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Research Article

Manufacturing Thermal-resistant Aluminum Alloy Wire for Overhead Line Conductor

Huynh Cong Khanh*, Ly Thai Phap, Do Thanh Toan

ABSTRACT

One of the overhead line conductor's tasks is to ensure high electrical conductivity and high tensile strength after repeated heating to 180^{o}C. However, conventional aluminum *conductor* steel reinforced (ACSR) does not meet the above requirements (operating temperature $\leq$ 90 ^{o}C). To solve this problem, foreign countries have used Zr-bearing aluminum alloy, adding other alloying elements, such as Si and Fe, to manufacture thermal-resistant wire for overhead line conductors. This paper aim is to study the manufacturing process of thermal-resistant Al-Zr-Si-Fe alloy wire for overhead line conductors. Al-Zr-Si-Fe alloy was manufactured in the electric furnace and then cast in the permanent mold. Al-Zr-Si-Fe alloy billets were extruded to a diameter of 4.5-4.7 mm at 470 ^{o}C. After that, the extruded rods were cold-drawn to a diameter of 2.5 mm. The wire samples were annealed for 10 hours in an electric furnace at a temperature ranging from 350 ^{o}C to 450 ^{o}C. The as-cast Al-Zr-Si-Fe alloy microstructures show that the alloy grain morphologies are fine and equiaxed, and there are no Al_3Zr crystals in the alloys. The electrical resistivity of the as-drawn Al-Zr-Si-Fe alloy wire is high because zirconium completely dissolves in an aluminum solid solution. After annealing the wire at 350 ^{o}C, the tensile strength of the wire decreases, and elongation slightly increases due to the reduction of lattice distortions. Resistivity slightly decreases because the metastable Al_3Zr particle precipitation from aluminum solid solution is relatively slow at temperatures < 400 °C. At an annealing temperature of 400–450 ^{o}C, the tensile strength increases significantly, the elongation slightly decreases, and the resistivity noticeably decreases due to the precipitation of metastable Al_3Zr ($L1_2$) particles. After annealing at 450 ^{o}C for 10 hours, the mechanical, electrical, and thermal-resistant properties of the wire meet the AT1 type requirements of standard IEC 62004.

Key words: Aluminum thermal-resistant wire, Aluminum-zirconium wire, Al-Zr-Si-Fe alloy, electrical conductor

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INTRODUCTION

According to the decision approving the National Electricity Development Plan of 2021-2023 and the vision for 2050 of the Vietnam Prime Minister on the construction volume of the transmission network: uilding 12,300 km new and renovating 1,324 km of 500 kV transmission line, along with 16,285 km newly built and 6,484 km renovated of 220 kV transmission line in the period 2021-2023. Orientation for the period 2031-2050: newly constructing 5,200-8,300 km of HVDC transmission line; having 9,400-11,152 km newly built and 801 km renovated of 500 kV transmission line, and 11,395-11,703 km newly built and 504-654 km renovated of 220 kV transmission line.

The development of the electrical industry in modern conditions is oriented to the use of electrically conductive materials, which should have high electrical conductivity and high tensile strength at operating temperatures. Since unalloyed aluminum (AA1350) has a low recrystallization-onset temperature (about 100 °C), it cannot be used due to the latter requirement. Promising thermally stable materials with high electrical conductivity and strength at an allowable continuous operating temperature of 150-230 °C are lightly alloyed zirconium aluminum alloys. A favorable combination of electrical and mechanical properties of such alloys is achieved by alloying and deformation-heat treatment [1,2].

Many researchers have conducted studies and developed heat-resistant wires according to International Standards IEC 62004 and ASTM B941-10. Such as the following works:

According to the patent US 4402763, an Al-Zr alloy is composed of 0.23–0.35 wt.% Zr, with the remaining portion being composed of common impurities and aluminum. This aluminum alloy has a 10 % softening temperature of at least 400 °C and an electrical conductivity of over 58 % IACS. A method for producing an aluminum alloy involves melting an Al-Zr alloy, casting it, and hot rolling the cast alloy at a minimum temperature of 530 ^{o}C. The rolled alloy is then cold-worked and aged for 50-400 hours at 310-390 ^{o}C [3].

