High-Strength and High-Conductive Material to Replace Beryllium-Copper Alloys

Takumi AKADA*, Hiromu IZUMIDA, Takashi WATANABE and Katsutoshi IWAMOTO

Copper alloys are widely used in the automotive, electronics, and various other sectors. Among these alloys, beryllium-copper alloys need to be replaced with other materials due to concerns over their effects on human health and the environment. However, they have excellent properties that have slowed the replacement efforts. From this view point, Sumitomo (SEI) Steel Wire Corporation has developed a new steel wire by covering the surfaces of the steel core with a thick layer of copper. This wire provides the strength and yield resistance of steel wire and the conductivity of copper. Moreover, by using different percentages of steel core and copper, the material's properties can be designed with ease. In fact, evaluations have revealed that the wire has mechanical properties comparable to or better than those of beryllium-copper alloys. This paper presents the results of mechanical property tests conducted on the wire.

Keywords: beryllium copper, copper-covered steel wire, stress relaxation resistance, fatigue characteristic

1. Introduction

Copper alloys are extensively used in components requiring conductivity and resilience in the automotive and communications equipment sectors. Among other copper alloys, beryllium copper possesses high strength, and high stress relaxation resistance*[1] and is highly resilient. Therefore, many components are exclusively composed of beryllium copper. In recent years, various excellent copper alloys have emerged. However, these alloys do not outweigh the exceptional properties of beryllium copper. As such, beryllium copper has never been completely replaced with other alloys.

First, as the name signifies, beryllium copper contains the toxic chemical component, beryllium. In fact, the RoHS Directive*[2] temporarily listed beryllium copper as a hazardous substance; although, the regulations have now unlisted the substance. In addition, there is a high probability that the REACH Regulation*[3] might categorize beryllium copper as an SVHC (substance of very high concern).*[4] In this situation, developing an alternative copper alloy to beryllium copper becomes a major challenge for copper alloy development projects.

2. Challenges Faced in Development of Alternative Material to Beryllium Copper

Figure 1 illustrates the relationships between the tensile strength and electric conductivity of general copper alloy wires. The figure reveals that beryllium copper has the highest tensile strength. This alloy can exhibit widely ranging properties according to chemical composition and heat treatment. Moreover, the alloy provides a high stress relaxation resistance because it possesses the age-hardening type,*[6, (1)] strengthening mechanism.

Consequently, alternative materials to beryllium copper need to meet two requirements: (1) a favorable trade-off between the tensile strength and electric conductivity with widely ranging properties and (2) higher stress relaxation resistance than beryllium copper.

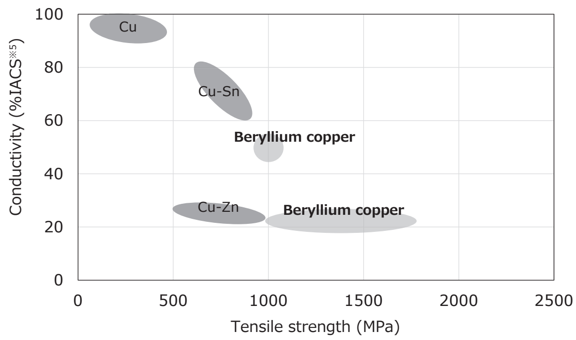

Fig. 1. Tensile strength vs. electric conductivity of general copper alloy wires

3. Development of Thick Copper-Covered Steel Wires

3-1 Concept of thick copper-covered wire

To meet the challenge of developing alternative materials to beryllium copper, the research and development division of Sumitomo Electric Industries, Ltd. has developed a material (thick copper-covered steel wires) that exceeds the existing copper alloys in terms of the trade-off between strength and electric conductivity. This was achieved by using a thick layer of copper to cover a piano wire,*[7] which has the highest tensile strength among all metal materials. Photo 1 shows the result of a cross-sectional structural observation of a thick copper-covered steel wire. The material can be tailored flexibly for the trade-off between the strength and electric conductivity by simply varying the copper layer thickness. Sumitomo Electric once attempted to develop a material based on this concept. However, the attempt did not develop towards the commercialization stage.[(2)]

