Composite Metal Wires Made by Cladding and Plating

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The composite metal wire is composed of multiple metallic phases and has multiple functions at a relatively low cost. The Sumitomo Electric Group offers a variety of composite metal wire products that are made by cladding and plating. This paper introduces the technologies and application examples of our wires.

Keywords: metal, cladding, plating, composite wire, conductor

1. Introduction

As the electronics industry has grown, wire materials for electronic components have been required to possess various characteristics. Accordingly, diverse kinds of wire materials have been produced. In addition to single-metal and alloy wires, wire materials include composite metal wires, which have multiple metallic phases (Fig. 1). Single-metal and alloy wires are generally excellent in performing a single function. However, when they are required to possess multiple characteristics, many challenges need to be overcome, including tradeoffs between characteristics and huge manufacturing cost. Composite metal wires possessing metallic phases with differing functions enable the realization of multiple characteristics at relatively low cost.

For example, alloys of iron and nickel have been used to form lead wires that pass through glass seals due to small differences in thermal expansion coefficient between the alloy and glass. Nonetheless, their electrical conductivity is low. In contrast, copper shows high electrical conductivity, although its thermal expansion coefficient is higher than the glass. If the metal were to be used through glass seals as it is, the result would be failure of the seal due to the difference in thermal expansion coefficients. By uniting these two metals through cladding, it becomes possible to manufacture a wire material with a thermal expansion coefficient that matches closely that of glass, and with high electrical conductivity. The product is known as the Dumet wire, which emerged about a century ago in the form of lead wires for light bulbs.

These cladding- or plating-based composite metal wires are extensively used in many sectors. This paper reports on the composite metal wire products supplied by the Electronics Components Department of the Sumitomo Electric Industries, Ltd., and their application examples.

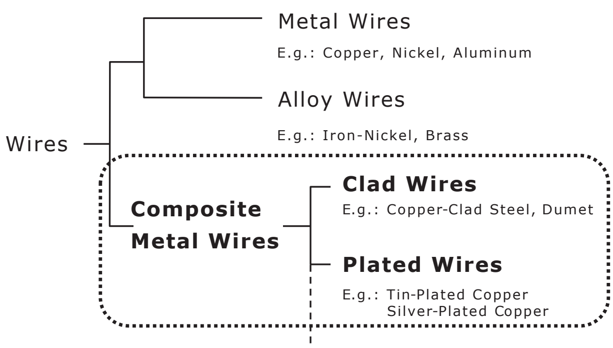


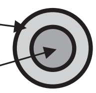
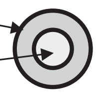
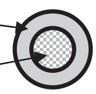
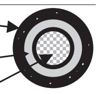
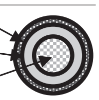
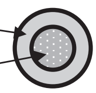
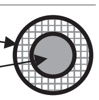
Fig. 1. Classification of wires

2. Clad Wires

2-1 Features of clad wires

Sumitomo Electric's methods of manufacturing clad wires are divided into two types: direct (DIR) and continuous welding (CW) methods. The DIR method inserts a core in a pipe material. The CW method provides a covering around a core with a tape material by means of continuous welding. Both achieve adhesion between the core and cladding by joining them and drawing them through a die to form a single piece of wire. Table 1 lists