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Known high-strength heat-resistant aluminum alloy contains, wt. %: 0.28-0.80 Zr, 0.10-0.80 Mn, 0.10-0.4 Cu, 0.16-0.30 Si[4]. This high-strength heat-resistant aluminum alloy has a conductivity of at least 50% IACS and a tensile strength of at least 28 kgf/mm2. After 400 hours of heat history at 180 °C, its tensile strength remains at least 90% of its initial level.

Patent RU 2 696 797 C2 recommends an aluminum-zirconium alloy containing, wt. %: 0.22-0.4 Zr, 0.2-0.4 Si, 0.62-0.8 Fe, aluminum-the rest, with an optimal zirconium content of 0.22-0.4 % and a ratio of silicon/iron equal to 0.3-0.5. It is necessary to form coherent Al_3Zr particles with an $L1_2$ lattice less than 20 nm in size. Particles provide good heat resistance and prevent the development of recrystallization processes at elevated temperatures. The excessive zirconium causes the precipitation of coarse Al_3Zr primary particles in the cast condition, which does not affect the strength characteristics of the alloy or the stability of the structures at elevated temperatures. Alloying the alloy with zirconium at less than 0.22 % leads to deterioration of heat resistance and a decrease in strength properties. Iron supplementation with silicon is necessary for a significant increase in strength characteristics while maintaining electrical conductivity at an acceptable level. The ratio silicon/iron = 0.3-0.5 ensures the formation of spherical particles Al_8Fe_2Si and Al_5FeSi less than 3 mm after annealing. In addition, doping with silicon leads to increased diffusion of zirconium, accelerates the nucleation and separation of Al_3Zr particles, thereby reducing thermal processing time[5].

The purpose of this work was to study the manufacturing process of thermal-resistant aluminum alloy wire that satisfies IEC 62004 standard AT1 type requirements.

MATERIALS AND METHODS

Materials

The raw materials for manufacturing thermal-resistant Al-Zr-Si-Fe alloys are commercial pure aluminum ingots, Al-Zr-Si master alloy produced from zircon concentrate (master alloys No. 1 and No. 2), and Al-Zr master alloy produced from potassium fluorozirconate K_2ZrF_6 (master alloy No. 3). Table 1 and Table 2 show the chemical composition of raw materials.

In the process of smelting Al-Zr-Si-Fe alloys, covering flux was prepared using the cryolite Na_3AlF_6 ($\geq$ 99.0 wt. %), sodium chloride NaCl ($\geq$ 99.5 wt. %), and potassium chloride KCl ($\geq$ 99.5 wt. %). Covering flux is composed of 42-46 wt. % NaCl, 43-47 wt. % KCl, and 7-15 wt. % Na_3AlF_6[6].

Methods

The thermal-resistant Al-Zr-Si-Fe alloys were melted in a graphite crucible using an electrical resistance furnace. In order to make Al-Zr-Si-Fe alloys, all aluminum samples were melted in the furnace under the cover of flux. Master alloys were introduced into the melt at temperatures of 850-900 ^{o}C[7]. After dissolving master alloys, slag was skimmed. The melts were poured into a 90-mm-diameter by 210-mm-length cylindrical iron mold. Table 3 shows the charge composition for manufacturing Al-Zr-Si-Fe alloys.

A 300-ton Cincinnati Milacron hydraulic extrusion press was used to extrude the redraw rod. The following were the working parameters of billet extrusion used to produce redraw rods: the billet temperature of 470 ^{o}C; extrusion speed of 15 m/min; die type: feeder plate die with 14 exit holes at 4.7 mm each; pressing capacity: 300 tons. Then, the redraw rod was subjected to cold drawing to ultimately produce wire 2.5 mm in diameter.

