ELECTRICAL WIRE PRODUCTION FROM Al - Ce - La ALLOY RODS AFTER ELECTROMAGNETIC MOLD AND COMBINED ROLLING - EXTRUSION

Denis Voroshilov[1], Sergey Sidelnikov[1], Dorzhizhab Darmazhapov[1], Stepan Pokshivanov[1], Vadim Bespalov[1], Alexander Durnopyanov[1], Viktor Berngardt[1], Sergey Lezhnev[2], Mikhail Motkov[1,3], Marina Voroshilova[1], Olga Novikova[1], Danil Klimov[1], Andrey Ashmarin[1], Evgeniy Panin[4]

[1]*Siberian Federal University, 95 Krasnoyarskiy rabochiy Ave. Krasnoyarsk, Russia, d.s.voroshilov@gmail.com (D.V.); sbs270359@yandex.ru (S.S.); vmbespalov@mail.ru (V.Bes.); darmazapovdorzizab@gmail.com (D.D.); poksh32217@mail.ru (S.P.); a.durnopyanov@yandex.ru (A.D.); berngardt19@mail.ru (V.Ber.); aniram1988@yandex.ru (M.V.); lebedewa-olya@mail.ru (O.N.); cd57.fg@gmail.com (D.K.); gara81@mail.ru (A.A.)*
[2]*Rudny Industrial University, 38, 50 let Oktyabrya St., Rudny, Kazakhstan, sergey_legnev@mail.ru (S.L.)*
[3]*LLC "RPC of Magnetic Hydrodynamics", 9a, Akademika Kirenskogo St. Krasnoyarsk, Russia, mikhail145@mail.ru (M.M.)*
[4]*Karaganda Industrial University, 30 Republic Ave. Temirtau, Kazakhstan, cooper802@mail.ru (E.P.)*

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ABSTRACT

The paper presents the results of the power parameters when producing rods and wires with Ø 2 mm from them and the mechanical and electrical properties of the resulting semi - finished products from an alloy of the Al - Ce - La system with a rare earth metal content of 1 %. The wire is produced using the method of combined rolling-extrusion (CRE) from the billet Ø 12 mm after electromagnetic mold (EMM), and further drawing. The results of experimental studies of the process of producing longish deformed semi-finished products from the Al - 1 % REM alloy using the CRE-200 combined processing unit are presented. Data were obtained on the mechanical properties of hot - extruded rods Ø 5 mm and Ø 9 mm, as well as wire Ø 2 mm obtained from these rods after implementing the combined processes of rolling - extrusion. It was found that the proposed processing modes make it possible to obtain rods with Ø 9 mm and Ø 5 mm using a combined rolling - extrusion method from workpieces after EMM with diameter 12 mm. The forces on the rolls and die were measured during the implementation of the investigated combined processes. The plasticity of the resulting rods Ø 5 and 9 mm after the CRE method was quite high (elongation to failure reached 14 - 26 %). When drawing wire up to Ø 2 mm, no intermediate annealing was required. The values of electrical resistance do not exceed 0.0271 Ω mm^2 m^{-1} for rods and from 0.0301 Ω mm^2 m^{-1} for wire with a diameter of 2 mm, depending on the processing modes. At all stages of the experimental studies, the structure of the metal was studied and the patterns of change in physical and mechanical properties depending on the processing modes were established.

Keywords: *aluminium alloys, cerium, lanthanum, wire, mechanical properties, combined rolling-extrusion, drawing.*

INTRODUCTION

Rare earth metals (REM) in aluminium alloys can reduce grain size, change the microstructure, improve the distribution of inclusion phases, improve conductivity and remove harmful impurities of Si and Fe [1 - 5]. It was previously found that the Ce content from 0.05 to 0.16 wt. % in an aluminium alloy is beneficial for increasing electrical conductivity and tensile strength, since Ce reduces the solubility of solid impurity elements (Fe, Si) in the aluminium matrix [6].

Analysis of scientific, technical and patent literature showed that aluminium alloys with REM should be considered as promising alloys for the production of wire for various purposes [7].

