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DEVELOPMENT AND RESEARCH OF NEW ALUMINIUM ALLOYS WITH TRANSITION AND RARE-EARTH METALS AND EQUIPMENT FOR PRODUCTION OF WIRE FOR ELECTROTECHNICAL APPLICATIONS BY METHODS OF COMBINED PROCESSING

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Abstract

Development of electrical alloys of system aluminium – rare-earth metals and aluminium-zirconium for production of electrotechnical application wire rod. Design of technological line for their manufacturing.
The effect of rare-earth and transition metals on the properties of the aluminium alloys containing such metals is analysed. New alloys with different content of zirconium, cerium, and other components featuring enhanced mechanical and electrophysical characteristics have been proposed. New technologies for production of long round-in-section items involving combined processing methods have been developed. The effects of the processing methods on the structure and properties of semi-finished products made of new alloys have been studied and recommendations for the modes of preparing alloys, casting, shaping, and thermal processing have been made for the set of the studied alloys. The method of combined casting and drawing-extrusion is shown to ensure, in laboratory conditions, improved mechanical properties and the required level of electric resistivity.

Introduction

Recent years saw a noticeable increase in the use of aluminium alloys in electrical engineering. This has been primarily the result of relatively high prices of copper and copper wire rod. Aluminium is, on average, almost 4 times cheaper than copper while aluminium wire rod is also more than 3 times lighter than copper wire rod. The main drawback of technical grade aluminium wire rod made of 1050 and 1070 alloys sold in the market today is that it has relatively low strength (its ultimate tensile strength is 80-110 MPa). Silicon and magnesium are added as alloying elements to aluminium (AVE alloys), which increases tensile strength to 120-130 MPa, but silicon and magnesium significantly reduce the electrical conductivity of the wire. Analysis of published scientific and technical materials has shown that aluminium alloys made with transition group metals and rare earth metals have increased heat resistance because they have a lower diffusion coefficient. In particular, adding minor amounts of zirconium or cerium significantly increases the tensile strength and thermal resistance of aluminium alloys; however, such alloys also have higher electrical resistance. This means that we need to develop alloys that would combine the mechanical and electro-physical properties required by our customers.

Two groups of aluminium alloys were proposed to fill this need in accordance with Russian Federation Patents No 2458151 and No 2458170 [1,2].

Properties of alloys of Al-Zr system

The first group includes Al-Zr low alloys because zirconium alloys are the most frequently used kind of thermal resistant alloys worldwide. One characteristic that is unique to this group of alloys is that the content of zirconium and iron in them is 0.10-0.19 wt.% and 0.21-0.35 wt.%, respectively, while the content of silicon is 0.11-0.15 wt.%. These amounts of alloying elements optimise the mechanical strength of the alloy (ultimate tensile strength of up to 150 MPa) and its electrical resistance (no more than 0.0285 Ohm·m/mm^2) while also giving it acceptable thermal resistance. At the same time, it has to be noted that high strength characteristics contributed by these alloying elements are not affected by high temperatures.

Features of Al-rare earth metals alloys

The second group of alloys are Al-REM (rare earth metals) alloys. These are characterised by high strength (ultimate tensile strength of up to 220 MPa) and thermal resistance. One feature of rare earth metals is that they do not dissolve easily in solid aluminium, which means that they do not significantly reduce the electrical conductivity of aluminium. On the other hand, rare earth metals actively react with aluminium and transition metals forming intermetallic compounds in the eutectic and in highly disperse form. The resultant $Al_{11}Me_3$ (Al_4Me) intermetallic transition phases, which have a very high melting point (over 1,200°C), ensure consistency of the mechanical and electro-physical properties of the alloys at temperatures of up to 200°C. The specific electrical resistance of these alloys does not exceed 0.0295 Ohm·m/mm^2 while the ratio of specific strength to ultimate tensile strength to the density of the wire material is 92.6 N·m·g^{-1}, whereas even the best grade plastically deformed and hardened 1050 aluminium alloy wire have a ratio of no more than 60 N·m·g^{-1}. Analysis of the mechanical and electro-physical properties of these allows has shown that as the content of cerium and lanthanum is increased, the ultimate tensile strength, hardness and specific electric resistance also increase.

