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IDENTIFYING THE INFLUENCE OF TECHNOLOGICAL FACTORS ON THE STRUCTURE AND PROPERTIES OF CONTACT WIRE FROM SECONDARY COPPER

This paper reports the analysis of studies on the use of secondary copper for the production of articles based on it, namely the contact wire for electric transport.

The effect of the drawing step on the macro- and microstructure and physical and mechanical properties of the copper wire was studied. The optimal draw pitch for continuous copper casting is 8.2 mm. At a temperature of the melt (casting) of 1200 °C and a draw step of 8.2 mm, the average crystallization rate is ~300 °C/s. This provides sufficient time for crystallization, and with such parameters, the heat transfer from the metal receiver does not have a noticeable effect on the structure. At the same time, it was established that Mg is a modifier for liquid Cu while all other elements do not have such an effect and form solid solutions with copper.

It is shown that the increase in the concentration of silver from 0.082 at% to 0.092 at% led to an increase in specific electrical resistance by 0.582 %. As for other elements, namely, iron, the change in its amount from 0.002 at% to 0.005 at% increased the specific resistance of copper by 1.733 %. The change in nickel concentration from 0.024 at% to 0.036 at% and tin from 0.0010 at% to 0.0035 at% led to its growth by 2.927 % and 1.269 %, respectively

Keywords: copper contact wire, electrical resistance of continuously cast copper blanks, copper modification

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1. Introduction

The specific weight of secondary raw materials in the production of copper and its alloys is constantly increasing. In the future, secondary raw materials should become the main source of obtaining copper, and the processing of ore raw materials will cover the deficit in the balance between consumption and its production.

Its involvement in the metallurgical production cycle is of great economic importance, as it allows economical use of natural resources, reduces the man-made burden on the environment, and helps obtains metal in simpler and cheaper ways.

The successful use of secondary raw materials in non-ferrous metallurgy depends on the level of organization of collection, sorting, storage and, to a large extent, preparation for metallurgical processing and obtaining a contact wire from it.

Secondary copper raw materials contain various impurities in their composition. For example: copper shavings contain copper and copper alloys, iron impurities, oxides of silicon, aluminum, etc. These impurities get into shavings during metal processing, scrap collection, and its storage. As a rule, secondary copper raw materials consist of various parts, gears, firearm casings, scraps, etc. In addition, it contains up to 10 % of earthy waste and up to 15 % of steel components.

During crystallization of the melt at a relatively low speed, the nuclei have time to coagulate, which leads to a decrease in the number of grain crystallization centers, an increase in supercooling, and the speed of crystal branching. It should be noted that the number of nuclei that grow and their growth rate under real conditions of metal hardening will be limited by soluble surface-active oxygen, which is adsorbed on the surface of crystals (grains) and as a result will inhibit their growth and coagulation. This occurs due to the increase in supercooling during the crystallization process. Subcooling will be greater, the higher the concentration of dissolved oxygen in the melt.

Such a structure is dangerous for plastic processing because it is characterized by much weaker intergranular bonds. This leads to the formation of cracks on the surface of the cast billet when it leaves the molding device, as well as during the first passes in the rolling process. Cracks and gas porosity on the surface of the cast workpiece reduce the quality of the wire. Therefore, one of the methods of effective action on the structure and properties of the metal at the stage of its hardening is the modification of the melt. As a result, it is necessary to ensure uniform distribution of modifying and alloying components during casting, as well as to obtain a structure of cast blanks favorable from the point of view of plastic processing.

Thus, the study of the influence of various chemical elements on the structure and properties of copper and its alloys, as well as the development of technological regulations for continuous casting of articles from these alloys is an important and urgent problem.

2. Literature review and problem statement

Articles made of copper and its alloys are widely used in almost all industries [1]. However, in publications there is no information about the properties of the contact copper wire for electric transport. It is known that copper occupies a special place in the production of this type of articles, namely due to its high electrical and thermal conductivity. In terms of electrical conductivity, Cu is second only to silver and therefore is the most important conductor. It has high corrosion resistance and manufacturability, which leads to its wide use in industry both in its pure form and in the form of alloys. For example, alloys of the Cu-Nb, Cu-Fe, Cu-Ag, and other systems exhibit high strength and electrical properties. This is due to the limited solubility of the components in each other, and therefore the copper matrix remains practically free of impurities, due to which sufficiently high electrical conductivity is ensured. At the same time, with sufficient dispersion, relatively high strength can be achieved. It is possible to obtain a high dispersion of the structure due to the use of increased plastic deformations.

The main volume of copper and its alloys is used in industry in the form of semi-finished articles, the production of which is continuously increasing. Scientific and technical progress in industries that use copper and its alloys requires an increase in the quality of articles, namely contact wire for railroad transport.

It is known that the main method of production of copper wire rod is the method of joint continuous casting and rolling, which is used to make approximately 96 % of this product in the world [2, 3]. This technology leads to an increase in the productivity of installations and a decrease in energy consumption. It makes it possible to obtain articles without preheating before rolling, the possibility of their production without welding seams, reducing production costs and compactly placing production lines [4, 5].

