High-Strength Conductive Wire with Excellent Bending and Settling Resistance

Kazuaki SUGIMURA*, Takayuki SHIWAKU, and Daigo SATO

Electric wires and conductive spring wires require high strength to withstand repeated bending and maintain high contact pressure. However, the higher the strength of general-purpose copper compound metals, the lower their conductivity. To overcome this challenge, we have developed a new composite wire with a stainless steel coating on a copper core wire by making full use of our wire drawing and heat treatment technologies. This new wire has higher strength and conductivity than beryllium-copper alloys, the strongest of the copper alloys, and is strong against bending and twisting outside stainless steel. This paper presents the results of an evaluation of its resistance to settling and repeated bending, assuming that the wire will be used as a conductive spring or electric wire.

Keywords: electric wire, spring, stress relaxation resistance characteristics, bending, corrosion resistance

1. Introduction

There has been growing demand for high-strength conductive electric wires which ensure conductivity, settling resistance, and bending resistance, to meet the need for electrification of vehicles, miniaturization of electronic devices, and the changes brought about by digital transformation (DX).

At present, beryllium copper alloy and gold-plated stainless steel wires are mainly used for these applications. However, there has been a growing need to develop new materials that can attain both strength and conductivity at higher levels due to recent trends, such as environmental considerations and the risk of resource depletion of rare metals.

Sumitomo Electric Industries, Ltd. began marketing thick copper-covered (TCC) wire (Fig. 1), a steel wire whose surface is covered with thick copper, in 2017.[(1),(2)] This is a composite material characterized by high strength and conductivity by combining wire manufacturing technology for high-strength steel wires and highly functional material-covering technology, both of which have been refined over many years.

This paper is a follow-up to our efforts to develop composite materials characterized by high strength and conductivity. To cope with various external forces applied to the surface of a wire (Fig. 2), we have developed "SUS*1-covered Cu wire," a new composite material whose outer surface is made from stainless steel with copper arranged in the core as a functional material.

We demonstrated that its characteristics are superior to conventional copper alloys in terms of bending resistance and settling resistance and that its electric heating performance is equivalent to that of conventional copper alloys in applications as electric heating wire. This paper also reports expected applications based on the characteristics of the material.

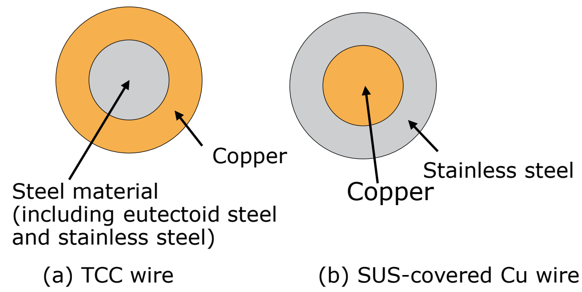

Fig. 1. Schematic diagram of the product cross section

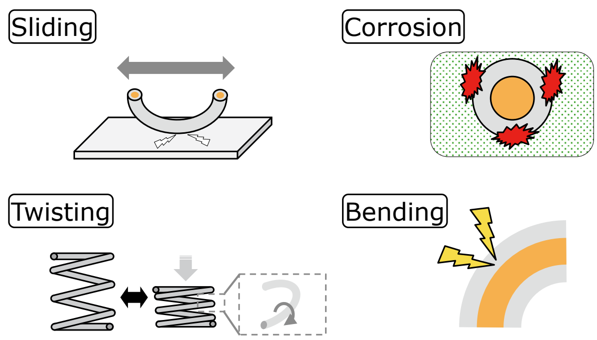

Fig. 2. Schematic diagram of a load that applies to a conductive material

2. Features of SUS-Covered Cu Wire

2-1 Issues posed by copper alloys

To reduce the size and weight of electronic devices, there has been growing demand for miniaturization of the respective parts and materials and integration of the respective component parts. This report describes the required characteristics of a conductive spring, which integrates the functionalities of a spring and a conductor.