These alloys are mainly focused on the production of electrical wire for the manufacture of wires, including those for critical purposes with improved mechanical characteristics and heat resistance [8]. In a recent study, it was found that when the La content is less than 0.3 wt. %, the electrical conductivity of Al - La alloy can maintain a high level of 60.35 % IACS due to the precipitation of compounds containing La, Si and Fe [9]. The authors of found that the maximum electrical conductivity of as-cast commercial pure aluminium is 59.7 % IACS with the addition of 0.2 wt. % Ce [10]. The T7 heat treatment can further improve the electrical conductivity to 60.7 % IACS, the main mechanism of which is the evolution of secondary phases after the introduction of Ce. In the study of heat treatment conditions, the Al - Ce alloy was annealed and held at high temperature, and it was found that the rare earth element plays an important role in the recrystallization of the Al - Ce alloy [11]. The data obtained in show that the addition of rare earth element Ce to aluminium alloy increases the tensile strength [12]. The content of Si has a great influence on its conductivity. It follows from the above that the corresponding content of La or Ce additives has advantages in removing harmful impurities of Si and Fe, deoxidation, dehydrogenation and grain refinement, improving tensile strength and relative elongation of aluminium alloys [13 - 17].

Conform and Extrolling are the most promising methods of wire production at the present time, which make it possible to eliminate the disadvantages of classical technologies [18]. The advantages of these methods are: the presence of active friction forces that facilitate the deformation process and reduce energy costs for production; high quality of the resulting pressed products; relatively low production costs due to the reduction of the technological processing cycle. However, there are also several disadvantages that significantly limit the industrial use of the described methods [19].

The idea of the Extrolling process was brought to industrial application due to its improvement by using a closed caliber, covered at the exit by a matrix, removing the matrix from the common axis of the rolls, and making the rolling elements of the rolls of different diameters [19]. This method is called combined rolling - extrusion (CRE) by the authors [18].

Considering the relevance of this problem, the goal of this work is to develop modes of combined processing and subsequent drawing of deformed semi-finished products for electrical purposes made of aluminium alloy containing 1 % rare - earth metals. To achieve this goal, the following tasks were envisaged:

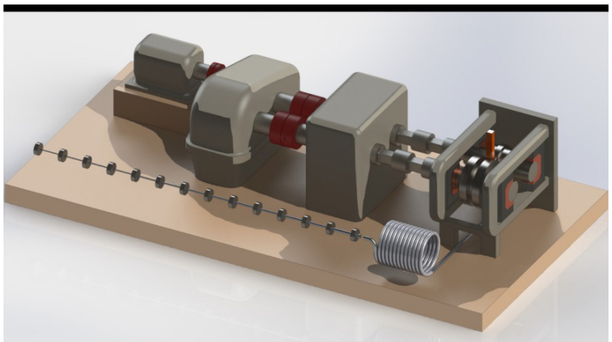
- Computer modelling of the CRE process.
- Conducting experimental studies on the production of rods from EMM using the CRE methods from the Al - 1 % REM alloy and wire from these rods.
- Investigation of the power parameters of the CRE process when obtaining rods.
- Investigation of the mechanical properties of the resulting deformed semi-finished products and select modes for maximum strength of the resulting wire.
- Investigation of the electrical resistance of rods and wires made from them obtained by CRE method and select modes for minimum electrical resistance of the resulting wire.
- Study of the microstructure of the obtained semi - finished products.

EXPERIMENTAL

To conduct experiments on the production of rods and wires and their further drawing, rods from an experimental alloy were obtained in the laboratory using the CRE method on the CRE - 200 unit (Fig. 1). REM (Ce and La) in the alloy contained up to 1 wt. %, the composition of the investigated alloy given in Table 1.

An Al-REM alloy with a reduced content of cerium and lanthanum was used for the studies (Table 1). The concentrations of Ce and La were determined using MRSA.

The alloy was prepared in a 25 kg capacity induction crucible furnace, which was part of the pilot industrial casting complex developed and commissioned at the Research and Production Center of Magnetic Hydrodynamics [20, 21]. The metal mixture introduction temperature was 850°C, and that of aluminium was 750°C. The melt was held for 40 minutes, and then



a)

b)

Fig. 1. Unit CRE (CCRE) - 200 (a) and rods with wire from alloy Al - 1 % REM (b).