Table 1. Sumitomo Electric's flagship clad wires

Product name (abbr.) / Feature/typical application	Composition	Schematic cross section
Copper-Clad Steel (CCS) Wire High electrical conductivity, high thermal conductivity, and superior strength and fatigue characteristics to copper wires → Leads for electronic components	Copper cladding Steel	
Copper-Clad Aluminum (CCA) Wire Light weight, high strength, and high electrical conductivity → Lightweight wiring harnesses	Copper cladding Aluminum	
Copper-Clad Iron-Nickel Wire (Dumet or Non-borated Dumet) Thermal expansion coefficient that matches glass closely and high electrical conductivity	Copper Cladding Iron-Nickel alloy	
Borated Dumet Wire Good heat resistance and glass adhesion imparted by borax and cuprous oxide surface layer → Light bulb leads and thermistors	Borax + Cuprous Oxide Copper cladding Iron-Nickel alloy	
Oxidized Dumet Wire Only cuprous oxide layer formed on surface No contamination by borax → Diodes	Cuprous Oxide Copper cladding Iron-Nickel alloy	
Copper-Clad Stainless Steel (CCSUS) Wire under development High electrical conductivity and high strength	Copper cladding Stainless Steel	
Nickel-Base Superalloy-Clad Nickel Wire under development Compatibility between high-temperature oxidation resistance and electrical conductivity	Nickel-base superalloy Nickel	

Sumitomo Electric's portfolio of principal clad wires.

2-2 Clad wire manufacturing processes

(1) DIR method

The DIR method places a core directly into a pipe material and joins them into a single piece. It is a simple process (Fig. 2), yet delivers high-reliability wires. However, the length produced by this method is generally restricted by the length of the manufacturing equipment, because before core insertion, the pipe must be straightened. Sumitomo Electric has its proprietary long equipment to ensure mass productivity. Meanwhile, with some types of metal, pipes are not readily available. To enable multi-product manufacturing, the DIR method is complemented by the CW method described below.

As a characteristic of its manufacturing, Sumitomo Electric has a system designed to prevent the contamination of the interface between the core and the cladding. This results in a lowered adhesion level, leading to the breakage of the cladding or the wire. To prevent these issues, it is necessary to keep both the pipe interior and core clean. Sumitomo Electric uses physical and chemical methods for this cleaning and achieves cladding using its proprietary fitting and tightening techniques.

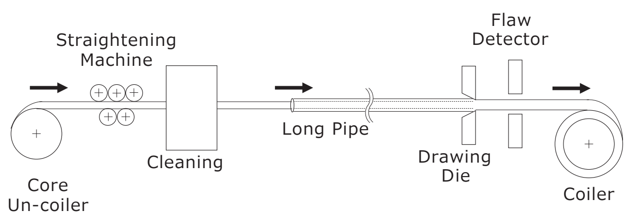


Fig. 2. Schematic of DIR method

(2) CW method

The CW method forms a tube through continuous welding of a covering tape material around a core. Production lengths achievable with the CW method are not restricted by the manufacturing equipment (Fig. 3). It is necessary to set forming conditions suitably for the material and size of the covering. Thus, Sumitomo Electric's forming equipment is adapted to various conditions.

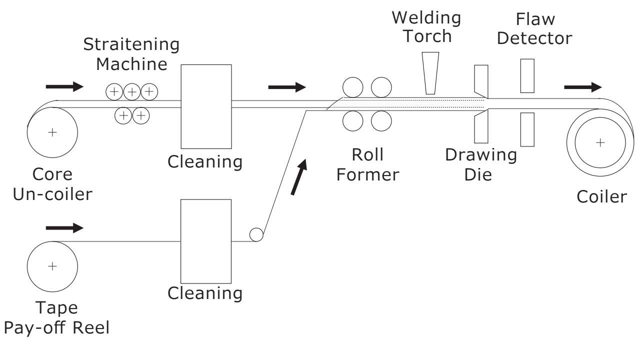


Fig. 3. Schematic of CW method

2-3 Clad wire products

(1) Copper-clad steel (CCS) wire

The CCS wire is a clad wire made of a high-strength low-carbon steel core covered with copper known for its high thermal and electrical conductivity. CSS wires are used where higher strength and fatigue resistance than those of copper wires are required. Sumitomo Electric's CCS wires are available in a wide range of copper and steel proportions, allowing our customers to choose from various electrical conductivity and strength levels (Table 2). Another feature of the CCS wire is its ferromagnetism owing to the steel core. If it is used to form miniature parts, such as IC pins, for example, the CCS wire is usable to automatic assembly machines.