Various technological aspects of the contact copper wire and the effect of some chemical elements on its properties are considered in works [6–10]. For example, paper [6] presents the features of obtaining long blanks from technical copper by processing welding seams, which very often lead to breakage. The authors of work [7] investigated the regularities of solidification of blanks during continuous casting from top to bottom and the features of the design of the crystallizer for such a process. As for works [8–10], they report the results of the influence of tin and magnesium on the properties of copper. It was established in [8] that the content of Sn in the alloy of about 0.4 at% often does not provide an opportunity to obtain the required level of physical, mechanical, and electrical properties. The influence of Mg on the properties of copper is given in the following papers. It was shown that the Cu-Mg alloy after mechanical processing at a temperature of 200 °C has a fine grain and the necessary electrical conductivity [9]. In [10], the parameters of strength, relative elongation, and electrical resistance of Cu-Mg alloys, which contained from 0.3 to 0.5 wt% magnesium, were determined and presented

It follows that the quality of copper wire in many cases depends on the chemical composition of the metal during continuous casting. At the same time, the following defects are most common: subcrustal gas sinks and pores, cracks, nonalloys, intracrystalline cracks, and transcrystallization. These defects lead to the appearance of cracks in the copper wire or to its breaking. The reason for the formation of this type of defects in cast blanks can be harmful impurities, low casting temperature, as well as heat removal conditions during crystallization.

It is known that the high speed and temperature of casting, as well as intensive cooling of the casting in the crystallizer leads to the formation of a large columnar structure, a significant temperature drop along the cut, and an increase in the probability of cracks in the cast blanks. The quality of articles is determined by their crystalline structure, the level of mechanical and operational properties, the uniformity of properties, and the chemical composition of the cross-section and length of the workpiece, as well as by the number of defects and the condition of the surface. All these factors mainly depend on the technological parameters of melting and casting.

Works [11, 12] report the results of obtaining copper articles using horizontal and vertical continuous and semi-continuous techniques of casting. The analysis showed that it is better to use the vertical casting method to study the process of growth of the hard crust of the casting, which crystallizes. This makes it possible to qualitatively control its growth and avoid damage to the workpiece.

As for papers [1, 13], they consider the theoretical and technological foundations of these processes. The authors of [1] studied the effect of Mg, Ti, RZM, and vibration on the properties of continuously cast copper. As a result, it was established that this type of processing led to a significant increase in mechanical properties and some increase in electrical resistance. In [13], the effect of modification and cooling rate on the hardening process, structure, and electrical properties of Cu was also investigated. It is shown that additions of Mg, Ti, Al-Ti-B ligatures, and mixed metal reduce the structural characteristics of M00 and M1 copper. However, at the same time, the electrical conductivity of the latter significantly decreases.

In connection with this, we investigated the influence of Mg, Ag, Fe, Ni, Sn, and Sb on the properties of secondary refined copper. This led to a significant strengthening of alloys and a slight decrease in electrical conductivity [14].

Based on the review of the above studies, the following has been established: questions related to the hardening of copper blanks remain unanswered, as a result of which subcrust shells and pores appear in them, which leads to a break in the casting process. In addition, the issue of modifying and alloying elements on the structural characteristics of the copper contact wire remains unresolved. However, the question of the impact of the step of pulling the copper blank on its structural and mechanical characteristics remains unanswered, which significantly reduces the quality of the blanks. The question of the effect of alloying additives of iron, tin, and other elements on the electrical resistance of copper blanks under special modes of continuous casting has also been insufficiently investigated. All this allows us to state that it is advisable to conduct a study of the above factors affecting the quality and productivity of the process of obtaining copper blanks.

Thus, the properties of copper and alloys based on it in the liquid state play a very important role in the process of obtaining a contact wire, namely in the melting and pouring technology. In this regard, the following issues require clarification and further research:

– it is necessary to establish the nature of the influence of Mg, Ag, Sn, Fe, Ni on liquid copper and the specific resistance of alloys based on it;

– to establish a relationship between the drawing step during continuous vertical casting of copper blanks and their structure;

– to improve the methodology for calculating the kinetics of hardening of copper blanks.

3. The aim and objectives of the study

The purpose of this work is to determine the influence of technological factors on the structure and properties of copper, which was obtained during the processing of copper waste and the production of a contact wire for railroad transport using the continuous casting method. This will make it possible to improve the contact line and increase the speed of electric transport.

To accomplish the aim, the following tasks have been set:

– to calculate the kinetics of hardening of copper blanks;

– to investigate the modifying properties of some chemical elements;

– to investigate the influence of the drawing step on the hardening process of copper blanks, their structure, and physical and mechanical properties;

– to investigate the effect of Ag, Fe, Ni, Sn, and Sb additives on the resistivity of copper.

4. The study materials and methods

Samples of secondary pre-refined copper (Table 1) and Cu with additives of silver, magnesium, tin, iron, and nickel were used for research, which were obtained at a vertical continuous casting installation. They were obtained at different cooling rates, that is, with different drawing steps. The latter varied from 3.3 mm to 16.8 mm. For example, in one minute at a 3.3 mm draw step, a one-meter-long workpiece with a diameter of 12.7 mm was obtained.