Equipment for combined processing

Equipment most often used in production of semi-finished aluminium products for the electrical engineering industry is comprised mainly of casting and rolling machines. However, wire rod that can be produced on currently available casting and rolling machines does not have the required mechanical properties for it to be used as wires in power transmission lines. Thus, additional measures still have to be taken to increase the strength of the cable by wrapping it up in various materials, complicating the design of the cable, or by using various cores etc., with all such methods increasing the production costs of finished cables. In addition, the casting and rolling equipment currently available at the production sites can only process aluminium and soft aluminium alloys.

The task of processing the new alloys using more energy efficient production processes and equipment can be accomplished by using combined processing methods [3,4], the most efficient of which is the combined casting, rolling and extrusion process (CREP).

To implement this method and research the technologies for processing the new alloys, a prototype CREP machine was designed and manufactured [5]. You can see what the new machine looks like in Figure 1.

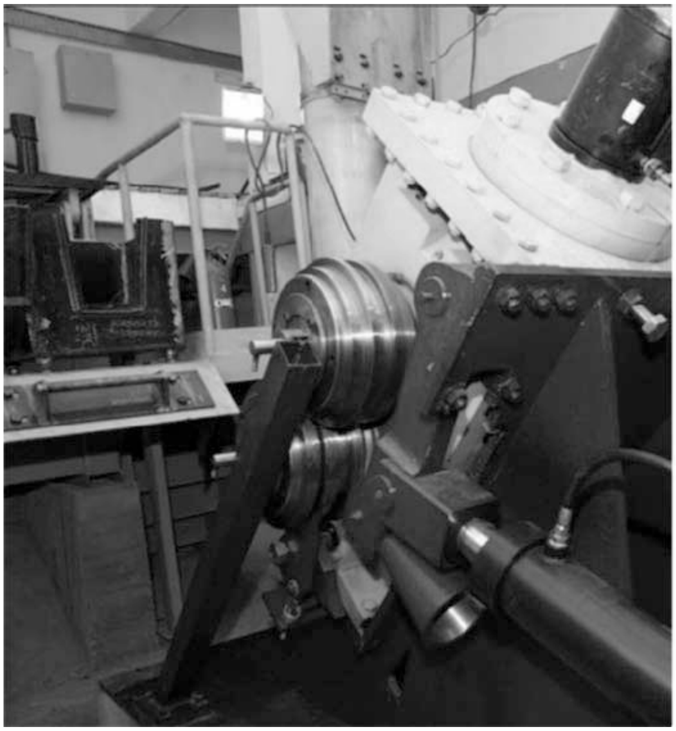


Figure 1. Industrial Prototype of a CREP Machine.

CREP-2.5 machine is a full scale prototype of an experimental combined casting, rolling and extrusion processing machine for producing electro-technical aluminium wire rod and is part of a combined processing line. The technical specifications of the CREP 2.5 machine are presented in Table 1.

A research was carried out into producing electro-technical wire rod from the new aluminium alloys using the combined casting, rolling and extrusion method and the newly developed equipment. Some of the unique findings of the research are presented below.

Table 1. Technical Specifications of the CREP 2.5 Machine

Parameter	Value
The initial diameter of the roll, mm	400
The length of the side of the roll, mm	350
Number of spins of the roll: - minimum - maximum	 1 15
Gear ratio	40
Power of the electric motor, kWt	45
Operating pressure of the hydraulic plant, MPa	200
Capacity, tonnes per hour	2,5
Dimensions, mm	3400 x 2350 x 627

