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Comparative Analysis of Properties of Wires from Alloys of Al-Rem System, Obtained Using the Methods of Continuous Extrusion

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Abstract - The article presents the results of experimental studies of the production technology of electrical wire made of aluminum alloy of the Al–REM system with content of rare earth metals in the range of 7-9% using continuous casting and extrusion processing methods. Continuous casting rods with a diameter of 12 mm, obtained by casting into an electromagnetic mold (EMM), were the starting material for research. Methods of continuous extrusion "Conform" and combined rolling-extrusion (CRE) were the main methods to obtain a billet for subsequent drawing. Deformation modes, methods of experiments and equipment for the implementation of two variants of the proposed technology using various methods of continuous extrusion described. At all stages of the technology, samples were taken and the mechanical and electrophysical properties of the obtained deformed semi-finished products (ultimate tensile strength, elongation to failure and electrical resistivity) were studied. Application of the "Conform" method in industrial conditions using standard drawing routes allows obtaining a wire of small diameters with high strength properties, however, the plastic properties and values of electrical resistance do not correspond to the existing requirements of the technical specifications for its production. On the contrary, the plastic properties of hot-extruded rods obtained by the CRE method allow cold deformation using only one intermediate annealing. At the same time, the developed technology using continuous casting, combined rolling-extrusion, drawing modes and final annealing of a wire with a diameter of 0.5 mm provides the required level of plastic and strength properties, as well as minimum values of electrical resistance. The developed modes of deformation and heat treatment can be recommended for the industrial production of electrotechnical wire from high-alloyed Al–REM alloys.

Keywords: aluminum, rare earth metals, wire, electromagnetic mold, continuous extrusion, combined rolling-extrusion, drawing, mechanical properties, electrical resistance.

I. INTRODUCTION

Electrical wires from alloys of the Al–REM system is widely used in the manufacture of wires for aircraft operating at elevated temperatures. At the same time, they have not only high heat resistance and low weight, but also are characterized by increased strength properties [1-11].

For the production of wire from such alloys, a multistage technology was applied, including 17 technological conversions, including casting of granules, degassing, sintering of granules, extruding and subsequent drawing to a specified size with intermediate anneals. Combined methods studied in the work (CRE and "Conform") significantly reduce the number of redistributions.

The most modern technologies for manufacturing wires from these alloys are the casting of long billets of small diameter (8-14 mm) into an electromagnetic mold (EMM) and subsequent pressure treatment using continuous extruding methods to the required diameters (0.1-0.5 mm) [12, 13].

This work presents the results of a study on the possibility of producing wire from cast billets 12 mm in diameter made from an electromagnetic mold from an Al–REM system alloy with a REM content of 7-9%, using two methods of continuous extrusion: the "Conform" method [12] and the combined rolling-extrusion method (CRE) [13, 14]. The aim of the work was to compare the properties of longish deformed semi-finished products made using various continuous extrusion technologies to ensure the subsequent processing stability and to eliminate breakage when producing small-diameter wires.

II. METHODS, RESULTS AND DISCUSSION FOR TECHNOLOGY USING THE "CONFORM" METHOD

The first version of the technology included the following steps: obtaining cast billets using EMM, getting blanks for drawing on the machine "Conform", annealing of billet in a continuous furnace, drawing of billet to the specified wire diameter.

The second variant of the technology, in contrast to the first, envisaged at the second stage the production of hot-extruded billet for drawing by the CRE method.

A continuous cast billet with a diameter of 12 mm from an experimental alloy (Fig. 1) obtained in an electromagnetic mold on the equipment of «RPC Magnetic hydrodynamics» LLC (Krasnoyarsk, Russia) and coiled into the bay (Fig. 1).

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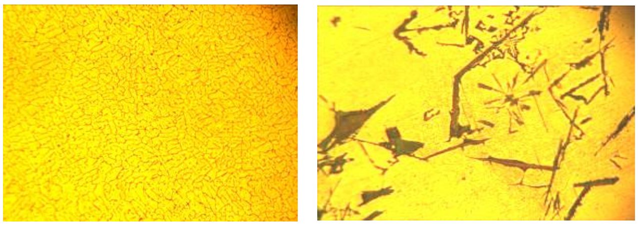
Figure 1. Experimental coil of alloy cast using EMM

The analysis of the microstructure of the castings from the experimental alloy (Fig. 2), cast in the electromagnetic mold (Fig. 2 a) and the ordinary chill mold (Fig. 2 b), has a cardinal difference. In contrast to the slowly cooled casting, a cast rod with a diameter of 12 mm, obtained by the casting method in an EMM, has a dendritic parameter 100 times smaller and homogeneous and fine with dispersed precipitates of particles of non-equilibrium phases. Metallurgical defects in the form of oxide captivity, non-metallic inclusions in the structure of the studied samples from cast billets in EMC not detected.



(a) **(b)**

Figure 2. The microstructure of cast billets obtained by casting in an electromagnetic mold (a) and a chill mold (b), ×200

Such a structure of cast billets obtained in EMM determines a high level of mechanical properties of the metal with satisfactory values of electrical resistivity (Table 1).