Table 2. Specifications for CCS wires

Product name	Electrical conductivity	Cross-section ratio of Copper	Feature/application
30CCS	Approx. 30% IACS*1	Approx. 20%	Uses include glass diode leads and bus wires connected to various plated wires. Processed and hardened products are used as cores of coaxial cables.
40CCS	Approx. 40% IACS	Approx. 30%	Used where the electrical conductivity of 30CCS is not sufficient
60CCS	Approx. 60% IACS	Approx. 55%	Developed to allow heat generated by diodes to escape efficiently. Applications include leads of glass diodes and plastic molded diodes.
70CCS	Approx. 70% IACS	Approx. 66%	
80CCS	Approx. 80% IACS	Approx. 77%	

(2) Copper-clad aluminum (CCA) wire

The CCA wire is a clad wire using copper as a covering over a lightweight aluminum alloy core. Primary uses of CCA wires are those where both light weight and electrical conductivity are required, such as in moving parts. Figure 4 illustrates characteristic changes as a function of the cross-section ratio of copper to the overall wire. The figure also shows how much lighter CCA wires can be than copper wires when they have the same level of conductivity. For example, at a cross-section ratio of copper of 50%, the CCA wire is 21% lighter than copper wires.

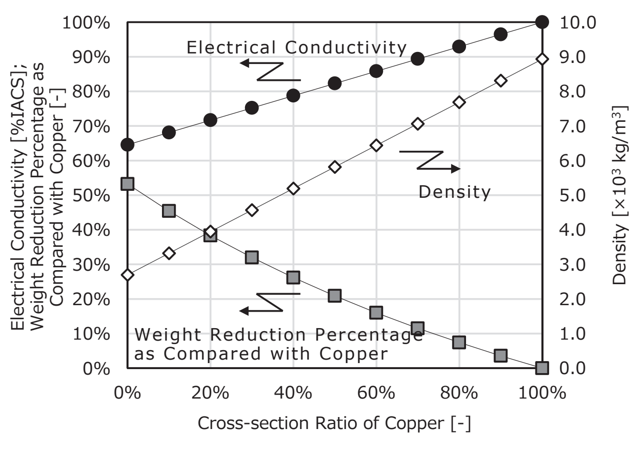


Fig. 4. CCA characteristics vs. cross-section ratio of Copper

(3) Copper-clad iron-nickel [Dumet (Du)] wire

The copper-clad iron-nickel wire was originally known as the "dual metal wire," which was later shortened to the Dumet wire. Iron-nickel alloys have a thermal expansion coefficient that closely matches glass. By covering an iron-nickel alloy with copper, the Dumet wire fulfills both the requirements of glass seal performance and electrical conductivity (Fig. 5). Dumet wires are used as lead-in wires that pass through the glass seals of thermistors and diodes.

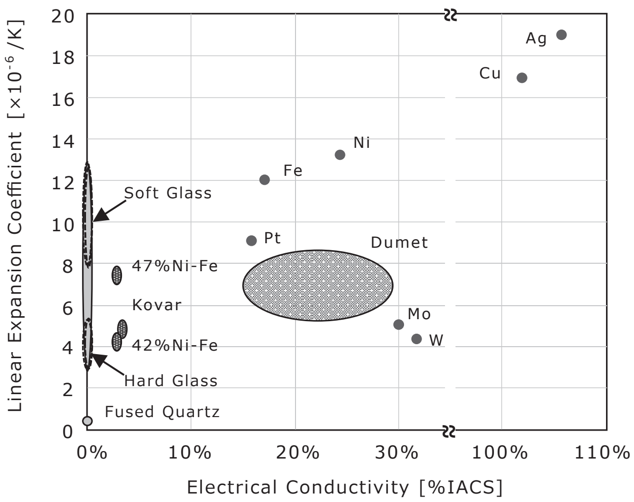


Fig. 5. Linear expansion coefficient vs. electrical conductivity[(1)-(3)]

