High-Conductivity, Thermal-Resistant Aluminum Alloy Wire That Reduces CO_2 Emissions in Overhead Transmission Lines

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With the ever-increasing demand for reducing the environmental impact, there is a need for overhead transmission lines that can reduce transmission loss. We have been working to improve the conductivity of aluminum alloys for overhead transmission lines. This time, by improving the alloy composition and processing methods, we have developed a new thermal-resistant aluminum alloy wire with an allowable continuous operating temperature of 150°C and high conductivity of 61%IACS. In this paper, we introduce the development of the aluminum alloy wire and the characteristics of overhead transmission lines using the new wire.

Keywords: overhead transmission line, transmission loss reduction, thermal-resistant aluminum alloy wire, conductivity improvement, decarbonization

1. Introduction

Today, reducing CO_2 emissions is required in all fields. In the field of electric power, there is an increasing need for power transmission loss reduction. To meet this need, differences in conductivity*1 at the 1%IACS level are becoming non-negligible. In this situation, Energy and Electronics Materials Laboratory and the Overhead Transmission Line Division of Sumitomo Electric Industries, Ltd. are working to improve the conductivity of aluminum alloy wires for overhead transmission line applications in collaboration with Sumitomo Electric Toyama Co., Ltd., its group company.

The authors have worked to improve the conductivity of a thermal-resistant aluminum alloy wire (60TAl), one of the aluminum alloy wires used for overhead transmission lines, and have succeeded in the development of a new alloy wire (61TAl), the conductivity of which is higher than that of 60TAl by 1%IACS. This paper describes the technology we used to develop the new alloy wire and the features of an overhead transmission line consisting of the new wires.

2. Background of the Development

2-1 Configuration of overhead transmission line

Overhead conductors are suspended between steel towers, as shown in Fig. 1, and transmit a large amount of power from a power plant to an urban area. From the viewpoint of balancing the strength, weight, and electrical resistance of the conductors, a stranded wire structure is adopted, and aluminum alloy wires are laid concentrically on the periphery, and a tension member, such as stranded aluminum-clad steel wires, is laid at the center, as shown in Photo 1. The aluminum alloy wires are mainly responsible for power transmission.

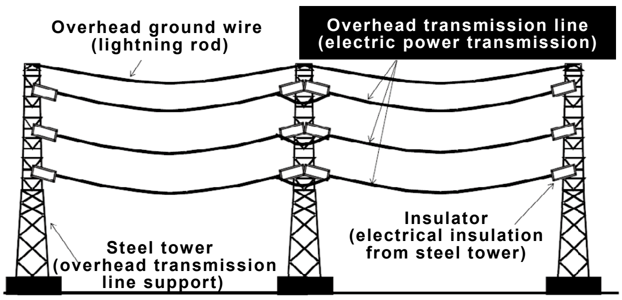


Fig. 1. Overhead power transmission system (schematic figure)

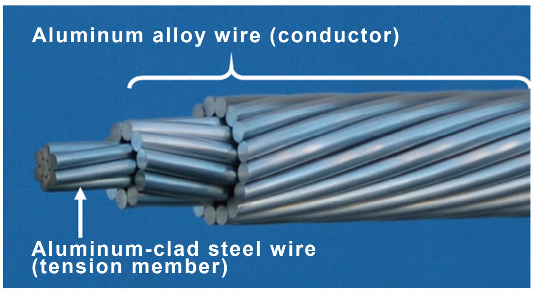


Photo 1. Overhead condector (Aluminum 2-layer structure)

2-2 Need for aluminum alloy wire with improved conductivity

To reduce the transmission loss of an overhead transmission line, it is necessary to lower the electrical resistance of the line by 1) increasing the cross-sectional area of the aluminum alloy wires and/or 2) increasing their conductivity. The low-loss conductor (Fig. 2) made by Sumitomo Electric is a product that is realized by pursuing method 1). This paper describes 2) improving the conductivity of an aluminum alloy wire. Since this approach does not lead to an increase in the weight of the overhead conductors, it is unnecessary to pay attention to the strength of steel towers in terms of weight and tension, and wires with improved conductivity can be used for various types of power transmission lines, including replacement of existing lines. Due to such features, there is a growing need for high-conductivity aluminum alloy wire.