Table 1

Chemical composition of secondary refined copper

Cu (99,9930 % mass share)					
Additive content, % mass share					
Ag	2.04×10^{-3}	Zn	2.64×10^{-4}	Cr	3.22×10^{-5}
Fe	1.33×10^{-3}	Mn	1.05×10^{-4}	P	2.86×10^{-5}
Pb	1.03×10^{-4}	Te	8.40×10^{-5}	Se	3.22×10^{-5}
Sn	2.52×10^{-4}	Bi	5.50×10^{-5}	Al	6.36×10^{-5}
Ni	5.39×10^{-4}	As	3.21×10^{-5}	Cd	9.70×10^{-6}
Sb	1.73×10^{-4}	Si	1.83×10^{-5}	Mg	3.90×10^{-6}
S	1.25×10^{-4}	Co	4.99×10^{-5}	O_2	1.71×10^{-7}

To reduce the concentration of oxygen in liquid copper and alloys based on it, the process of melting and obtaining blanks from it was carried out in a protective atmosphere. In this case, flake graphite served as flux. This led to the formation of a reducing environment due to the increased content of carbon monoxide, which in this case has the function of a deoxidizer.

The general view of the installation fragment is shown in Fig. 1.

This equipment uses a mobile crystallizer. In it, the hardened crust is stationary relative to the surface of the crystallizer, and therefore the strength of the crust does not imitate the maximum possible productivity of the method. The maximum possible productivity in such a crystallizer is determined only by the intensity of heat removal and its volume.

Fig. 1. A fragment of a laboratory installation for vertical casting of copper rods

5. Research results of continuously cast copper samples

5. 1. Calculation of hardening kinetics of copper blanks

The theoretical analysis of the kinetics of solidification of copper billets was based on the solved equations of the heat balance of the liquid metal-solidified billet-liquid system:

$$dQ_l+dQ_s-\alpha(T_{sam}-T_{env})SdT, \quad (1)$$

where dQ_l is the change in the heat content of the liquid metal; dQ_s – change in the heat content of the solid workpiece; α is the heat transfer coefficient from the casting surface to the cooling medium; T_{sam} – workpiece temperature; T_{env} is the temperature of the environment; S is the surface area.

The effective specific heat of crystallization was determined taking into account the accumulated heat, which is released during the solidification process, according to the known formula:

$$q_{ef}=q+c/2(T_L-T_C), \quad (2)$$

where q is the actual heat of crystallization; c is the specific heat capacity of liquid copper.

When using high-purity copper, that is, if it melts congruently, then equation (2) takes the following form:

$$q_{ef}=q+cT_{mel}/2, \quad (3)$$

where T_{mel} is the melting temperature.

The specific heat of overheating of the liquid metal was determined using the following expression:

$$q_{over}=c(T_0-T_{cr}), \quad (4)$$

where T_0 is the temperature of the metal that was in the crystallizer.

Using the equality of the specific heat flows through the solid surface crust and from the surface of the workpiece into the cooling medium, the surface temperature of the workpieces at a given moment of time was calculated according to the following equation:

$$\lambda/h\ (T_{cr}-T_{sam})=\alpha(T_{sam}-T_{env}), \quad (5)$$

$$T_{sam}=(\lambda T_{cr}+\alpha h T_{env})/(\lambda+\alpha h), \quad (6)$$

where λ is the specific heat of fusion; h is the crust thickness.

The initial thermophysical data were taken according to reference data, q_{ef} – calculated according to equations (2), (3). Calculations are given for workpieces with a diameter of 12.7 mm.

The analysis of solidification kinetics showed that at a temperature of the melt (casting) of 1200 °C, the average speed of solidification in 5 s is ~300 °C/s with a draw step of 8.2 mm. As the pouring temperature and the drawing step increase, the rate of solidification decreases, and crust growth is accompanied by a decrease in surface temperature. At the initial moment of hardening, a sharp decrease in the temperature of the surface of the copper billet is observed, and subsequently the rate of temperature change is not significant and is approximately 1–1.5 °C.

5. 2. Modifying activity of some chemical elements

Magnesium, silver, tin, iron, and nickel have different effects on the structure and properties of continuous copper. They were selected and analyzed according to the electronic modification theory. Based on it, elements that have a lower value of the effective ionization potential U_{ef} than the metal base of the alloy will have a modifying effect during crystallization to one degree or another. Elements that have a higher U_{ef} than the metal base of the alloy will not act as modifiers, that is, contribute to the consolidation of the crystal structure. This is due to the fact that the lower the value of the ionization potential, the easier the chemical element gives up its valence electrons, and vice versa. The second factor that characterizes the ability of a chemical element to influence the formation of a structure is its solubility in a matrix alloy or metal. An element exhibiting the properties of a modifier must have low solubility in solid metal and limited solubility in liquid. Both of these factors are included in the semi-empirical formula for calculating the modifying activity of elements:

$$\mu=(U_{me}-U_{mod})/C_s, \quad (7)$$

where μ is the coefficient of modifying activity, eV/at%; U_{me}, U_{mod} – effective ionization potentials of matrix and modifier, eV; C_s is the solubility of a chemical element in a solid metal, % at.

The value of the modifying activity (μ) for Mg, Ag, Sn, Fe, and Ni is given in Table 2.

Based on the data above, it can be concluded that magnesium is a modifier for liquid copper, and all other elements are not modifiers.