The Al-Zr-Si-Fe alloy wires were annealed in an electric muffle furnace at t = 350, 400, 450 °C for 10 hours with the accuracy of maintaining temperature within $\pm$5 °C.

An optical emission spectrometer (SPECTROLAB) and an inductively coupled plasma-optical emission spectrometer (ICP-OES) were used to analyze the composition of Al-Zr-Si-Fe alloys.

The samples for microstructural analysis were grinded with various grades of grinding papers, from P100 to P2000. Then, samples were polished by using the Buehler Ecomet 6 polishing machine. To examine the microstructure under an optical microscope (OLYMPUS MPE3), these prepared samples were etched using 3 wt. % HF in water. The mean grain size was determined in accordance with the method specified in ASTM E112-13[8].

With the use of a Shimadzu tensile testing machine, mechanical testing was carried out at room temperature. Tensile tests were conducted according to the method specified in IEC 62004 using 250-mm gauge length samples.

The electrical resistivity of Al-Zr-Si-Fe alloy wires was measured using the resistance tester RESISTOMAT 2304 in accordance with the method specified in the IEC 60468 standard[9]. The samples were straightened and measured to a minimum length of 1 meter.

RESULTS AND DISCUSSION

The chemical composition of the experimental Al-Zr-Si-Fe alloys is shown in Table 4.

Figure 1 shows that during casting alloys No.1 and No.2 with zirconium contents of 0.1884 and 0.2800

Table 1: Chemical composition of aluminum

Aluminum grade	Chemical composition, wt. %						
	Al	Zr	Fe	Si	Cu	Zn	Ti
Pure Al	99,8	0.01	0,10	0,04	0,01	0,01	0,01

Table 2: Chemical composition of master alloys

Master alloy No.	Chemical composition, wt. %						
	Zr	Fe	Si	Cu	Mn	Mg	Zn
1	2.2700	1.2050	1.0680	0.0060	0.0050	0.0040	0.0050
2	2.0300	0.2240	1.1510	0.0060	0.0030	0.0040	0.0170
3	2,604	-	-	-	-	-	-

Table 3: Charge composition for manufacturing Al-Zr-Si-Fe alloys

Al-Zr-Si-Fe alloy No.	Pure Al (g)	Master alloy No. 1 (g)	Master alloy No. 2 (g)	Master alloy No. 3 (g)
1	2793	242	-	231
2	2800	-	524	-

Table 4: Chemical composition of the experimental Al-Zr-Si-Fe alloys

Al-Zr-Si-Fe alloy No.	Chemical composition (in wt.%)							
	Zr	Fe	Si	Cu	Mn	Mg	Zn	Ti
1	0.1884	0.1880	0.2240	0.0030	0.0020	0.0020	0.0090	0.0028
2	0.2800	0.0990	0.2760	0.0020	0.0020	0.0020	0.0160	0.0073