Additionally, to allow the product to have a good stress relaxation resistance, Sumitomo Electric's original high silicon-containing Si-Cr steel wire, named very high strength (VHS) wire, which is a steel spring wire, was used as a steel core during the development of the thick copper-

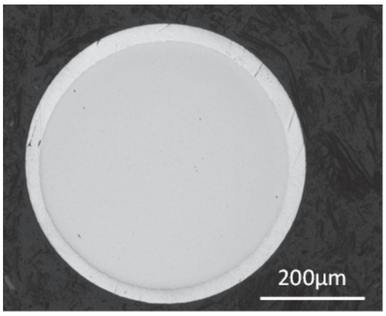

Photo 1. Cross-sectional structure of a thick copper-covered steel wire

covered steel wire. A steel grade developed as an oil-tempered wire*[8, (3)] for valve springs, the VHS exhibits high heat resistance when converted into a hard-drawn wire. Table 1 lists the chemical compositions of an SWP-B*[9] wire and VHS wire, both of which have been analyzed in this study.

Table 1. Chemical composition of an SWP-B wire and a VHS wire (mass %)

	C	Si	Mn	Cu	Cr	V
SWP-B	0.80-0.85	0.12-0.32	0.30-0.60	≤0.20	-	-
VHS	0.63-0.68	1.80-2.20	0.70-0.90	-	0.50-0.80	0.05-0.15

4. Testing Properties of VHS Wire as Alternative to Beryllium Copper

4-1 Tensile strength and electric conductivity properties after low-temperature annealing

Figure 2 shows the tensile strength and yield stress of two wires after low-temperature annealing, the cores of which were the SWP-B wire and VHS wire, respectively. Their electric conductivity was conditioned to 20% IACS (International Annealed Copper Standard).*[5] The graph shows a trend that after low-temperature annealing, the wire with the SWP-B wire core shows a decrease in both tensile strength and yield stress. The probable reason behind it was that the decrease in the tensile strength of the copper-covered layer due to annealing was greater than the increase in the strength of the steel core due to the same low-temperature annealing. In contrast, the wire with a VHS core underwent strain-aging owing to low-temperature annealing, and it showed an increase in both tensile strength and yield stress with an increase in the annealing temperature. However, at higher annealing temperatures, the wire's tensile strength and yield strength decreased with increasing temperature.

Next, thick copper-covered steel wires with a VHS core were prepared for electric conductivities of 20% and 50% IACS, and these are referred to as VHS-L (20%) and VHS-H (50%), respectively, in the following discussion. Figure 3 shows the plots between the tensile strength and the yield stress of these wires, and Fig. 4 shows their electric conductivities, both observed after low-temperature annealing. The tensile strength and yield stress of the VHS-L wire first increased and then decreased with increasing temperature, as mentioned above. In comparison, the VHS-H wire exhibited a trend similar to the VHS-L wire in terms of the yield stress, but the tensile strength of the VHS-H wire decreased with increasing annealing temperature. This can be interpreted to mean the following: the improved electric conductivity, implying a