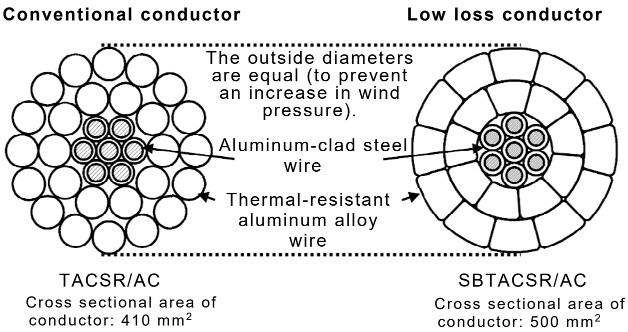


Fig. 2. Low loss conductor

2-3 Properties required of aluminum alloy wires and product lineup

Aluminum alloy wires for overhead transmission line applications are required to have 1) high electrical conductivity to reduce transmission loss, 2) tensile strength sufficient to allow tension-stringing between distant steel towers, and 3) thermal resistance to withstand heat generation and maintain tensile strength when carrying a high current.

In general, elements other than aluminum are added to increase tensile strength and thermal resistance. This inevitably reduces electrical conductivity. In other words, there is a trade-off relationship between tensile strength and thermal resistance and electrical conductivity, and the optimum type of alloy wire is selected according to the usage environment of the overhead transmission line. Table 1 shows Sumitomo Electric's lineup of aluminum alloy wires for overhead transmission line applications. HAl (hard-drawan aluminum wire) is used for general purposes.

Table 1. Sumitomo Electric's lineup of aluminum alloy wires for overhead transmission line applications

Alloy type	Abbreviation	Required properties				
		Tensile strength†1 (MPa)		Elongation†1 (%)	Continuous permissible temperature†2 (°C)	Conductivity (%IACS)
		Minimum	Average			
Hard-drawn aluminum wire	HAl	159	165	2.0	90	61
Thermal-resistant aluminum alloy wire	TAl				150	60
Super thermal-resistant aluminum alloy wire	ZTAl		-		210	60
Extra thermal-resistant aluminum alloy wire	XTAl				230	58
High strength thermal-resistant aluminum alloy wire	KTAl	225	-		150	55
I-aluminum alloy wire	IAl	309	-	4.0	90	52
SI-aluminum alloy wire	SI-33	309	-	3.0		54
	SI-26	235	-	3.0		58.5

†1: The required properties differ depending on wire diameter. The properties required of Φ4.5 mm wires are given as a typical example.
†2: A temperature that lowers tensile strength by 10% when an aluminum alloy wire is maintained at this temperature for 36 years (statutory durable years for overhead transmission lines)

TAl (thermal-resistant aluminum alloy wire), which has slightly lower conductivity but higher thermal resistance (continuous allowable temperature), is selected if maximum current is required.

3. Development of New Thermal-Resistant Aluminum Alloy Wire

3-1 Development target

A Current thermal-resistant aluminum alloy wire (60TAl) is made by adding a small amount of zirconium (Zr) to a HAl. Compared to HAl, 60TAl significantly increases the continuous allowable temperature from 90 to 150°C in exchange for a 1% decrease in conductivity. Due to its excellent features, 60TAl is widely used both in Japan and overseas.[1]

We worked on the development of a new thermal-resistant aluminum alloy wire (61TAl) since improving the conductivity of this widely used 60TAl was expected to contribute to significant reduction of transmission losses on a worldwide scale. The target properties of the alloy wire that was to be developed are listed in Table 2. The conductivity was set to 61% IACS or higher, which was equivalent to that of HAl but higher than that of 60TAl by 1% IACS. With the aim of accelerating widespread use of the new alloy wire, its tensile strength, elongation, and thermal resistance were set to the values equal to those of 60TAl, thereby enabling it to replace existing overhead conductors without changing the structure of the lines or the design of the steel towers.