The surface of copper needs to be modified because its untreated surface has poor affinity (wettability) for glass. The surface of a borated Dumet wire has borax ($Na_2B_4O_7 \cdot 10H_2O$) baked on it (boration) to form a borax glass ($Na_2B_4O_7$) layer and a cuprous oxide (Cu_2O) layer, which ensure good adhesion with glass even at elevated temperatures. For diode and other applications that require avoidance of contamination by sodium, oxidized Dumet wires are used. These wires improve adhesion at glass seals by forming only Cu_2O layer continuously on the surface.[(4)] Other products from Sumitomo Electric include non-borated Dumet wires, which skip surface modification depending on the intended use, and nickel-plated Dumet wires, which are described later.

3. Plated Wires

3-1 Features of plated wires

Plated wires are wires provided with a covering on a base metal wire by means of plating using nickel, copper, silver, or tin (Table 3). While electroplating is typically used, hot dipping is also performed with tin. Using plating, it is easier to achieve a thin outer layer than with cladding. Therefore, plating is used when it is desirable to improve only the surface properties.

Table 3. Sumitomo Electric's flagship plated wires

Product name (abbr.) / Feature/typical application	Composition	Schematic cross section
Nickel-Plated Copper (NPC) Wire High electrical conductivity and high heat resistance → Heat-resistant electric wires	Nickel plating Copper	
Silver-Plated Copper (AgPC) Wire High electrical conductivity, oxidation resistance, and lower cost than pure silver wires →High-frequency conductors and shields	Silver plating Copper or Copper alloy	
Tin-Plated Copper (TPC) Wire Good solderability and high electrical conductivity → Flexible flat cables and equipment wiring	Tin plating Copper or Copper alloy	
Nickel-Plated Dumet (NP-Du) Wire Good glass adhesion and solderability → Leads for glass seals	Nickel plating Copper cladding Iron-Nickel alloy	
Silver-Plated Copper-Clad Steel Wire High electrical conductivity, high thermal conductivity, high strength, and oxidation resistance → High-frequency conductors	Silver plating Copper cladding Steel	

3-2 Plated wire manufacturing processes

(1) Electroplating

Electroplating is easy to control the plating thickness by adjusting electric current and time. The method achieves a uniform covering even at a relatively thin layer. Figure 6 presents a schematic diagram of an electroplating line. The wire material undergoes degreasing and pickling to clean the surface thoroughly, and is activated for improved adhesion of the plating metal. Primer plating is added in some cases for improved adhesion between the bare wire and the plating metal or as a barrier layer to prevent mutual diffusion. Rinsing baths are placed between baths to prevent chemicals from contaminating the following baths (Fig. 6).

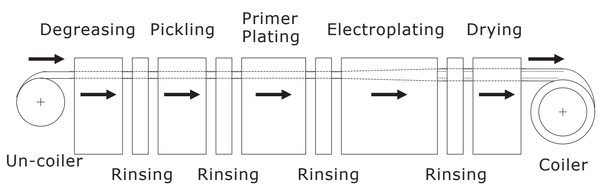


Fig. 6. Schematic of electroplating

It is important to ensure routine control of chemicals including rinse water, because their conditions are crucial to product quality. Moreover, poisonous substances, such as sulfuric acid, chloric acid, and cyanides are frequently used. Sumitomo Electric has built a dedicated wastewater treatment system to address this issue.

(2) Hot dipping

Hot dipping is the method of immersing a wire material in a dipping bath that contains molten low-melting metal, such as tin (Fig. 7). The product wire diameter can be controlled to a constant value by passing the wire coated with the molten metal through a die, although it is difficult to control the plating thickness. Hot dipping is a less expensive manufacturing method than electroplating because of the use of simple equipment without the need to control the electric current.