The elements presented above were introduced into liquid copper at a rate of 0.05–0.10 wt%. The samples were placed in a copper tube, pressed, and introduced into the melt at a temperature of 1200±10 °C.

Table 2

Coefficients of modification activity of the investigated elements in copper

Chemical element	C_s, at%	U_{mod}, eV	μ, eV, at%
Mg	3.00	2.42	0.050
Ag	13.60	7.58	–0.369
Sn	0.0001	3.31	–7500
Fe	0.30	3.00	–1.470
Ni	100	3.20	–0.006

Note: for copper U_{Cu}=2,56 eV

5. 3. The influence of the drawing step on the hardening process of copper blanks, their structure, and physical and mechanical properties

The analysis of the kinetics of solidification showed that at a temperature of the melt (casting) of 1200 °C, the average speed of solidification is optimal at a draw step of 8.2 mm. As the pouring temperature and the drawing step increase, the rate of solidification decreases, and crust growth is accompanied by a decrease in surface temperature. In the future, the rate of temperature change is not significant and is approximately 1–1.5 °C.

After different drawing speeds, samples were cut out to study physical, mechanical properties, and macro- and microstructure [15–17]. Fig. 2–7 show the dependence of the drawing step on these characteristics. As for the mechanical properties, they do not significantly depend on the drawing step. However, studies have shown that the maximum values of the obtained values are observed at a step of the draw of 8.2 mm.

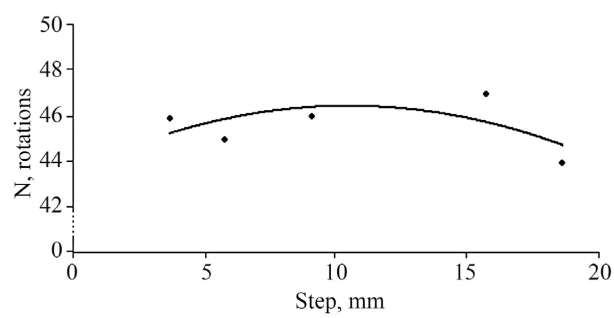

Fig. 2. Dependence of the number of rotations of twisting before the breakdown of a cast copper wire on the drawing step

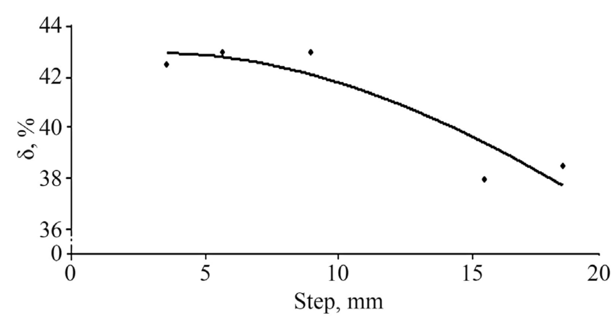

Fig. 3. Dependence of the relative elongation of the cast copper wire on the drawing step

In addition, the analysis of the obtained results shows that the specific electrical resistance of copper can be adjusted by changing the cooling rate. It can be seen from the presented experimental data that it increases with the increase of the drawing step, that is, the electrical conductivity decreases, but not significantly by only 0.086 %. Thus, since electrical conductivity is sensitive to changes in structure and phase composition, a change in the cooling rate affects its value.

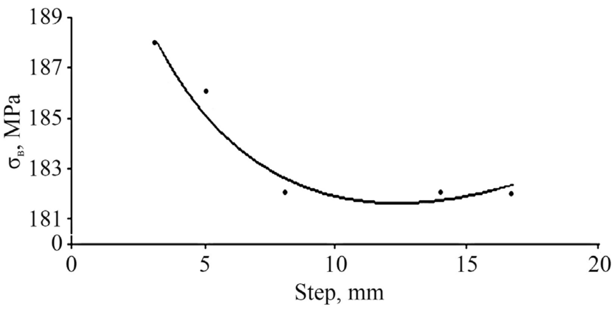

Fig. 4. Dependence of the tensile strength of a cast copper wire on the drawing step

Fig. 6, *a–f*, 7, *a–f* show the micro- and macrostructures of samples of contact copper wire, which was obtained with different drawing steps in the process of continuous casting. All of them have a polyhedral shape in the center of the grain. The area occupied by these grains also depends on the drawing step and decreases with its growth. Starting from the drawing pitch of 3.3 mm to 8.2 mm, the copper grains become thinner and spherical (8.2 mm pitch). When the drawing pitch is increased to 16.8 mm, the grains are crushed and become a little shorter.

