# Modified aluminum alloys of Al – Zr system for power transmission lines of Uzbekistan

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The energy sector of Uzbekistan has undergone significant changes in recent years. To diversify the electricity generation sources of the country, it is planned to bring atomic energy sector to the country and further expand more traditional energy production sources, such as wind, solar and other mixed sources. The effectiveness of electricity generation sources is determined by the consumers as well as by the quality and the number of ways to transfer the generated electricity from the source to the consumer. The power lines are considered as an effective tool for transmitting the electricity all around the globe. The main conductive part of the power lines is composed of steel wires that possess a combination of high electrical conductivity and sufficiently high strength. However, the development of new materials with increased conductivity and preferable strength-to-weight ratio compared to steels is an urgent task. The aluminium, owing to its higher electrical conductivity than that of steel, can be alternative material, even though the strength of aluminium and its alloys is noticeably inferior to those of steel. In addition, the Al alloys are widely used in the electrical industry, particularly, cable industry, due to their low density, low melting point, high corrosion resistance and good mechanical properties. The aim of this work is to develop Al-based alloy with high electrical conductivity and enough level of strength for use as a material to produce power lines. The work established the possibility of producing the ingots from Al alloy containing Zr in industrial scale, and then, through subsequent processing of the ingots, obtaining a wire having a combination of preferable strength and electrical conductivity that meet the requirements of the energy sector of Uzbekistan. Mass production of wire for power lines requires significant adjustment and control of the modes of melting and casting of ingots compared to conventional alloys.

***Key words:*** aluminium, zirconium, alloys, composition, structure, properties, energy, power lines, benefit.

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## Introduction

Significant changes have been taking place in the energy sector of Uzbekistan in recent years to diversify the electricity generation sources in the economy. On top of developing more traditional ways of energy production from wind, solar and other mixed sources, the atomic energy production is recently planned to be launched in near future to meet the growing demand for electricity in the country [1–3]. Recently initiated construction of a 100 MW solar power plant in the Navoi region is a clear example of that. Diversifying the sources of electricity enhances the effectiveness of the country's energy sector as a whole [4–6]. However, the effectiveness of electricity sources is also determined by consumers as well as the quality and number of ways to transfer generated electricity from the source to consumer. The power lines are considered as an effective tool for transmitting electricity almost all over the world. The main conductive part of power lines are steel wires that satisfactorily combine electrical conductivity and strength. However, due to the comparably higher electrical resistance of steel, large amounts of electricity are lost in power lines [7–9]. Therefore, the development of new materials with increased electrical conductivity compared to steels is an urgent task. The basis of such materials may be aluminum, whose electrical conductivity is higher than that of steel, although they are noticeably inferior in terms of strength properties to steels. In addition, Al alloys, owing to their low density, low melting point, high corrosion resistance and good mechanical properties, are widely used in the electrical industry, particularly, cable industry.

The aim of this work is to develop an Al-based alloy, displaying a combination of high electrical conductivity and good strength properties, for use in the production of power lines in Uzbekistan. The following tasks were solved to reach this goal:

– the choice of alloying elements and their contents that provide a combination of good strength and high electrical conductivity to Al-based alloys;

– development of technology for casting ingots and production of wire rod from ingots;

– semi-industrial production of ingots and industrial testing of wire for power transmission lines.

## Materials and methods

Aluminum of grade A7 and higher was used as the base materials, in which, the content of impurities in total remained below 0.3 wt.%. Alloying elements in low levels were introduced either in the form of Al — an alloying element, where the amount of the alloying element did not exceed 2.5% by mass, or in the form of a chemical compound, such as potassium fluorozirconate.

Alloys were prepared in chamotte-graphite crucibles with a capacity of at least 20 grades in laboratory and industrial electric resistance furnaces. The melting temperature did not exceed 850 °C and the melt was poured at a temperature, ranging between 720–740 °C.

The microstructure of the alloys was investigated using light optical microscope (LOM). The fine structure, elemental, *X*-ray microspectral and phase analyses were performed using a TESCAN Vega 3 SB scanning electron microscope (SEM).

Thermo-Calc software (Sweden), with a TCal-4 database, was used to conduct equilibrium analyses of stable phases in alloys investigated in the present study.

The electrical conductivity of the alloys was determined according to GOST (State Standart) 27333–87 "Non-destructive testing. Measurement of the electrical conductivity of non-ferrous metals by the eddy current method".