Table 2. Target properties of the alloy wire that was to be developed

	60TAl (current alloy wire)	61TAl (alloy wire that was to be developed)
Conductivity (%IACS)	60%IACS	61%IACS
Tensile strength†1	Minimum: 159 MPa Average: 165 MPa	Minimum: 159 MPa Average: 165 MPa
Elongation†1 (%)	2.0%	2.0%
Thermal resistance†2	90%	90%

†1: The target properties differ depending on wire diameter. The properties required of Φ4.5 mm wire are given as a typical example.
†2: Residual ratio of tensile strength after heat treatment at 230°C for 1 h (equivalent to 150°C over 36 years)

3-2 Development policy

This section describes the tensile strength improvement mechanism for aluminum alloy wires for overhead transmission line applications, their tensile strength reduction mechanism due to heat, and the thermal resistance improvement mechanism for Current 60TAl. Then, the 61TAl development policy is described.

(1) Tensile strength improvement mechanism

When a metallic material such as aluminum is subjected to an external force above a certain level, the metal is deformed since atoms slide along a specific crystal plane. This sliding is caused by movement of "dislocation," which is the movement of the regions of disordered atomic arrangement (Fig. 3).

As the number of dislocations in the material increases as the deformation progresses, the dislocations gradually get entangled with each other, making it difficult for the dislocations to move. As a result, the sliding of atoms along the crystal plane becomes difficult, making the metal less deformable. This phenomenon, which is called "work hardening," is used to increase the tensile strength of aluminum alloy wires for overhead transmission line applications.

(2) Thermal resistance improvement mechanism for Current 60TAl

Since aluminum is work hardened without adding any elements, this processing is a method for strengthening aluminum without significantly reducing its electrical conductivity. On the other hand, dislocations tend to move and disappear when heated. This means that if the tensile strength of alloy wires is increased only by work hardening, it is prone to decrease at high temperatures.

60TAl is an alloy wire for which the above shortcoming is minimized by adding a small amount of Zr to HAl. Zr in 60TAl is contained in a solid solution state*2 in the aluminum matrix, and the difference in radius between Zr atoms and aluminum atoms creates a strain field in the crystal lattice as shown in Fig. 4. This strain field attracts dislocations through interaction with them, preventing their movement in the vicinity of the solid soluted Zr. As a result, dislocations in 60TAl are less likely to move or disappear even when heated. Since the tensile strength of this wire is less likely to decrease, it can be used in high-temperature environments.

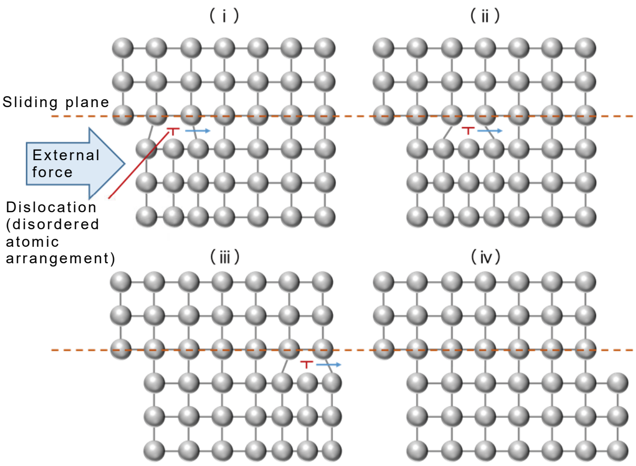


Fig. 3. Deformation of a metal due to the movement of dislocation

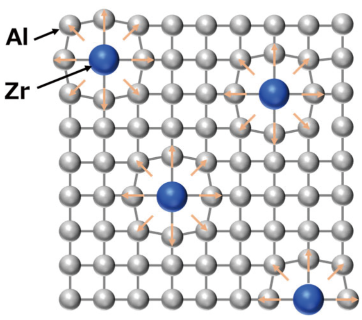


Fig. 4. Strain fields created by solute element atom

(3) 61TAl development policy

To improve conductivity, it is effective to reduce the amount of the additive element. However, since this method leads to a decrease in thermal resistance and tensile strength, it is necessary to implement this method in conjunction with proper compensation measures.

