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Research on New Al-Ag-Mo Alloys Dedicated to Wire Applications in Overhead Power Lines

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Abstract

The latest research work in the field of electric power systems focuses on the development of new wire materials which will allow the increase of the transmission capacity of power lines currently in use. The reason for this research was the often limited possibilities of continuous and failure-free transmission of electricity. In this paper, the authors present research on a new aluminium-based alloy dedicated for use as a conductive braid in the HTLS cable group. There are many technical solutions for this group of cables on the market, although they are solutions with a number of disadvantages, ranging from their high price, various operational shortcomings, complicated installation techniques, and ending with the risk of monopolistic practices, which is related to the inability to attract several competitive suppliers. The main aim of the research was to develop a new alloy based on aluminium with the addition of silver and molybdenum dedicated for use in special overhead power cables. Experimental research on new materials focused on obtaining the necessary knowledge to produce an overhead wire from these alloys with higher current carrying capacity in relation to the currently used conventional wire materials based on aluminium.

Keywords:

aluminum, silver, molybdenum, continuous casting, drawing, wire, conductivity, thermal resistance, temperature coefficient of resistance, rheological properties, HTLS conductors

1. INTRODUCTION

Any material dedicated to wire applications should meet a number of requirements, including high electrical and thermal conductivity, high tensile strength and high permissible operating temperature [1–3]. This material should also be corrosion resistant, while the relatively low cost of material used for the conductor is also important [4, 5]. The modern power industry expects new, dedicated aluminum based alloys with non-standard properties, including increased resistance to temperature [6, 7]. Analyzing the examples of solutions patented in recent years, two trends in the field of electric power systems can be observed [8–10]. The first one focuses on the search for high-strength wire materials and the second on the search for alloys with increased thermal resistance, which is closely related to the development of high temperature cables. The thermal resistance of the conductor material is the rate of permanent degradation of the macroscopic strength properties of the material (hardness, tensile strength, yield point) in the work-hardened state as a result of exposure to elevated temperatures. The slower the rate at which the strength properties of the material degrade as a result of increased temperatures proves the higher heat resistance of such a material. Materials with higher heat resistance enable increases in the operating temperature of power cables made from them, thus increasing their current carrying capacity. The most frequently used additive and most widely tested is zirconium, which has a strong influence on increasing the temperature recrystallization of aluminum. There are four types of heat resistance wires made of aluminum-zirconium alloy with working temperatures between 150°C to 230°C without decreasing their properties [11, 12]. The properties of these types of alloys are shown in Table 1.

High-temperature cables are usually bimaterial, with the core of the cable made of steel, invar or a composite, and the conductive layer uses special aluminium alloys with increased heat resistance in the hard state (most often AlZr alloys) or technical purity aluminium after recrystallization [13–17]. Based on research on the synthesis of aluminium alloys with various additives, the addition of silver and molybdenum were selected in order to design a material dedicated for use in overhead power cables [18–22]. Molybdenum, similarly to zirconium, whose effect on increasing the heat resistance of aluminium is widely known, belongs to the group of transition elements. Both metals also belong to the same 5th period of the periodic table, which indicates the similar properties of the two elements. The choice of the silver addition is dictated by its effect on increasing the recrystallization temperature and rheological properties and also reducing the temperature coefficient of resistance after adding it to copper (CuAg alloys) [23–25].

Table 1
Coparison of the properties for standard conductive materials and for higher heat resistance materials [26]

Material	AT1 (Al-Zr)	AT2 (Al-Zr)	AT3 (Al-Zr)	AT4 (Al-Zr)	A1 (Al)
Density [g/cm^3]	2.703	2.703	2.703	2.703	2.703
Resistivity [nΩ·m]	28.735	31.347	28.735	29.726	28.264
Temperature coefficient of resistance [°C^{-1}]	0.00400	0.00360	0.00400	0.00380	0.00403
Tensile strength [MPa]*	159–171	225–248	159–176	159–169	160–200
Elongation [%]*	2.0–1.3	2.0–1.5	2.0–1.5	2.0–1.5	–**
Coefficient of linear expansion [K^{-1}]	23×10^{-6}	23×10^{-6}	23×10^{-6}	23×10^{-6}	23×10^{-6}
Maximum operating temperatures for forty years [°C]	150	150	210	230	80–90
Maximum operating temperatures in 400°C	180	180	240	310	–**

* value depends on the wire cross-section
** non-normalized property

2. MATERIALS AND METHODS

The study was carried out on an aluminium alloy with silver (0.15 wt.%) and one with molybdenum (0.05 wt.%) additives. Cast-rods of 14 mm diameter were obtained using a laboratory workstation for continuous casting. The reference material was high purity aluminium (99.99 wt.%). During the continuous casting process, parameters such as the temperature of the liquid metal, speed, and sequences of continuous casting, conditions of cooling in the crystallizer and macrostructure of ingot were recorded. The continuous casting parameters are presented in Table 2.