Table 1. Mechanical and electrical properties of molded billet from an experimental alloy

Sample diameter, mm (average)	Ultimate tensile strength R_m, MPa	Elongation to failure *A*, %	Electrical resistivity ρ, Ohm· mm^2/m
11.34	210	7	0.03617
11.54	212	7	0.03620

For the production of extruded rods (billets for wire drawing) from a continuously cast billet with a diameter of 12 mm, cast by the EMM method, according to the first variant of the technology, the "Conform" continuous extrusion machine used (Fig. 3), technical characteristics of the machine presented in Table 2.

Figure 3. Machine of continuous extrusion "Conform"

Table 2. Characteristics of the industrial installation "Conform"

Parameter	Value
Nominal wheel diameter, mm	300
Nominal torque, kN·m	63
Wheel speed, rpm	2-12.5
Main motor power, kW	90

The extruding of the billet with a diameter of 12 mm from an experimental alloy on the installation "Conform" carried out in two channels to the diameter of the resulting wire 2.65 mm according to the technological regimes of the existing industrial enterprise. At the same time, the filling and launching of the "Conform" unit carried out according to the standard proven technology in accordance with the technological instruction. In the manufacturing process, it was noted that the outer diameter of a continuously cast billet is unstable in length, the deviation from the nominal size varied from 0.5 to 1.5 mm. The heating temperature of the billet was Tb = 400 ·C with wheel speed · = 9 rpm. When implementing these technological regimes, pilot batches of wire were obtained.

Analysis of the surface appearance of the obtained wire showed that, along with a flat and smooth surface, there are areas with cuts and tears, which, apparently, can be explained by the instability of the diameter of the billet along the length.

The microstructure of the wire samples investigated using an optical microscope with an increase of 1000 times. As a result of extruding, as shown by microstructural studies (Fig. 4), intracrystalline segregation is eliminated and conditions for their subsequent cold deformation processing (drawing) are provided.

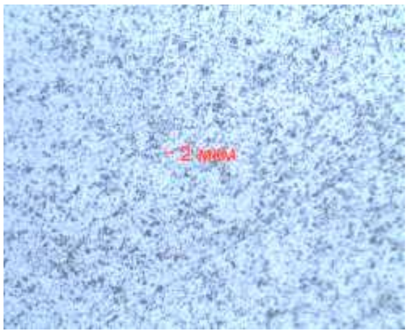


Figure 4. The microstructure of the metal after processing on the unit "Conform", ×1000

Mechanical tensile tests performed on a universal testing machine with a force of 20 kN. Analysis of mechanical properties shows that hot deformation of continuously cast billets at the "Conform" unit leads to a significant increase in the mechanical properties of the metal. In this case, elongation to failure increases by almost 2 times, and ultimate tensile strength increases on average by 10 MPa (Table 3).

Wire drawing to a diameter of 0.5 mm using the wire drawing method carried out according to the serial technology of an industrial enterprise on the drawing machine (Fig. 5).

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Filling the billet with a diameter of 2.65 mm on the drawing machine carried out by pulling along a standard drawing route with a single crimp of about 20%, and the output was wound onto a cylindrical coil using L71-03 technological lubricant.

Figure 5. Aggregate for wire drawing

The manufacture of wire carried out according to the technology of drawing with a slip in polycrystalline fibers with the use of coolant UNOPOL AL 570. The drawing carried out continuously, without intermediate annealing, at the same time during the work two breaks were recorded during drawing. Next, the wire was heat treated in the furnace chamber of the unit with a length of six meters. The number of wire passes through the furnace in the process of work varied from 4 to 10, the speed in the range • = 26-104 m/min and the temperature of the furnace chamber Tanneal = 400-470 •C. Thus, controlling the parameters of the unit, the number of wire passes through the furnace, and the temperature in the furnace chamber, the mode of heat treatment of the wire selected. As a result of experimental studies, 3 bays of wire with a diameter of 0.5 mm and a total weight of 48.3 kg obtained. The properties of the wire that has undergone processing in three modes are given in Table 3.

Table 3. Mechanical and electrical properties of the wire from an experimental alloy of the Al–REM system

Diameter, mm	Processing mode	Ultimate tensile strength R_m, MPa	Elongation to failure A, %	Electrical resistivity ρ, Ohm·mm^2/m
Extruding on the installation "Conform"				
2.65	T_b = 400 °C, ω = 9 rpm, 2 channels	214	15.0	0.03183
2.65	T_b = 400 °C, ω = 9 rpm, 2 channels	221	15.0	0.03226
2.65	T_b = 400 °C, ω = 9 rpm, 2 channels	221	14.0	0.03218
Drawing and annealing				
0.50	T_{anneal} = 470 °C, υ= 26 m/min,	263	1.6	0.03413
0.50	T_{anneal} = 450 °C, υ = 80 m/min,	233	1.7	0.03420
0.50	T_{anneal} = 450 °C, υ = 104 m/min,	195	2.0	0.03399
Required properties of wire with a diameter of 0.5 mm				
0.50	Annealed	No less 142	No less 8.0	No more 0.0320

Analyzing the level of the obtained properties of the wire, we can conclude that the pilot tests according to the first variant of the technology did not allow obtaining the required plastic properties (elongation to failure of at least 8%) and electrical resistance characteristics (no more 0.0320 Ohm • mm2/m), due to the structural features of the alloy and its hardening when using standard industrial drawing routes.

