the alloy material is determined by the welding conditions and the ratio of the copper and chromium content. The scaly and linearly elongated microstructure is observed at a chromium content not exceeding 30%, and the cellular and dendritic are characteristic of areas with a higher chromium concentration. All these types of eutectic microstructure are observed under the conditions of welding with a moving electron beam. Heating one of the metals and additional heat removal from the other leads to the preferential formation of cellular and quasi-spherical microstructures in the eutectic grains. During welding between copper and chromium with a stationary defocused electron beam, only the quasi-spherical type of microstructure is observed in the weld. To analyze the processes of forming the alloy material, it is advisable to determine the main processes that will be considered determining within the framework of this analysis. Among the processes that determine the formation of a weld in a melt that forms an electron beam, one can distinguish the redistribution of elements from the composition of the materials being joined and thermodynamic conditions (temperature and its changes). During the formation of a weld under the influence of a moving electron beam, melts with local large temperature gradients are formed, which move due to the electron beam. This can cause turbulent mixing at the macro level of the weld pool by flows of liquid copper and chromium. The importance of taking into account the mixing processes during welding of metals that form intermetallics was noted in [11]. The duration of the period of such movement is determined by the speed of movement of the mixing zone and its size. This affects the efficiency of the redistribution of elements.

For a weld formed by a moving electron beam, the distribution of copper and chromium at the macro level is characterized by inhomogeneity. It is probably determined by incomplete mixing throughout the melt volume, which is limited by the duration of the process. Such inhomogeneity is reduced by preheating chromium to 900°C and increasing heat removal from copper. Such conditions probably cause an increase in the period of the weld pool being in the liquid state and an intensification of diffusion processes in the alloy material.

The quasi-dendritic microstructure of the copper eutectic in chromium is observed in areas with a significant concentration of chromium (Fig. 1). During the crystallization of the chromium-containing phase, the liquid phase based on copper enters the boundaries of chromium grains and forms a network similar to dendrites. During the formation of a linearly elongated eutectic in regions with a lower chromium concentration, a likely influencing factor may be the local temperature gradient, which is caused by the influence of the electron beam. As is known [12], the temperature gradient is a factor that determines directional crystallization. In regions with a more inhomogeneous temperature distribution, the eutectic may crystallize in a direction along the temperature gradient – linearly elongated. In other regions, the directionality will be lower, and a scaly microstructure may form.

Under the conditions of preheating chromium and enhanced heat removal from copper, conditions are created for more intensive crystallization of the chromium-based phase from the copper side. Taking into account the existing tendency to separate chromium and copper in the liquid state [7], the process of crystallization of the chromium phase can occur in many micro-areas without restrictions on diffusion support for its growth. During the growth of copper-based grains, new crystals can displace chromium microcrystals at the boundary of their growth, which will contribute to the formation of a cellular microstructure (Fig. 6, *a*). Heating of chromium and enhanced heat removal from copper leads to the formation of a weld with a significant non-uniform distribution between copper and chromium by a moving electron beam. The most characteristic microstructure of the alloy material formed under such conditions is a cellular structure (Fig. 6, *a*), which includes thin (3–5 μm wide) long layers along the weld (Fig. 5), similar in microstructure to the material of the cell walls (Fig. 7). As a result of the preliminary heating of copper and enhanced heat removal from chromium, a concentration heterogeneity of the distribution between copper and chromium is observed. Enhanced heat removal from chromium did not show an effective effect, since, taking into account the low thermal conductivity of chromium, the determining factor of heat transfer in the weld zone under such conditions will be turbulent mass flows of chromium and copper. The grains of the copper-chromium mixture in the material of the resulting weld have a larger size range than in the weld obtained without heating and additional heat removal. But the general nature of the materials of both welds has similar features. It should be noted that under the condition of heating chromium, a high concentration of chromium in the alloy material is observed only in linear layers and cell walls. However, under the condition of heating copper, individual chromium-containing grains with a typical structure shown in Fig. 7 are observed. The microstructure of the scaly and linearly elongated type is observed in small grains with a chromium concentration of 2–4%.