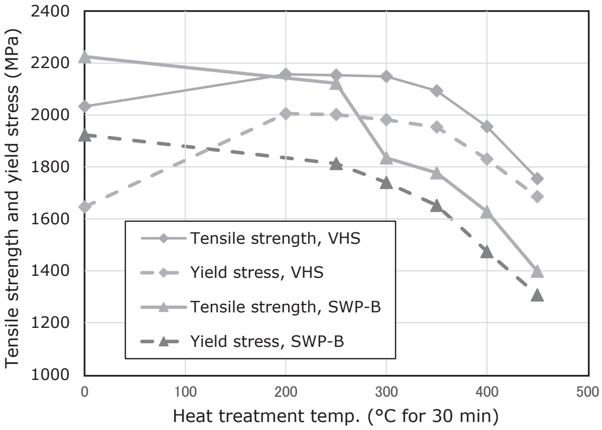

Fig. 2. Tensile strength and yield stress of wires with SWP-B or VHS core

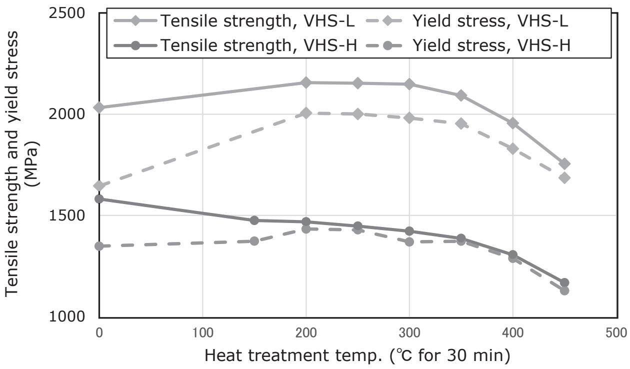

Fig. 3. Tensile strength and yield stress of VHS-L and VHS-H wires after low-temperature annealing

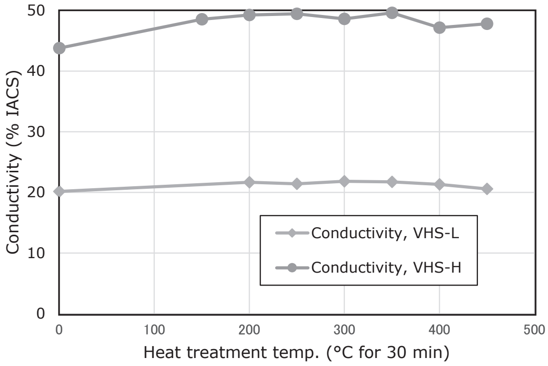

Fig. 4. Electric conductivity of VHS-L and VHS-H wires after low-temperature annealing

thicker copper layer, resulted in a decrease in the copper layer strength owing to annealing, and this decrease outweighed the increase in the strength of the steel core. Figure 4 shows that the electric conductivity of both VHS-L and VHS-H wires increased owing to annealing. Specifically, the electric conductivity of the VHS-H wire increased by 5% IACS or more owing to annealing. A process carried out after covering the core with copper introduces dislocation. When the wire is annealed, the introduced dislocation is relieved due to copper recrystallization, and consequently, the electric conductivity increases.[4] Hence, there is a high probability that the said effect would be more noticeable in the VHS-H wire with a thicker copper layer and higher electric conductivity.

4-2 Strength-conductivity trade-off

The tensile strength and electric conductivity of thick copper-covered steel wires, investigated in Section 4-1, were compared, additionally, with those of existing copper alloys, as shown in Fig. 5. Thick copper-covered steel wires exhibited a highly favorable tradeoff between the strength and electric conductivity as compared with the beryllium copper alloys. Moreover, as presented in this paper for two materials, i.e. high-strength and high-electric conductivity types, varying the percentages of the steel core and copper layer enables the produced materials to have properties within the intermediate range between the aforementioned two sets of property values.

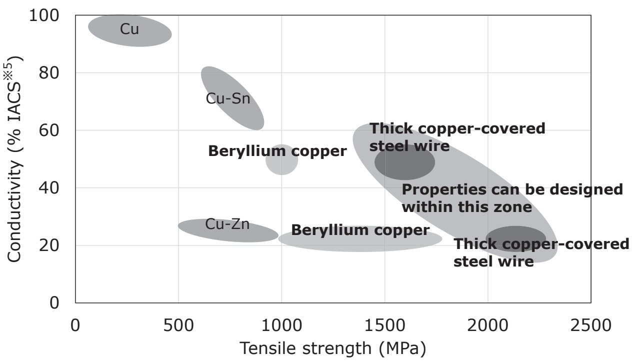

Fig. 5. Strength-conductivity tradeoff for thick copper-covered steel wire

4-3 Stress relaxation resistance

Figure 6 shows the results of the stress relaxation resistance tests for a wire with an SWP-B wire core and a VHS-L wire. The test conditions included heat treatment at a temperature between 150°C and 400°C for 30 min and the subsequent application of a shear stress of 700 MPa and exposure to a temperature of 150°C thereafter for 24 h. Figure 6 plots the residual shear strain*10 of each tested wire. Beryllium copper subjected to similar testing conditions exhibited a minimum residual shear strain of 0.05. Consequently, the graphs reveal that SWP-B wire core and the VHS-L wire developed stress relaxation resistances that were higher than that of beryllium copper, through a heat treatment at 350°C or higher and 300°C or higher, respectively.