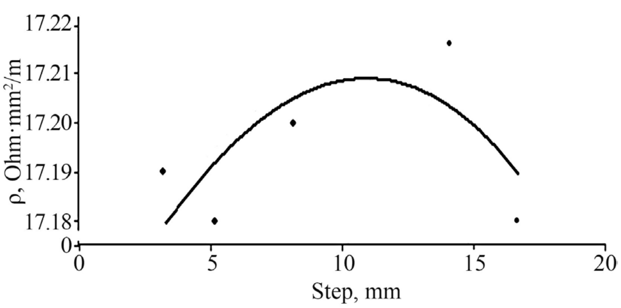

Fig. 5. Dependence of specific electrical resistance ($\rho = a \cdot 10^{-4}$ Ohm·mm^2/m) of cast copper wire on the drawing step

As for the macrostructure of the contact copper wire samples, they all have a coarse crystal structure. It is characterized by a columnar structure in cast blanks and shows that the nature of solidification changes from directional crystallization (from the edges of the sample to the center) to partially volumetric. Decreasing the drawing step on the one hand increases the time of exposure to the cooling workpiece from the side of the crystallizer, and on the other hand, increases the time of exposure from the side of the metal receiver. Based on this (Fig. 7, *a–f*), it can be concluded that with small values of the drawing step, the influence of heat from the metal receiver is dominant on the workpiece, and with large values, it is insufficiently cooled in the crystallizer. Experimentally, it has been shown that the optimal draw step for continuous casting of copper and Cu with additions of silver, magnesium, tin, iron, and nickel is 8.2 mm, which provides sufficient time for crystallization and at the same time heat transfer from the metal receiver does not cause a corresponding effect. This fact is confirmed by the data shown in the Fig. 6, *a–f*, 7, *a–f*.

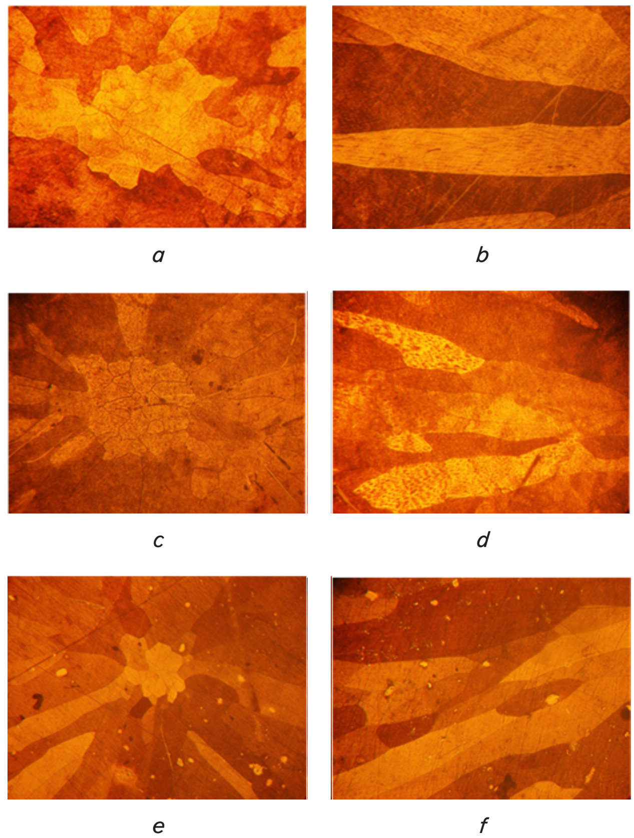

Fig. 6. Microstructure of copper ingots after drawing with a step: *a* — 3.3 mm cross section; *b* — 3.3 mm longitudinal section; *c* — 8.2 mm cross section; *d* — 8.2 mm longitudinal section; *e* — 16.8 mm cross section; *f* — 16.8 mm longitudinal section

The analysis of the surface of the cast blanks showed that an increase in the casting temperature and the step of drawing also leads to an increase in the size of cracks on the surface of the articles. A high-quality surface is observed at draw steps of 3.3 mm and 8.2 mm. This is probably due to the fact that the cast billet obtained at high drawing speeds (16.8 mm) and casting temperature (1200 °C) at the exit from the crystallizer has an insufficiently strong hard crust, which leads to the formation of cracks.

To confirm the obtained data, the microhardness of the samples was measured at different drawing steps. It was established that at low drawing steps, the hardness of the cast billet in the cross section increases (HB changes from 44 to 49 units) at a reduced casting speed. At a high casting speed, i.e., at a high drawing step, the hardness decreases and is 43–44 HB. This is probably due to the appearance of porosity. As a result of the conducted research, it was established that in the blanks obtained at a draw step of 16.8 mm, there is an accumulation of a relatively large number of pores in the upper and side zones of the billet.