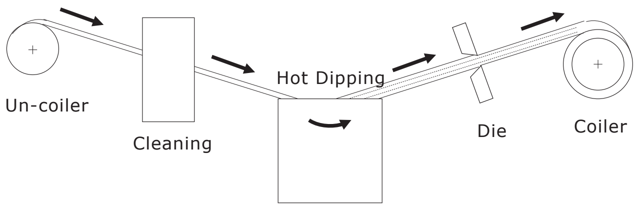


Fig. 7. Schematic of hot dipping

3-3 Plated wire products

(1) Nickel-plated copper (NPC) wire

Nickel plating of a copper wire provides both electrical conductivity of at least 70% IACS and heat resistance of up to 500°C. Specifically, for high-temperature applications, Sumitomo Electric offers wires provided with thick plating of 28% nickel by volume. These wires are used to form leads for use at high temperatures, such as in proximity to an automobile engine.

(2) Silver-plated copper (AgPC) wire

AgPC wires have the oxidation resistance of silver, yet are less expensive than pure silver wires. Since silver exhibits the lowest specific electrical resistance among all metals, AgPC wires come with favorable high-frequency characteristics. These wires are used as leads and shields in high-frequency circuits.

(3) Tin-plated copper (TPC) wire

Either electroplating or hot dipping is used to manufacture TPC wires. If hot dipping is used, TPC wires are free of the effect of stress in electro-deposits and are therefore less likely to develop whiskers.*2 Since the tin layer is highly suitable for soldering, TPC wires are used as leads of surface-mounted components, such as resistors and capacitors. They are also used as connector pins, taking advantage of their low frictional resistance.

(4) Nickel-plated Dumet (NP-Du) wire

The NP-Du wire is a Dumet wire provided with nickel plating. The nickel layer is favorable in terms of both adhesion to glass and connectivity to external devices, eliminating the need for the borax or the cuprous oxide removal process. Moreover, NP-Du wires exhibit resistance to heat and oxidation at elevated temperatures. Their applications include wedge base bulbs with which leads are directly used as connection terminals.

With NP-Du wires, surface smoothness is of prime importance because they are used at glass seals. Surface unevenness is a cause of leak defects at the seal. Sumitomo Electric reviewed equipment designs to eliminate flaws incurred during the manufacturing process and developed an inspection device, which simulates the glass sealing process. This way, Sumitomo Electric has attained a large share of the world's NP-Du wire market.

4. New Products

4-1 Nickel-base superalloy-clad nickel wire

Heat-resistant wires used with an engine in a high-temperature and corrosive environment include nickel wires. However, extended use in a high-temperature environment causes oxidation of the wires, resulting in a reduced effective cross-sectional area and increased conductor resistance. In contrast, nickel-base superalloys, produced by adding chromium, iron, and/or yttrium to nickel, exhibit superb resistance to heat and corrosion, showing virtually no decrease in effective cross-sectional area. However, the alloy's electrical conductivity is low.(5) By applying its cladding technology to forming a single piece from a nickel wire and a nickel-base superalloy, Sumitomo Electric has developed a heat-resistant wire that combines both electrical conductivity and useful life at a high level.

4-2 Nickel-clad aluminum (NCA) wire

Nickel-aluminum alloys have superb resistance to heat and oxidation. Among others, nickel and aluminum alloyed to the ratio of one Ni to one Al have a melting point of 1,638°C, which is higher than that of unalloyed nickel or aluminum (Fig. 8). Additionally, the alloy is relatively light due to the high proportion of aluminum. The alloy's uses include aircraft turbines. However, the high melting point is a factor involved in the difficulty in processing the alloy. Notably, the cost of nickel-aluminium alloy welding wires intended for build-up welding is high due to their low processability, although, when used, they melt in an arc.

