Effect of cold rolling on the structure and properties of the UFG Cu-0.5wt%Cr alloy

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Abstract. The results of studying the microstructure, mechanical and electrical properties of the UFG alloy Cu-0.5wt.%Cr, obtained by equal-channel angular pressing (ECAP), followed by cold rolling and subjected to aging, are presented. It was found that, as a result, the average size of the fragmented structure is 160 nm. The results showed that the tensile strength increases with increasing degree of deformation. The maximum strength value of 605 MPa was achieved after a combination of 8 ECAP passes followed by rolling by 95%, while ductility was reduced to 13%. The number of ECAP passes and subsequent rolling practically do not affect the electrical conductivity and is 34-39% of IACS.

1. Introduction
An analysis of the literary published over the past decade indicates a great interest of researchers in studying different methods of increasing strength while maintaining the electrical conductivity of Cu-Cr alloys, which are actively used in various industries [1-3]. The main way to increase the strength of copper materials without compromising electrical conductivity is to grind the microstructure and increase the density of dislocations due to plastic deformation. An additional increase in strength properties can be ensured by using severe plastic deformation (SPD) as the main processing method, which leads to the formation of an ultrafine-grained (UFG) structure with a high dislocation density [4, 5]. However, industrial production requires further processing of semi-finished products to bars, tapes, sheets, plates, etc. In this regard, research aimed at analyzing the evolution of the microstructure and properties of UFG electrotechnical materials during subsequent deformation is relevant. This work is devoted to the study of the effect of cold rolling on the microstructure, mechanical properties and electrical conductivity of the UFG Cu-0.5wt.% Cr alloy.

2. Method of experimental research
As the material for research, we chose the industrial electrotechnical Cu-0.5wt.% Cr alloy. Samples 10×10×60 mm in size in the form of rectangular parallelepipeds with an exposure time of 0.5 hours at
1000 °C, followed by quenching in a 5% NaCl solution to form a supersaturated solid solution were used as the initial state (IS).

ECAP was carried out in a die with an internal angle $\psi = 90^\circ$ along route Bc (turning the workpiece 90° clockwise along the longitudinal axis after each pass) at room temperature at a speed of 0.2 mm/s with the number of passes 1, 2, 4 and 8. Subsequently, cold rolling (CR) was carried out at room temperature with a total reduction ratio of 95%. In one pass during rolling, the reduction in thickness was approximately 5%. The final thickness of the samples was 0.5 mm. Between the passes, billets were cooled in air to minimize the effect of deformational heating on the microstructure. The rolling direction was parallel to the direction of extrusion. The equivalent deformation in one pass of ECAP was 1.15, and after rolling by 95% - 3.5.

An OLIMPUS GX51 optical microscope (OM), a JEOL JSM-6490LV scanning electron microscope (SEM) and a JEOL 2100 transmission electron microscope (TEM) were used to study the microstructure. Studies of the microstructure and properties were carried out in the rolling plane. Tensile tests were performed at a strain rate of $10^{-3}$ s$^{-1}$. Samples were cut parallel to the direction of deformation from the central part of the ECAP blanks and sheets after rolling. Uniaxial tensile tests were carried using small specimen on an Instron 8801 tester at room temperature at a speed of $10^{-3}$ s$^{-1}$. Conductivity studies were carried out at a temperature $T = 23^\circ$C by the eddy current method. The measurement error was ± 2%.

3. Results and discussion

The metallographic study showed the coarse-grained microstructure with an average grain size of 260 ± 11 μm in the initial state (figure 1, a). In the microstructure, inclusions of 4.3 ± 0.1 μm size based on chromium are visible [6].

Deformation by the ECAP method led to a significant refinement of structural elements and transformed the microstructure of the initial state into the UFG structure. After one ECAP pass, the elongated subgrain microstructure was formed, most of the boundaries were curved and thick, which can be explained by their small misorientation. After two ECAP passes, the microstructure became more equiaxed, but most of the boundaries retained their appearance. An increase in the degree of deformation as a result of four ECAP passes led to the formation of small equiaxial fragments along with elongated ones. The boundaries became thinner and clear, possibly because of an increase in their misorientation.

![Figure 1](image-url). The microstructure of the alloy: a) the initial state; SEM; b) after 8 ECAP passes, TEM.

After 8 ECAP passes, a homogeneous, almost equiaxed microstructure with an average size of structural components of 250 ± 15 nm was formed (figure 1, b). An analysis of microstructure photographs after ECAP revealed the presence of particles of the secondary phases (figure 1, b). Therefore, during SPD, diffusion processes were activated, leading to the decomposition of the...
supersaturated solid solution and the formation of particles with a size of about 5-10 nm. The volume fraction of precipitated particles increased with an increase in the degree of deformation.