Table 1. Chemical composition of the studied alloy Al - 1 % REM.

Mass fraction of an element , %														
Ce	La	Fe	Si	Cu	Mn	Mg	Cr	Ni	Zn	Ti	V	Ga	B	Al
0.6	0.4	0.106	0.058	0.0007	0.0013	0.0016	0.0004	0.0041	0.0392	0.0050	0.0098	0.0159	0.0017	Balance

casting was carried out.

To obtain rods with a diameter of 5 and 9 mm from a continuously cast billet with a diameter of 12 mm, CRE - 200 unit was used, and to produce wire with a diameter of up to 2 mm, a chain drawing mill was used.

The following parameters were adopted as modelling the process of combined rolling and pressing of rods from a billet with a round cross section: billet temperature 480 and 550°C; tool temperature 100°C; degree of deformation during rolling ε = 50 %; billet diameter 12 mm; the diameter of the calibrating hole of the matrix is 5 mm; the length of the working belt of the matrix is 3 mm; the rotation frequency of the rolls is ω = 4 and 8 rpm [23].

The process was modelled under the following conditions and assumptions: the workpiece material is isotropic; the material of the rolls and the matrix is rigid-plastic; the Siebel friction coefficient when moving the metal along the die mirror is $\psi_d = 0.3$; the Siebel friction coefficient on the rolls and the calibrating belt of the die is $\psi_r = 0.9$; no cooling of the rolls is provided; the number of finite elements into which the billet is divided is 20000 pcs [23].

As a result of the modelling, the distribution of temperatures and stresses along the deformation zone was obtained for various deformation and speed parameters of the CRE process.

RESULTS AND DISCUSSION

The results of modelling the metal deformation, temperature and stress distribution along the deformation zone at different roll speeds and pressed rod diameters are shown in Fig. 2.

Analysis of the modelling results showed that the CRE process is feasible in the specified range of process parameters. In this case, the workpiece temperature along the deformation zone varies in the range from 480 to 200°C.

Analysis of the temperature distribution along the deformation zone (Fig. 2) showed that the average temperature of a product with a diameter of 9 mm in the zone in front of the die is about 270°C at a roll speed of 4 rpm and about 325°C at 8 rpm. When extruding a product with a diameter of 5 mm, the average temperature at the exit from the die is about 320°C at 4 rpm and about 380°C at 8 rpm.

The highest temperature values and the lowest stress values in the zone in front of the die are observed at a roll speed of 8 rpm and a product diameter of 5 mm. This can be explained by the increased deformation heating of the metal at the maximum value of drawing during extrusion and the resulting decrease in deformation resistance.

Increasing the rotation speed of the rolls to 8 rpm leads to a decrease in stresses to values of about 53 - 62 MPa. For the case of pressing a rod with a diameter of

5 mm, the stress values in the zone in front of the die were 81 MPa at a roll rotation speed of 4 rpm and 45 MPa at 8 rpm.

It is necessary to pay attention to the conditions under which the maximum stress values observed in the deformation zone in front of the die are realized. Here it can be noted that for the case of CRE at a workpiece temperature of 480°C, a roll rotation speed of 4 rpm and