In the development of 61TAl, the amount of additive element was reduced to improve conductivity. On the other hand, 1) iron (Fe) was mixed as an impurity to compensate for a decrease in thermal resistance and 2) work hardening was promoted to compensate for a decrease in tensile strength.

The following sections mainly describe the measures implemented to compensate for a decrease in thermal resistance caused by a decrease in component concentration and details of the measures implemented to compensate for a decrease in tensile strength.

3-3 Improvement of thermal resistance

(1) Policy to improving thermal resistance

Fe is inevitably present in industrial pure aluminum raw material. In general, Fe is viewed as an element that has little effect on the properties of aluminum since this element tends to form compounds with aluminum and other additive elements and exists in a crystal precipitation state.*3 On the other hand, we paid attention to the magnitude of the lattice strain of solidly dissolved Fe.

The effect of a solute element on the movement of dislocation, as discussed in the previous section, was considered to be positively correlated with the magnitude of the lattice strain of the solute element. Table 3 shows the magnitude of the lattice strain and examples of the maximum thermodynamic solid solution amount of each element added to aluminum, as estimated by first-principles calculation.(2) Since Fe is an element with extremely high lattice strain, we concluded that solidly dissolved Fe in aluminum would significantly improve the thermal resistance of aluminum and thus compensate for a decrease in thermal resistance caused by a decrease in the amount of additive element.

Table 3. Lattice strain and maximum solid solution amount of each element

Element	Lattice strain (%)	Maximum solid solution amount (at%)	Element	Lattice strain (%)	Maximum solid solution amount (at%)
Li	0.7	14	Fe	3.9	0.03
Mg	1.0	18.6	Ni	2.9	0.11
Si	0.6	1.5	Cu	1.6	2.48
Sc	1.0	0.2	Zn	0.4	67
Ti	1.0	0.7	Ga	0.6	9
V	2.5	0.3	Ge	0.2	2
Cr	3.2	0.37	Se	1.8	0.003
Mn	3.5	0.62	Zr	1.0	0.09

However, the equilibrium solid solution amount of Fe in aluminum is extremely small. In other words, Fe is a difficult element to solidly dissolve. In addition, a simple and highly reproducible method for evaluating the solid solution ratio had not yet been established. These factors were obstacles to the establishment of a process for solidly dissolved Fe.

In the above situations, we have developed a solid solution state evaluation method and improved the manufacturing process in order to produce aluminum alloy wires with a sufficient solid solution amount of Fe.

(2) Development of a solid solution state evaluation method for Fe

The electrical resistance method and the phenol method have been widely used to evaluate the solid solution amount of an element added to aluminum.(3) The former method utilizes the fact that the electrical resistance of a material changes with the change from solid solution to crystallization and vice versa. However, as the electrical resistance is affected by not only the target element but also the other elements and the amount of dislocation, it is difficult to evaluate the solid solution amount when these factors change simultaneously. The latter method selectively dissolves only the aluminum matrix and extracts only the solid solution by separating the remaining crystallized precipitates with a filter. The drawback of this method is that fine precipitates pass through the filter, resulting in a measurement error.

We took advantage of the fact that Sumitomo Electric has a proprietary beamline*4 at the Kyushu Synchrotron Light Research Center of Saga Prefecture in order to use synchrotron radiation*5 to evaluate the solid solution amount of Fe.(4)

In X-ray absorption spectroscopy (XAFS), an analysis method using synchrotron radiation, the absorption rate of X-rays irradiated on the specimen is measured while scanning energy. In this way, information on the electronic state and surrounding structure of the element of interest is obtained from the X-ray absorption spectrum near the absorption edge*6 of the element.

This method does not require any special pretreatment for the measurement, and is therefore expected to evaluate the amount of solid solution with high accuracy, including the effect of fine precipitates.

In the laboratory, we made two types of Al-Fe alloy wires having different solid solution amounts of Fe, and measured the X-ray absorption spectra at Sumitomo Electric's hard X-ray beamline BL16 using the fluorescence method. The measurement results are shown in Fig. 5. This figure clearly shows the difference in spectrum between two specimens having different solid solution amounts of Fe. By comparing the spectrum of an unknown specimen with these standard spectra, we succeeded in evaluating the solid solution amount of Fe.