![Image](image1.png)  
**Figure 2.** The microstructure: a) the initial state after cold rolling; c) 8 ECAP passes and cold rolling. TEM.

As a result of rolling of the initial state, an elongated structure with nonequilibrium boundaries was formed (figure 2, a). The use of rolling after 8 ECAP passes led to a decrease in the size of structural elements to 160±10 nm (figure 2, b). The analysis of the fine structure after 8 passes of ECAP in combination with cold rolling indicates the formation of a strongly deformed UFG microstructure with a high density of dislocations that are unevenly distributed, most of the dislocations accumulate near the boundaries. The inhomogeneous diffraction contrast in the bright field image of structural elements indicates large internal stresses, the source of which is the boundaries of the fragments. Most boundaries are not clearly defined, they are uneven and curved.

| State        | Hv, MPa | σUTS, MPa | σYS, MPa | ε, % | IACS, % |
|--------------|---------|-----------|----------|------|---------|
| IS           | 710±10  | 160±10    | 60±5     | 42±2 | 37      |
| ECAP1        | 1160±11 | 325±18    | 318±16   | 15±1 | 34      |
| ECAP2        | 1250±10 | 400±5     | 385±7    | 14±1 | 39      |
| ECAP4        | 1390±13 | 425±5     | 370±20   | 14±1 | 36      |
| ECAP8        | 1480±6  | 475±10    | 450±10   | 17±1 | 35      |
| CR           | 1460±15 | 490±7     | 480±12   | 8±2  | 39      |
| ECAP1+CR     | 1550±12 | 445±13    | 435±16   | 11±1 | 37      |
| ECAP2+CR     | 1560±15 | 500±5     | 475±5    | 13±1 | 37      |
| ECAP4+CR     | 1500±18 | 550±10    | 520±10   | 13±1 | 37      |
| ECAP8+CR     | 1550±10 | 605±18    | 565±13   | 13±1 | 37      |

Table 1 shows the properties of the Cu-0.5wt.%Cr alloy in various states. Microhardness with an increase in the number of ECAP passes increases from 710 MPa to 1480 MPa. At the same time, the strength also increases and reaches saturation already after the second ECAP pass, reaching 475 MPa. Subsequent rolling increases the strength by 100-150 MPa, depending on the number of ECAP passes. The ultimate strength value is 605 MPa. The microhardness remains approximately at the same level of ~ 1500 MPa. In this case, rolling of the initial state leads to a strength value of 490 MPa. From table 1 it can be seen that the number of ECAP passes and subsequent rolling practically do not affect the electrical conductivity, which is 34-39% of IACS. The same value is characteristic of the rolled initial
state. Consequently, the contribution of the size of the fragments and dislocations to the electrical conductivity is negligible and the solid solution makes a significant contribution. The obtained electrical conductivity values are unacceptable for industrial production. Since alloys of the Cu–Cr system are heat-hardening, it is possible to precipitate small dispersed hardening particles of the secondary phases during post-deformation heat treatment, as a result of which, on the one hand, the strength of these alloys increases, and on the other hand, the electrical conductivity is restored [1-3, 6]. It is also known that materials subjected to SPD are characterized by high internal stresses due to the high density of structural defects [1, 3]. Therefore, in the following studies, it is necessary to analyze the effect of aging on the microstructure and the formation of the optimal combination of strength and electrical conductivity of the studied alloy Cu-0.5wt.% Cr.

Thus, rolling after ECAP makes it possible to increase the strength by 100-150 MPa depending on the number of ECAP passes, while the ductility of the rolled UFG samples is greater than the ductility of the rolled initial state.

4. Conclusions
As a result of the study of the effect of cold rolling on the microstructure, mechanical properties and electrical conductivity of the UFG Cu-0.5wt.% Cr alloy, it was revealed that the microstructure obtained by 8 ECAP passes with subsequent rolling was characterized by the strength which is 1.2 times higher, and the ductility which is 1.6 times higher in comparison with the rolled initial state.

Acknowledgments
Authors are grateful for the financial support of the Ministry of Education and Science within the frame work of project No. 16.1969.2017/4.6. W Wei is grateful to be supported by the National Natural Science Foundation of China under Grant No. 51561001, the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), the Top-notch Academic Programs Project of Jiangsu Higher Education Institutions (TAPP), and the Science and Technology Project of Changzhou, P. R. China under grant No.CZ20180016 and CE20170028.

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