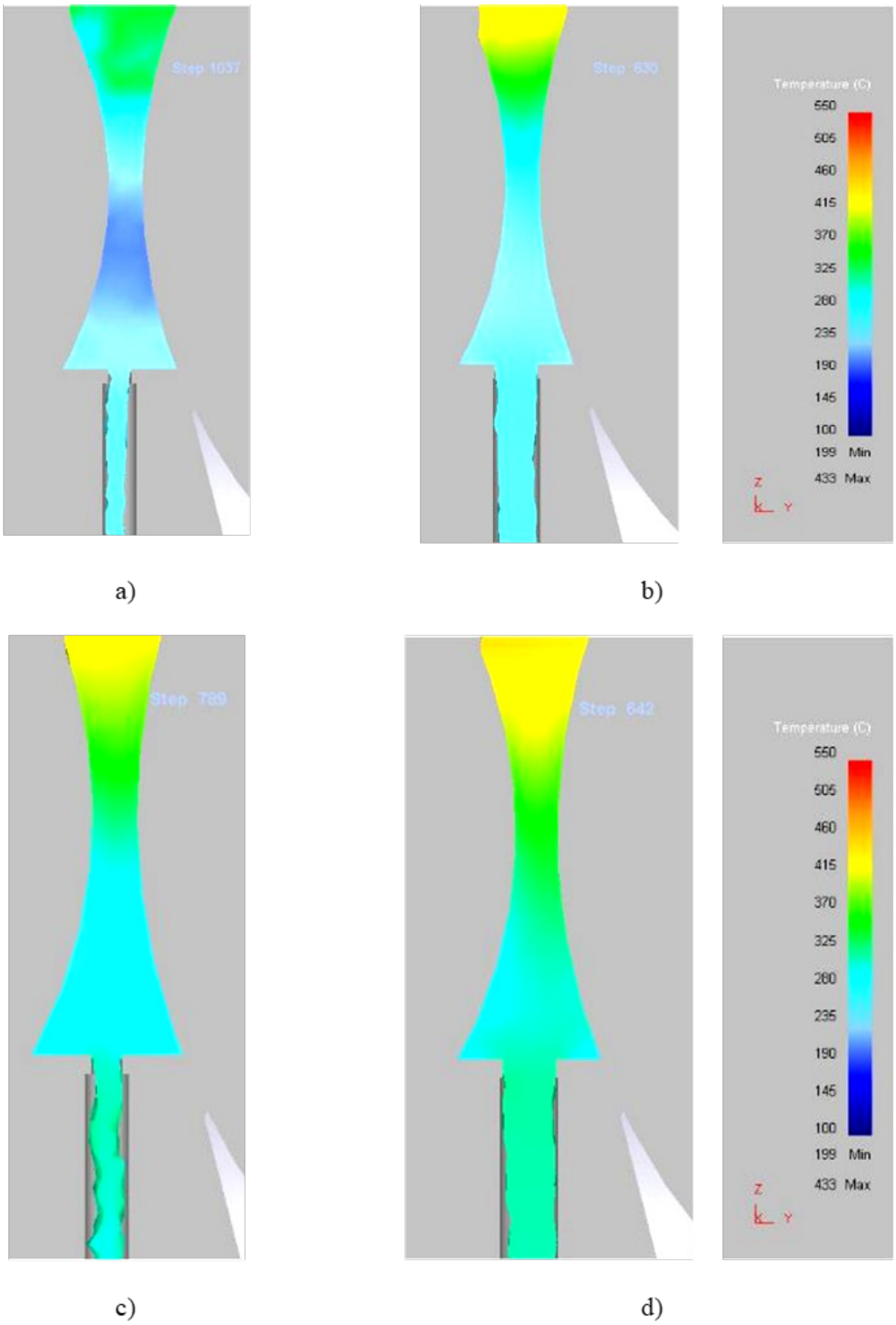


Fig. 2. Metal shaping and temperature distribution during processing of a billet made of Al - 1 % REM alloy at a roll rotation speed of ω = 4 rpm (a, b) and ω = 8 rpm (c, d): a, b - rod diameter 5 mm; a, b - rod diameter 9 mm.

obtaining a pressed product with a diameter of 9 mm, the stress values are in the range of 75 - 90 MPa.

When analysing the results of modelling the process of the CRE of a billet with a temperature of 550°C, it was found that at a roller rotation frequency of 4 rpm during the extrusion process, a gradual cooling of the workpiece in the zone in front of the die occurs. Thus, the temperature of the metal in the zone in front of the die at the beginning of the extruding process is about 330°C and then drops to a temperature of 250°C, while the temperature of the pressed product with a diameter of 5 mm is about 280°C [23].

When implementing the CRE process at a roll rotation speed of 8 rpm, as in the previous case, as the deformation zone is filled with metal, an increase in the forces acting on the rolls and the die is observed. As a result of the release of deformation heat in the extrusion zone, the metal is heated in the zone in front of the die, and the force on the rolls decreases to 150 kN, and the process becomes stable.

Based on the obtained results of computer and mathematical modelling, the tool parameters and processing modes of the studied alloy on the CRE - 200 unit for conducting experimental studies were determined [23].