These results prove that the properties of thick copper-covered wires are more favorable than those of beryllium copper in terms of the strength-conductivity tradeoff and stress relaxation resistance.

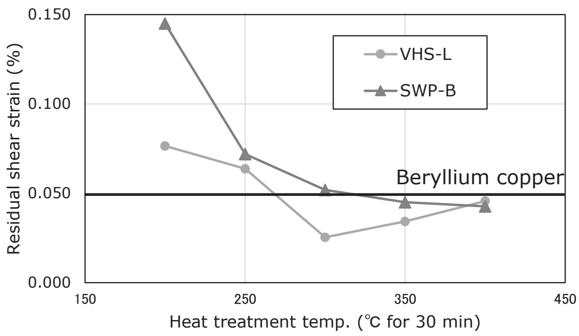

Fig. 6. Stress relaxation resistance of VHS-L and SWP-B wires

5. Conclusion

Sumitomo Electric has developed thick copper-covered steel wires. Although these wires are designed based on the simple concept of covering a steel core with copper, they outperform beryllium copper wires in several mechanical properties.

Meanwhile, samples of the thick copper-covered steel wire have been made available on a limited scale by Sumitomo (SEI) Steel Wire Corporation for use in automotive and electronics components. We expect that it will find applications in various other fields as well.

Technical Terms

*1 Stress relaxation resistance: The permanent residual strain occurring in a material is tested by applying a load to the material in an operating environment that generates a certain displacement for a certain period of time. The smaller the permanent strain in the tested material, the more favorable is the stress relaxation resistance of the material.

*2 RoHS Directive: The regulations enforced by the European Union to restrict the use of hazardous substances in electrical and electronic equipment. The directive also limits the use of products that contain lead, mercury, and/or cadmium, among others.

*3 REACH Regulation: The regulation enforced by the European Union for registration, evaluation, authorization, and restriction of chemicals.

*4 SVHC: Substances of very high concern designated by the REACH Regulation; to use an SVHC in a European Union member country, a special permission is required.

*5 % IACS (International Annealed Copper Standard): A unit of electric conductivity with reference to pure copper; % IACS = (Electric conductivity of material in question)/(Electric conductivity of standard annealed copper)

*6 Age-hardening type: A form of strength provided by precipitation, resulting from ageing (heat treatment); the age-hardening type materials, characterized by the disappearance of dislocations, generally possess a high stress relaxation resistance than the work-hardening and solid solution strengthening types, for which dislocation is the strengthening factor.

*7 Piano wire: The most versatile and highest-strength wire material among all other practical metals; it finds applications in springs, as well as musical instruments.

*8 Oil-tempered wire: A wire with refined mechanical properties that are imparted by quenching and tempering; an oil-tempered wire exhibits a greater fatigue resistance than a piano wire.

*9 SWP-B: A type of piano wire regulated by JIS; SWP-A and SWP-V also exist. Each type is specified by several mechanical properties.

*10 Residual shear strain: An index used to evaluate the resistance of a permanent set of spring materials; strain remaining in the direction of shear of a tested material.

References

(1) T. Ochiai, "Transactions of Japan Society of Spring Engineers," Vol.40, p.33-40 (1995)

(2) S. Sawada, T. Shinoda, Y. Takahashi, "Transactions of Japan Society of Spring Engineers," p.33-39 (1966)

(3) H. Izumida, S. Matsumoto, and T. Murai, "SEI TECHNICAL REVIEW No. 82," p.20-24 (2016)

(4) The Japan Institute of Metals and Materials, "Hitetsuzairyo," p.62-64 (1987)

(5) M. Nishihata, "Journal of the Society of Materials Science, Japan," Vol. 14, No. 145, p.820-826 (1965)

Contributors

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

T. AKADA*

• Advanced Materials Laboratory

H. IZUMIDA

• Group Manager, Advanced Materials Laboratory

T. WATANABE

• Sumitomo (SEI) Steel Wire Corp.

K. IWAMOTO

• Assistant Manager, Sumitomo (SEI) Steel Wire Corp.