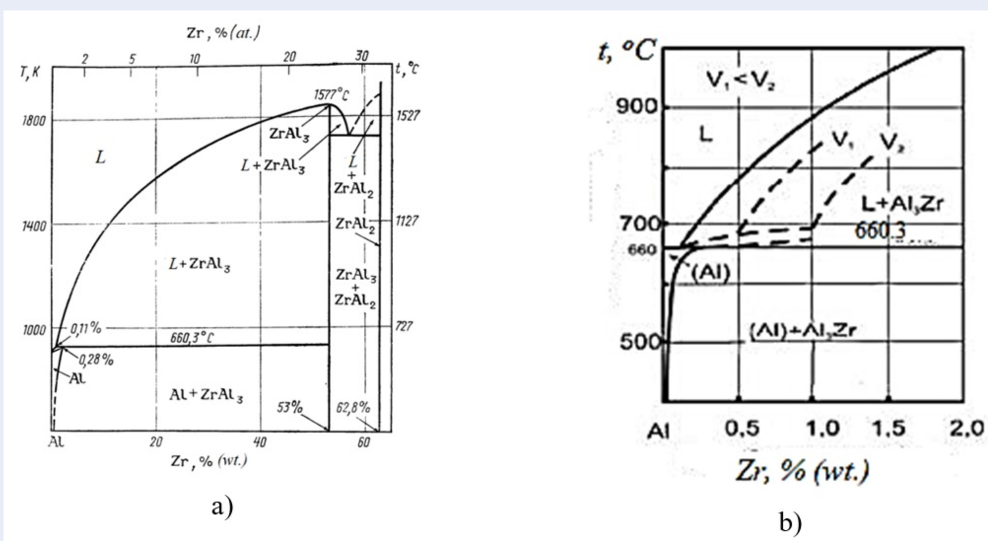

Figure 1: Al-Zr phase diagram [10,11]

wt. %, the primary Al_3Zr phase is beginning to precipitate from the liquid. At 660.3 ^oC, a peritectic reaction occurs:

L + Al_3Zr = a-Al (1)

Al_3Zr decomposes to form a-Al, which the solvus line indicates will precipitate the secondary, dispersive Al_3Zr. However, during the rapid crystallization of Al-Zr alloys, the expansion of the area of the aluminum solid solution occurs, which makes it possible to obtain a structure without primary Al_3Zr crystals[7]. In this case, the transition of the crystallization region of the Al_3Zr phase directly into the crystallization region of the aluminum solid solution is observed.

The as-cast Al-Zr-Si-Fe alloys microstructure in Figure 2 showed that primary Al_3Zr crystals are almost absent in alloys. Only a small number of inclusions of the Fe and Si-containing phases were arranged around the boundaries of α-Al because zirconium completely dissolves in aluminum solid solution during solidification at a high enough cooling rate in an iron mold[7]. Figure 2 also shows that the grain morphologies of the Al-Zr-Si-Fe alloys exhibit a fine and equiaxed grain structure, with the determined mean grain size of alloys No. 1 and No. 2 being about 150 mm and 190 mm, respectively, while the mean grain size of pure aluminum is 1100 μm[12]. This is because zirconium acts as a grain refiner, introducing stable Al_3Zr particles that exhibit a small lattice parameter mismatch with the α-Al and are coherent to the aluminum matrix. As a result, they act as effective heterogeneous nucleants during the aluminum solidification process[12].

The obtained results of the tensile strength measurement of the experimental Al-Zr-Si-Fe alloy wire are presented in Table 5 and Figure 3. After annealing wires at a temperature of 350 ^oC for 10 hours, their tensile strength decreases, while their elongation slightly increases. This is due to cold drawing producing wire hardening, i.e., distortion of the crystal lattice. An annealing at 350 ^oC can eliminate lattice distortions, such as the reduction of density of dislocations owing to their mutual annihilation, coalescence of blocks, reduction of internal stresses, decrease in the number of vacancies, etc. It results in a slight decrease in the strength of the alloy wire and an increase in ductility[13].

The higher values of resistivity are in the alloy wire at the initial state, which is explained by the presence of zirconium in the aluminum solid solution. For the alloy wire sample, the resistivity does slightly change up to a temperature of 350 °C (Figure 4). Since, at low temperatures (< 400 °C), the diffusion of zirconium in aluminum solid solution is relatively small, the process of complete zirconium precipitation from aluminum solution requires significantly more time[14].

At an annealing temperature of 400-450 ^oC, the tensile strength considerably increases and the elongation slightly decreases, probably due to the precipitation hardening process of the alloy during annealing. This can be explained by the precipitation of metastable Al_3Zr particles. The metastable Al_3Zr phase ($L1_2$) has an identical structure to the aluminum matrix. When the metastable Al_3Zr particles are coherent with the aluminum matrix, there is a significant precipitation-hardening effect and enhanced thermal stability[14].