Industrial results were obtained using modern technological equipment from manufacturers, such as Sautware (USA) — continuous casting and rolling line, SAMP (Italy) – rough drawing line, Nokia (Finland) production line, Rozendahl (Austria) — extrusion and twisting equipment, "Scandinavian Recycling AB" (Sweden) — cable waste recycling line, "SKET" and "Wiedenbach Apparateba U GMBH" (Germany) — equipment for marking the parts. Thus, the equipments utilized within this study, ensured the reliability of the release of high-quality products that meet the standards of the Republic of Uzbekistan and the Russian Federation.

## Results and Discussion

According to the archival literature [10–12], there is an increasing interest in the development of high-temperature-resistant aluminum alloys that possess a combination of high electrical conductivity and enough strength at both room and elevated temperatures of up to 300 °C to provide high efficiency in electricity transmission to consumers. The latter requirement, i.e sufficiently high strength at both room and elevated temperatures, excludes the use of commercially available pure aluminium as the recrystallization temperature of the wires from these alloys can be as low as 250 °C. Therefore, in this work, various alloying elements, such as Mn, Cu, Mg, Zr, Sc and Y, were separately added to the base Al alloy as these elements are known to provide significant hardening to aluminum [13–16]. It has been experimentally established that to solve the problem of ensuring a low recrystallization temperature, the most promising direction is the development of low-alloyed aluminum alloys with the addition of zirconium. In Refs. [17–19], it was shown that the preparation of such alloys requires elevated melting and casting temperatures. The Al – Zr phase diagram, constructed using the Thermo-calc software and its transformation into a nonequilibrium state showed that there is a specific phase diagram characterized by a sharp increase in liquidus temperature with increasing zirconium concentration (Fig. 1, *a*). In order to impart the alloy high strength, all Zr solutes must be supersaturared in the α-Al solid solution during solidification, and, according to the scheme in Fig. 1, *b*, a different cast billet preparation technology is required in comparison with conventional grade Al alloys.

In Fig. 1 dashed lines show the position of the experimental alloys, whereas points 1, 2, 3 show the casting temperature of the alloys.

As part of the joint work between NUST "MISiS", Moscow, a branch of the Russian Chemical Technical University in Tashkent, a representative of a Canadian university and an industrial enterprise in Tashkent (JV UZCable JSC, the largest universal enterprise in the Central Asian region, a manufacturer of cable and wire products), the low-alloyed aluminum alloy with the Al content of about 99% and the technology for producing ingots from this alloy with subsequent metal forming processes were tested. Due to its high performance, the continuous casting method was chosen to produce ingots. According to positive results, an industrial experiment was carried out in laboratory conditions. Zirconium addition was carried out at three different levels: 0.25 wt.% (melt No. 1), 0.31 wt.% (melt No. 2) and 0.29 wt.% (melt No. 3). In the first and third melts, zirconium was introduced into the melt in the form of Al – 1.5 wt.% Zr master alloy, and

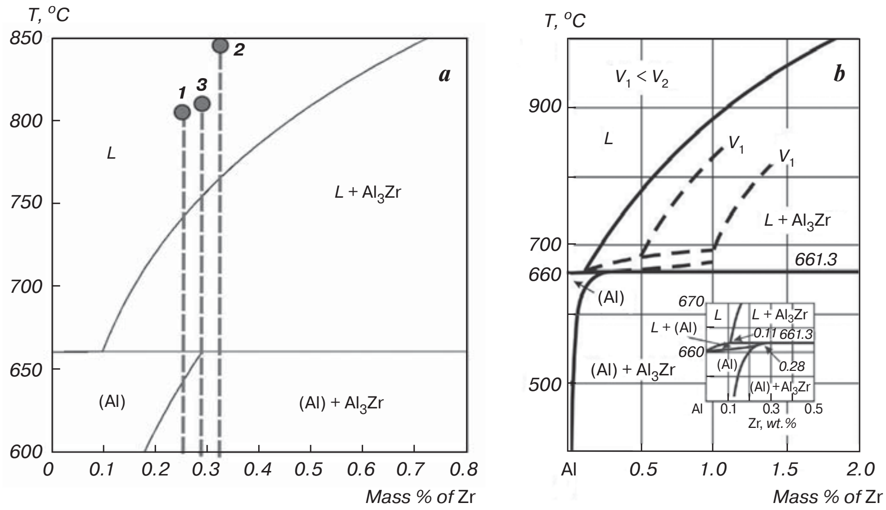


**Fig. 1.** Al – Zr phase diagram:
*a* — equilibrium calculations with Thermo-Calc; *b* – phase transformations diagram for non-equilibrium solidification conditions

in the second melt — in the form of a potassium fluorozirconate salt ($K_2ZrF_6$).