The modes for obtaining rods are given in Table 2. The obtained rods with a diameter of 5 mm and 9 mm were subjected to cold drawing until wire with a diameter of 2 mm was obtained.

It should be noted that the cast blanks obtained in the electromagnetic mold had a sufficiently high plasticity, which made it possible to obtain wire with a diameter of 2 mm from them without intermediate annealing.

It was also found that the electrical resistance values for wire with a diameter of 2 mm after cold deformation are higher than those of rods obtained by hot deformation. Therefore, in order to obtain a set of properties that meet current standards, it is necessary to study and establish the parameters of final annealing [23].

For this purpose, studies were conducted on the heat treatment parameters of the obtained rods and wire under various processing and annealing modes: annealing temperature of 230ºC, holding time of 1 h; annealing temperature of 300ºC, 1 h; annealing temperature of 400ºC, 1 h; annealing temperature of 450ºC, 10 h.

Table 3 presents data on the mechanical properties and electrical resistance of wire with a diameter of 2 mm in the cold - worked and annealed states.

Thus, the results of the studies showed that to meet the requirements of the IEC 62004 - 07 standard for the

Table 2. Parameters of the Al - 1 % REM alloy processing mode on the CRE - 200 unit.

Parameters	Heating temperature, °C			
	480		550	
Rod diameter, mm (at roll rotation speed of 4 rpm)	9	5	9	5
Rod diameter, mm (at roll rotation speed of 8 rpm)	9	5	9	5

Table 3. Values of mechanical properties and electrical resistance of wire made of Al - 1 % REM alloy with a diameter of 2 mm, obtained from rods with a diameter of 9 and 5 mm by combined processing methods, under different annealing conditions.