After annealing at 400–450 °C, there is a noticeable decrease in resistivity, which can be explained by the solid solution decomposition and zirconium atoms diffusing into the particles. This reduces the number of point defects in the matrix and reduces electron scattering[14].

Furthermore, the addition of 0.20-0.3 wt. % Si promotes substantial hardening and a decrease in resistivity of the Al-Zr-Si-Fe alloy wire. This may be related to an increase in the amount of phase Ll_2 (Al_3Zr) nanoparticles that are formed during annealing[15].

After annealing at 450 ^oC for 10 hours, the tensile strength, elongation, and electrical resistivity of Al-Zr-Si-Fe alloy wire meet the requirements of Standard IEC 62004 for a wire of type AT1 with a diameter up to and including 2.6 mm (169 MPa, 1.5%, and 28.735 nWm). The residual ratio of the tensile strength after heating the wire at 230 ^oC for 1 hour also meets the requirements of Standard IEC 62004 ($\geq$ 90 %).

CONCLUSION

The manufactured thermal-resistant Al-Zr-Si-Fe alloy wire meets the requirements of Standard IEC 62004 for a wire of type AT1.

The research results show:

- The efficiency of zirconium in grain refinement, precipitation hardening, and heat resistance of aluminum alloy.
- The effects of the annealing regime on the mechanical properties and electrical resistance of Al-Zr-Si-Fe alloy. With suitable annealing temperatures and times, Al-Zr-Si-Fe alloy wire meets the requirements of AT1 wire.
- The potential for industrial production of aluminum alloy wire with thermal resistance for overhead line conductors in our nation's factories. However, a complete study and trial production are required.

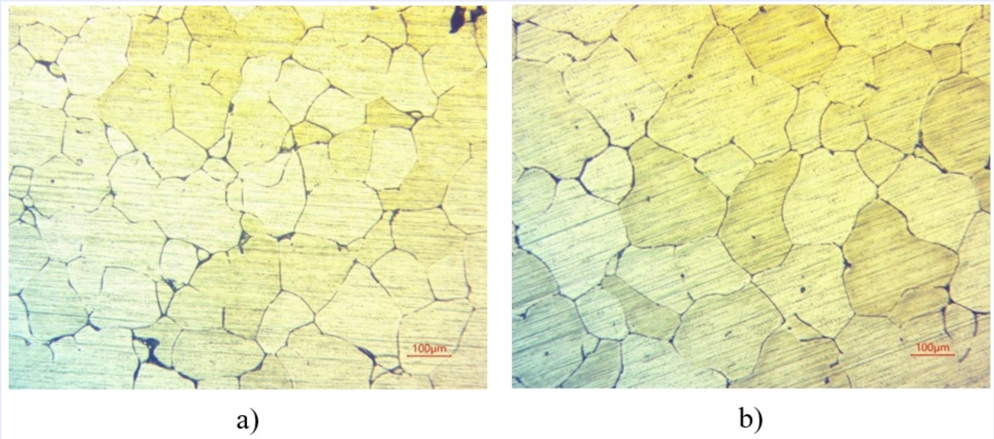

Figure 2: Microstructure of as-cast Al-Zr-Si-Fe alloys (x50): a) Al-Zr-Si-Fe alloy No. 1, b) Al-Zr-Si-Fe alloy No. 2.