Results of examinations of Al-Zr alloys

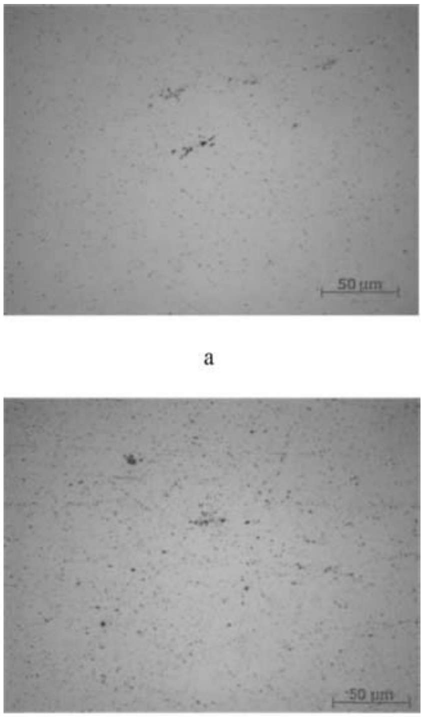
For the first group of alloys of Al-Zr system, technology of the combined casting, rolling and extrusion process was implemented by pouring the molten metal between the rolls, which was consistently crystallized in the groove of rotating rolls, pressed out by them and squeezed out through a matrix in the form of a hot-pressed product (wire rod) of 9 mm in diameter. In order to check the technological effectiveness of the made semi-finished products, their drawing on a chain drawbench without intermediate annealing was carried out, and a wire of 2 mm in diameter was made. Subsequently, according to recommendations [6.7], stepped annealing of the wire was done at a fixed holding time, firstly at a temperature of 300°C, and then at a temperature of 450°C. The mechanical properties and electrical resistivity of the deformed semi-finished products were measured at each processing step by using the LFM400 testing machine with a tensile load of 400 kN (Table 2). Thus, the performed studies were aimed to investigate influence of technology features for making the deformed semi-finished products with combined casting, rolling and extrusion method on mechanical and electrophysical properties of samples of Al–Zr system alloys, in which zirconium in an amount of 0.1-0.3 wt % was chosen as a basic alloying element [8].

Table 2. Properties of the deformed semi-finished products of Al-0.15%Zr alloy

Mechanical properties of wire rod, Ø 9 mm		Mechanical properties of wire Ø 2 mm in strained and annealed state		Micro-hardness of wire rod and wire	Electrical resistivity of wire
UTS, MPa	El., %	UTS, MPa	El., %	kgf/mm^2	Ohm·mm^2/m
121	21	194 73	3 36	35.9±0.7 41.9±1.4	0.0284 0.0275
106	29	212 80	3 34	35.9±0.7 41.9±1.4	0.0294 0.0282

Metallographic studies showed that the structure of all samples made with combined casting, rolling and extrusion method is characterized by non-uniform distribution of phases across a section of aluminum solid solution (Figure 2), and also more rough conglomerations of iron-containing particles and zirconium aluminides are observed here. In addition, small particles of Al_3Zr

phase which are extended along the deformation direction are found in the samples. Precipitation of some quantity of Al_3Zr inclusions is apparently connected with technology features used for melt preparation and its pouring between the rolls. Cold drawing when making a wire leads to crushing of Al_3Zr particles, therefore they form lines of small particles similar to a roundish form whereas in the samples of a wire rod made with combined casting, rolling and extrusion method, the majority of particles has a needle form. Unevenness of structural components distribution is inherited by the structure of a wire as well.



a

b

Figure 2. – Microstructure of wire rod (a) and wire (b) of a test sample of Al-0.15%Zr, made with combined casting, rolling and extrusion process, x500

In order to evaluate properties of wire rod of aluminium alloy containing 0.15 % zirconium, received at a pouring temperature of 720°C, high-temperature tests were performed at the LFM400 universal testing machine with a tensile load of 400kN. Test results are shown in Figure 3.

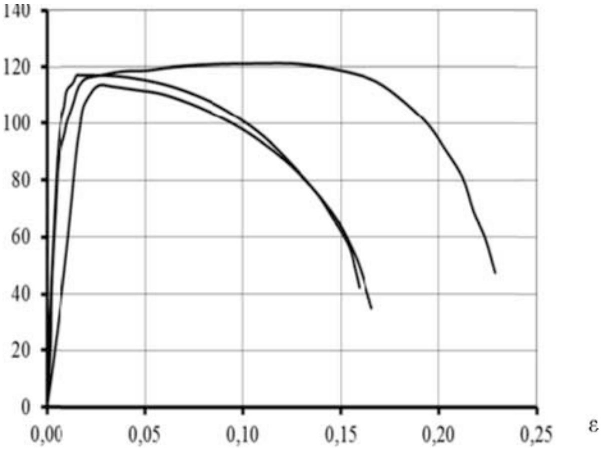


Figure 3. Dependence of deformation degree on yield strength for samples made with combined casting, rolling and extrusion method from Al - 0.15%Zr alloy (pouring temperature is 720°C), at different test temperatures: 1 – 20°C; 2 – 200°C; 3 – 350°C

