Cobalt Alloy Wire for High-Current Reed Switches

Hajime OTA*, Tetsuya KUWABARA, Yoshihiro NAKAI, Norimasa KAWANO, Naoki SUGIHARA and Kazuo YAMAZAKI

Recent years have seen increases in electronically controlled system equipment and electric current capacity. Therefore the demand for switches capable of handling high current is rising. Mercury reed switches have been used for high-current switch until now. Since mercury is a substance of concern, mercury reed switches have been changed to reed switches in which mercury is not used. However, when a temperature rises largely as energization progresses by Joule heat effect, lead wires lose their ability to carry magnetic flux, and reed switches become less sensitive. Due to these problems, reed switches were not used for high-current switches. We have developed cobalt-nickel-iron alloy wire for high-current switches that demonstrate excellent characteristics similar to the conventional alloy lead wire. The new alloy wire suppresses heating due to energization and has high Curie temperature, i.e. less susceptibility to lose magnetic characteristics. The reed switch using the new alloy wire is expected to be applied to LEDs in automobile stop lamps.

Keywords: reed switch, cobalt alloy, Curie temperature, glass sealability

1. Introduction

With the recent growing need for higher electric current capacity and further integration of electronic control systems used in industrial equipment, conducting wires used in these control systems are required to be more heat-resistant. Thanks to their superior oxidation resistance and corrosion resistance under high-temperature conditions, nickel alloys, ferrous alloys, and cobalt alloys and their composites are used as heat-resistant alloy wires in high-temperature environments where ordinary conducting wires cannot be used.

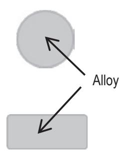
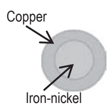
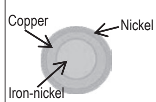
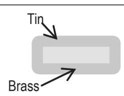
Sumitomo Electric Industries, Ltd. develops and sells heat-resistant alloy wires for automotive spark plugs, diodes, and many other applications. To meet the recent need for reed switches capable of controlling the flow of high electric currents, we have developed a cobalt alloy for heat-resistant alloy wire that can ensure both a higher current capacity and superior glass sealability. This paper discusses the excellent properties of the newly developed alloy.

2. Heat-Resistant Alloy Wire

The major product lines of Sumitomo Electric's heat-resistant alloy wires are shown in **Table 1**. The company has been striving to develop heat-resistant alloy wire by combining copper, silver, and other conductor materials with cobalt, nickel, iron, and other heat-resistant conductor materials in order to meet the performance required of the final products.

In the development of an electrode material for automotive spark plugs, improving both the high-temperature oxidation resistance and spark consumption resistance[*1] of the alloy wire is essential to extend the service life of plugs. Adding to the alloy wire an element capable of suppressing the separation of oxidized films is effective in improving its high-temperature oxidation resistance. However increasing the added amount of such an element deteriorates the heat dissipation performance of the alloy wire. As a result, the spark consumption resistance of the alloy wire deteriorates. The yttrium-dispersed nickel alloy wire developed by Sumitomo Electric for spark plug applications is a revolutionary alloy wire.[(1)]

Table 1. Major product lines of heat-resistant alloy wires

Alloy system		Feature	Cross-sectional structure
Nickel alloy	High nickel	Has both high-temperature oxidation resistance and spark consumption resistance. Suppresses grain coarsening	
	Nickel-manganese	Softening temperature is higher than nickel. Has excellent heat resistance.	
	Kovar	Has high thermal expansion compatibility with hard glass.	
Ferrous alloy	Iron-nickel	Has high thermal expansion compatibility with soft glass.	
Cobalt alloy	Cobalt-nickel-iron	Has high heat-resistance and mechanical strength.	
Composite wire	Dumet (iron-nickel core clad in copper)	Exhibits high thermal expansion compatibility with glass while maintaining excellent electrical conductivity.	
Plated wire	Nickel-plated Dumet	Product made by plating Dumet wire with nickel. Surface treatment of external lead wires is unnecessary because no cuprous oxide exists.	
	Tin-plated square brass wire (TPBS)	Product made by tinning square brass wire Lead free.	