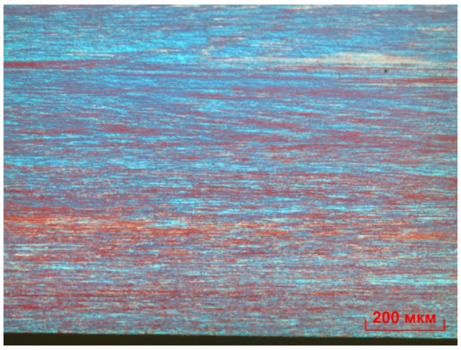
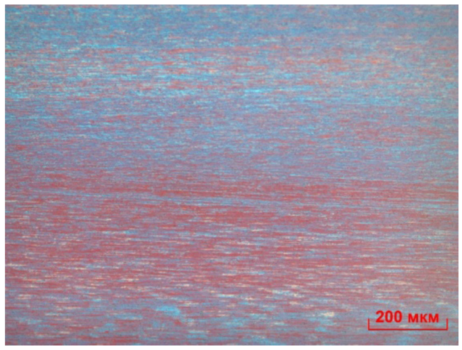
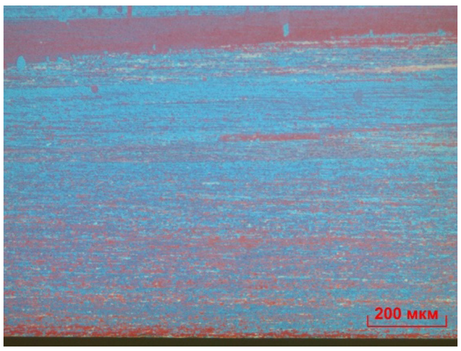
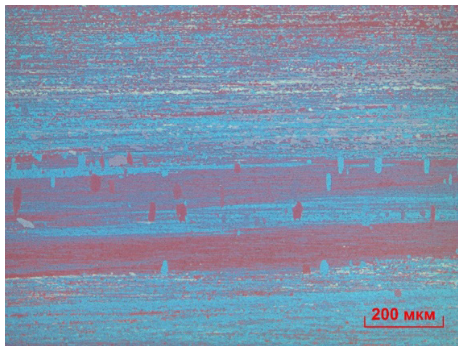
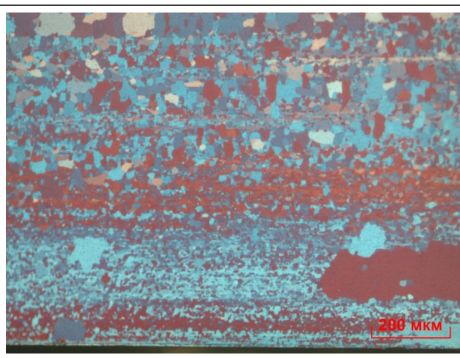
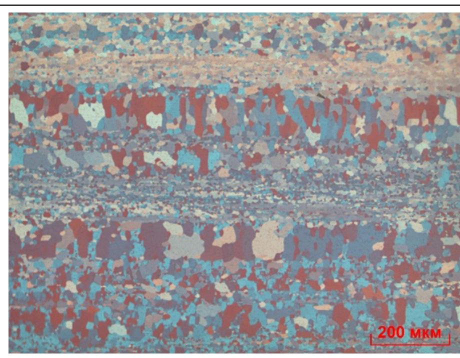
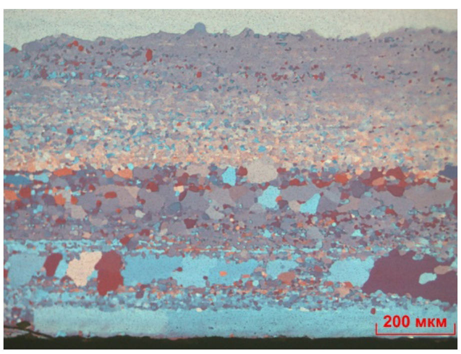
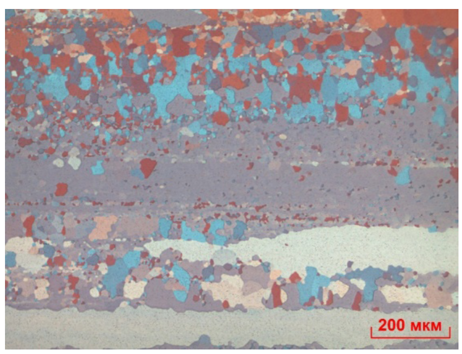
Type of processing	Condition	Mode	UTS, MPa	Elongation to failure A, %	Electrical resistance ρ, Ω mm^2 m^{-1}
Wire diameter 2 mm from rod diameter 9 mm					
EMM + CRE	Hardened	–	191	3.0	0.02990
	Annealed	230ºC, 1 h	163	9.5	0.02784
	Annealed	300ºC, 1 h	108	15.0	0.02786
	Annealed	400ºC, 1 h	87	28.3	0.02757
	Annealed	450ºC, 10 h	84	29.5	0.02753
Wire diameter 2 mm from rod diameter 5 mm					
EMM + CRE	Hardened	–	198	3.0	0.03000
	Annealed	230ºC, 1 h	155	3.5	0.02775
	Annealed	300ºC, 1 h	97	24.5	0.02750
	Annealed	400ºC, 1 h	93	31.0	0.02745
	Annealed	450ºC, 10 h	89	38.0	0.02705

AT1 mode, it is recommended to use the annealing mode at a temperature of 230ºC and a holding time of 1 h.

The microstructure studies were carried out on an Axio Observer A1.m, Carl Zeiss light microscope at magnifications of ×200 and ×500 in polarized light after film application [23].

After annealing at a temperature of 230ºC and a holding time of 1 h, the entire wire retains a deformed fibrous structure, which indicates good thermal stability of the Al - 1 % REM alloy (Tables 4 and 5).