A rather uncommon shape of the graphs means that when the temperature is increased at the initial stage of deformation, it barely affects the tension 0.2% YS and more significant effects can only be observed at later stages. This can be put down to the very specific way in which the structure of the rods forms during accelerated crystallisation and deformation of the metal being processed using the combined casting, rolling and extrusion method. Earlier studies [9] allowed us to establish that using combined casting, rolling and extrusion ensures the formation of a stable sub-granular structure that is related to the temperature at which recrystallization of the metal begins. The experimental research that we carried out demonstrated that 99.7% grade aluminium extrusions produced using the CREP method begin and stop recrystallising at the temperatures of Tr^b = 290°C and Tr^s = 350°C respectively, which is 40-70°C higher than the recrystallization temperature of wire rod produced using the traditional process of making rolled bars and rods. This is an indication of a more stable sub-granular structure of extrusions produced using the combined casting, rolling and extrusion process. The same effect can probably be achieved by using combined processing of Al-Zr aluminium alloys.

Assessment of the strength properties when the test temperature is increased from 20°C to 350°C is shown in Figure 3. It should be noted that the tendency for the temporary tensile strength to fall by 3-7% is present regardless of the casting method (the melt temperature and the temperature at which the melt is poured between the rolls of the casting, rolling and extrusion machine) used to make wire rod from 0.15% zirconium alloy (Figure 4).

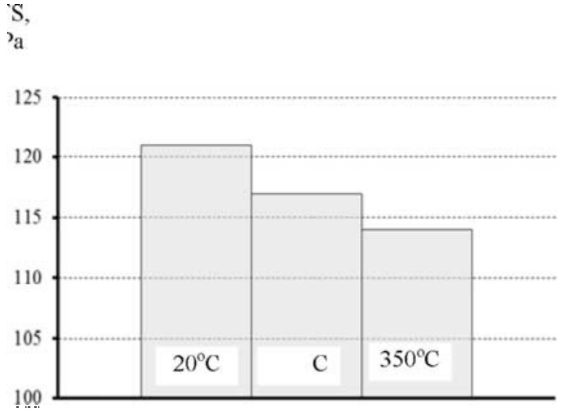


Figure 4. Tensile strength properties of wire rod made from Al-0.15Zr alloy using the combined casting, rolling and extrusion method at different test temperatures

The tests also demonstrated that as the zirconium content in the alloy increases from 0.15 to 0.25%, the temporal tensile strength increases by 5-7% reaching UTS=125-130 MPa, but the electric conductivity of the material decreases at the same time.

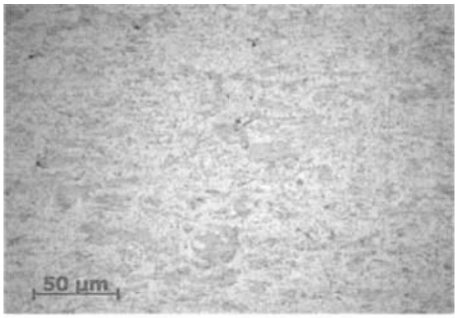
Results of examinations of Al-REM alloys

For the second group of aluminium alloys with a content of rare earth metals of up to 5.0% of the mass we researched the effect the temperature and the rate of deformation have on the structure and properties of wire rod produced using the combined casting, rolling and extrusion process at melt temperatures of 750°C and 780°C and deformation rates of $\xi = 0.74\ s^{-1}$ и $\xi = 1.49\ s^{-1}$ [10].

The structure of deformed semi-finished samples is shown in Figure 5.

Deformation at 750°C at different rates causes the formation of a structure that varies greatly between the middle of the wire rod and its edges. Along the edges small particles are evenly distributed over the solid solution. In the middle, there are lighter areas α of the solid solution and darker areas of eutectic ($\alpha + Al_4Mm$), where Mm represents a mishmetal comprising cerium, lanthanum, praseodymium and other metals. At 780°C the lack of uniformity of structure in various layers of the metal is less pronounced. In the samples of 5 mm in diameter there are large lumpy particles of 9x3 μm to 15x7 μm in size. This probably has to do with the high rate at which the metal cools off as it crystallises in the rolls and the high degrees of deformation that the metal undergoes as it is extruded through the calibration hole of the matrix. The optimal metal structure is achieved at 780°C and a high rate of deformation of $1.49\ s^{-1}$.