Terminals in electronic devices require materials that serve as springs to force electrical contacts to be pressed against each other and stabilize contact. Because a load is constantly applied to a spring, if the shape of the spring changes due to a load, the electrical contact becomes unstable. Thus, the strength of a conductive spring is considered to be one of the most important characteristics from the viewpoint of stability of electrical signals.

The mechanical characteristics of copper alloys have been improved by adding various elements.[3] The higher the purity of copper, the higher the conductivity. The strength can be improved by the effect of alloy components. Thus, there is a trade-off between strength and conductivity.

When a copper alloy is used for a contact pressure spring, the surface of the copper alloy is damaged due to the sliding friction during insertion and removal, resulting in decreased conductivity and strength and causing issues in terms of long-term reliability and durability.

This paper explains the details of a newly developed material that resolved the abovementioned issues.

2-2 Fabrication method

The SUS-covered Cu wire was fabricated by fitting anoxic copper into SUS 304,*2 which was formed into a pipe, performing wire drawing, and conducting heat treatment under appropriate conditions.

The wire was subjected to wire drawing and heat treatment repeatedly to create a wire of the intended size (wire diameter) and tensile strength.

2-3 Tensile strength

Figure 3 shows the electrical conductivity and tensile strength of general-purpose copper alloys and SUS-covered Cu wire. For the unit of electrical conductivity, % IACS*3 was used.

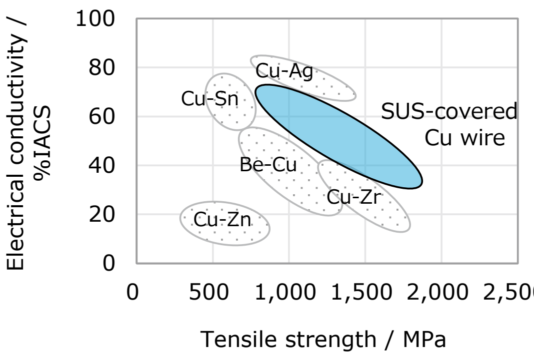

Fig. 3. Relationship between electrical conductivity and tensile strength of general-purpose copper alloys and SUS-covered Cu wire

When wire drawing is performed, the strength of stainless steel on the surface increases due to work hardening. The balance between strength and electrical conductivity is high compared to general-purpose copper alloys such as beryllium copper alloys, although it is inferior to that of expensive copper-silver alloy (Cu-Ag).

The results of the measurement of electrical conductivity and copper content are shown in Table 1. Although stainless steel, which has low conductivity, was used on the outer surface, its conductivity indicated the same value as that of the copper content.

Table 1. Copper content and electrical conductivity of SUS-covered Cu wire and a beryllium copper alloy wire

	Copper content / volume%	Electrical conductivity / % IACS
Prototype 1	30.3	31.8
Prototype 2	61.5	60.6
Beryllium copper alloy[4] wire	80	25

These results show that we have succeeded in achieving a strong metallic bond between the outer surface and the core without decreasing electrical conductivity and in performing wire drawing without changing the cross-section configuration of the composite material, which consisted of materials of different hardness. This was achieved by combining wire-making technology, which is Sumitomo Electric's core technology, with structure control and processing technologies for conductive materials, which are the technologies Sumitomo Electric started its business with.

2-4 Modulus of transverse elasticity*4

When a wire is used as a coil spring for retaining contact pressure, it is subjected to a force in the twisting direction. Thus, the strength of the spring is determined by the repulsion of the wire in the twisting direction (transverse elasticity).

Figure 4 shows the electrical conductivity and the modulus of transverse elasticity of general-purpose copper alloys and SUS-covered Cu wire.

The transverse elasticity of a spring is mainly determined by the surface strength. Thus, the transverse elasticity of SUS-covered Cu wire, whose outer surface is made from high-strength stainless steel as discussed above, is high.

