Development for Expansion of Aluminum Wiring Harness

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As the demand for the reduction of CO_2 emissions from vehicles is ever increasing, lightweight wiring harnesses have been in high demand. Effective weight reduction can be expected by replacing conventional copper electric wires with aluminum electric wires. However, aluminum wires have several drawbacks such as low electrical conductivity and low tensile strength, as well as the thick oxide film on the surface and galvanic corrosion. To solve these problems, we have developed an aluminum alloy with improved electrical conductivity and tensile strength. We have also developed a unique terminal for a splice that maintains low contact resistance and sufficient wire retention force even on a thick oxide film. We have established an anti-corrosion technology that prevents galvanic corrosion by coating a new anti-corrosive onto the crimped joint of the terminal. This paper explains respective solutions in detail.

Keywords: aluminum electric wire, crimping, wiring harness, vehicle, anti-corrosion

1. Introduction

Under recent increasingly tight regulations on CO_2 emissions from vehicles, the need to reduce the weight of wiring harnesses has been growing. In this situation, the price of copper is soaring. In 2006, Sumitomo Electric Industries, Ltd. launched an R&D project for aluminum wiring harnesses aimed at reducing their weight and price by replacing conventionally used copper conductive wires with aluminum wires.(1)

Since then, we have expanded our lineup of automotive aluminum electric wires, including standard aluminum wires and high-strength aluminum wires. Our high-strength aluminum wires can be used as signal lines and for engine wiring harnesses. To further expand the use of aluminum electric wires, we have developed key components that make it possible to fabricate automotive aluminum wiring harnesses comprising electric wires of any size. This paper describes the technological development of automotive electric wires and terminals, as well as their anti-corrosion technology.

2. Development of Automotive Aluminum Electric Wire

2-1 History of development

In 2006 when we started the development of an aluminum electric wire, this kind of wire was rarely used, and mainly only in Europe for large size automotive battery cables. General-purpose thin aluminum electric wires were not used on a permanent basis, but rather were tentatively used for limited purposes.

Four Sumitomo Electric Group companies established a joint development system to devote our efforts to the development of thin aluminum electric wires (Fig. 1).

2-2 Development of new aluminum alloy

Sumitomo Electric has lined up standard and high-strength aluminum alloys as automotive aluminum electric wire materials, and uses them properly according to the purpose of use, location, and required performance.

Our standard aluminum alloy has a good balance between strength and electric conductivity. We have developed an aluminum-iron-magnesium (Al-Fe-Mg) alloy that has the composition of Al-1.05mass%Fe-0.15mass%Mg (Fig. 2). To enhance the strength of the new alloy, we added Mg to an Al-Fe alloy that has excellent electrical conductivity and is used in transmission lines.

Electric wires made of our standard aluminum alloy (standard aluminum electric wires) have a tensile strength of 120 MPa while maintaining an electrical conductivity*1 of

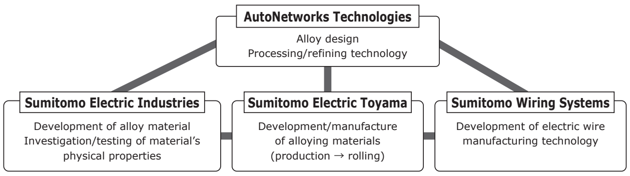


Fig. 1. Aluminum Electric Wire Development System

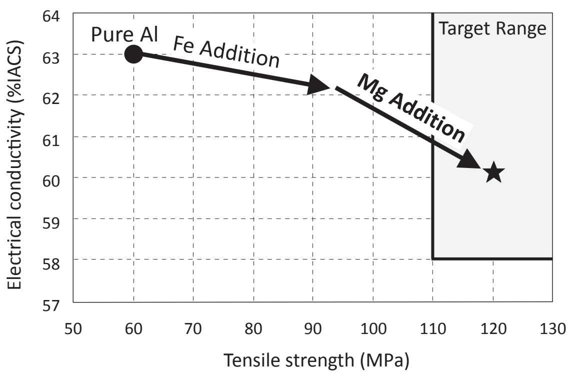


Fig. 2. Standard Aluminum Alloy Design

60%IACS. They can be used as a substitute for a roughly one-size larger conventional annealed copper electric wire.

Since the specific gravity of aluminum is one-third that of copper, aluminum reduces the wire weight dramatically even if the wire size is increased by one-size when compared to the corresponding copper electric wire.