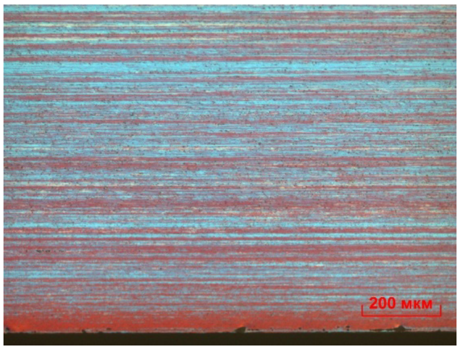
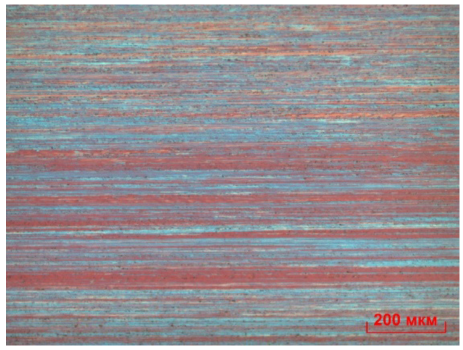
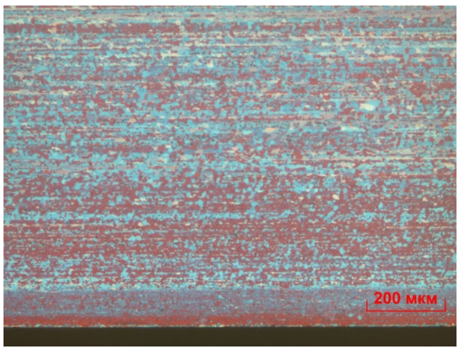
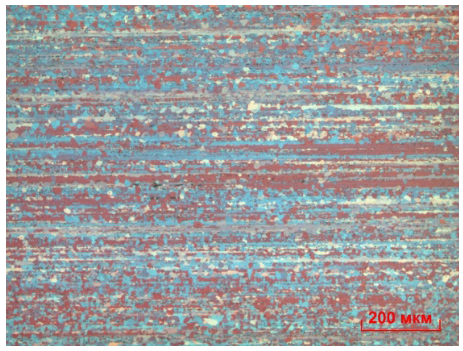
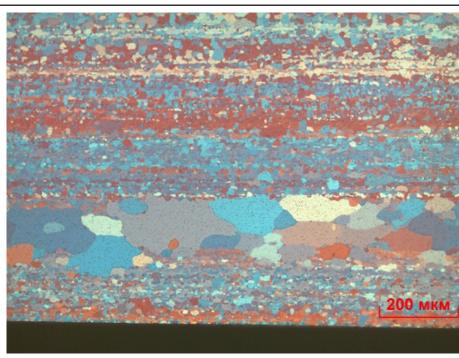
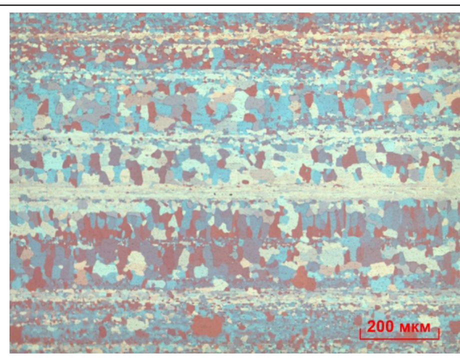
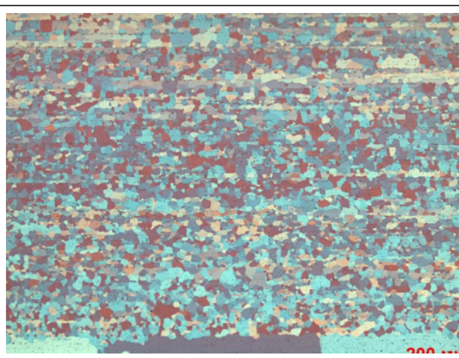
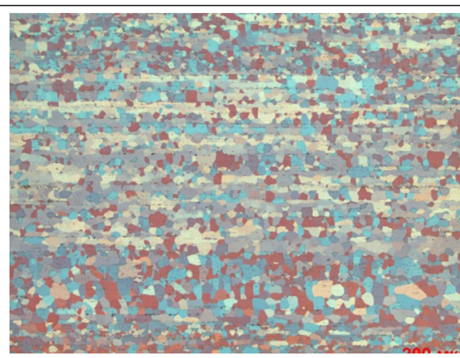
Table 4. Microstructure of 2 mm diameter wire from 9 mm diameter rod after heat treatment.

Mode of heat treatment	Periphery	Center
230ºC, 1 h		
300ºC, 1 h		
400ºC, 1 h		
450ºC, 10 h		

The microstructure of the wire made of the studied Al - 1 % REM alloy, obtained by the EMM + CRE method from rods with diameters of Ø 9 and 5 mm, consists of an aluminium matrix and dispersed particles of intermetallic phases $Al_4(Ce, La)$, the volume fraction of which in the structure is ~ 2.5 %, some of the particles are oriented in the direction of deformation.