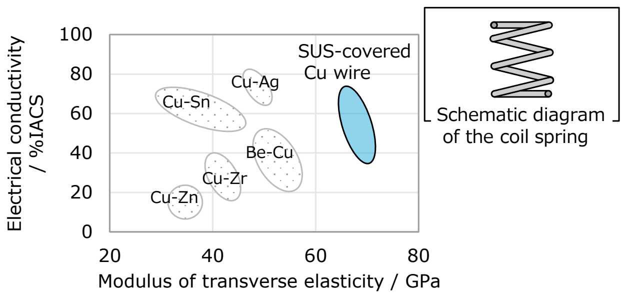

Fig. 4. Relationship between electrical conductivity and modulus of transverse elasticity of general-purpose copper alloys and SUS-covered Cu wire

The structure, wherein copper inside ensures conductivity and stainless steel on the surface ensures strength, attains both a high modulus of transverse elasticity and high electrical conductivity, which cannot be attained by general-purpose copper alloys, including beryllium copper alloy.

The results show that SUS-covered Cu wire is a product suitable for conductive spring material.

2-5 Processing example

A processing example of SUS-covered Cu wire is shown in Photo 1 below.

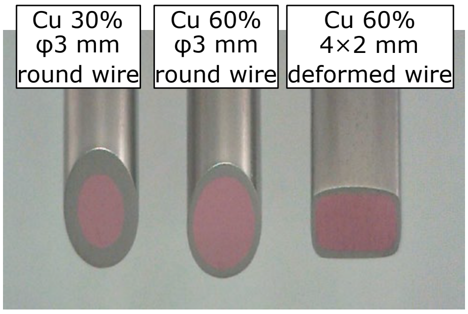

Photo 1. Manufacturing examples of SUS-covered Cu wire

Wires were fabricated with the copper content in the range between 30% and 60%.

We succeeded in fabricating wires with the diameter in the range between φ3 mm and φ50 µm while maintaining the cross-section structure, including the copper core position and copper content.

We fabricated a spring with a center coil diameter of 6 mm (D/d = 3) by using a wire φ3 mm in diameter and with electrical conductivity of 50% IACS. Photo 2 shows the appearance of the spring. No breakage or cracks occurred when the small-diameter spring was fabricated.

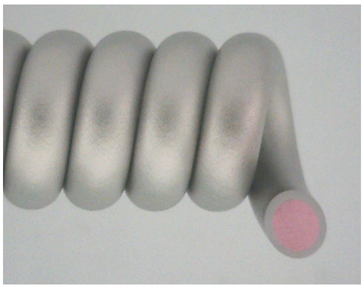

Photo 2. Processing example of SUS-covered Cu wire as a spring

Table 2 presents the results of the measurement of electrical conductivity before and after fabrication of the spring. The table shows that the electrical conductivity do not change after fabrication of the spring and that it is possible to fabricate the spring without any problem. It shows that it has good spring workability.

Table 2. Changes in electrical conductivity before and after processing into a spring

	Electrical conductivity / % IACS
Before processing into a spring	51.3
After processing into a spring	50.4

3. Performance Evaluation

The results of evaluating characteristics in the respective applications are discussed below.

3-1 Settling resistance

In usage as a conductive spring, the stress relaxation resistance (settling resistance), which prevents the spring shape from changing against a stress load, is an important factor. When the settling resistance is low, contact pressure cannot be maintained, resulting in defects such as contact failure.

Figure 5 shows the details of the experiment in which settling resistance was evaluated.

