T. KNYCH, A. MAMALA, A. KAWECKI, B. SMYRAK, K. KORZEŃ, E. SIEJA-SMAGA

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INFLUENCE OF PLASTIC DEFORMATION ON THE CHANGE OF ELECTRICAL AND MECHANICAL PROPERTIES OXYGEN-FREE (OF) COPPER AND COPPER ALLOY WIRES

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This article is devoted to the comparison of changes in mechanical and electrical properties due to the applied deformation of copper and copper alloy rods. Bars from four different production technologies were deformed in the drawing process, including oxygen-free (OF) copper, electrolytic copper ETP, copper from cable granulate and silver copper with a high silver content up to 15 wt. % obtained in laboratory technology. The article presents the chemical purity, physical and electrical properties of rods before deformation. The summary of the research on the selected materials are changes in mechanical properties and electrical conductivity as a function of deformation up to 3,5 on a logarithmic scale and the coefficient of electromechanical efficiency W_{EM}.

Keywords: Cu-Ag alloys, rods, wires, electrical properties, mechanical properties

INTRODUCTION

Global research conducted in the last 10 years in the field of special-purpose wire harnesses and cables has shown that the most promising conductive materials exhibiting a set of above-standard mechanical and electrical properties may be Cu-Nb, Cu-Ag-Nb and Cu-Ag alloys [1-3]. Materials made of Cu-Ag alloy, in addition to the widely used wires, microdrows and sheets based on copper with the addition of other elements, i.e. niobium, zirconium, chromium, tin, are among the group presenting the highest strength properties mentioned above [4].

Materials produced by conventional metallurgical processes, including copper, aluminum and their alloys, have potential applications as elements of the construction of strong magnetic field generators or in the construction of overhead cables.

In addition to the specialized requirements of operational properties, in both application cases, i.e. creep resistance, current carrying capacity, corrosion resistance and fatigue resistance, the material requirements are primarily focused on high electrical and strength properties.

Based on the cited world literature, both the power cables industry and strong magnetic field generators use in their construction traditional materials based on pure aluminum, aluminum alloys, including Al-Mg-Si alloys for round and profile power cables (e.g. type AAC or EHC) whether bimaterial cables, the ones currently in use include aluminum-steel cables or Al_2O_3 fiber cables in an aluminum matrix (ACCR type overhead cable) [5-8]. In turn, copper and its alloys have been used as sheets or wires of the cores of conductive high-field electromagnets [9-11].

Currently, however, there is a tendency to look not only for new combinations of chemical materials, but also to design structures with the use of multi-material solutions. Thanks to this, it is possible to complement the properties of the materials used, which fully protects the working conditions of devices, structures and a set of devices.

EXPERIMENTAL WORK

The aim of the research was to evaluate the influence of the degree of deformation on the change of electrical and mechanical properties of copper alloy with the addition of silver in the amount of 15 wt. % as well as determining the coefficient of electromechanical efficiency.

The reference material was copper rods manufactured in three separate production technologies, including: ETP-grade oxygen-free copper rods, OF oxygen-free copper rods from the UpcastÒ line and rods from a demonstration installation for continuous casting of copper granules into wires and cable cores, for the charge of which was high-quality cable scrap. The third technology is mainly based on the Rautomead® technology supplemented with additional elements enabling deoxidation of the charge material in the form of granules and structures facilitating its fusion into the liquid bath. Copper rods obtained in this technology are marked with the symbol OF II. Rods from CuAg15 alloy were obtained in the process of continuous casting

T. Knych, A. Mamala, A. Kawecki, B. Smyrak, K. Korzeń, E. Sieja-Smaga (e-mail: esmaga@agh.edu.pl), AGH University of Science and Technology, Faculty of Non-Ferrous Metals, Cracow, Poland