Added yttrium that finely disperses in the nickel, this wire maintains heat dissipation performance and electric properties comparable to pure nickel, and it exhibits an excellent spark consumption resistance and superior high-temperature oxidation resistance, i.e. suppression of oxidized film separation.

In the development of lead wires for diodes, capacitors, and reed switches, it is essential to use a material that can be hermetically sealed in a glass tube. So, the material must have a thermal expansion coefficient compatible with that of the glass tube and must be easy to bond to the glass tube by diffusion.(2) The iron-nickel alloy wire developed by Sumitomo Electric has a thermal expansion coefficient close to that of the glass tube and thus has excellent glass sealability.

In the development of a resistance wire for glow plugs, it is necessary to enhance the electric resistance characteristics and high-temperature oxidation resistance of the resistance wire to downsize the plug and extend its service life. Pure cobalt exhibits optimal electric resistance and excellent oxidation resistance in the working temperature range. However, the crystal structure of pure cobalt is hexagonal*2 and has difficulty in plastic working. In the development of a cobalt-nickel-iron alloy wire,(3) Sumitomo Electric achieved a cubic crystal structure by optimizing the composition of the wire. This alloy wire is a material that is easy to do plastic working and combines excellent electric resistance characteristics with a high oxidation resistance.

3. Heat-Resistant Alloy Wire for Reed Switch Applications

3-1 Increased need for higher current capacity reed switches

As shown in **Figure 1**, a reed switch consists of a pair of ferromagnetic lead wires*3 with contacts draped like a reed that face each other at a specific gap and are hermetically sealed and fixed in a glass tube containing an inert gas. When the contacts of the lead wires are magnetized in the longitudinal direction by a magnetizing coil located near the reed switch, the contacts are attracted by a magnetic force and come into contact with each other, closing the switch. When the magnetic field is removed, the contacts of the lead wires separate from each other under their own springiness, opening the switch.

Reed switches are usually built into liquid level sensors for automotive and other industrial applications, and are used under severe environmental conditions. The control current of equipment that contains reed switches is increasing recently. When the reed switches are closed, the lead wires are often heated to high temperatures due to Joule heat.*4 In these applications, preventing deterioration of the reed switch's characteristics is important when the lead wires are exposed to high temperatures.

There are two major factors that cause the degradation of a reed switch —surface contamination of the lead wire contacts and loss of the magnetic properties due to a rise in the lead wire temperature. To protect the lead wire contact surfaces from pollutants in the outside environment, the glass tube is filled with an inert gas. To prevent the lead wires from being heated to a high temperature by Joule heating, on the other hand, the heat dissipation performance of the lead wires must be enhanced.

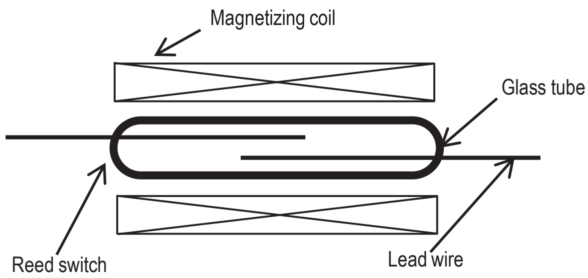


Fig. 1. Construction of a reed switch

In traditional mercury reed switches, which are high current switches having a current switching capacity of 5 A or more, the contacts are covered with mercury to dissipate heat from the lead wires. In this way, the lead wires are kept at a low temperature to maintain their magnetic properties. However, due to the need to completely eliminate the use of mercury, a substance of concern, mercury reed switches are being replaced by switches with mercury-free contacts. However, to enhance the heat dissipation performance of mercury-free switches, their dimensions must be increased. The increased miniaturization of devices has increased the need for smaller reed switches that can control a current flow of 5 A or more without any increase in size.