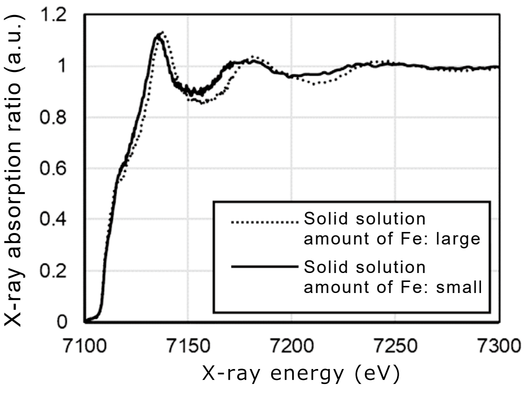


Fig. 5. XAFS spectra of Al-Fe alloy wires

(3) Improvement of casting and rolling conditions

To increase the solid solution amount of Fe whose equilibrium solid solution is low, it is important to design a process that 1) achieves a supersaturated solid solution by rapid solidification and 2) minimizes precipitation during heat treatment and processing. The Properzi continuous casting machine (Fig. 6), which is used by Sumitomo Electric Toyama, easily satisfies the above solid solution conditions since this mill 1) casts metals with a relatively small cross-sectional area of 5000 mm^2 or less and quenches the molten metal with water-cooled copper, and 2) does not require reheating because it uses residual casting heat for the hot processing.

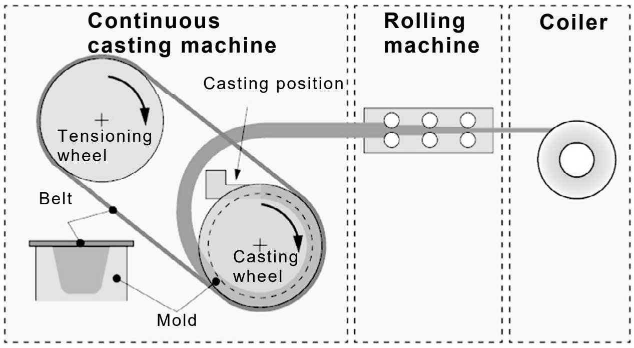


Fig. 6. Schematic illustration of Properzi continuous casting machine

We optimized the conditions of the Properzi continuous casting machine using the solid solution ratio of Fe as an index. This solid solution ratio was determined by the newly developed evaluation method described in the previous section. As a result, we succeeded in further increasing the solid solution ratio of Fe and improving the thermal resistance that had been reduced due to the lower concentration of the alloying elements. Examples of the items optimized include mold shape, pouring method, faster solidification by improving the cooling water injection method, and adjustment of hot rolling conditions.

3-4 Improvement of tensile strength

The simplest way to increase the amount of work hardening is to increase the amount of processing itself and thus reduce the final wire diameter. However, since we intended to commercialize 61TAl by meeting the wire diameter specifications for 60TAl, we worked to improve the tensile strength by increasing the efficiency of dislocation introduction during processing rather than reducing the wire diameter. We finally succeeded in improving the tensile strength by reducing the processing temperature in the process from rolling to drawing and utilizing simulation and other techniques for pass schedule optimization.

3-5 Properties of the developed alloy wire

Table 4 shows the properties of the aluminum alloy wires prototyped in the mass production machine based on the alloy composition and manufacturing process described above. The developed wires have an electrical conductivity of 61% or more, and their mechanical properties and thermal resistance meet the 60TAl specifications.

Table 4. Basic properties of developed alloy wires†1

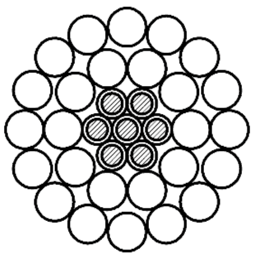
	Actual property	Target property
Conductivity	61.4%IACS	61.0%IACS
Tensile strength†2	Minimum: 171 MPa Average: 173 MPa	Minimum: 159 MPa Average: 165 MPa
Elongation†2	2.6%	2.0%
Thermal resistance†3	93.7%	90.0%