The mechanical properties of wire rod with a diameter of 5 mm, 7 mm and 9 mm produced using the combined casting, rolling and extrusion process at different deformation rates and at melt temperatures of 750°C and 780°C are presented in Table 3.



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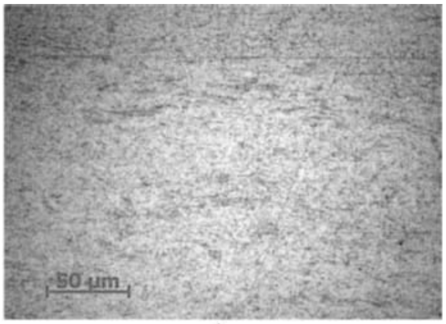

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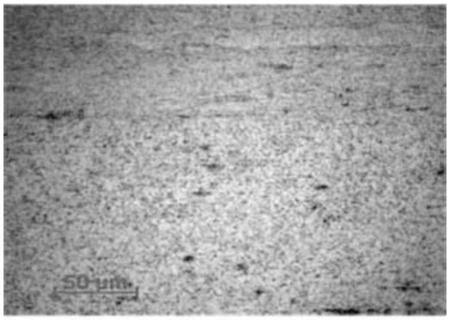

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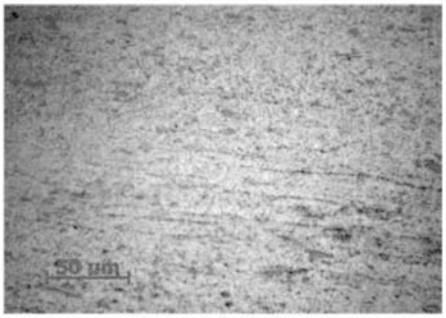

d

Figure 5. The microstructure of wire rod of 9 mm in diameter (a,b) and 5 mm in diameter (c,d) produced using combined casting, rolling and extrusion process at temperatures of 750°C (a,c) and 780°C (b,d) at a deformation rate of $1.49\ s^{-1} \times 500$

Table 3. Mechanical Properties of Wire Rod made of Al-REM Alloys

Parameters		T=750 ^{0}C			T=780 ^{0}C		
		d=9 mm	d=7 mm	d=5 mm	d=9 mm	d=7 mm	d=5 mm
$\xi = 0,74\ s^{-1}$	UTS, MPa	212,37	237,92	253,27	212,78	232,55	241,92
	El., %	13,34	13,49	12,82	13,53	12,8	11,86
$\xi = 1,49\ s^{-1}$	UTS, MPa	198,58	226,01	246,78	191,56	218,45	231,72
	El., %	10,2	10,52	9,64	11,72	10,62	10,29

As the table shows, the ultimate tensile strength of wire rod samples made using the combined casting, rolling and extrusion process is on average between 190 and 250 MPa, while the relative elongation is 9-14%. Values of electrical resistivity were within 0,0294-0,0310 Ohm·mm^2/m.

Conclusion

1.New aluminium alloys with transition and rare earth metals were developed that have better mechanical and operational characteristics and the correlation between various modes of combined processing and the properties and structure of wire rod made from these alloys was studied.

2.A prototype combined casting, rolling and extrusion machine was built for making elongated products with improved strength properties from the new aluminium alloys.

3.Aluminium alloys with 0.1-0.3% zirconium content can be used for making electrical conductors, while the temporal tensile strength of hot-deformed semi-finished products made by using the combined casting, rolling and extrusion method reaches up to 120-130 MPa, while the tensile strength of cold extrusions deformed to a degree of 95-98% reaches 200-210 MPa, in the meantime their specific electrical resistance is within 0.0285-0.0295 Ohm·mm^2/m.

4.Wire rod produced by using combined processing from aluminium alloys with rare earth metals has high tensile strength (up to 200-250 MPa in a state of hot deformation) and can be used for production of electrical conductors to be operated at increased temperatures.

5.The estimated mechanical properties of the new alloys and the way they change depending on the processing parameters were used in the design of prototype combined processing equipment and in the development of production processes for making elongated electrical engineering products.

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