Ingots with a diameter of 100 mm were cast in accordance with the technical instruction (TI 303.36.0105-03) into a graphite system of 8 molds. The system provided a warm top in an ordinary tray due to lining with asbestos sheet. The casting parameters used to produce ingots are given in Table. 1. The temperature of the molten metal, the casting speed, and the water pressure in the cooling system were selected based on factory practice to maximize compliance with industrial conditions [20].

Table 1.
**Casting regimes used to produce ingots for wire productio**

| Melt No. | Ingot dimensions ($D \times L$), mm | $T_{mel}$, °C | $V_{casting}$, mm/min | Water pressure, kgf/mm$^2$ | Quantity of cast billets |
|---|---|---|---|---|---|
| 1 | 100 × 4300 | 800–810 | 90–91 | 0.3 | 5 |
| 2 | 100 × 3300 | 850–840 | 140 | 0.5 | 5 |
| 3 | 100 × 3400 | 810–820 | 140–160 | 0.5 | 5 |

The preparation of alloys containing Zr requires strict adherence to the technological parameters of casting during melting. Therefore, to obtain a reliable result, 5 ingots were cast (Table 1). In ingots from melt No. 1, despite the lowest Zr content, coarse primary $Al_3Zr$ particles are observed in the microstructure (Fig. 2). Since primary $Al_3Zr$ particles formed during solidification leads to the depletion of Zr from the remaining liquid metal, this reduces the supersaturation level of Zr in α-Al matrix. The reason for this probably lies in the combination of a low casting temperature (Fig. 1, *a*) and the presence of the hard-dissolving, coarse Zr-rich particles in Al – Zr based master alloy. Another reason for the formation of primary $Al_3Zr$ particles could be insufficient cooling of the mold with water and, as a result, insufficient cooling rate of the ingot (Table 1), at which, Zr remains not to completely supersaturate in the α-Al solid solution during solidification (see Fig. 1, *b*) [21]. These ingots were therefore scrapped and were not used for further analyses.

In ingots from two other melts (No. 2 and No. 3), only α-Al grains are observed in the microstructure, which indicates much higher level of supersaturation of Zr in the α-Al matrix. These ingots were found to be suitable to produce wires. The best results on strength and electrical conductivity were obtained on a wire obtained from ingots of melt No. 2, which corresponds to the maximum casting temperature.

In general, if we talk about the structure of wire rod, it should be noted that alloying with zirconium gives an excellent result in terms of ensuring its heat resistance. Considering the high cost of zirconium, it is better to use low-grade raw materials in the form of scrap aluminum alloys, which contains impurities of iron and silicon, to reduce the cost of the final product. In this case, we are talking about a complex Al – Zr – Fe – Si system. It is known [22–24] that impurities increase the electrical resistance of alloys. Therefore, it was necessary to optimize the phase composition and structure of alloys in order to reduce the negative effect of impurities.

In the process of studying the cast structure, it was found that at a cooling rate of the ingot of 15 ± 5 °C, all iron crystallizes in the form of the $Al_8Fe_2Si$ phase with a silicon content of 0.25 — 1% by weight. So, for example, in an alloy with 1% iron and 0.25% silicon, the volume

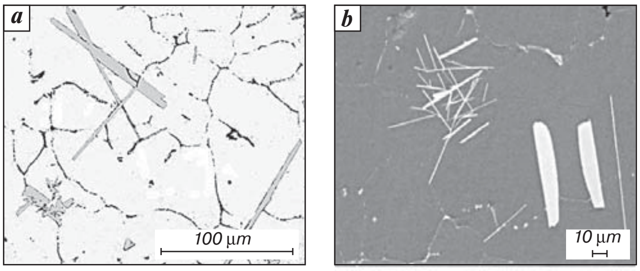


**Fig. 2.** Microstructure of alloy from the melt No. 1 (bottom part of ingot):
*a* — LOM image; *b* — SEM image

fraction of the $FeAl_3$ phase is insignificant — about 0.2%. As the silicon content increases, the volume fraction of the (Al) + $Al_8Fe_2Si$ eutectic increases, which in the process of annealing is the basis for the formation of globular $Al_8Fe_2Si$ particles. If the alloy does not contain silicon, then the eutectic (A1) + $A1_6Fe$ is formed. In the process of annealing at high temperatures — about 500 °C — the $A1_6Fe$ phase transforms into the $FeAl_3$ phase, which affects the electrical conductivity of the aluminum alloy more than the $Al_8Fe_2Si$ phase. Therefore, the presence of silicon in the alloy is preferable. It was also found that the presence of silicon makes it possible to obtain the structure of the alloy without primary crystals of $Al_3Zr$ (Fig. 2 — gray needles on LOM, white on SEM). With a content of 0.4% (by weight) zirconium, the silicon content can be limited to between 0.4 and 0.6%.