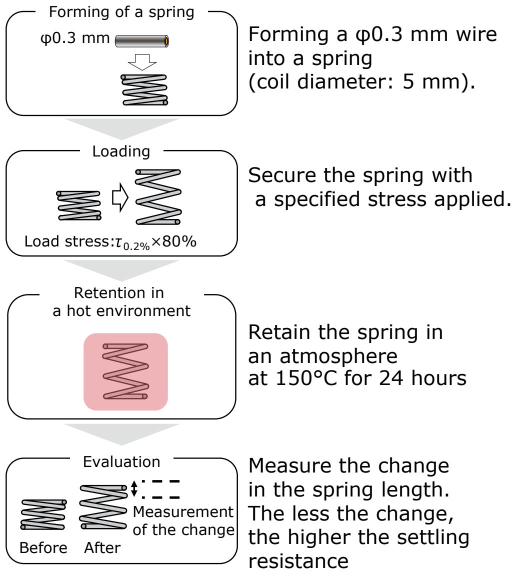

Fig. 5. Details of an experiment to evaluate settling resistance

SUS-covered Cu wire and a beryllium copper alloy wire of the same diameter of φ0.3 mm were used. After a spring with a coil diameter of 5 mm was fabricated, it was retained under stress (80% of the stress which causes yielding in the twisting direction (τ0.2%)) at 150°C for 24 hours. The shape change after retention under stress was defined as the settling amount. The lower the value, the higher the settling resistance.

The results of comparison of the change in the spring length are shown in Fig. 6.

The settling resistance of the SUS-covered Cu wire was found to be markedly higher than that of the beryllium copper alloy wire.

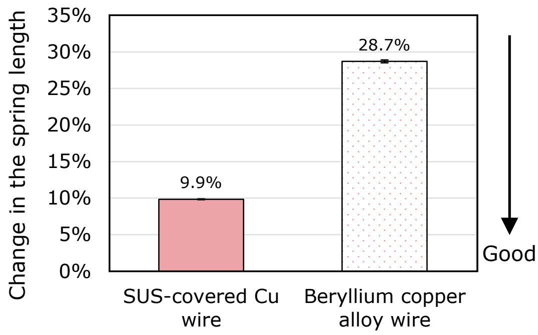

Fig. 6. Results of the settling resistance evaluation

Subsequently, only the SUS-covered Cu wire was retained under a higher load at 200°C for 100 hours for evaluation. The change in the spring length was only 14.2%. The settling resistance was higher than that of the beryllium copper alloy wire under a high load.

We also evaluated changes in electrical conductivity after the experiment. As shown in Table 3, the electrical conductivity remained almost unchanged (less than 2% IACS). Thus, SUS-covered Cu wire is considered to provide superb performance as a conductive spring material.

Table 3. Change in electrical conductivity after the lapse of settling resistance

Electrical conductivity of the SUS-covered Cu wire / % IACS	
Before retention	31.8
After retention at 200°C for 100 hrs.	33.7

3-2 Repeated bending resistance

The use of high-strength steel material on the surface is considered to ensure high resistance against repeated bending.

Figure 7 shows the details of the evaluation of repeated bending durability. Twisted wires consisting of seven wires, each measuring 50 µm in diameter, were fabricated by using SUS-covered Cu wire and copper-silver alloy wire, whose characteristics are as shown in Table 4, on the assumption that such twisted wires would be used as electric wires and cables.

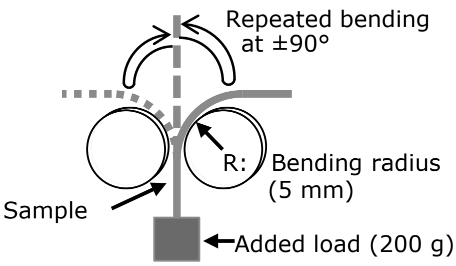

Fig. 7. Details of an experiment to evaluate bending resistance

Table 4. Results of the bending sample solid wire evaluation

Material	Tensile strength / MPa	Electrical conductivity / % IACS
SUS-covered Cu wire	1,198	51.8
Copper-silver alloy wire	1,470	61.2

The twisted wires were bent repeatedly (bending radius: 5 mm) while applying a 200 g load. The number of cycles (up to one million cycles) until the twisted wires ruptured was compared.

The results are shown in Fig. 8.