3-2 Properties required of heat-resistant alloy wire for higher current capacity reed switches and target properties

3-2-1 Required properties

Low electrical resistivity, high Curie temperature,*5 excellent glass sealability, and superior plasticity workability are required of the heat-resistant alloy wire used in reed switches. Low electrical resistivity is necessary to suppress Joule heating and prevent the lead wires from heating to high temperatures when the switches are energized. A high Curie temperature is required to prevent the lead wires from losing their magnetic properties even when the wires are heated to high temperatures, thereby raising their maximum allowable working temperature. Excellent glass sealability is required to protect the lead wire contact surfaces from contamination. Enhancing the compatibility of the thermal expansion coefficient of the lead wires with that of the glass tube prevents any cracking of the glass tube after the lead wires contacts are sealed in the tube. Hermetically sealing the lead wires contacts in the glass tube by improving the diffusion bondability prevents contaminants from entering the glass tube from the external environment. Superior plasticity workability is required of the lead wires since their ends must be pressed to form springy contacts.

3-2-2 Properties of conventional heat-resistant alloy wire

The properties of the iron-nickel alloy wire used in conventional low-current capacity reed switches are shown in **Table 2**. In this table, a rate of thermal expansion compatibility with the glass tube is defined by the thermal expansion coefficient of the glass tube divided by that of the wire as a percentage. As the rate of thermal expansion compatibility approaches 100%, the difference in the thermal expansion coefficient between the wires and the glass tubes decreases and the glass sealability of the wires is enhanced.

It is easy to form contacts in iron-nickel alloy wire by pressing. It also has a high rate of thermal expansion compatibility with glass tubes and is easy to bond to the tube by diffusion. In addition to these favorable properties, iron-nickel alloy wire has a Curie temperature of 520°C and an electrical resistivity of 34 μΩcm. Reed switches using this alloy wire for their lead wires function well as switches for controlling current flows of less than 5 A.

Table 2. Properties of iron-nickel alloy wire for low-current reed switches

Alloy wire	Conventional iron-nickel
Crystal structure	Cubic crystal
Curie temperature (°C)	520
Electrical resistivity (μΩcm)	34
Rate of thermal expansion compatibility with glass tube (%)	94
Diffusion bondability to glass tube	Excellent
Estimated current capacity of reed switch (A)	2-4

3-2-3 Guidelines for setting target properties of lead wires for higher current capacity reed switches

Development of a new lead wire was started with the aim of realizing a reed switch with a current capacity 2.5 times or more that of the conventional reed switch. To achieve the above target current capacity, the Curie temperature and electrical resistivity of the lead wire was improved, while the production-related properties of the new lead wire including the rate of thermal expansion compatibility with glass tubes, diffusion bondability to glass tubes, and plasticity workability were maintained at the same level as those of the conventional material. **Table 3** lists the design target specifications that were set for the new heat-resistant alloy wire. The practical procedures for setting the target specifications are described later.

Table 3. Target design specifications set for the new heat-resistant alloy wire

Alloy wire	New alloy to be developed
Crystal structure	Cubic crystal
Curie temperature (°C)	930 min.
Electrical resistivity (μΩcm)	9.5 max.
Rate of thermal expansion compatibility with glass tube (%)	85 min.
Diffusion bondability to glass tube	Excellent
Estimated current capacity of reed switch (A)	5-10

3-2-4 Setting the target Curie temperature and electrical resistivity

The target current capacity of the new lead wire to be developed was determined by tentatively calculating the dependence of the maximum current capacity of the lead wire on its electrical resistivity and Curie temperature.