Table 1 **Chemical composition of rods all materials**

Impurities	Alloy content / wt. %			
	Upcast ®	Contirod ®	Rautomead ®	DCC-AGH
	Cu OF	Cu ETP	Cu OF II	CuAg15
Ag	9,0	9,0	10,0	14,9
	Element content / ppm			
Bi	0,10	0,10	0,20	0,2
Pb	0,90	0,70	0,50	0,4
Sb	0,80	0,60	0,40	0,2
As	0,40	0,60	0,50	0,3
Fe	1,60	1,60	2,00	1,2
Ni	1,50	1,70	1,02	0,3
Sn	0,30	0,30	0,50	0,3
Zn	1,40	1,80	1,05	1,0
Cd	0,01	0,01	0,40	0,0
Co	0,04	0,03	0,40	0,0
Cr	0,02	0,09	0,10	0,0
Mn	0,03	0,04	0,20	0,4
P	0,10	2,00	0,10	1,3
Se	0,10	0,10	0,11	0,1
Si	0,00	0,00	9,00	1,0
Te	0,10	0,20	0,20	0,0
S	1,20	2,80	3,00	1,6
O_2	1,50	190	2,00	13

in a laboratory line located at the Faculty of Non-Ferrous Metals of the AGH University of Science and Technology.

The research material consisted of rods made of CuAg15 alloy with a diameter of 9,5 mm and copper rods with a diameter of 8 mm. Table 1 shows a comparison of the chemical compositions of all these materials. The content of Cu-Ag alloys and rods of copper was conducted in Centrum Badań Jakości Ltd "Legnica" which is a Qualitative Analysis Department localized in Lubin. The silver content in the CuAg15 alloy was determined at the level of 14,91 wt. %, which in the nomenclature of the article was assumed to be 15 wt. % hence the designation - CuAg15 alloy. The process of melting and casting in a laboratory installation allowed to obtain a material with a reduced oxygen content (Table 1), which reaches a value of 13 ppm. The remaining content of impurities in the CuAg15 alloy does not exceed 9 ppm. It is also worth paying attention to the chemical composition of rods obtained in the technology of oxygen-free copper production from cable waste. The use of appropriate operations made it possible to obtain high-quality materials, which is confirmed by the level of impurities in the form of iron (up to 2 ppm), sulfur (up to 9 ppm), zinc (1-9 ppm), nickel (1-3 ppm), silver (6-16 ppm) and arsenic, bismuth, selenium, antimony, tellurium, tin in an amount below 0,5 ppm each. Chemical impurities reduce the technological properties and electrical conductivity of copper and copper alloys. Chemical composition tests have shown that the oxygen content of the rods in the so-called oxygen-free copper did not exceed 2 ppm.

The rods obtained in the casting processes were tested for electrical and mechanical properties especially

Table 2 **Mechanical and electrical properties of rods all materials after casting**

Material	ε_{rz} / -	R_m / MPa	r / nWm	g / MS/m
Cu OF	0	173	17,01	58,8
Cu ETP	0	218	16,93	59,1
Cu OF II	0	171	16,63	60,1
CuAg15	0	291	21,45	46,6

Table 3 **Mechanical and electrical properties of wires of all materials**

Materiał	ε_{rz} / -	R_m / MPa	r / nWm	g / MS/m
Cu OF	3,35	430	17,21	58,1
Cu ETP	3,35	450	17,42	57,4
Cu OF II	3,40	461	17,123	58,4
CuAg15	3,48	827	24,162	41,4

ultimate tensile strength presented in Table 2 and of wires all materials - Table 3.

The use of an alloying addition in the form of silver has a visible effect on the tensile strength level of almost 300 MPa at the cost of a decrease in the electrical conductivity level by approx. 14 MS / m to 46,6 MS / m. In the case of copper rods, it is confirmed that the level of impurities has a direct impact on the value of electrical conductivity of copper.

The deformation process of all rods was carried out by drawing with a unit deformation of 20 % up to 3,4 on a logarithmic scale, to the limiting diameter of 1,5 - 1,65 mm.