For welding, which was performed by a stationary electron beam linearly deployed along the joint of metals, it is characteristic to obtain a weld with a material in the form of a mixture of a copper base with quasi-spherical inclusions based on chromium. Such welds are characterized by a material with concentration uniformity at the macro level and a chromium content of up to 5%. This is probably due to the absence of turbulent mixing of the weld pool at the macro level, characteristic of the movement of the electron beam. It should be noted that, as was shown earlier, diffusion processes are insufficient to form a weld in 7 seconds of exposure to a stationary defocused electron beam. However, if we take into account that the electron beam is formed by a beam of electrons that scans the impact surface with a frequency of 170 Hz, then the conditions for mixing the melt are preserved only at the micro level. This explains the lower concentration of chromium in the alloy material, the uniform distribution of elements in it (Fig. 8, 11) and the stability of the microhardness of the alloy material of the copper-chromium joint (Fig. 12).

Under the condition of heating of chromium and enhanced heat removal from copper, the alloy material is characterized by a homogeneous distribution between copper and chromium at the macro level. At the micro level, the structure is characterized only by a quasi-spherical type. The concentration of chromium in the weld varies from 3.99% to 4.98%, which is accompanied by an increase in the concentration of quasi-spherical inclusions with a size of 0.5 μm to 5 μm with a chromium content of 35–50%. Such inclusions are usually evenly distributed over copper grains with a low concentration of chromium, which exceeds its solubility under equilibrium conditions. Copper grains with low chromium concentrations tend to be anisotropy, which is expressed in their elongation in the direction of the temperature gradient due to heating of chromium and heat removal from copper. This is likely due to the directional crystallization of copper grains in the temperature gradient field.

Preheating of copper and enhanced heat removal from chromium also leads to the formation of a weld with a quasi-spherical type microstructure.

It is important to note that light quasi-spherical inclusions with an increased chromium content contain only about 40% chromium (Fig. 9, *c*). This probably means that light quasi-spherical phase formations are also eutectic. This hypothesis agrees well with one of the results of the magnification of images of chromium-containing formations (Fig. 10, *b*). This type of phase formation may be characteristic of the eutectic between copper and chromium. Another form of the chromium-containing phase remains more incomprehensible (Fig. 10, *a*, 14). The main question in this regard is the smooth nature of the surface of these inclusions. A faceted form of such surfaces would be more expected.

Analysis of the features of the formation of a welded joint under the influence of a moving and stationary electron beam gives grounds to believe that the movement of the beam enables the formation of a weld without macro defects. At the same time, there is a significant heterogeneity in the distribution of copper and chromium in the alloy material. Under such conditions, with all types of additional thermal exposure, the formation of various types of microstructures of the copper-chromium alloy is observed in different areas of the alloy material. This leads to the appearance of areas with a non-optimized microstructure in the joint, and accordingly – with reduced mechanical characteristics.

The optimized structure of the alloy material can be considered a concentrically homogeneous material with a microstructure that provides better mechanical characteristics [7].

Welding of copper and chromium with a stationary electron beam leads to the formation of a weld with a defect-free material that has a homogeneous distribution of copper and chromium at the macrolevel with a microstructure of the same type. In such material, quasi-spherical formations based on chromium are fairly evenly distributed in the copper matrix, which, according to the results reported in [7], act as obstacles that inhibit the movement of copper grain boundaries even at elevated temperatures. And smaller formations based on chromium, dispersed in the matrix (Fig. 8, *a*), fix dislocations.

The material of such a weld has a microhardness 75–100% higher than that of copper (Fig. 12), and the grains of the copper matrix have an elongated nature and are oriented across the weld, which probably provides additional strengthening in this direction.

