High-Strength Thermal-Resistant Aluminum Alloy Wire with Improved Conductivity and New Conductor Design

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The span length of an overhead transmission line crossing a strait can exceed 1000 m. In order to suppress the sag of the line, higher strength conductors are required than those used for the wland part. High-strength thermal-resistant aluminum alloy wires with a conductivity of 55% IACS are used for conductors passing through such spans, but their conductivity is lower than that of the wires used in the land part (60% IACS), which limits the transmission capacity. This time, in collaboration with J-Power Transmission Network Co., Ltd., we have developed a new type of high-strength thermal-resistant aluminum wire with an improved conductivity of 58% IACS. This paper reports on the development of technology and examples of new conductor design.

Keywords: overhead transmission line, across a strait, high-strength thermal-resistant aluminum alloy wire, improved conductivity

1. Introduction

A span length of overhead transmission lines across a strait occasionally exceeds 1000 m due to the restrictions of the space to build the transmission towers. The span is longer than that of ordinary onshore overhead transmission lines. As the sag of overhead conductor increases in the long span, to ensure electrical safety, it is necessary to carefully study the clearance between the conductor and the structures above sea.

One of the solutions is to increase the height of transmission towers, but this method causes the construction cost to soar. For this reason, conductors are strung with high tension to reduce the sag. When stringing a conductor with high tension, the use of a standard conductor results in shortage of the safety factor against the breaking load. Thus, high-tension conductors with high breaking load are often used.

One of the aluminum alloy used for high-tension conductors is high-strength thermal-resistant aluminum alloy (hereinafter referred to as “55KTAL”) and its feature is the higher tensile strength than that of ordinary thermal-resistant aluminum alloy. However, the conductivity*1 of 55KTAL is 5% IACS lower than 60% IACS which is the conductivity of thermal-resistant aluminum alloy due to the influence of various additives. The decrease in conductivity results in the decrease of the transmission capacity, which poses a bottleneck in the entire transmission grid.

We have conducted a joint research with J-Power Transmission Network Co., Ltd. and developed a new high-strength thermal-resistant aluminum alloy wire whose conductivity has been improved to 58% IACS while maintaining the mechanical properties, such as tensile strength, of 55KTAL. This paper presents the characteristics of the new alloy wire and examples of conductor design.

2. Conventional High-strength Thermal-resistant Aluminum Alloy Wires

The continuous permissible temperature and short-time permissible temperature of 55KTAL are 150°C and 180°C, respectively as same as those of thermal-resistant aluminum alloy wires (hereinafter referred to as “60TAL”).

The tensile strength of 55KTAL is about 1.5 times that of 60TAL. Developed in Japan in the 1970s,(1) 55KTAL has been applied to the sections across a strait or a river. The properties of 55KTAL and 60TAL (φ4.8 mm) is shown in Table 1.

Table 1. Comparison of properties between 55KTAL and 60TAL

Item	Properties	
Type	55KTAL	60TAL
Wire diameter (mm)	4.8	4.8
Conductivity (%IACS)	55 ≤	60 ≤
Tensile strength (MPa)	225 ≤	159 ≤
Elongation (%)	2.0 ≤	2.0 ≤
Thermal resistance (%) †1	90 ≤	90 ≤

†1: Rate of tensile strength remaining after thermal history of 36 years at the conductor temperature of 150°C (equivalent to thermal history of 230°C × 1 h)

3. Development of new High-strength Thermal-resistant Aluminum Alloy Wire(2)

3-1 Development target

For the target size of conductors, the improvement of conductivity by 3% IACS can be converted into the improvement of transmission capacity by 3 to 5%, contributing to increased capacity. Thus, the target value of conductivity for the new high-strength thermal-resistant aluminum alloy wire was set to 58% IACS (hereinafter referred to as “58KTAL”).