As shown in Table 4, the tensile strength of SUS-covered Cu wire as a solid wire was inferior to that of copper-silver alloy wire. However, the test demonstrated the high bending resistance of SUS-covered Cu wire. This

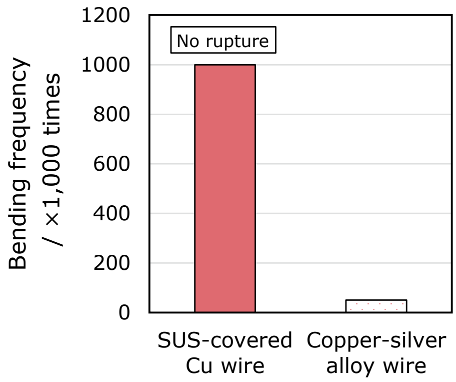

Fig. 8. Results of the bending resistance evaluation

is attributable to the effect of arranging high-strength stainless steel on the surface.

3-3 Electric heating characteristics

The electric heating characteristics were evaluated on the assumption that the SUS-covered Cu wire would be used as a heating element conductive material.

Figure 9 shows the details of the evaluation of electric heating characteristics using SUS-covered Cu wire and copper-silver alloy wire.

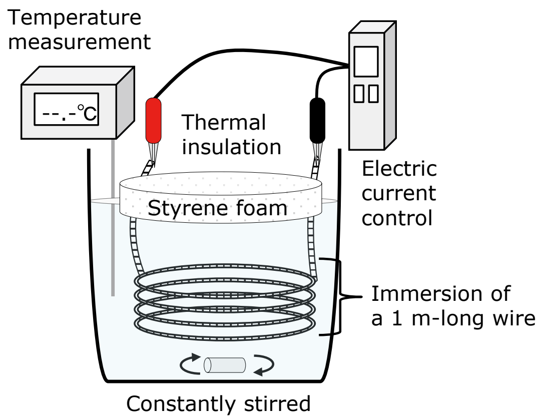

Fig. 9. Details of an experiment to evaluate electric heating characteristics

A twisted wire of 1 m long consisting of seven wires, each measuring 50 µm in diameter, was immersed in water. The change in water temperature over time was measured while applying the same amount of electric power (21 W).

The measurement results are shown in Fig. 10.

For both materials, the water temperature increased in proportion to the electric power input. The figure shows little difference in the speed of the temperature increase. The results show that SUS-covered Cu wire can be used in the same electric heating applications as those of conventional copper alloys.

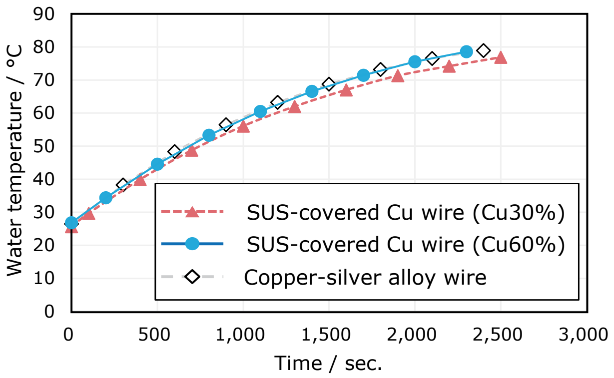

Fig. 10. Results of the electric heating characteristics evaluation

4. Examples of Applications

Based on the results discussed above, SUS-covered Cu wire is considered to demonstrate superb characteristics as a high-strength conductive material. Table 5 presents possible examples of applications using these characteristics.

Table 5. Examples of applications of SUS-covered Cu wire

Performance	Product example	Aim
Conductivity + Settling resistance	Contact pressure retention spring	Stabilize the contact pressure Support multi-point signals
	Contact probe	
Conductivity + Bending resistance	Robot cable	Support small bending radius → Reduce the required space and expand the movable range
	Flex cable for single axis operation	
	Wearable device	
Conductivity + Corrosion resistance	Medical applications	Surgical instrument inserted into the body
	Corrosion-resistant conductor	• Wiring in functional clothes (e.g., working clothes with a built-in cooling fan) • Mesh electrode

Due to the excellent settling resistance, SUS-covered Cu wire may be applied to springs for retaining contact pressure and for semiconductor contact probes. For the latter, the number of electrical contacts per unit area can be increased by miniaturization. Thus, SUS-covered Cu wire is expected to meet the need for further refinement of semiconductor devices.