The deformation process of all bars was carried out by drawing with a unit deformation of 20 % to the limit value of 3,4 on a logarithmic scale, to a diameter of 1,5 / 1,65 mm. It was made a comparison of the electrical properties and tensile strength of all materials presented in the figures below (Figures 1 and 2). The decrease in electrical conductivity as a function of true strain is well known, but the nature of these changes, individual for a specific group of metals or alloys, is unknown. Oxygen (Cu ETP) and oxygen-free copper (Cu OF) rods have an electrical conductivity of > 101 % on the international IACS scale. The electrical conductivity of ETP copper is slightly above 101 %. A slight decrease in electrical conductivity was recorded for the oxygen-free copper Cu OF rods, deformed in the drawing process to 3,4 on a logarithmic scale. The difference was approx. 1 %, as shown in Figure 1 Cu OF. The applied deformation in the case of Cu OF II and Cu ETP copper rods resulted in a 2 % decrease in electrical conductivity. The addition of silver to copper, apart from the 20 % difference in the output conductivity, caused, in connection with the deformation process, an additional 11 % decrease in its value from the initial value (Figure 3).

In the case of tensile strength, the addition of silver (mechanisms of solution strengthening) in combination with the deformation process allowed to obtain tensile strength at the level of 830 MPa. The strengthening curve of the CuAg15 alloy is presented in the figure below (Figure 4). The difference in the strengthening of

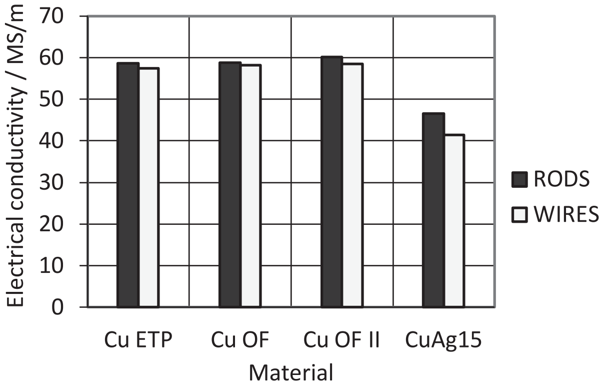

Figure 1 Electrical conductivity in %IACS of rods and wires of presented materials like: oxygen free copper Cu-OF, Cu ETP, copper from recycling technology Cu OF II and CuAg15 alloy

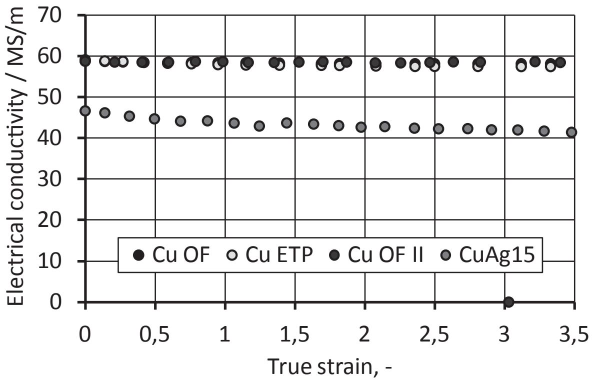

Figure 3 Change of electrical conductivity as a function of true strain of wires of various materials: oxygen free copper Cu-OF, Cu ETP, copper from recycling technology Cu OF II and CuAg15 alloy

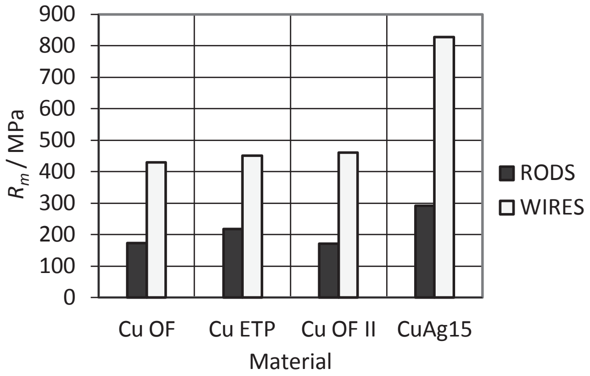

Figure 2 Comparision of ultimate tensile strength of rods and wires presented materials including: oxygen free copper Cu-OF, Cu ETP, oxygen-free copper Cu OF II and CuAg15 alloy

