Development of High Strength Invar Alloy Wire for High Voltage Overhead Power Transmission Line

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In recent years we have seen a worldwide increase in the demand for electric conductors which have a large transmission capacity to meet rapidly growing electricity consumption.
The use of ZTACIR (Aluminum Conductor Invar Reinforced) can double the capacity of overhead power transmission line without extra infrastructure construction. In particular, aluminum clad invar alloy wire, which is highly resistant to corrosion, reduces transmission loss, and produces less CO_2 emissions, is increasingly demanded.
The authors have worked to develop a high-strength aluminum clad invar alloy wire by enhancing the durability of the conventional invar alloy wire. The newly developed wire is as strong as steel wire and can therefore be used as the core wire of high voltage overhead transmission line.
This paper features the characteristics of the developed invar alloy wire.

Keywords: invar alloy, low thermal expansion, high strength

1. Introduction

Since 1980, Aluminum Conductor Invar alloy Reinforced (ZTACIR), developed by Sumitomo Electric, has been used as a high voltage power line. As electricity consumption increases, the power line has increasingly been installed in order to boost the capacity of overhead power transmission line. **Figure 1** shows a cross sectional structure of a general conductor. With the ZTACIR, the core steel wires are replaced by Fe-Ni alloy wires (so-called invar alloy wires), and the aluminum wires by super thermal resistant aluminum alloy wires.

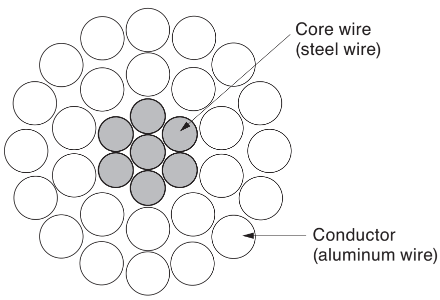

Fig. 1. Cross-sectional structure of a power transmission line

A ZTACIR is composed of invar alloy wires which have a low thermal expansion coefficient and aluminum alloy wires with high thermal resistance. This structure prevents the conductor from sagging more than conventional steel conductor do, even when twice the amount of electricity runs through the conductor. Furthermore, the ZTACIR requires no extra infrastructure construction, such as installation of new power transmission lines or reinforcement of steel towers to support the conductor. Therefore, power transmission capacity can be doubled simply by replacing existing conventional conductor with the ZTACIR.

However, the conventional invar alloy wire used in the ZTACIR is not as strong as steel wire and cannot be used as the core wire of high voltage power transmission line. The invar alloy wire needs to be galvanized to gain the strength that steel wire has.

Due to this, demand has grown for aluminum clad invar alloy wire which has a thick corrosion resistance layer, high strength and good electric conductivity, and reduces transmission loss and CO_2 emissions.

We have succeeded in the development of a reinforced invar alloy wire which has strength comparable to that of steel wire by adding vanadium. With this wire, we have created a high-strength aluminum clad invar alloy wire to be used as the core wire of high voltage power transmission line. This paper outlines the development of the reinforced invar alloy wire and reports its characteristics.

2. Development Challenges and Goals

Figure 2 illustrates the target characteristics of the aluminum clad invar alloy wire. We aimed to develop an invar alloy wire which is as strong as steel wire and has the same thermal expansion coefficient that the conventional invar alloy wire has. The low thermal expansion of the conventional invar alloy wire is an important characteristic to enable it to double the capacity of the overhead power transmission line.

In addition to the aforementioned low thermal expansion, the invar alloy wire also needs to have ductility to withstand repeated bending and twisting in the production process. A torsion property, which is evaluated by the twisting times applied to sample wire until it breaks, is used as the index of the ductility in electric wires. We aimed to have the same level of torsion property that the conventional invar alloy wire has.

However, as mentioned above, strength of the conventional invar alloy wire is lower than that of steel wire. Since ductility is degraded in the process of strengthening the wire by adding C and drawing intensively, balancing high strength and ductility in the Fe-Ni alloy wire is difficult.