For 55KTAL, several elements such as zirconium (Zr), silicon (Si), copper (Cu), and, iron (Fe), are added to the molten base metal of conductor grade aluminum. Wire rods are manufactured by using a Properzi continuous casting and rolling mill.*2 Subsequently, first wire drawing, aging treatment,*3 and second wire drawing are performed. A schematic diagram of the manufacturing process is shown in Fig. 1.

There are three main factors that affect the basic performance of 55KTAL: 1) alloy composition (type and concentration of added elements), 2) aging treatment conditions (heating temperature and time), and 3) wire drawing process (reductions, before and after aging). We decided to attain high conductivity by optimizing these three factors.

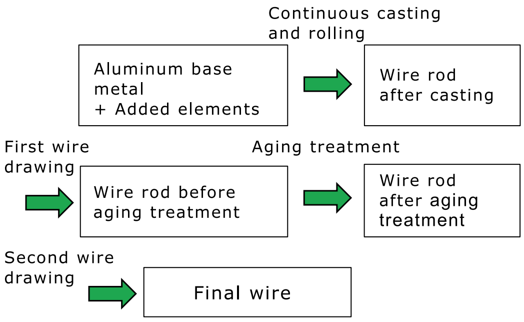


Fig. 1. Manufacturing process of 55KTAL

3-2 Achievement of proper alloy composition

In general, conductivity of aluminum alloy tends to decrease when the amount of added elements increases. In the development of 58KTAL, we fabricated samples by reducing elements added to 55KTAL in a small-scale experimental casting equipment and made evaluations. The main elements added and their effects are shown in Table 2.

Table 2. Main alloying elements of 55KTAL and their effects

Added elements	Effect
Zr	Improvement in thermal resistance and tensile strength
Si	Promotion of aging
Cu	Improvement in tensile strength
Fe	Improvement in tensile strength

After a cast material (φ30 mm) was manufactured, samples were made by cutting, cold forging, and wire drawing. The wire diameter was set to 9.3 mm. Aging treatment was then performed, and the diameter was reduced to 3.8 mm by wire drawing. We made the samples by reducing the concentration of the main alloying elements (Zr, Si, Cu, and Fe) of 55KTAL and measured conductivity, tensile strength, and thermal resistance. Table 3 presents a part of the results.

We confirmed that the conductivity was improved by the decrease in concentration of the added elements. We also confirmed that the tensile strength and thermal resistance decreased significantly in line with the decrease in the Zr concentration and that the tensile strength decreased in line with the decrease in the Cu and Fe concentrations. It was also found that there were limitations in the reduction of the volume of each added element.

We also evaluated the influence of trace elements other than the main elements (Zr, Si, Cu, and Fe) added on the basic properties and reduced the concentration of elements contributing to improved conductivity with minimal reduction in tensile strength and thermal resistance to achieve the proper alloy composition.

Table 3. Evaluation of influence of alloy composition

Evaluation sample	Concentration reduction rate of added elements	Changes in performance of a φ3.8 mm wire		
		Conductivity (%IACS)	Tensile strength (MPa)	Thermal resistance†1 (%)
Reduction in Zr	-0.06 %	+0.6	-22	-5.0
Reduction in Si and Cu ①	-0.04 % (Si) -0.06 % (Cu)	+0.3	-8	-1.4
Reduction in Si and Cu ②	-0.04 % (Si) -0.09 % (Cu)	+0.5	-14	+2.7
Reduction in Fe	-0.14%	+0.3	-7	+0.7

†1: Rate of tensile strength remaining after heating at 230°C × 1 h

3-3 Achievement of proper aging conditions

The basic performance of 55KTAL is significantly influenced by the heating temperature and time of aging treatment after manufacture of wire rods. Samples of φ15 mm fabricated using a Properzi continuous casting and rolling mill were subjected to cold wire drawing to reduce the diameter to 11.7 mm. An experiment was conducted in a small experimental heating furnace (parameters: heating temperature and time of aging treatment).