†1: Samples ware taken from the prototype wire and evaluated with the number of measurements n = 10.
†2: The properties differ depending on wire diameter. The properties of Φ4.5 mm wires are given as a typical example.
†3: Residual ratio of tensile strength after heat treatment at 230°C for 1 h (equivalent to 150°C over 36 years)

4. Trial Calculation of CO_2 Reduction Effect of Overhead transmission line Consisting of 61TAl

A trial calculation was performed for the reduction of transmission loss and CO_2 when the developed alloy wire is put into practical use in a power transmission line (Table 5). For the calculation, it was assumed that general-purpose TACSR/AC (thermal-resistant aluminum conductor aluminum clad steel reinforced) conductors would be used for the transmission line. On the assumption that the conductor's cross-sectional area is 410 mm^2, the transmission distance is 50 km, and three-phase two-circuits are used, it became clear that a large CO_2 emissions reduction of more than 4000 tons per 10 years can be expected.

Table. 5. Trial calculation results for transmission loss and CO_2 emissions of overhead transmission line consisting of developed alloy wires

conductor structure		 TACSR/AC Cross sectional area of conductor: 410 mm^2	
Wire used		60TAl (current alloy wire)	61TAl (alloy wire that was to be developed)
Maximum current capacity†1	A	1,391	1,391
Average AC resistance†2	Ω/km	0.0794	0.0782
Power loss per year†3	MWh	61,772	60,838
Extra CO_2 emissions per 10 years for power loss†4	ton-CO_2	290,329	285,939
CO_2 emissions reduction per 10 years (Developed alloy wire – Current alloy wire)	ton-CO_2	4,390	

†1: A current value that raises the temperature of a alloy wire to 150°C
†2: The yearly average load factor f (= average current capacity/maximum current capacity) was assumed to be 30%.
[Calculation conditions: ambient temperature: 40°C; wind velocity: 0.5 m/s; wind direction angle: 45°; amount of solar radiation: 0.1 W/cm^2; frequency: 60 Hz]
†3: Transmission distance: 50 km; three-phase two circuits
The loss coefficient was assumed to be $F = 0.153$ (= $0.3f + 0.7f^2$).
†4: The CO_2 emissions factor was assumed to be 0.000470 (t-CO_2/kWh)(5)

5. Conclusions

In response to the growing need for power transmission loss reduction, we have developed a new thermal-resistant aluminum alloy wire that can withstand a continuous allowable temperature of 150°C and is also highly conductive with a conductivity of 61% IACS or more.

Use of the developed alloy wire for overhead transmission lines will greatly contribute to the reduction of power transmission costs and CO_2 emissions. In the future, we will apply the knowledge we acquired in this development work to various types of aluminum alloy wires for power transmission line applications, in order to improve the conductivity of these wires and thus contribute to greater sales through expanded use of them in overhead transmission lines.

6. Acknowledgment

The BL16 beamline installed at the Kyushu Synchrotron Light Research Center was used to evaluate the solid solution amount of Fe by synchrotron radiation (subject No. SEI2018B-005).

Technical Terms

∗1 Conductivity: A measure of a material's ability to carry an electric current, which is the ratio to 100 representing the conductivity of soft copper with an electrical resistivity of 1.7241×10^{-2} μΩm, and is measured in %IACS.

∗2 Solid solution state: A state in which an additive element is uniformly dissolved in a matrix metal at the atomic level.

∗3 Crystal precipitation state: A phenomenon in which an additive element dissolved in a molten or solid metal in an atomic state forms a compound different from the matrix metal and emerges out of the metal.

∗4 Beamline: An experimental facility for the use of synchrotron radiation.

∗5 Synchrotron radiation: An extremely strong electromagnetic wave produced in the tangential direction when the orbit of an electron moving at nearly the velocity of light is bent. Compared to ordinary X-ray sources, synchrotron radiation has a higher intensity and its energy is variable.

∗6 Absorption edge: Energy at which the absorption rate of X-rays changes discontinuously and significantly. Absorption edge corresponds to the phenomenon in which atoms surrounding the nucleus transit to the orbit of the outer shell when they receive a certain amount of energy from X-rays.

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