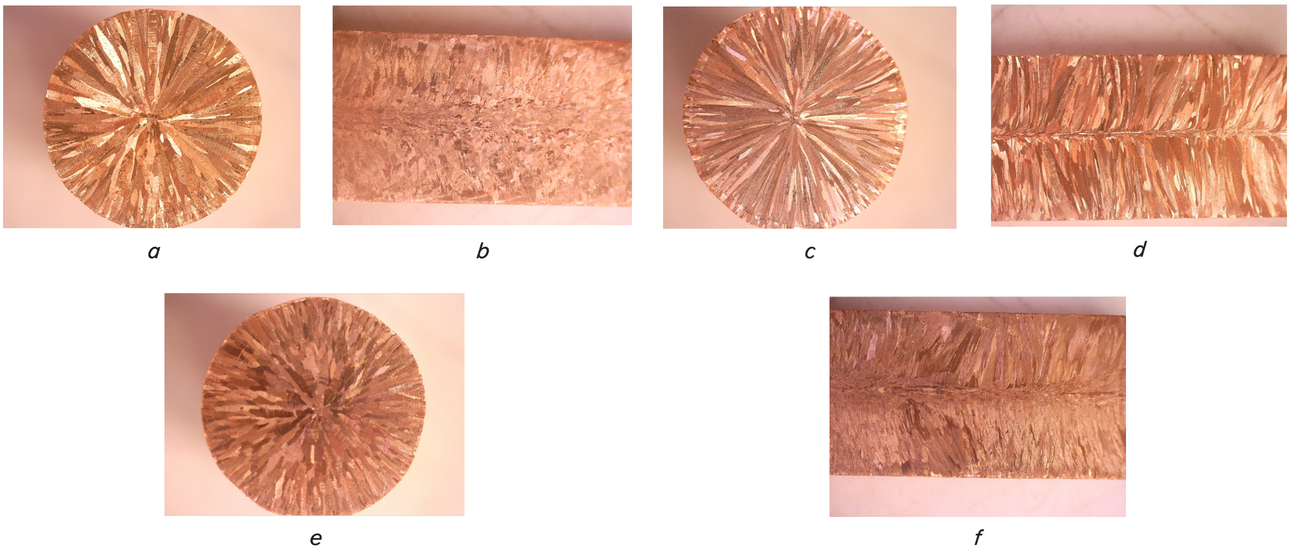

Fig. 7. Macrostructure of copper ingots after drawing with a step: *a* – 3.3 mm cross section; *b* – 3.3 mm longitudinal section; *c* – 8.2 mm cross section; *d* – 8.2 mm longitudinal section; *e* – 16.8 mm cross section; *f* – 16.8 mm longitudinal section

5. 4. The effect of additives Ag, Fe, Ni, Sn, and Sb on the resistivity of copper

As for the influence of the chemical elements presented above on the resistivity of copper, they are shown in Fig. 8–12. Samples for research were obtained at a draw step of 8.2 mm.

Black line – averaged data, black confidence intervals – error of the mean value for 95 % confidence probability, red confidence intervals – scatter of experimental points for 95 % confidence probability.

Mathematical processing of experimental data made it possible to represent them in the following analytical form:

$$p=0.01646+0.01022\cdot[Ag], \quad (8)$$

$$p=0.01708+0.16221\cdot[Fe]-8.58715\cdot[Fe]^2, \quad (9)$$

$$p=0.01712+0.04578\cdot[Ni], \quad (10)$$

$$p=0.01719+0.0888\cdot[Sn], \quad (11)$$

$$p=0.01717+0.304\cdot[Sb]. \quad (12)$$

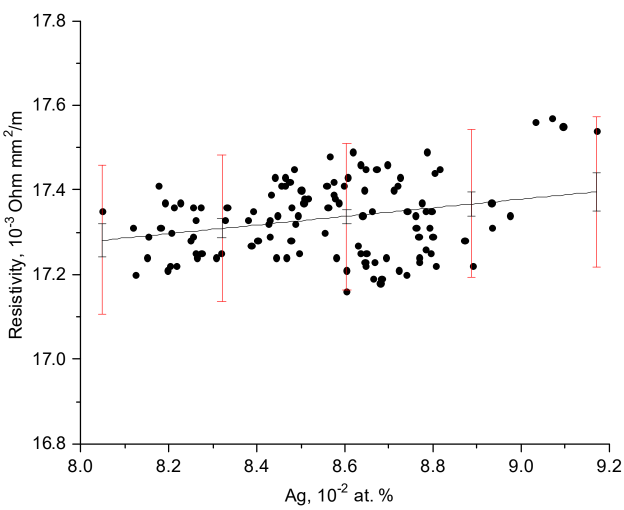

Fig. 8. The effect of silver on copper resistivity

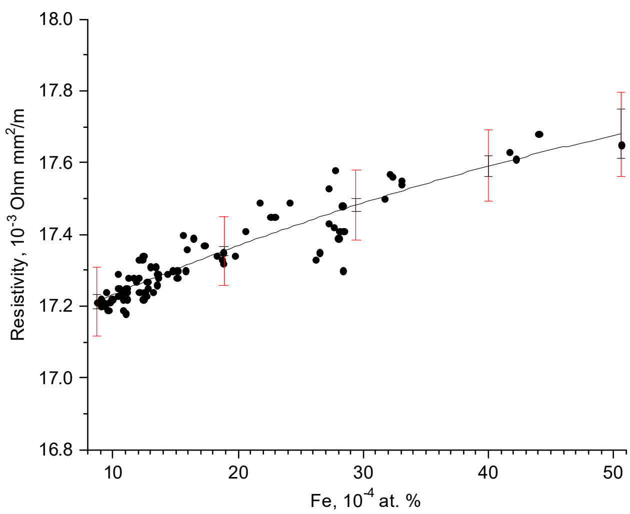

Fig. 9. The effect of iron on copper resistivity

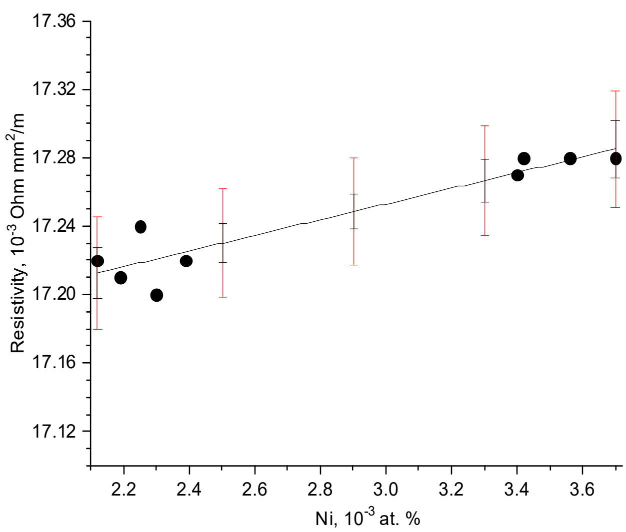

Fig. 10. The effect of nickel on copper resistivity

Table 3 gives the influence of the concentration of the studied elements on the electrical properties of copper.