The obtained cast-rods were tested in terms of their chemical composition and heat treatment. The chemical composition of Al cast-rods was tested on the SPECTROTEST spectrometer, while the new AlAg0.15Mo0.05 alloy was tested on an emission spectrometer with inductively excited plasma OPTIMA 7300 DV by Perkin Elmer. Materials in an as-cast state and after homogenization were subjected to hardness and electrical conductivity tests. The hardness of the obtained alloys was determined using the Vickers method, the electrical conductivity was carried out using the eddy current method. The obtained bars were drawn to the diameter of the wire rod (ϕ = 9.5 mm), then the homogenization procedure was carried out (temperature 600°C, time 100 h, cooling to water) and then these bars were drawn to the final diameter ϕ = 2.4 mm. Electrical properties, rheological properties and heat resistance of the wires were tested. The electrical properties of the wires were tested at an ambient temperature using the Thomson bridge method. The temperature coefficient of resistance were determined for wires in the deformation-hardened state (after drawing) and in an annealed state (after recrystallization), wires with a diameter of 2.4 mm were placed in the measuring rail of the Thomson bridge and placed in a heating chamber at temperatures of 40, 60, 80 and 100°C (for wires in the recrystallized state, additionally at 120 and 140°C). After the thermal state of the wires was stabilized, their electrical resistance was measured. Accurate reading of the temperature of the wires was possible due to the placement of a thermocouple on the surface of each of them. The measuring base of the wire samples was 0.3 m. From the point of view of the application of the tested materials for the purpose of electric power, a material with high electrical conductivity and a correspondingly low temperature coefficient of resistance has a beneficial effect in increasing the current carrying capacity of the conductor. The next step was to test the stress relaxation of aluminium alloy wires, with the test was carried out at on initial stress level of 100 MPa for 14 h at a stabilized temperature of 21°C, the measuring length of the wire between the jaw clamps was l = 600 mm. The heat resistance test was examined for materials heated at 250°C for the following time intervals: 0.3; 1; 3; 10; 24 and 100 h. The uniaxial tensile test was then carried out on a Zwick Roell Z020 testing machine. The measuring base of the wire was 50 mm, and the test was carried out with a tensile speed of 10 mm/min.

Table 2
The continuous casting parameters of AlAg0.15Mo0.05 and Al cast-rods

Parameter	Al	AlAg0.15Mo0.05
Feed [mm]	10	15
Standstill [s]	10	10
Casting speed [mm/s]	10	10
Liquid metal temperature [°C]	775	811
Cast temperature [°C]	154	168
Water temperature T1* [°C]	7.6	8.3
Water temperature T2** [°C]	13.5	10.9
Primary cooling velocity [min^{-1}]	0.66	0.72
Secondary cooling velocity [min^{-1}]	0.31	0.20

* temperature of the cooling medium before entering the crystallization system
** temperature of the cooling medium after leaving the crystallization system

3. RESULTS AND DISCUSSION

The chemical compositions of the obtained alloy Al99.9 and AlAg0.15Mo0.05 and are presented in Table 3 and Table 4, respectively. The chemical composition of the materials is at the expected level. The actual silver and molybdenum content in the alloys was close to the assumed nominal value, proving that there are no disturbances in the technological process of casting materials.