Our high-strength aluminum alloy was developed to achieve a strength higher than that of annealed copper. Conventional high-strength aluminum alloys are inappropriate for use in wiring harnesses since these alloys break accidentally when bent sharply in the working process due to a low elongation rate and insufficient toughness. As the material of our high-strength aluminum alloy having a good balance between strength and toughness, we selected an aluminum-magnesium-silicon (Al-Mg-Si) heat-treatable alloy*[2] (precipitation-strengthened alloy) (Fig. 3).

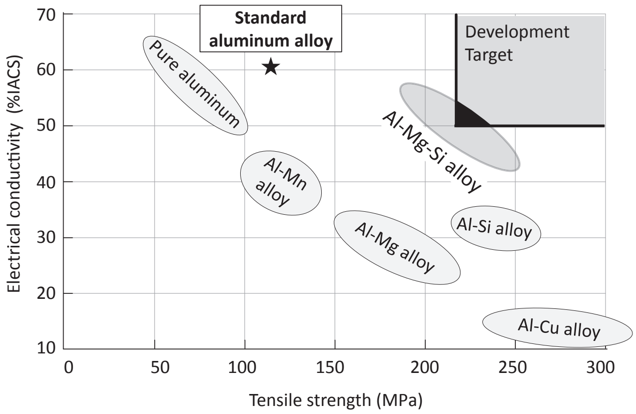


Fig. 3. Selection and Development Target of High-strength Aluminum Alloy

Finally, we developed a high-strength aluminum alloy (Al-0.6mass%Mg-0.5mass%Si) having a tensile strength of 250 MPa or higher, an elongation rate of 8% or higher, and an electrical conductivity of 50%IACS or higher, all of which are higher than those of annealed copper (Fig. 4).

The newly developed high-strength aluminum alloy, the strength of which is higher than that of annealed copper, has made it possible to produce thin electric wires

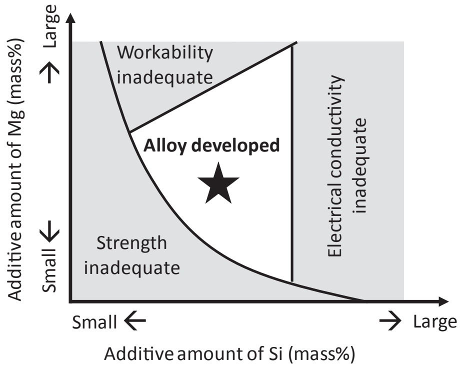


Fig. 4. Optimization of Composition for High-strength Aluminum Alloy

(high-strength aluminum electric wires) having a cross-sectional area of 0.5 mm^2 or less. Our high-strength thin aluminum electric wires and standard aluminum electric wires can dramatically reduce the weight of wiring harnesses.

2-3 Aluminum electric wire lineup

Wiring harnesses made of the standard aluminum electric wires have been used in vehicle interiors since November 2010, while wiring harnesses made of the newly developed high-strength aluminum electric wires have been used in engine compartments since December 2015.

Tables 1 and 2 show the types of aluminum electric wires we mass-produce at present.

Table 1. Standard Aluminum Electric Wire Lineup

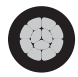
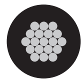
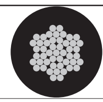
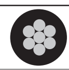
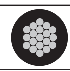
Cross-Section Structure			
Conductor	Compression type	Standard type	Standard type
Insulation	Ultra-thin wall type	Thin wall type	Thick wall heat resistance type
Heat Resistance Temperature	80℃	80℃	120℃, 150℃
Electric Wire Size	0.75～1.5 mm^2	2.0～2.5 mm^2	16～30 mm^2

Table 2. High-strength Aluminum Electric Wire Lineup

Cross-Section Structure			
Conductor	Compression type	Standard type	Flexible type
Insulation	Ultra-thin wall type	Thin wall heat resistance type	Thin wall heat resistance type
Heat Resistance Temperature	80℃	100℃	100℃
Electric Wire Size	0.35～0.5 mm^2	0.5 mm^2	0.35f～0.75f mm^2

2-4 Summary

Since 2010 when our aluminum electric wires were first used in vehicles, we have expanded the use of these wires in vehicles. In parallel with the above activity, we have expanded our aluminum electric wire lineup. To further expand the application of aluminum electric wires, we have already established an electric wire production system that can make all sizes of electric wires of up to 160 mm^2, the maximum size specified under the ISO standard.