Table 3

The effect of addition of chemical elements on the electrical properties of copper

No. of emtry	Additive	Concentration (1), at%	Concentration (2), at%	$p{\cdot}10^3$ (1), Ohm·mm²/m	$p{\cdot}10^3$ (2), Ohm·mm²/m	*E* (1), MCm/m	*E* (2), MCm/m	*E* (1), % IACS	*E* (2), % IACS	Change in electrical properties, %
1	Ag	0.082	0.092	17.29804	17.40024	57.81	57.47	99.67	99.09	0.582
2	Fe	0.002	0.005	17.3700714	17.67637125	57.57	56.57	99.26	97.57	1.733
3	Ni	0.024	0.036	17.21872	11.76808	54.89	53.28	94.64	91.86	2.927
4	Sn	0.0010	0.0035	17.2788	17.5008	57.87	57.14	99.77	98.52	1.269
5	Sb	0.00015	0.00035	17.2456	17.7264	58.00	57.88	100	99.79	0.352

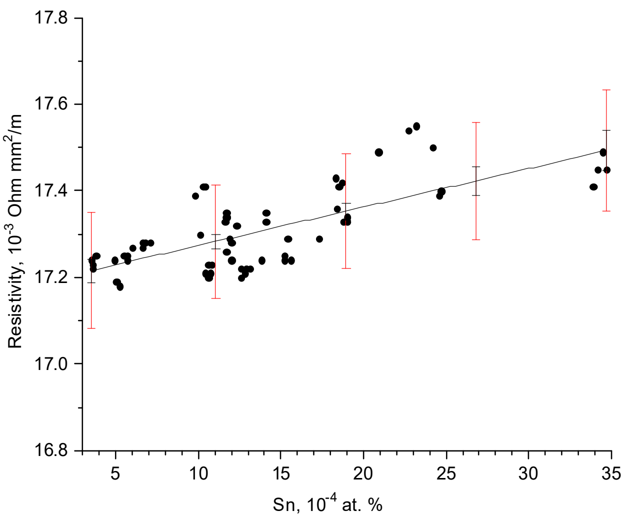

Fig. 11. The effect of tin on copper resistivity

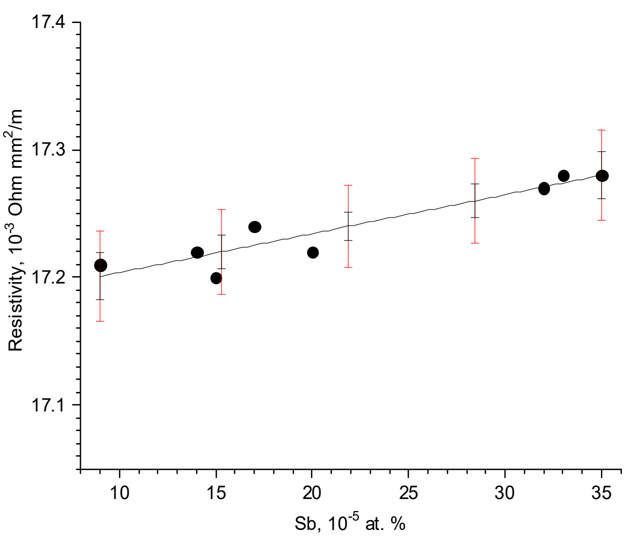

Fig. 12. The effect of antimony on copper resistivity

The data above (Table 3) show that a slight increase in the concentration of the studied elements leads to a decrease in the electrical conductivity of the copper samples. For example, the increase in the amount of silver from 0.082 at% to 0.092 % at% led to a decrease in electrical conductivity by 0.34 MSm/m; iron, the change in its amount from 0.002 % at% to 0.005 at% – by 1.00 MSm/m; tin from 0.0010 at% to 0.0035 at% – by 0.73 MSm/m.

6. Results of studying the effect of modification and cooling on the physico-mechanical and electrical properties of copper

A feature of the proposed method and our results is, compared to work [1], minor changes in electrical conductivity and a significant increase in the mechanical characteristics of copper samples, which is associated with the optimization of the thermal conditions of the drawing process. In addition, the establishment of the optimal step of drawing of copper blanks and modifying additives made it possible, compared to work [13], to ensure the creation of such a structure that provides its necessary mechanical properties and increased electrical conductivity.