Therefore, we aimed to develop an invar alloy wire which is comparable to the conventional invar alloy wire in terms of low thermal expansion and torsion property, and is comparable to or greater than the galvanized invar alloy wire or steel wire in terms of strength (1078N/mm^2 or higher).

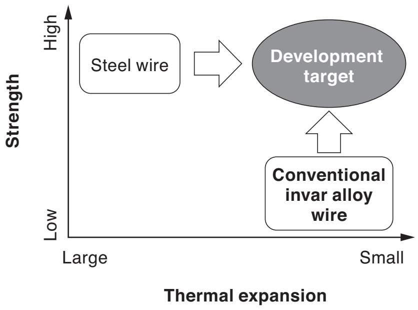

Fig. 2. Development target

Table 1. Development goal

	Tensile strength N/mm^2	Thermal expansion coefficient ×10−6/°C	Twisting times /100D
Development target	≧1078	<3.7	≧20
Conventional invar alloy wire (aluminum clad)	1029～1078	<3.7	≧20
Steel wire	1225～1325	11.5	≧20

2-2 Alloy design

Firstly, the effect of alloying elements on thermal property of invar alloy was studied to find the best proportion that meets the low thermal expansion standard at the operating temperature of the overhead power transmission line. Fe-36%Ni alloy, a well-known invar alloy, is a strong magnetic substance at the Curie point Tc and lower, showing a low thermal expansion property. However, at over Tc, it turns into a paramagnetic substance, showing a high thermal expansion property as general FCC alloy does.

Although the thermal expansion of Fe-36% Ni alloy, whose Tc is about 200°C, is large above Tc, the invar alloy wire must have a low thermal expansion property even at 240°C, the continuous allowable temperature of an aluminum clad invar alloy wire. **Figure 3** shows the thermal expansion properties of Fe-36% Ni and Fe-38% Ni alloys. This graph illustrates that these alloys exhibit low thermal expansion properties at temperature lower than their Tcs, while they exhibit high thermal expansion properties at over their Tcs. Therefore we concluded that Fe-38% Ni alloy, which has its Tc around 240°C, is ideal for maintaining the low thermal expansion property even at 240°C.

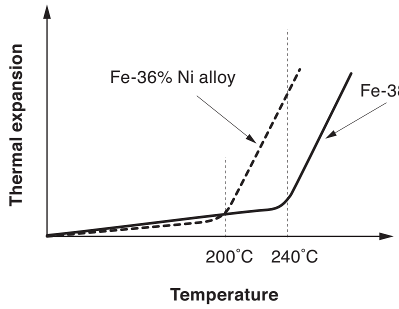

Fig. 3. Thermal expansion characteristics of Fe-36% Ni and Fe-38% Ni alloys

Next, we investigated ways of strengthening invar alloy. The conventional invar alloy wire does not have sufficient torsion properties to be used as electric wires because the solid solution hardening alone does not provide ductility. Recent studies have revealed that this phenomenon is due to the decrease of bonding strength among crystal grains resulting from carbide precipitation caused by a reinforcement element C. Therefore, in addition to the solid solution and work strengthening methods, we employed precipitation strengthening method using fine alloy carbide particles in crystal grains aiming for a good torsion property.

Fe-Ni invar alloy is an FCC alloy with a lattice constant of about 0.36 nm. For a better matched precipitation, alloy carbide needs to have crystal structure and lattice constants similar to those of the invar alloy. After testing various carbides, vanadium carbide (VC) was selected. VC has B1 structure (NaCl type) that is similar to that of FCC and the lattice constant of 0.416 nm, which is close to the matrix lattice constant. **Figure 4** shows **(a)** an electron microscope photograph of the precipitated VC (an extraction replica sample) and **(b)** an electron beam diffraction image of a matrix and VC (a film sample) after precipitation heat treatment of invar alloy containing V and C. As seen in **Fig. 4 (a)**, VC particles of 20-30 nm are precipitated in the crystal grain. **Figure 4 (b)** was obtained by narrowing down an electron beam to a field where both a matrix and VC existed. The diffraction spots of VC are observed next to the spot of a matrix along with the zone axis [111], and they are in similar figures in the same orientation. Although the miss fitting ratio is calculated to be 15%, the coherence precipitation of VC and matrixes is enough to be used for strengthening invar alloy.