Table 5: Mechanical properties and electrical resistivity of the experimental Al-Zr-Si-Fe alloy wire

Al-Zr-Si-Fe alloy No.	State	Tensile strength, [MPa]	Elongation, [%]	Tensile strength after heating at 230 °C for 1 h, [MPa]	Residual tensile strength, [%]	Resistivity at 20 °C, [nWm]	Conductivity, [%IACS]
1	Initial state	160	2.4	158	98.8	33.840	51.0
1	Annealed at 350 °C, 10 h	150	2.8	149	99.3	32.040	53.8
1	Annealed at 400 °C, 10 h	168	2.4	163	97.0	30.190	57.1
1	Annealed at 450 °C, 10 h	171	2.0	166	97.1	28.640	60.2
2	Initial state	164	2.2	161	98.2	34.490	50.0
2	Annealed at 350 °C, 10 h	152	2.8	152	100	31.580	54.6
2	Annealed at 400 °C, 10 h	163	2.4	162	99.4	30.260	57.0
2	Annealed at 450 °C, 10 h	173	2.0	167	96.5	28.740	60.0

CONFLICT OF INTEREST

The authors confirm no conflicts of interest in publishing the article.

AUTHORS' CONTRIBUTION

The manuscript was written and edited by Huynh Cong Khanh, who also conceived the research idea, provided research instructions.

Ly Thai Phap performed experiments on melting and manufacturing Al-Zr-Si-Fe heat-resistant aluminum alloy wire. He also examined the chemical composition, microstructure, mechanical and electrical properties of Al-Zr-Si-Fe heat-resistant aluminum alloy wire.

Do Thanh Toan helped with the raw material and equipment preparation for the research. Additionally, he participated in experiments on smelting and manufacturing Al-Zr-Si-Fe heat-resistant aluminum alloy wire.

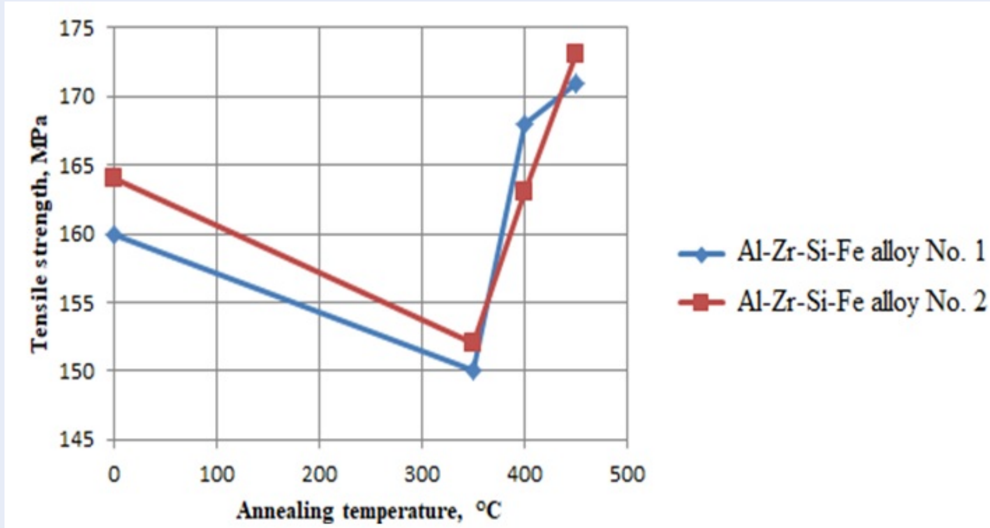

Figure 3: Influence of the annealing temperature on the tensile strength of the experimental alloy wire