The samples after wire drawing (φ11.7 mm) were used to perform aging treatment (parameters: heating temperature and time of aging treatment). They were subjected to wire drawing to φ4.8 mm.

The experiment revealed that it was necessary to deposit and reduce the elements dissolved in the aluminum base metal in order to improve conductivity and that this would require aging treatment at higher temperature or for a longer period than that of 55KTAL.

We also confirmed that aging treatment at excessively high temperature or for longer period caused the tensile strength and thermal resistance to decrease.

Based on the above experiment, we determined the conditions to improve conductivity while ensuring the tensile strength and thermal resistance equivalent to those of 55KTAL.

3-4 Achievement of proper wire drawing

The basic performance of 55KTAL is affected by the wire diameter during wire drawing and aging treatment. Thus, we fabricated wire rods of multiple sizes by using a Properzi continuous casting and rolling mill and made the samples before and after aging treatment (parameters: reduction of the first and second wire drawing) to make evaluations. We conducted a study based on the assumption that the processing for 55KTAL could be followed as much as possible by taking productivity into consideration.

Aging treatment was performed in a small experimental heating furnace. The performance was evaluated using the samples of φ4.8 mm (final wire diameter after second wire drawing).

We confirmed that increase in the reduction for the first wire drawing, as shown in Fig. 1, promoted deposit of Zr and other elements and resulted in high conductivity and that increase in the reduction for the second wire drawing increased the tensile strength.

Based on the above experiment, we established an optimal wire drawing process, which ensured a certain level of margin for the target performance.

3-5 Prototype production and evaluation on a mass production line

Based on the abovementioned study results of 1) achievement of proper alloy composition, 2) achievement of proper aging conditions, and 3) achievement of proper wire drawing, we manufactured wire rods using a Properzi continuous casting and rolling mill. We then performed aging treatment by using a heating furnace for mass production and conducted continuous wire drawing by using a wire drawing machine for mass production. The wire diameter after continuous wire drawing was set to 4.8 mm. The evaluation results of conductivity, tensile strength, elongation, and thermal resistance are presented in Table 4.

The results indicated that 58KTAL, the newly developed material, attained the target conductivity (58% IACS or more) and that its tensile strength, elongation, and thermal resistance met the standard value for 55KTAL.

Table 4. Performance of 58KTAL manufactured by mass production equipment (φ4.8 mm)

Item	Measured value†1	Target value
Conductivity (%IACS)	58.6 (58.6~58.7)	58.0 ≤
Tensile strength (MPa)	230 (230~231)	225 ≤ (55KTAL standard value)
Elongation (%)	3.6 (3.4~3.8)	2.0 ≤ (Same as above)
Thermal resistance (%)	95.3 (94.9~95.7)	90 ≤ (Same as above)

†1: Mean value when N (number of evaluated samples) = 10. Values in the parentheses show minimum and maximum values.

4. Conductor Design Using 58KTAL

4-1 Design of the sections across a strait

One of the objectives in developing 58KTAL was to replace existing conductors for the sections across a strait of a 220 kV transmission line owned by J-Power Transmission Network Co., Ltd. This chapter introduces an example of conductor design. There are two strait-crossing sections and the conductors used are among the biggest size of high tension conductors in Japan. The span lengths are both over 1,000 m. Figure 2 shows the profile of the strait crossing sections.

While twin-bundled thermal-resistant aluminum alloy conductors 610 mm^2 (TACSR 610 mm^2) with 60TAL is employed for the onshore section of the transmission line, a single high strength thermal-resistant aluminum alloy conductor, extra high-strength steel reinforced 1,300 mm^2 (KTACSR/EST 1,300 mm^2) with 55KTAL is employed for the sections across the strait. It is necessary to suppress the sag of the conductors since the span length of the sections are long. To withstand the high-tension stringing, extra-high-strength galvanized steel wire (EST) is used for its steel core. Anticorrosive grease is filled in the internal and external layers of the conductor as a measure against corrosion caused by sea salt.