It should be noted that the ratio of V to C is also important. Excess V remains in the solid solution without precipitating as vanadium carbides, which results in an increase of the thermal expansion coefficient. An excess of C, on the other hand, leads to the grain boundary precipitation of Fe carbides and deteriorates the torsion property. Therefore, we carefully optimized the ratio of V and C.

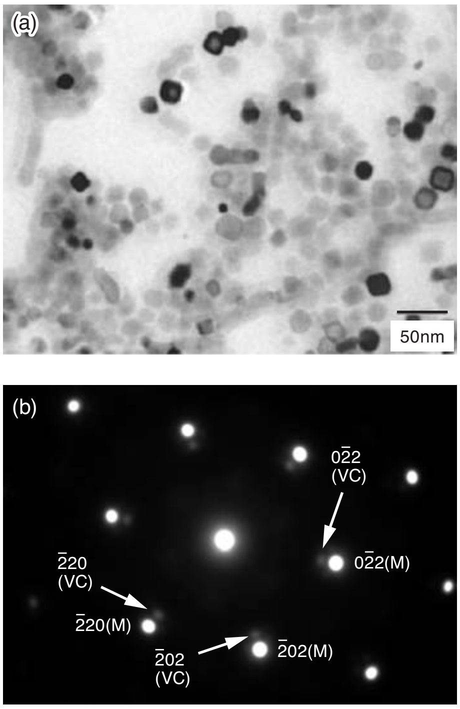

Fig. 4. (a) Electron microscope photograph of precipitated VC and (b) Electron beam diffraction image of a matrix and VC

2-3 Process design

To balance high ductility and strength, VC needs to be precipitated finely in a grain. Accordingly, optimizing the production process is as important as optimizing the alloy composition. **Figure 5** shows an outline of the production process of the developed invar alloy wire. To maximize the effects of the VC precipitation hardening, precipitation of fine VC is essential. For this purpose, solution heat treatment was carried out to obtain a perfect VC solid solution followed by the drawing process to create work strains.

Every process indicated in **Fig. 5** is important because they can influence the characteristics and quality of final products. However, when it comes to VC precipitation, hot rolling and heat treatment processes are of the utmost importance. Therefore, this section focuses on the desired conditions in these two processes and describes the influence on the characteristics of vanadium added inver alloy wire.

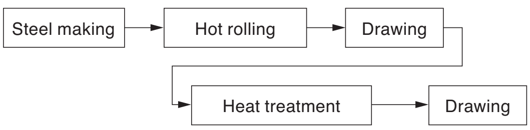

Fig. 5. Production process of invar alloy wire used for overhead transmission line

Firstly, we explain the hot rolling process. As mentioned above, the point of this process is to make precipitated VC into a perfect solid solution. For this purpose, a billet has to be heated in a heating furnace before hot-rolling into a wire rod. Immediately after that, the wire rod is cooled off so that the VC does not precipitate. The relationship between age hardness and heating temperature is given in **Fig. 6**. It indicates that age hardness increases with a rise in heating temperature. This happens because the quantity of the VC solid solution increases with a rise in temperature. However, since excessively high temperature can cause unnecessary oxidation to the billet surface, the heating temperature must be selected carefully.

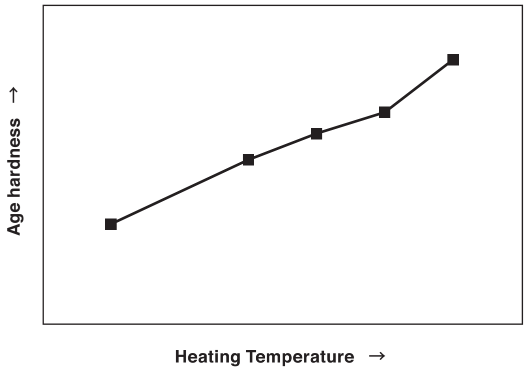

Fig. 6. Relationship between heating temperature and age hardness of a V and C added inver alloy wire

Next, we address the age hardening heat treatment process followed by the drawing process. **Figure 7** shows the relationships between heat treatment temperature and the tensile strength and twisting times of a wire.