With ρ defined as the electrical resistivity of the alloy wire and T as the temperature of the alloy wire after equilibrium between Joule heating by a current of i and the heat dissipated into the atmosphere, the maximum allowable working temperature of the wire T_{max} is equal to the Curie temperature T_c. The relationship between the maximum current capacity i_{max} and electrical resistivity ρ is expressed by **Equation (1)**.[4]

$$i_{max}^2 \propto T_c / \rho \quad (1)$$

When the Curie temperature is assumed to be twice that of the conventional wire and the electrical resistivity is assumed to be one quarter that of the conventional lead wire, **Eq. (1)** suggests the possibility of a lead wire with a maximum current capacity approximately 2.8 times larger than the conventional wire. This value was set as the target current capacity for the new lead wire.

However, since it was impossible to achieve the above target value with conventional iron-nickel alloy wire, use of a new heat-resistant alloy wire became crucial.

3-2-5 Setting the target plasticity workability and glass sealability

Each alloy has its own plasticity workability and thermal expansion coefficient. We estimated that a new alloy wire that has the same crystal structure as that of conventional alloy wire would provide the required plasticity workability. Regarding the thermal expansion coefficient, we estimated by simulation the distribution of residual stress in the glass tube in the case where lead wires that have a thermal expansion coefficient different from that of the glass tube are sealed with the glass tube. Based on the simulation results, the target thermal expansion coefficient of the new alloy wire was determined so that it would expand at a nearly the same rate as the glass tube and prevent cracking of the glass tube.

For sealing the new lead wire with the glass tube, we planned to fuse the glass at a specific part of the lead wire by heating the glass on the surface of the lead wire to a high temperature, form it into the required shape, and cool it. If the thermal expansion coefficient of the lead wire differs significantly from that of the glass tube after the tube is cooled, the residual stress in the seal glass will exceed the breaking strength of the glass tube and crack the tube.

Figure 2 shows the simulation results for the distribution of residual stress in a glass tube in which a lead wire with a thermal expansion coefficient incompatible with that of the glass tube is sealed. This figure shows that a high stress will remain in a specific part of the glass tube.

To prevent cracking of the glass tube, it is necessary to make the thermal expansion coefficient of the lead wires compatible with that of the glass tube, thereby suppressing the maximum residual stress to below the breaking stress of the glass tube. **Figure 3** shows the relationship between the rate of thermal expansion compatibility and the maximum residual stress obtained from the above simulation results. To ensure that the maximum residual stress does not exceed the breaking stress of the glass tube, the rate of thermal expansion compatibility of the alloy wire to be developed was set at 85% or higher.

Since a ferromagnetic material has excellent diffusion bondability to glass, the new alloy wire was estimated to have a bondability equivalent to that of conventional lead wire.(2)

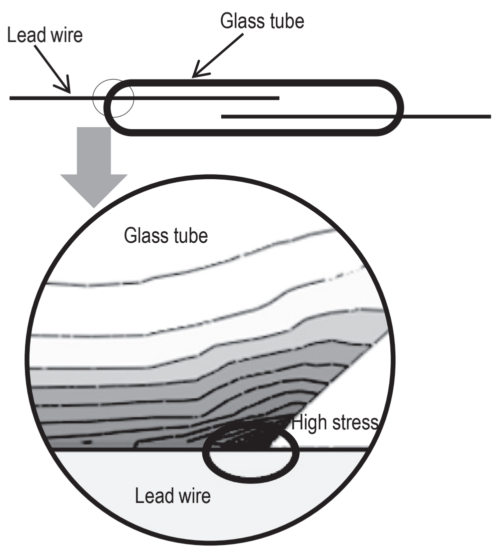


Fig. 2. Simulation results for residual stress distribution in the sealed glass tube

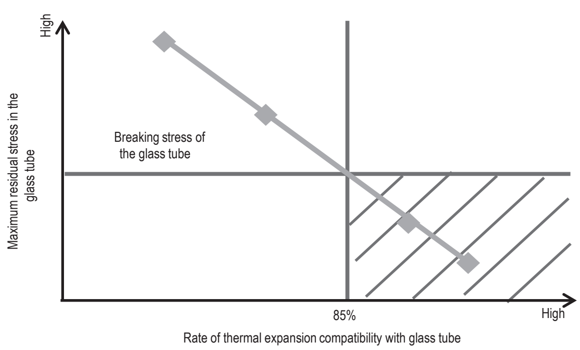


Fig. 3. Relationship between the rate of thermal expansion compatibility and residual stress in the sealed glass tube