After annealing at 300ºC and holding for 1 h, the wire obtained from a 5 mm rod using the EMM + CRE technology acquires a partially recrystallized structure

Table 5. Microstructure of 2 mm diameter wire from 5 mm diameter rod after heat treatment.

Mode of heat treatment	periphery	center
230ºC, 1 h		
300ºC, 1 h		
400ºC, 1 h		
450ºC, 10 h		

(Table 4), while in the wire with a greater draw, obtained from a 9 mm rod, the recrystallization processes are only at the initial stage (Table 3).

When annealing at 400ºC, holding for 1 h and 450ºC, holding for 10 h for the wire obtained by the CRE method, this dependence is preserved. In the wire obtained by the CRE method from a 9 mm rod, the structure is recrystallized fine - grained and uniform in cross-section (Table 4), and in the wire obtained by the CRE method from a 5 mm rod, some increase in grain is observed in the more deformed peripheral layers, which indicates a more intense recrystallization process (Table 5). In the wire obtained from a 5 mm rod, the structure is finer - grained (Table 5), while in the EMM + CRE wire from a 9 mm rod, when annealed at 450ºC, held for 10 h, a significant coarsening of grain in the peripheral and central parts is observed, which indicates the beginning of secondary recrystallization (Table 5).

In general, wire obtained by the CRE method maintains higher thermal stability when heated to 230 - 450ºC, which is characterized by a more uniform and fine - grained structure across the wire cross - section [23].

CONCLUSIONS

Thus, as a result of the conducted research, the following main results were obtained:

- using the created computer 3D model of the CRE process for deformation of a billet with a round cross - section, obtained in EMM, the features of shaping, temperature distribution, stresses were studied and force parameters along the length of the deformation zone were determined at different roll rotation speeds using data on the rheological characteristics of the experimental alloy;
- using the results of computer modeling, the design parameters of the rolling and extruding tool, as well as the technological modes of rolling and extrusion for conducting experimental studies were determined;
- using the developed technological modes of continuous casting in an electromagnetic crystallizer, continuous extrusion by the CRE method, drawing, intermediate and final annealing, experimental studies were conducted to obtain wire with a diameter of 2 mm from an experimental alloy;
- cast billets obtained in an electromagnetic mold and rods made from them by the CRE method have sufficiently high ductility, which makes it possible to obtain wire with a diameter of 2 mm from them without intermediate annealing.
- at all stages of these experimental studies, the structure of the metal was studied and patterns of change in UTS, elongation to failure and electrical resistance of longish deformed semi-finished products in the hot and cold deformed state were established depending on the processing modes;
- the level of strength characteristics of hot - extruded rods is in the range of 123 - 140 MPa, plastic - 14 - 26 %, and electrical resistance - from 0.0271 to 0.0301 Ω mm^2 m^{-1};
- it was found that during deformation of a continuously cast billet in EMM, which has a fine - grained structure, the grains of the solid solution are refined and stretched in the direction of deformation, in addition, it was found that the tested modes of thermal deformation treatment lead to a structure with a fairly uniform distribution of secondary phases throughout the volume of the wire when manufacturing wire with a diameter of 2 mm.
- it was found that with sufficiently high characteristics of mechanical properties, the values of electrical resistance for wire with a diameter of 2 mm after cold deformation are higher than those of rods obtained by hot deformation, therefore, to obtain a set of properties that meet current standards, it is necessary to use annealing at a temperature of 230ºC and hold for 1 h.

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Authors' contribution: *D. V. - funding acquisition, investigation, methodology, writing - original draft, writing - review & editing, resources, data curation; S. S. - conceptualization, methodology; D. D., S. P., D. K. and A. A. - investigation; V. Bes. - project administration, investigation, visualization; A. D. - investigation, writing - original draft; V. Ber. - investigation, writing - original draft, resources, validation; S. L. and E. P. - formal analysis, writing - review & editing, visualization; M. M. - resources, validation; M. V. - investigation, writing - review & editing, formal analysis; O. N. - investigation, software.*

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