Table 3
Chemical composition of the Al99.9, wt.%

Al	Si	Fe	Cu	Mn
99.94	0.00486	0.01720	0.01150	0.00127
Mg	Zn	Cr	Ni	Ti
<0.00010	0.00232	0.00557	0.00189	<0.00020
Be	Ca	Li	Pb	Sn
<0.00010	0.00197	0.00013	0.00067	<0.00050
Sr	V	Na	Bi	Zr
0.00101	<0.00050	0.00456	<0.00080	<0.00050
B	Ga	Cd	Co	Ag
0.00022	<0.00040	<0.00010	<0.00020	0.00093
Hg	In	Sb	P	As
<0.0005	<0.0005	<0.0050	<0.0020	<0.0030
Ce	La	Mo		
<0.00100	0.00107	<0.00200		

Table 4
Chemical composition of the AlAg0.15Mo0.05, wt.%

Al	Si	Fe	Cu	Mn
99.74	0.00524	0.01300	0.00690	0.00128
Mg	Zn	Cr	Ni	Ti
<0.00010	0.00071	0.00435	0.00128	0.00020
Be	Ca	Li	Pb	Sn
<0.00010	0.00219	0.00013	0.00113	<0.00050
Sr	V	Na	Bi	Zr
0.00101	<0.00050	0.00416	<0.00080	<0.00050
B	Ga	Cd	Co	Ag
0.00030	<0.00040	<0.00010	0.00023	0.15520
Hg	In	Sb	P	As
<0.00050	0.00086	<0.00500	<0.00200	<0.00300
Ce	La	Mo		
<0.00100	0.00103	0.04900		

The results of the Vickers hardness and electrical conductivity tests are shown in Figures 1 and 2. On the basis of the results obtained for the samples in the as-cast condition, there is an increase in hardness for the aluminium alloy with Ag and Mo additions (20 HV5) compared to the reference aluminium sample (18 HV5). After homogenization, the hardness of the AlAg0.15Mo0.05 slightly decreased to 19.7 HV5. Molybdenum in the tested amount may be located, depending on the conditions of heat treatment, in a solid solution or in a separate phase. Based on the Al-Ag and Al-Mo binary equilibrium systems and on the results of the electrical conductivity tests, it is postulated that both components are deposited in an aluminium solid solution after homogenization. The heat treatment slightly lowers the electrical properties of the material. AlAg0.15Mo0.05 alloy in the as-cast state generally have acceptable electrical properties (their resistivity does not exceed the level of 29 nΩ·m), although the electrical conductivity of the ternary alloy is slightly above the expected maximum limit. Heat treatment causes a slight decrease in the electrical properties of the material.

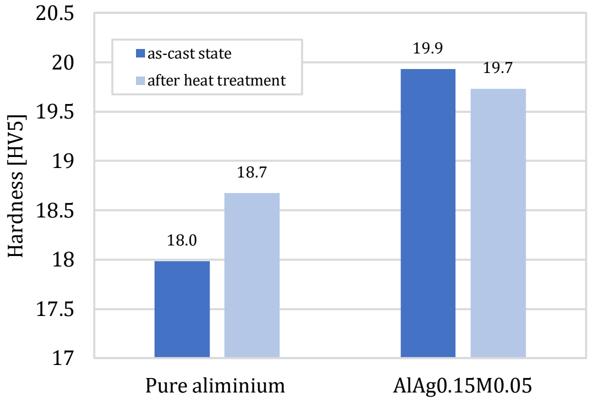

Fig. 1. Vickers hardness results in the as-cast state and after heat treatment (homogenization and cooling to water) of the AlAg0.15M0.05 alloy

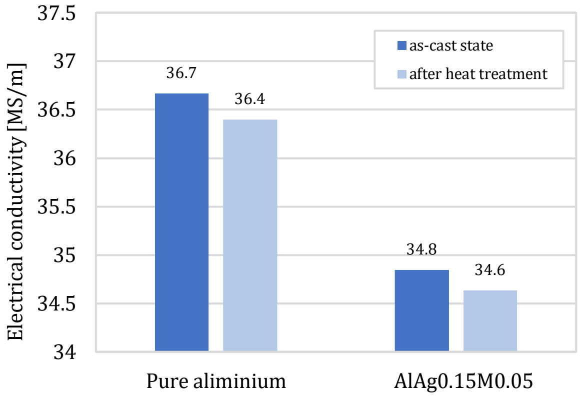

Fig. 2. Results of the electrical conductivity in the as-cast state and after heat treatment (homogenization and cooling to water) of the AlAg0.15M0.05 alloy

Table 5 shows the results of the tested electrical properties of aluminium alloy wires in the deformation-hardened state (after drawing). Electrical properties of heat-resistant wires AlZr type AT1 according to Table 1 are at the level of 28.735 nΩ·m (before the drawing process, this value oscillates around the level of 28.1 nΩ·m), while the resistivity of the new alloy AlAg0.15M0.05 is higher than expected and amounts to 29.48 nΩ·m.