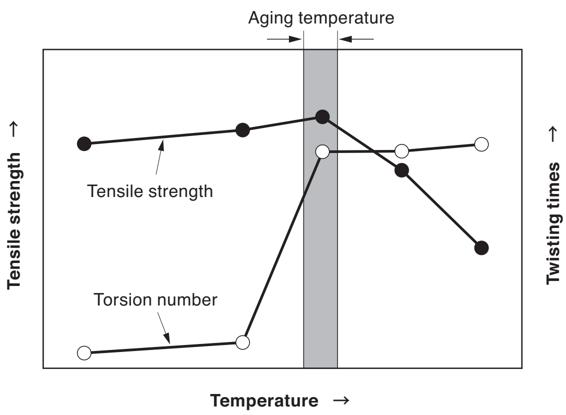

Fig. 7. Relationship between heating temperature and tensile strength / the twisting times of a V and C added inver alloy wire

Although tensile strength slightly increases with a rise in heat treatment temperature, it falls suddenly after passing its peak. The increase of tensile strength in the low temperature area is due to the precipitation of fine VC in crystal gains, while the sharp drop of tensile strength in the high temperature area is attributed to the relaxation of working strains and weakened hardening ability resulting from the precipitation of coarse VC particles.

The twisting times, on the other hand, increases with a rise in heat treatment temperature and reaches a plateau after the maximum point of tensile strength. This is because twisting times increases when working strains are sufficiently released by heat treatment. Because the optimal heat treatment temperature varies depending on the alloy composition and other factors, it must be selected and controlled with a great care. In addition, keeping the temperature constant is also important to balance high tensile strength and good torsion property.

3. Characteristics of Developed Invar Alloy Wire

Table 2 shows characteristic examples of an aluminum clad invar alloy wire using our developed invar alloy. This aluminum clad invar alloy wire exhibits strength equivalent to that of steel wire and a thermal expansion coefficient comparable to the conventional invar alloy wire. Its torsion property also meets the requirement for electric wire.

Table 2. Characteristic examples of the developed wire

	Tensile strength N/mm^2	Thermal expansion coefficient $\times 10^{-6}$/°C	Twisting times /100D
Developed aluminum clad invar alloy wire	1175～1225	2.3～3.0	≧20
Development target	≧1078	＜3.7	≧20

This developed invar alloy wire has passed a long term reliability test and has been adopted in domestic and international market. The wire accounts for about 80% of the world share in the ZTACIR market, in particular. This success is partly attributed to the several environmental advantages which the wire has: 1) conductor with this invar alloy wire requires neither tall steel towers nor large tower bases, and can therefore reduce adverse impacts on the natural environment where these infrastructures are otherwise installed, 2) this invar alloy wire is 100% recyclable after dismantling conductors, and 3) none of harmful chemicals listed in the Pollutant Release and Transfer Register (PRTR), Restriction on Hazardous Substances (RoHS), and Registration, Evaluation and Authorization of Chemicals (REACH) are used.

4. Conclusions

1) We have optimized the conditions of designing and producing invar alloy and have succeeded in the development of a reinforced invar alloy wire capable of overhead power transmission line. This wire features the highest strength among the existing invar alloy wires, with good ductility and thermal expansion characteristics well balanced. We have also established the mass production process of this wire aiming to ensure the stable supply of high quality invar alloy wire.
2) The developed invar alloy wire is comparable to steel wire in terms of strength. It is therefore ideally used as the core wire of aluminum clad invar alloy wire for which demand is growing particularly in overseas to cope with increasing power transmission line.

References

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