Our research provided a comprehensive solution to the tasks set in terms of hardening of copper blanks, modification, the influence of the drawing step on the hardening process and their structure, as well as the influence of iron, nickel and other element additives on electrical resistance. Analysis of thermal conditions and heat flows in the solidification zone (6) showed that the solidification rate of the copper billet largely depends on the temperature of the melt and its drawing speed. By adjusting the temperature of the melt or the speed of drawing, it is possible to control the temperature of the melt near the crystallization front of the copper billet. This contributes to the creation of such a structure that provides its necessary mechanical characteristics. An alternative to the researched process can be the Chochralsky method, but at the same time, a sharp decrease in the productivity of the process is observed. When analyzing the structure of the samples, the influence of various elements, such as silver, iron, nickel, on the grain shape and properties of cast copper blanks was studied. It was established that the elements with a low value of the ionization potential show the properties of the modifier, that is, they contribute to the improvement of the quality of the structure of the copper billet. In addition, it is shown that an element that exhibits the properties of a modifier should have low solubility in solid metal and limited solubility in liquid. To calculate the modifying activity of elements, it is advisable to use equation (7). An alternative to the performed studies is the use of special methods of crystallization of the copper billet, in which the drawing speed and the temperature at the crystallization front vary. However, this method makes it difficult to control the structure of the copper billet due to the uncontrolled growth of copper grains at the crystallization front. The disadvantage of performing such studies is the complexity of the experimental sequence of introducing elements into the melt in a given single and group version, as well as in a quantitative ratio.

The structure and mechanical characteristics of the copper billet, as shown above, are significantly affected by the drawing step. This is due to its average rate of hardening. It was established that with an increase in the drawing step, the rate of hardening of the copper drawing decreases, which is reflected in the structural characteristics of the articles. The analysis of the surface of the cast blanks showed that increasing the step of drawing also leads to an increase in the size of the cracks on their surface. A high-quality surface is observed at draw steps of 3.3 mm and 8.2 mm (Fig. 6, *d*). If the cast billet obtained at high drawing speeds (16.8 mm) and casting temperature (1200 °C), it, at the exit from the crystallizer, has an insufficiently strong hard crust, then this leads to the formation of cracks. In addition, the analysis of the research results also shows that the specific electrical resistance of copper can be adjusted by changing the cooling rate. It can be seen that it increases with the increase of the drawing step, that is, the electrical conductivity decreases, but not significantly by only 0.086 % (Fig. 5). Thus, since electrical conductivity is sensitive to changes in structure and phase composition, a change in the cooling rate affects its value.

Regarding the shortcomings of the performed research, the incomplete use of methods of controlling the structure of copper, remote non-contact control of the electrical resistance of copper blanks should be attributed. The use of such control methods would provide more efficient measurement of various material characteristics and adjustment of technological drawing modes. Additional disadvantages of the study include the use of an air environment for growing copper blanks, without the use of an inert or reducing environment, such as argon, hydrogen, etc.

One of the important characteristics of the contact wire of power transmission lines is their electrical conductivity – the electrical resistance of copper. In the process of research, such elements as additives to the original melt Ag, Fe, Ni, Sn, and Sb were tested. Samples for research were obtained with a draw step of 8.3 mm. This mode was chosen after previous studies, which showed the most acceptable structural and mechanical characteristics for the contact wire of power networks.

As for the influence of the chemical elements presented above on the resistivity of copper, it is presented in Fig. 8–12. Mathematical processing of experimental data made it possible to represent them as (8) to (12). As a result of the research, it was established that only the addition of silver, Fig. 8, ensures the constancy of the electrical conductivity of the copper drawing. The addition of other elements, even with a slight increase in concentration, leads to a significant decrease in the electrical conductivity of the copper hood. This is caused by the atomic structure of copper and alloying elements and the creation of appropriate electron shells in the matrix of the product.

The limitations of the study are that the experimental results were obtained only for one composition of secondary copper.

The disadvantage of our research is the use of highly purified copper for drawing copper blanks. It would be appropriate to use other copper samples with preliminary control of impurity elements. This would allow taking into account the complex influence of a group of alloying elements on the electrical conductivity of copper samples.

It is advisable to consider advancing our research in a more in-depth and comprehensive analysis of the influence of various factors on the technology of obtaining a contact copper wire. The analysis of the results regarding the hardening of copper blanks, the effect of various elements on their structure, the speed of drawing on structural, mechanical characteristics and their electrical conductivity, made it possible to significantly reduce the load on the contact wires.

7. Conclusions

1. It was established that at a temperature of the melt (casting) of 1200 °C and a draw step of 8.2 mm, the average solidification rate is ~300 °C/s. As the pouring temperature and the drawing step increase, the rate of solidification decreases, and crust growth is accompanied by a decrease in surface temperature. Subsequently, the rate of temperature change is not significant and is approximately 1–1.5 °C.

2. The modifying activities of magnesium, silver, tin, iron, and nickel in liquid copper were calculated. It was established that Mg is a modifier, and all other elements do not have a modifying effect.

3. It is shown that the optimal drawing step during continuous casting is 8.2 mm, which provides sufficient time for crystallization, and with such parameters, the obtained samples have the maximum values of mechanical properties.

4. It was established that Ag, Fe, Ni, Sn, and Sb additives have different effects on the resistivity of copper. For example, the increase in the concentration of silver from 0.082 at% to 0.092 at% led to its increase by 0.582 %. As for iron, the change in the amount of Fe from 0.002 at% to 0.005 at% – by 1.733 %.

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 and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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