It should be noted that the conductivity and strength properties of alloys are inversely proportional to values — an attempt to increase the strength of wire for power lines due to alloying with zirconium led to a decrease in electrical conductivity. Therefore, the effect of heat treatment modes on the properties of wire rod has been studied.

It has been established that the electrical resistivity of alloys with an increase in the annealing temperature from 100 to 600 °C continuously decreases, starting from a temperature of 350 °C, while the hardness of the alloys in the temperature range from 350 to 500 °C passes through a maximum. The invariability of the electrical resistance at the initial stage can be explained by the presence of zirconium in the solid solution, which does not affect the electrical conductivity up to this temperature. A further decrease in the electrical resistance can be explained by the decomposition of $Al_3Zr$ phase from the solid solution. Analysis shows that the silicon content accelerates the decomposition of the solid solution into zirconium.

Table 2.
**Report on expected financial results in the form No. 2 of the enterprise**

| Name of indicator | Line code | For the corresponding period last year | | During the reporting period | |
|---|---|---|---|---|---|
| | | Income (profit), UZS | Expenses (losses) | Income (profit), UZS | Expenses (losses) |
| Estimated net sales revenue | 010 | 284291225.5 | x | 352188512.2 | x |
| Expected gross profit (loss) from product sales | 030 | 65924874.2 | 0 | 89911861.5 | 0 |
| Expected foreign exchange gains | 150 | 926443.9 | x | 1182142.7 | x |
| Expected net profit (loss) of the reporting period | 270 | 15186357.5 | 0 | 29504940.9 | 0 |

Regarding the change in hardness, it was found that the maximum hardness of 58 HB was achieved during annealing at 400 $^{o}$C, keeping the level up to 450 $^{o}$C. This can be explained by the transition of silicon into a solid solution based on aluminum.

To optimize the chemical composition and heat treatment regime, alloys with the fixed content of 0.3 weight % Zr and a varying Si concentration were selected. The calculation was carried out for the characterization of physical and mechanical properties of cast billets in the temperature ranges of heat treatment, which ensures the maximum decomposition of Zr from solid solution to form $Al_3Zr$ phase, which renders the alloy enhanced resistance to high-temperature. Experimental data have shown the best combination of the basic properties of conductive alloys, namely: electrical resistivity and hardness. The selected alloy is the one with the addition of 0.25 weight % Si after a stepwise annealing at a temperature of 450 $^{o}$C.

The average properties of the an aluminum alloy wire with Zr with a diameter of 4.5 mm, preheated to 200 $^{o}$C for 1 hour, can be represented in the following values with a relative conductivity coefficient above 0.58%: ultimate tensile strength, $\sigma_{UTS}$, of 166 MPa, elongation, δ, of more than 2%. The same wire at room temperature showed electrical resistance, ρ, of 1.87 Ohm/cm and withstood tensile loads, *P*, of 266 kgf. The value of the permissible current was *I* — 2080 A. With this level of characteristics and above, experimental cable-conductor products such as uninsulated wires A (wire twisted from aluminum-zirconium wires) and AC (wire consisting of a steel core and aluminum zirconium wire), which are designed to transmit electrical energy in overhead electrical networks — GOST (State Standart) 839–80.

In addition, in accordance with the technical conditions of the enterprise (TU) 64-14825031–001:2004, power and control cables with aluminum-zirconium conductors, with plastic insulation of reduced fire hazard, in a plastic sheath of reduced fire hazard for the designed nuclear power plants and the needs of the economy of Uzbekistan were manufactured. The expected results of the introduction of new products are given in Table 2.

The calculations were made by specialists of the enterprise, considering the service life of the products, which is 45 years. It should be noted that the calculation was made in accordance with [22], considering the decrease over the last three months of the year (before the calculation), the cost of a tonnage of primary aluminum decreased by 304 conventional units. Moreover, the expenditure part is not shown in the table, because (*a*) it can be estimated based on the results of the financial year and (*b*) during the experimental period, there were no additional costs for the production of experimental products, it went according to the schedule and line of traditional products of the enterprise. In general, the prospects and quality of new products are accepted by the enterprise JV Uzcable, Tashkent.

## Conclusions

1. The possibility of industrial production of ingots of an aluminum alloy with zirconium to produce a wire that combines the strength properties and electrical conductivity that meets the requirements of the energy sector of Uzbekistan has been established.
2. Mass production of new wire for the needs of power engineering requires adjusting the modes of melting, casting and heat treatment of aluminum alloy ingots with additions of zirconium, impurities of iron and silicon, as well as small additional costs for its production.

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