Table 5
Electrical properties of the wire

Alloy	**Resistivity [nΩ·m]**	**Electrical conductivity [MS·m^{-1}]**	**IACS [%]**
Al	27.96	35.77	61.67
AlAg0.15Mo0.05	29.48	33.93	58.49

Figures 3 and 4 show the results of the temperature coefficient of wire resistance test for both materials, while the test results are summarized in Table 6. The angle of slope of the line is the temperature coefficient of resistance. Based on the research, it is worth noting that the synergistic effect of Ag and Mo allowed the temperature coefficient of resistance to be reduced by approx. 10%. This is a reduction that is beneficial from a utilitarian point of view.

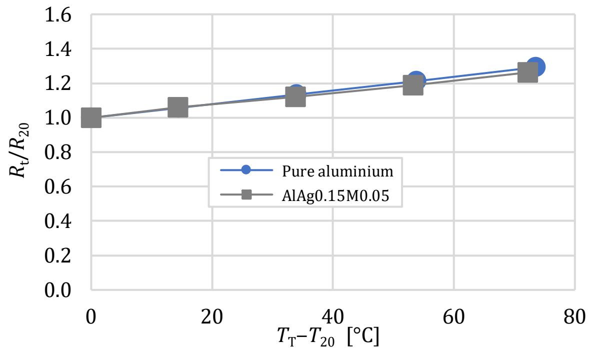

Fig. 3. Temperature coefficient of resistance of the tested materials in the deformation-hardened state

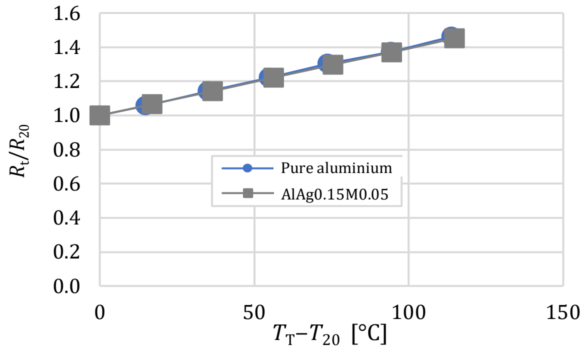

Fig. 4. Temperature coefficient of resistance of the tested materials in the annealed state

Table 6
Temperature coefficient of resistance of the tested materials in the deformation-hardened/annealed state

Alloy	Temperature coefficient of resistance $[K^{-1}]$ (deformation-hardened state)	Temperature coefficient of resistance $[K^{-1}]$ (annealed state)
Al	0.0040	0.0041
AlAg0.15Mo0.05	0.0036	0.0039

Figure 5 presents the results of the thermal resistance test of wires in a graphic form, while the obtained values are also summarized in Table 7.

The tensile strength of the deformation-hardened wires is respectively 116 MPa for the aluminium wire and 120 MPa for the AlAg0.15Mo0.05 wire, which shows a significantly higher stability of the strength properties. The AlAg0.15Mo0.05 alloy shows significantly higher stability in terms of strength properties, after holding at 250°C for 100 h, it showed a decrease in tensile strength by 17% (100 MPa) compared to the wire in the hard state (120 MPa). The reference aluminium wire with a purity of 99.9% is characterized by a decrease in strength properties by 24%. The achieved result proves the significantly higher heat resistance of the developed three-component aluminium alloy compared to the reference aluminium. Therefore, it can be concluded that the AlAg0.15Mo0.05 wires show about a 1.5 times lower strength decrease compared to pure aluminium wires.

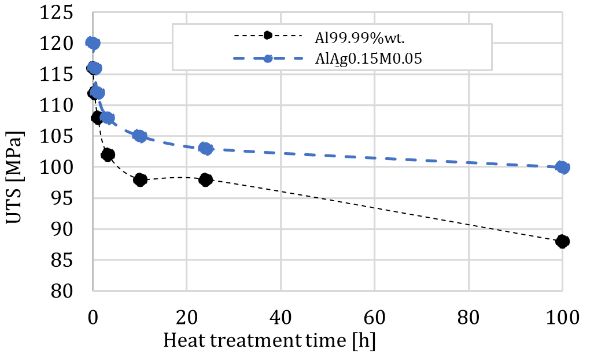

Fig. 5. Thermal resistance of Al99.99%wt. and AlAg0.15Mo0.05 wires

Table 7
Thermal resistance of Al99.99%wt. and AlAg0.15Mo0.05 wires

Heat treatment time [h]	Material	
	Al	AlAg0.15Mo0.05
	UTS [MPa]	
0	116	120
0.3	112	116
1	108	112
3.1	102	108
10	98	105
24	98	103
100	88	100