4. Development of Heat-Resistant Alloy Wire for Reed Switch Applications

4-1 Selection of the alloy

The Curie temperature, electrical resistivity, and thermal expansion coefficient of an alloy depend on its constituent atoms. The properties of ferromagnetic pure metals and alloys are shown in **Table 4**.

Since pure cobalt and a cobalt-nickel-iron alloy have higher Curie temperatures and lower electrical resistivity than those of conventional iron-nickel alloys, these two metals are promising as materials that could increase the current capacity of reed switches.

Of the above two materials, pure cobalt has a high Curie temperature of 1,100°C but the rate of thermal expansion compatibility with glass tubes is inferior to that of iron-nickel alloys. Hence, the glass sealability of pure cobalt was considered to be lower than that of iron-nickel alloy. In addition, since the crystal structure of pure cobalt is hexagonal, this metal was considered to be unsuitable for lead wires that need to be drastically deformed. In contrast, because of its cubic crystal structure, a cobalt-nickel-iron alloy was anticipated to provide excellent plasticity workability. This alloy is also superior in thermal expansion compatibility with and diffusion bondability to glass, as well as having a high Curie temperature and low electrical resistivity. With the above favorable properties taken into account, this alloy was optimal for enhancing the current capacity of reed

Table 4. Properties of ferromagnetic materials

Pure metal or alloy	Pure cobalt	Cobalt-nickel-iron	Pure iron	Iron-nickel	Pure nickel
Crystal structure	Hexagonal crystal	Cubic crystal	Cubic crystal	Cubic crystal	Cubic crystal
Curie temperature (°C)	1,115	950 -1,050	770	450-550	354
Electrical resistivity (μΩcm)	6.2	7.6-9.0	9.6	34-58	6.9
Rate of thermal expansion compatibility with glass tube (%)	75	80-91	92	94-99	85
Diffusion bondability to glass tube	Excellent	Excellent	Excellent	Excellent	Excellent

switches while ensuring the same level of glass sealability and plasticity workability as with conventional alloy wire. Hence, we selected this alloy system as the material for the new heat-resistant alloy wire, and looked for a composition that would ensure the optimal thermal expansion coefficient.

4-2 Making thermal expansion compatible with glass tube

Since the thermal expansion coefficient of a cobalt-nickel-iron alloy depends on its composition, we looked for a composition that would ensure an 85% or higher rate of thermal expansion compatibility with glass tube.

As a result, it was found that for cobalt-nickel-iron alloy, the rate of thermal expansion compatibility with the glass tube would exceed the target rate after adding an amount of nickel and iron in the appropriate range, as shown in **Figure 4**. Based on this finding, we decided to develop a new lead wire with a composition that falls within the above range.

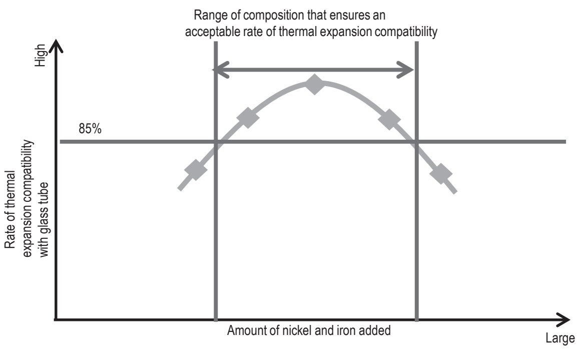


Fig. 4. Relationship between the amount of nickel and iron added to cobalt-nickel-iron alloy wire and the rate of thermal expansion compatibility with glass tube