In terms of outstanding bending resistance, SUS-covered Cu wire can be applied to cables for industrial robots. Industrial machines must meet the requirements of a larger operation range, smaller space, and high-speed movement. Thus, wires must meet the requirement of a smaller bending radius. SUS-covered Cu wire is considered to be suitable due to its superb durability in repeated operation.

With stainless steel used on the outer surface, SUS-covered Cu wire offers superb corrosion resistance and protects the copper, which is the conductive material, inside. Thus, it is also suitable for usage in a corrosive environment.

There is a possible application as a catalyst material(5) with a high surface area by fabricating mesh electrodes with braided wires and distributing and supporting the catalyst on the surface. It is also possible to heat only the area near the catalyst. This may lead to energy-efficient catalyst reaction compared to heating the entire reaction liquid.

5. Conclusion

This paper reported the characteristics and possible applications of SUS-covered Cu wire, which is designed to separate the material for retaining strength from the material for retaining the functionality (conductivity) in its configuration. Characterized by excellent settling resistance and repeated bending resistance, the wire demonstrated characteristics superior to those of general-purpose high-strength conductive materials in various applications. It was also found that the copper consumption could be minimized to attain the intended electrical conductivity.

While the evolution of electric vehicles (EVs) is likely to increase the requirements for miniaturization and higher electric current, SUS-covered Cu wire is expected to ensure high electrical conductivity for the same strength and demonstrate outstanding characteristics that meet such requirements.

Higher energy efficiency and the longer service life of materials are expected to help reduce CO_2 emissions. Widespread use of products that achieve both high conductivity and strength with less copper consumption compared to copper alloys will help conserve scarce resources.

Sumitomo Electric has been working to achieve mass production and will make efforts to further expand applications.

Technical Terms

*1 Stainless Used Steel (SUS): It refers to stainless steel.

*2 SUS 304: JIS steel grade of a typical austenitic stainless steel.

*3 % IACS: IACS is an abbreviation of International Annealed Copper Standard. The volume resistivity of standard annealed copper 1.7241 × 10^{-2} μΩm is specified as 100% IACS as the reference of electrical conductivity.

*4 Modulus of transverse elasticity: A physical property that determines the difficulty of deformation by shearing force. It is also referred to as modulus of rigidity.

References

(1) T. Akada, H. Izumida, T. Watanabe, and K. Iwamoto, "High-Strength and High-Conductive Material to Replace Beryllium-Copper Alloys," SEI TECHNICAL REVIEW, No. 84, pp.156-159 (Apr. 2017)
(2) K. Matsuoka, A. Hoshima, and D. Sato, "Copper-Coated High-Strength Electrical Wire," SUMITOMO ELECTRIC TECHNICAL REVIEW, No. 92, pp.57-61 (Apr. 2021)
(3) Tsuneo Takahashi, "New edition Hi kinnzoku zairyou senntaku no point Second edition," pp.115-232, JSA GROUP (2002)
(4) JSA GROUP ed., "Kinzoku zairyo data book the revision 6th edition," pp.374-377 (2004)
(5) NIPPON SEISEN CO LTD., "COMPOSITE WIRE TYPE CATALYST MEMBER AND CATALYST REACTOR FOR MANUFACTURING HYDROGEN USING THE SAME," Japan patent 6783292 (Nov. 11 2020)

Contributors

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

K. SUGIMURA*
• Advanced Materials Laboratory

T. SHIWAKU
• Department Manager, R&D Planning & Administration Division

D. SATO
• General Manager, Special Steel Wire Division