Our results give reason to believe that the microstructure of the alloy material obtained during welding of copper and chromium under mode 2 is the most optimal for the welded joint. To obtain such a microstructure, it is necessary to provide preheating of chromium and heat removal from copper.

To obtain an optimal weld structure by electron beam welding, it is advisable to use a static or low-motion electron beam. This will ensure the uniformity of the redistribution of copper and chromium and a quasi-spherical type of the microstructure of the alloy material. It is advisable to provide heating of chromium and cooling of copper to form a temperature gradient, which will promote directional crystallization in the weld. The recommended mode of electron beam welding for copper and chromium is welding with a stationary electron beam, linearly deployed along the metal joint, with through-penetration. Mode: $U_{acc} = 60$ kV, $I_{eb} = 40$ mA, $v_{eb} = 10$ mm·s^{-1}, $P = 5 \cdot 10^{-3}$ Pa, beam sweep 2 × 20 mm, scanning frequency 170 Hz, duration 7 s. Heat treatment: preheating temperature of chromium 900°C, additional heat removal from copper during welding.

The scope of application of our results is mechanical engineering. In most cases, this concerns the manufacture of structural elements that are operated at high temperatures and require heat removal. The results could be used in the manufacture of relevant parts from copper and chromium by fusion welding in a vacuum using electron beam or laser heating. Achieving an optimized type of alloy material will ensure the presence in the part of a transition zone from heat-resistant chromium to non-heat-resistant heat-conducting copper from an alloy that has transitional properties in terms of heat resistance and thermal conductivity. This will contribute to increasing the operational characteristics of copper-chromium parts.

The study used a limited number of options for welding cycle parameters – modes 1 and 2 and three options for thermal conditions: no additional exposure, heating of chromium to 900°C with additional heat removal from copper and heating of copper to 600°C with additional heat removal from chromium. One electron beam welding mode is recommended for copper and chromium. There are probably other fusion welding modes that make it possible to obtain a welded joint between copper and chromium with an optimized version of the microstructure of the alloy material. This limitation will be eliminated in the process of compiling technological recommendations for the production of specific articles.

It should be noted that the uncertainty of temperature fields in the weld area and the heat affected zone can be considered a disadvantage of our study. This does not allow us to accurately determine the conditions for the formation of an optimized microstructure of the alloy material. To eliminate this drawback, possible areas for future research include computer modeling of changes in the temperature distribution over time in the material of the welded joint, taking into account preheating and subsequent heat removal.

7. Conclusions

1. Our study on the influence of heating each welded metal on the structure of the alloy material showed that the welding of copper and chromium with a moving electron beam leads to the formation of a weld with a significant non-uniformity of the distribution of copper and chromium. Determining the dependence of the microstructure of the alloy material on the conditions of electron beam welding demonstrated that under the conditions of heating of chromium and enhanced heat removal from copper, the characteristic microstructure of the alloy material is a cellular type structure, which also includes thin long layers along the weld, which are similar in microstructure to the material of the cell walls. As a result of the preliminary heating of copper and enhanced heat removal from chromium, a microstructure of scaly, linearly elongated and quasi-spherical types is observed in the alloy material. This makes it possible to achieve structural homogeneity only in local zones of the weld, which is due to incomplete and uneven mixing by a moving electron beam throughout the volume of the weld pool melt.

2. Welding of copper and chromium with a stationary electron beam, linearly deployed along the metal joint, leads to the formation of a structurally homogeneous weld with two types of residual chromium precipitates in the matrix. Unlike other welding conditions, when chromium is heated and heat is removed from copper, the characteristic microstructure of the alloy material is quasi-spherical inclusions based on chromium, evenly distributed over copper grains with small chromium additions, elongated in the direction across the weld. As a result of preheating copper and heat removal from chromium, segregation of quasi-spherical inclusions based on chromium is observed along the boundaries of copper grains. This is explained by the peculiarities of crystallization of a weld of uniform composition under quasi-equilibrium conditions of temperature gradient.

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, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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