4-3 Properties of the newly developed lead wire

Table 5 compares the properties of the newly developed cobalt-nickel-iron alloy wire with those of conventional wire. This table shows that the new alloy wire increased the Curie temperature to approximately two times that of conventional wire while decreasing the electrical resistivity to one quarter. We also confirmed that the new lead wire achieved the target rate of thermal expansion compatibility with glass tubes and the target diffusion bondability to glass tubes. Using **Eq. (1)**, we calculated the maximum current capacity of a reed switch constructed using the new lead wire. The calculation results showed that the new lead wire will be able to carry a current of approximately three times that which can be carried by the conventional lead wire. From the above properties of the new lead wire, we confirmed that this wire will make it possible to increase the current capacity of reed switches.

Table 5. Properties of newly developed cobalt-nickel-iron alloy wire

Alloy wire	Conventional iron-nickel alloy	Newly developed cobalt-nickel-iron alloy
Curie temperature (°C)	520	980
Electrical resistivity (μΩcm)	34	8.5
Rate of thermal expansion compatibility with glass tube (%)	94	88
Diffusion bondability to glass tube	Excellent	Excellent
Estimated current capacity of reed switch (A)	2-4	6-12

5. Conclusions

Sumitomo Electric has developed a cobalt-nickel-iron alloy wire, a heat-resistant alloy wire for reed switch applications, which will meet market needs for higher current reed switches. In addition to excellent processability and glass sealability comparable to conventional alloy wire, the new lead wire has a high Curie temperature of 980°C and a low electrical resistivity of 8.5 μΩ cm. Thanks to these superior properties, the new alloy wire is expected to triple the current-carrying capacity of conventional reed switches.

Promising applications for the new alloy wire include reed switches for controlling automotive LED lamps, for which the market is expected to expand.

The company has already obtained a patent for the newly developed alloy wire.

Technical Terms

*1 Spark consumption: Consumption of the electrode material of a spark plug as a result of fusion and dispersion of the material by spark energy

*2 Hexagonal crystal: A crystal structure that is generally fragile and difficult to deform. Materials of hexagonal crystal structure are said to be unsuitable for parts that must be drastically deformed during manufacture. Nickel, iron, and other metals of cubic crystal structure have superior processability.

*3 Ferromagnetic material: A material in which the magnetic moments of the constituent atoms are aligned in the same direction and collectively produce a large magnetic moment

*4 Joule heat: Generation of heat from a conductor due to its electric resistance when an electric current is passed through. The amount of heat generated is proportional to the square of the current multiplied by the electric resistance.

*5 Curie temperature: The direction of the magnetic moments of all atoms constituting a ferromagnetic material begins to fluctuate as its temperature rises. The temperature at which the alignment of the magnetic moments is completely disturbed and the material loses its magnetic property is called the Curie temperature of the material.

References

(1) T. Tanji, "Development of Nickel-Based Alloy for High-Performance Electrodes," SEI TECHNICAL REVIEW No. 65, pp. 31-35 (2007)

(2) K. Yamazaki, "Basic Characteristics and Applications of an Iron-Nichel Lead Material," SUMITOMO DENKI REVIEW No. 125, pp. 125-133 (1984)

(3) Patent No. Japan: 4854459

(4) H. Torazawa, "Development of reed switch with a large load current,"OKI Technical Review No. 216, p. 38 (2010) (in Japanese)

Contributors (The lead author is indicated by an asterisk (*).)

H. OTA*

• Assistant Manager, Energy and Electronics Materials R&D Laboratories

T. KUWABARA

• Ph.D.
Group Manager, Energy and Electronics Materials R&D Laboratories

Y. NAKAI

• Manager, Energy and Electronics Materials R&D Laboratories

N. KAWANO

• Sumiden Fine Conductors Co., Ltd.

N. SUGIHARA

• Section Manager, Sumiden Fine Conductors Co., Ltd.

K. YAMAZAKI

• Director, Sumiden Fine Conductors Co., Ltd.