Table 5 shows a design example of conductor in which 58KTAL (newly developed material) is applied to

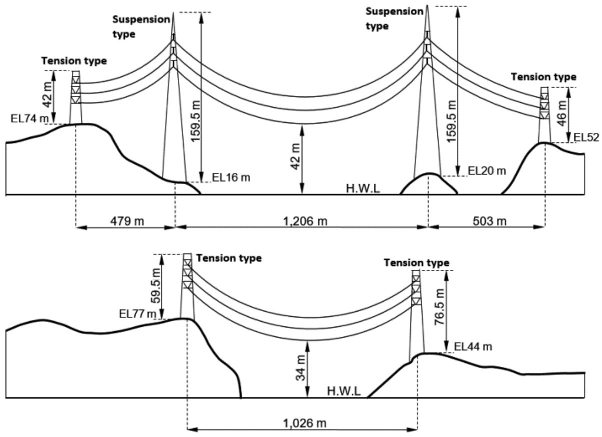
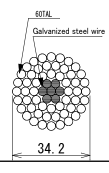
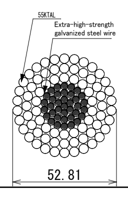
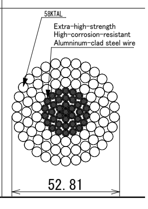


Fig. 2. Profile of the section across a strait

Table 5. Example of conductor design for the section across a strait (voltage: 220 kV)

Scope of application		Onshore section	Section across a strait	
Classification		Existing conductor	Existing conductor	Newly developed conductor
Name		Thermal-resistant Aluminum Alloy Conductor, Steel Reinforce	Thermal-resistant Aluminum Alloy Conductor, Extra-high-strength Steel Reinforced (inner and outer layers greased)	Thermal-resistant Aluminum Alloy Conductor, Extra-high-strength Corrosion-resistant Aluminum-clad Steel Reinforced
Code		TACSR	55KTACSR/EST	58KTACSR/EHRAC
Size (mm^2)		610	1300	1300
Number of conductors		2	1	1
Maximum working tension (kN)		54	255	255
Transmission capacity (MW)†1	Continuous†3	1220	1010	1060
	Short-time†4	1390	1170	1230
Sag (m)†2	Continuous	-	65.5	63.8
	Short-time†4	-	67.0	65.5
Cross sectional view				

†1: Transmission capacity calculated based on a general calculation method for overhead transmission lines.
†2: Sag of the 1,206 m length intermediate span of three continuous spans (479 m–1,206 m–503 m).
†3: Maximum transmission capacity with double-circuit operation. The conductor temperature is 150°C.
†4: Transmission capacity permissible only for a short time during one-circuit operation in the event of another circuit's failure. The conductor temperature is 180°C.

the conductive part for the purpose of up-rating. The continuous transmission capacity at the conductor temperature of 150°C is 1,060 MW, and the short-time transmission capacity at 180°C was 1,230 MW, making it possible to increase the capacity by approximately 5% compared to that of the existing conductor using 55KTAL.

Extra-high-strength corrosion-resistant aluminum-clad steel wires*4 (EHRAC) are used for the steel core of the newly developed conductor and no anticorrosion grease is used in the internal and external layers of the conductor.

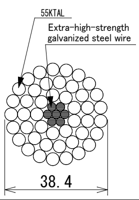
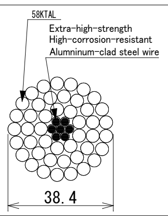
4-2 Design example for standard size

For 810 mm^2, one of the standard size of ACSR, Table 6 shows a design example of conductor using 58KTAL for conductive part and EHRAC for steel core as well as a design example with conventional 55KTAL. The continuous current capacity of the conductor with 58KTAL is 2,057 A which is around 3% higher than 1,991 A with 55KTAL. Transmission capacity calculated from the current capacity multiplied by the voltage is not considered in this case study. Focusing on the sag of the new design with 58KTAL, it is almost the same as that of the conventional design.