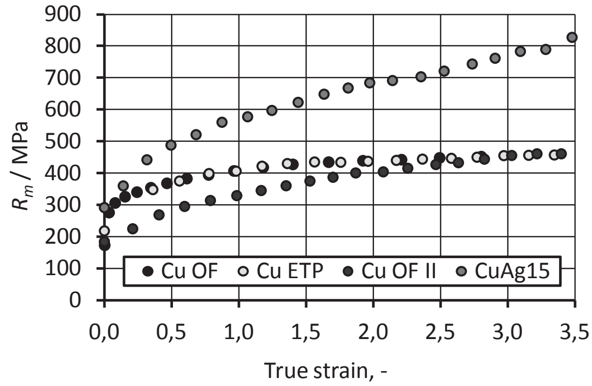

Figure 4 Strengthening curve of wires of oxygen free copper - Cu OF, Cu ETP, oxygen-free copper - Cu OF II and CuAg15 alloy

wires made from copper-silver alloy is more than twice the final tensile strength of the pure copper wires.

The work is summarized with the calculation of the electro-mechanical efficiency coefficient (equation 1), which allows to compare copper alloys of different purity with CuAg15 alloy wires.

$$W_{EMF} = \frac{R_m}{\gamma} \cdot \frac{1}{\rho} \tag{1}$$

where: R_m - ultimate tensile strength / MPa
γ - density / kg/m^3,
ρ - resistivity / nΩm.

The high properties of the W_{EMF} electromechanical efficiency coefficient result from the density comparable to that of copper but twice as high as the tensile strength - Table 4.

Table 4 **Mechanical and electrical properties of wires of all materials**

Material	R_m / MPa	Density / kg/m^3	Resistivity / nWm	W_{EMF}
Cu ETP	450	8920	17,42	296
Cu OF	430	8890	17,21	287
Cu OF II	461	8911	17,12	308
CuAg15	827	9113	24,16	383

CONCLUSION

The exceptional high strength parameters of Cu-Ag alloys have been emphasized many times in the literature. By directing our attention to the hypoeutectic range, using the mechanisms provided by the equilibrium system (overlapping the strengthening effects), we obtain the full initial characteristics of the strengthening and changes in electrical properties of the tested CuAg15 alloy as a function of the given strain. The analysis of ownership changes showed that:

– the relationship between electrical conductivity and the level of impurities in copper alloys obtained by metallurgical melting and casting processes was confirmed - the highest electrical conductivity was obtained in the case of Cu OF and OF II oxygen-free copper,
– the deformation process causes a decrease in electrical conductivity in the range of 1 to 2 % in the case of pure copper deformation,
– in the case of CuAg15 alloy wires, the decrease in electrical conductivity for the same deformation as in the case of copper (3,5 on a logarithmic scale) was almost 30 %,

- the deformation process allowed for the strengthening of pure copper wires, visible in the increase in tensile strength by 230 to 290 MPa,
- the deformation process allowed to obtain an increase in tensile strength for the CuAg15 alloy by over 530 MPa,
- CuAg15 wires have the highest level of the electromechanical efficiency coefficient among the compared.

In order to increase the properties of CuAg15 alloys, thermo-mechanical treatment should be applied, which enables the shaping of very high electrical and strength properties. Cu-Ag alloys have potential applications in overhead cables or elements used in strong electromagnetic field generators as structures that combine several materials, including aluminum, steel, composites or superconductors.

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Note: The translator responsible for English language: Andrzej Nowak, Kraków, Poland