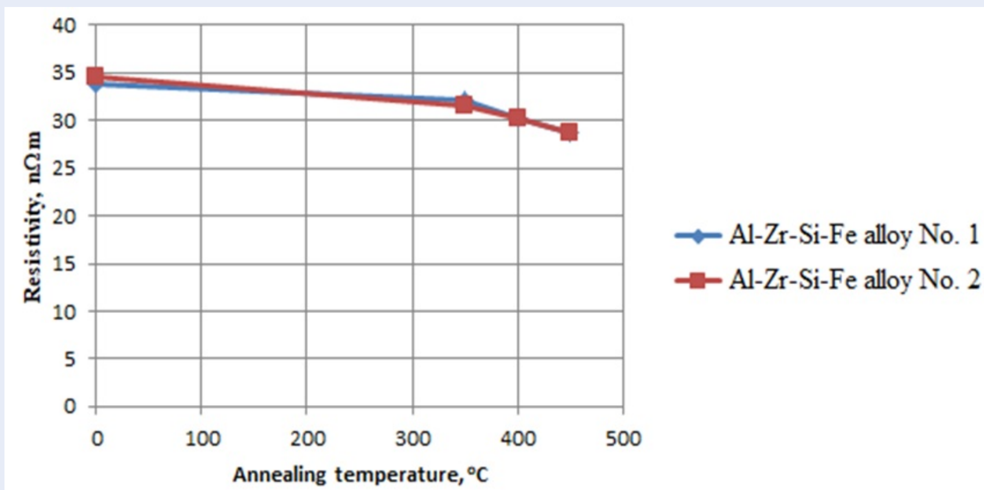

Figure 4: Influence of the annealing temperature on the electrical resistivity of the experimental alloy wire

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Bài nghiên cứu

Chế tạo dây hợp kim nhôm chịu nhiệt làm dây dẫn điện trên không

Huỳnh Công Khanh*, Lý Thái Pháp, Đỗ Thành Toàn

TÓM TẮT
Một trong những nhiệm vụ của dây dẫn điện trên không là đảm bảo độ dẫn điện và giới hạn bền kéo cao khi bị nung nóng nhiều lần đến 180 ^{o}C. Tuy nhiên, dây nhôm lõi thép (ACSR) không đáp ứng được yêu cầu trên (nhiệt độ làm việc $\leq$ 90 ^{o}C). Để giải quyết vấn đề này, nước ngoài đã sử dụng hợp kim Al-Zr, bổ sung thêm các nguyên tố hợp kim khác như Si và Fe để chế tạo dây chịu nhiệt làm dây dẫn điện trên không. Mục đích của bài báo này là nghiên cứu quy trình chế tạo dây hợp kim nhôm chịu nhiệt Al-Zr-Si-Fe làm dây dẫn điện trên không. Hợp kim Al-Zr-Si-Fe được nấu luyện trong lò điện trở và được đúc trong khuôn kim loại. Phôi hợp kim Al-Zr-Si-Fe được ép đùn thành dây có đường kính 4,5-4,7 mm ở 470 ^{o}C. Sau đó, dây nhôm ép được kéo nguội đến đường kính 2,5 mm. Các mẫu dây được ủ trong lò điện ở nhiệt độ từ 350 ^{o}C đến 450 ^{o}C trong 10 giờ. Tổ chức tế vi của hợp kim Al-Zr-Si-Fe ở trạng thái đúc cho thấy hạt nhỏ mịn và đều trục, không có các tinh thể Al_3Zr. Điện trở suất của dây hợp kim Al-Zr-Si-Fe kéo nguội cao là do zirconi hòa tan hoàn toàn trong dung dịch rắn nhôm. Sau khi ủ dây ở nhiệt độ 350 ^{o}C, giới hạn bền kéo của dây giảm, còn độ giãn dài tương đối tăng nhẹ do giảm xô lệch mạng. Điện trở suất giảm không nhiều do quá trình tiết pha giả ổn định Al_3Zr từ dung dịch rắn của nhôm tương đối chậm ở nhiệt độ < 400 °C. Ở nhiệt độ ủ 400–450 ^{o}C, giới hạn bền kéo tăng đáng kể, độ giãn dài tương đối giảm nhẹ, còn điện trở suất giảm rõ rệt do sự tiết pha giả ổn định Al_3Zr ($L1_2$). Sau khi ủ ở nhiệt độ 450^{o}C trong 10 giờ, các đặc tính cơ, điện và chịu nhiệt của dây đạt yêu cầu loại dây AT1 của tiêu chuẩn IEC 62004.
Từ khoá: Dây nhôm chịu nhiệt, dây nhôm-zirconi, hợp kim Al-Zr-Si-Fe, dây dẫn điện

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