III. METHODS, RESULTS AND DISCUSSION FOR TECHNOLOGY USING THE CRE METHOD

In connection with the above, we carried out experimental studies on the second variant of the technology using the method of combined rolling-extrusion [12] and obtained blanks for drawing using the following method. In the electric chamber furnace, several blanks were simultaneously heated to a temperature of 550 °C with a holding time of 10-15 min. In this case, with the help of a specially developed furnace, the rolls heated to 100 oC. When the preset temperature in the furnace was reached, the rolls of the CRE-200 installation rotated at a frequency of 4 rpm, and then the blanks were set into the roll gauge. The metal was precipitated in height during rolling, pressed out in front of the die and extruded with drawing ratio equal to 10 through it in the form of a rod 5 mm in diameter. Further, a wire with a diameter of 5 mm was made from a wire with a diameter of 5 mm obtained by the CRE method by drawing on a single action chain drawing machine with one intermediate annealing. In the last stage of research in order to achieve the desired properties of the wire, the obtained samples were annealed at temperatures 350, 400, 450 and 500 °C and holding time 1 hour (heating with furnace, air cooling). At each stage of the technology, the mechanical properties of rods and wires were determined by static tensile testing of samples at room temperature using universal testing machines Walter+Bai AG LFM 400 kN and LFM 20 kN ("Walter + Bai AG"), and the electrical resistivity ρ measured on samples with a length of 1 m using an ohmmeter "Vitok". The obtained values of mechanical properties and electrical resistivity at 20 °C for rods and wires of the experimental alloy according to the second variant of the technology presented in Table 4

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Table 4. Mechanical and electrical properties of deformed semi-finished products from an experimental alloy of the Al–REM system, obtained using the CRE method

The diameter of the semi-finished product, mm; and condition	Degree of deformation ε, %	Ultimate tensile strength R_m, MPa	Elongation to failure *A*, %	Electrical Resistivity ρ, Ohm·mm^2/m
CRE, *T*=550 °C, 4 rpm				
5 mm, hot deformed	Drawing ratio 10	174	27.9	0.03023
Drawing process				
4.5 mm, cold deformed	19	204	17.0	0.03075
3.6 mm, cold deformed	48.16	215	6.1	0.03095
3.0 mm, cold deformed	64	222	5.3	0.03105
2.5 mm, cold deformed	75.4	231	4.6	0.03162
Intermediate annealing at a temperature 500 °C and holding time 1 h				
2.5 mm, annealed	-	135	28.6	0.02987
1.8 mm, cold deformed	47.3	159	23.4	0.03067
1.6 mm, cold deformed	58.4	223	3.8	0.03092
1.0 mm, cold deformed	83.7	235	1.4	0.03110
0.5 mm, cold deformed	95.9	250	1.3	0.03183
Final annealing at temperatures 350, 400, 450, 500 °C and holding time 1 h				
0.5 mm, annealed, 350 °C, 1 h	-	152	13.0	0.02924
0.5 mm, annealed, 400 °C, 1 h	-	144	14.3	0.02931
0.5 mm, annealed, 450 °C, 1 h	-	142	12.9	0.02923
0.5 mm, annealed, 500 °C, 1 h	-	142	16.3	0.02914
Required properties of wire with a diameter of 0.5 mm				
0.5 mm, annealed	-	No less 142	No less 8.0	No more 0.0320

Data analysis of Table 4 suggests that the wire obtained by the second variant of the technology with all modes of annealing provide the required level of properties, but the greatest elongation to failure (16.3%) has a wire annealed at 500 °C with a holding time of 1 hour. For the same wire obtained minimum values of electrical resistance (0.02914 Ohm • mm2/m).

IV. CONCLUSION

Thus, studies conducted to assess the effect of deformation and heat treatment on the mechanical and electrophysical properties of electrical wires made of high-alloyed aluminum alloy with a content of 7-9% REM, allowed us to draw the following conclusions:

- proposed and experimentally tested a new technology for manufacturing electrical wire of small diameters (up to 0.5 mm) from alloys of the Al-REM system using continuous metal processing methods;
- the use of the continuous casting method with the use of an electromagnetic mold, the methods of continuous extrusion of "Conform" and CRE, as well as cold drawing using this technology, allows to obtain small diameter wires under production conditions;
- when using continuous extrusion methods, it is advisable to use a continuous-cast billet with a diameter of 12 mm obtained in an EMM, having a uniform structure and length and high ductility in the cross section and length;
- comparative analysis of the use of various methods of continuous extrusion in the implementation of the developed technology has shown that the wire obtained using the method of combined rolling-extrusion has the required level of mechanical and electrical properties specified in the existing technical conditions for its production.

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