As discussed above, the new design using 58KTAL offers the advantages, such as 1) increasing the capacity with the same sag and 2) eliminating the need for different accessories, such as strain clamps, and stringing tools because the outer diameter is the same as that of the conventional design.

Given that renewable energy sources are expected to be increasingly connected to the transmission grid, application of 58KTAL is considered as an effective solution to increase the transmission capacity of the bottleneck sections crossing a strait or a big river.

Table 6. Example of the newly developed 58KTAL conductor design

Item	Conventional design	New design
Name	Thermal-resistant Aluminum Alloy Conductor, Extra-high-strength Galvanized Steel Reinforced	Thermal-resistant Aluminum Alloy Conductor, Extra-high-strength Corrosion-resistant Aluminum-clad Steel Reinforced
Code	55KTACSR/EST	58KTACSR/EHRAC
Size (mm^2)	810	810
Construction (number of stranding /mm)	55KTAL-45/4.8 EST-7/3.2	58KTAL-45/4.8 EHRAC-7/3.2
Tensile strength (kN)	254.6	254.6
Weigth (kg/km)	2700	2662
Electrical resistance (Ω/km)	0.0395	0.0369
Modulus of Elasticity (GPa)	72.9	70.6
Coefficient of Liner Expansion ($\times10^{-6}$/°C)	20.9	21.3
Current capacity (A) †1 Continuous at 150°C	1991	2057
Sag (m) †2	46.0	45.9
Cross sectional view		

†1: Current capacity calculated based on a general calculation method for overhead transmission lines.
†2: Sag calculated based on the span length of 600 m and the maximum working tension of 49.0 kN.

5. Conclusion

We have developed a new high-strength thermal-resistant aluminum alloy wire, whose conductivity has been improved from 55% IACS to 58% IACS, for high-tension conductors to be installed in the sections across a strait.

The transmission capacity of the strait-crossing section used to be in some cases a bottleneck of the entire transmission grid since it is smaller than that of the normal onshore sections, but application of the newly developed alloy helps improves the transmission capacity by approximately 3 to 5% and contributes to clearing the bottleneck.

We will work for expanding the application of this newly developed conductor to actual overhead lines, and in the meantime, contribute to designing and developing a wide variety of conductors that meet the needs of replacement for the power utilities.

6. Acknowledgements

The results of the development in Chapter 3 and subsequent chapters were derived from joint research with J-Power Transmission Network Co., Ltd. We would like to express our appreciation to the parties concerned.

Technical Terms

*1 Conductivity: An index that indicates the ability to conduct electricity. It is indicated by percentage with the conductivity of the International Annealed Copper Standard as 100. The unit is % IACS.

*2 Properzi continuous casting and rolling mill: Equipment for manufacturing wire rods made from aluminum by continuously performing the casting, rolling, and coiling processes. It achieves outstanding thermal resistance due to rapid solidification and eliminates the need for reheating during rolling. It also ensures high productivity and energy conservation performance.

*3 Aging treatment: A treatment process in which solute components supersaturated in a metal matrix are allowed to deposit in a heterogeneous phase in the order of nanometers to improve the properties, such as strength and thermal resistance. Heat treatment is performed for Al-Zr alloys, such as KTAL, to cause the deposition reaction.

*4 Corrosion-resistant aluminum-clad steel wire: A steel wire characterized by superb anticorrosion performance and used for the steel core of ACSR. While an aluminum-clad steel wire represents a steel wire cladded with electrical conductor grade aluminum, a corrosion-resistant aluminum-clad steel wire features an aluminum clad with a trace amount of Mn added. The corrosion resistance is about 1.6 times that of an aluminum-clad steel wire.(3)

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