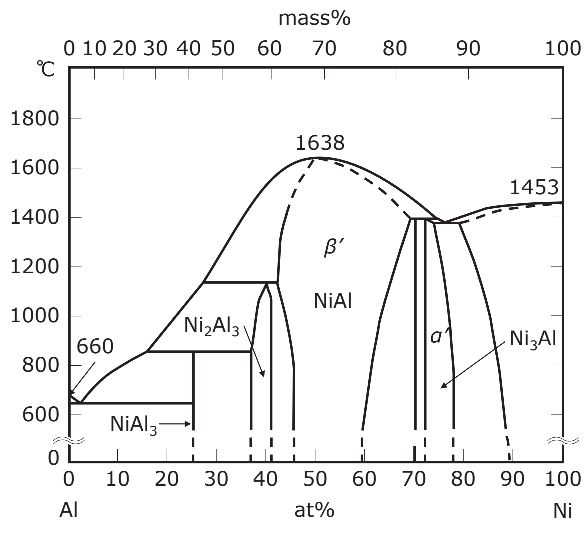


Fig. 8. Al-Ni binary phase diagram
Figure from reference(6), modified with permission.

As a solution to this challenge, Sumitomo Electric cladded an aluminum core with a nickel outer layer in suitable proportions to fabricate a wire. The cross-section ratio of this wire conforms to the aforementioned alloy composition. NCA wire melted by arc discharge solidifies at the weld as a nickel-aluminum alloy.

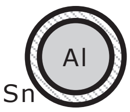
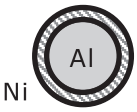
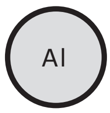
When cladding involves metals with substantially different strengths, such as nickel and aluminum, their cross-section ratio is highly subject to change after passing through a drawing die due to the reactive force of the stronger metal (nickel), resulting likely in a break in the core (aluminum). Nonetheless, Sumitomo Electric has overcome this difficulty utilizing its proprietary manufacturing method.

4-3 Plated aluminum wire

Aluminum wires draw attention as lightweight conductors. The surface of an aluminum wire is densely covered with a nonconductive oxide film. This requires special treatment when establishing an electrical connection.[7] Clad wires such as copper-clad aluminum (CCA) wires, if the cross-sectional percentage of the outer layer is 10% or less, are prone to break and difficult to manufacture, posing a limitation to weight reduction. The double zincate treatment is a commercialized method of plating aluminum. However, few cases of applying this method to wire materials have been known.

Sumitomo Electric has setup a prototype plating line and ensured conditions that allow for various types of plating (e.g., tin, nickel, and copper) onto aluminum wires. Examples include a tin-plated solderable aluminum wire and a nickel-plated aluminum wire that exhibits high plating adhesion even at nearly 500°C owing to Sumitomo Electric's proprietary plating method. Sumitomo Electric has begun shipping samples of these products (Table 4).

Table 4. Examples of plated Aluminum wire products

	Tin-Plated Aluminum Wire	Nickel-Plated Aluminum Wire	Aluminum Wire (Core)
Cross-sectional configuration			
Wire diameter [mm]	0.5-1.2	0.5-1.2	0.5-1.2
Plating thickness [μm]	1-10	1-10	–
Density [g/cm^3]	2.7-3.1	2.7-3.2	2.7
Tensile strength [N/mm^2]	Almost same as that of core	Almost same as that of core	Soft material: 130-180 Hard material: 300-400
Electrical conductivity [%IACS]	56-59	58-61	65
Feature	Favorable solderability	Surface heat resistance up to nearly 500°C	–

5. Conclusion

Composite metal wires formed by applying Sumitomo Electric's proprietary cladding and plating technologies to join commonplace materials such as copper, iron, nickel, and aluminum into a single piece simultaneously exhibit multiple characteristics such as electrical conductivity, thermal conductivity, strength, heat resistance, and adhesion to glass, although at low cost. These materials are expected to continue to be useful in various sectors as well as in electronics.

Technical Terms

＊1 %IACS: The electrical conductivity of a material of interest is expressed as a percentage of the electrical conductivity of the International Annealed Copper Standard (100% IACS) (specific resistance at 293 K: 1.7241×10^{-8} Ω·m)[8]

＊2 Whisker: Needle-like crystals that grow over time. Whiskers cause short-circuiting if they develop in a terminal block.

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