Figure 6 shows the stress relaxation of the aluminium alloy wires test results. The relaxation test was carried out at on initial stress level of 100 MPa, the test was carried out for 14 h at a stabilized temperature of 21°C, the measuring length of the wire between the jaw clamps was l = 600 mm. The obtained test results showed the higher rheological resistance of the AlAg0.15Mo0.05 alloy wires than wires made of pure aluminium.

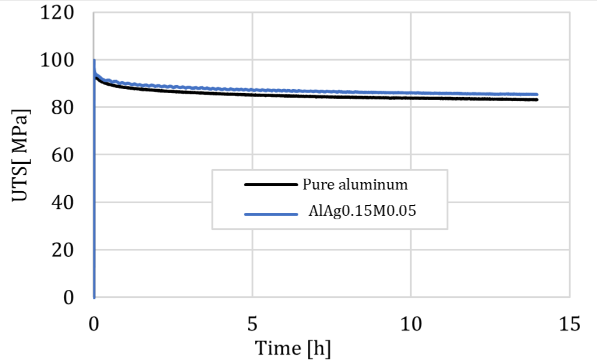

Fig. 6. Stress relaxation test results

4. CONCLUSIONS

Currently, the braids of high-temperature cables are made of aluminium-zirconium alloys, with four types of such wires having been developed so far (AT1-AT4). These alloys are a solution to current electricity problems – they allow for a significant increase in the transmission capacity of power lines. The addition of zirconium increases the heat resistance of aluminium by increasing its recrystallization temperature (heat-resistant AlZr alloys allow for the working temperature of the wires to be increased up to 230°C), while the permissible long-term working temperature of commonly used aluminium and steel-aluminium wires is +80°C. AlZr alloys, despite many advantages, also have a number of drawbacks, ranging from their high price, various operational shortcomings, complicated installation techniques, and ending with the risk of monopolistic practices, which is associated with the inability to acquire several competing suppliers. It is these shortcomings, together with the deficit of the transmission capacity of the currently used systems, that have become the inspiration to look for new, alternative aluminium-based alloys in recent years that will be able to meet the growing operational requirements.

As part of the research, alloys with nominal alloying additions of silver (0.15 wt.%) and molybdenum (0.05 wt.%) were produced by continuous casting in laboratory conditions with the use of 99.9% pure aluminium matrix (this aluminium was also produced as a reference material). The quality of the castings was satisfactory. The tested materials in the as-cast state generally have acceptable electrical properties (their resistivity does not exceed 29 nΩ·m), although the electrical conductivity of the ternary alloy is slightly above the expected maximum – the preferred value in the pre-drawing condition is a maximum of 28.1 nΩ·m (as for AT1 reference material). No effective increase in the strength properties of the material was observed due to the addition of Mo and Ag in the tested range in the as-cast state, although a similar situation occurs in the case of the high-temperature AlZr alloys – AT1 and AT3, which are used in practice. The heat resistance of the wires with the addition of Mo and Ag is higher than pure aluminium wire, it can be postulated that this resistance is comparable to the heat resistance of AlZr0.05 (AT1). Alloy additions in the form of silver and molybdenum lower the temperature coefficient of resistance, which reduces the increase in the resistance of the conductor along with its temperature increase resulting from the heat balance, allowing a favourable current carrying capacity of the target high-temperature conductor to be achieved. The lower temperature coefficient of the AlAgMo material resistance in the annealed state compared to aluminium wire has potential advantages from the point of view of using such material in low-sag high-temperature ACSS cables, where the braid is made of recrystallized aluminium. The developed AlAg0.15Mo0.05 alloy shows higher rheological resistance than pure aluminium. On the basis of the conducted research, it is possible to design an AlAgMo alloy with a resistivity similar to AlZr (AT1) wires currently used for high temperature low sag conductors.

Cables made of the new alloy AlAg0.15Mo0.05 would enable the increase of their current carrying capacity and the operation of cables at elevated temperatures without the risk of the degradation of their strength properties. Based on the knowledge obtained during the research, it is possible to design a high-temperature cable with a braid made of the new material and to simulate its operation in an overhead power line.

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