3. Aluminum Electric Wire Connection Method

Two types of methods are used to connect electric wires. One is terminal connection in which a wire is attached to a terminal made of copper or a copper alloy, while the other is a splice in which two or more pairs of wires are connected to each other. In particular, a crimp connection method is used to connect copper electric wires. In this method, the end of the wire to be connected is placed in a U-shape terminal called a "wire barrel," and then the barrel is crimped together with the wire, as shown in Fig. 5.

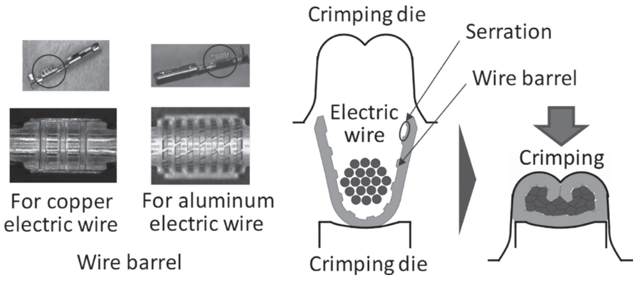


Fig. 5. Crimp Connection Method

However, crimped aluminum electric wires cannot ensure the necessary electrical connection performance in some applications. As an alternative to the conventional crimp connection method, we have developed a new aluminum electric wire connection method.

3-1 Challenges

This section starts with a description of the challenges to be addressed when successfully connecting aluminum electric wires. The physical properties of copper and aluminum, as well as those of oxide films*[3] formed on the surface of these materials, are shown in Table 3.[(2)] Since an aluminum oxide film is strong and non-conductive, it interferes with the electrical connection of the aluminum electric wire. To ensure stable electrical connection, it is necessary to break the oxide film.

Table 3. Copper and Aluminum Oxide Films

Conductor material	Copper	Aluminum
Oxide film	Cu_2O	Al_2O_3
Electrical conductivity	10 S/cm	10^{-7} S/cm
Hardness	160 Hv	1,800 Hv

Irregularity Grooves formed on the inner wall of the wire barrel of each crimp terminal, which are known as "serration,"*[4] are used as a means of breaking the oxide film. We have elaborately designed the configuration of the serration to give it a depth sufficient for connecting various types of electric wires.[(3)] However, the above connection method raises a problem when used for the terminal connection of large size electric wires and splice involving the crimping of multiple electric wires together. In particular, this method leaves some element wires out of contact with the serration in the terminal and hence increases the contact resistance of the electric wire, as shown in Fig. 6.

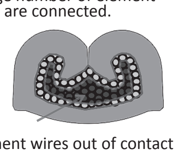
Type of connection	Terminal connection		Splice connection
Electric wire	Thin aluminum electric wire	Thick aluminum electric wire	2 or more
Cross-section of crimped connection	A small number of element wires are connected.  Excellent electrical connection by the contact of all element wires with the serrations	A large number of element wires are connected.  Element wires out of contact with the serration increase the contact resistance.	

Fig. 6. Problem Associated with Crimp Connection

3-2 Ultrasonic welding

We selected ultrasonic welding as a method for the terminal connection of thick aluminum electric wires composed of many element wires. Figure 7 shows schematically the construction of the ultrasonic welding machine we use.

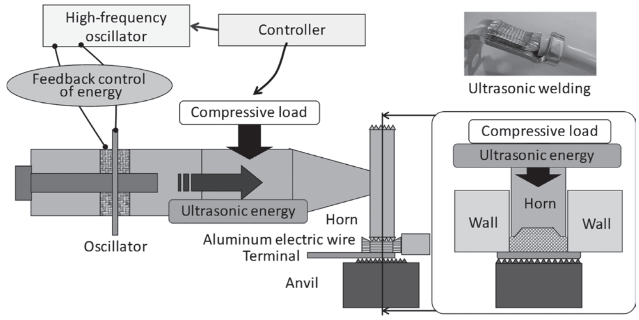


Fig. 7. Schematic Illustration of the Construction of the Ultrasonic Welding Machine

The ultrasonic welding machine encloses all the element wires to be connected with a wall and exposes them to ultrasonic energy while exerting a compressive load onto them by a tool called a "horn." The ultrasonic energy breaks the oxide films formed on the element wires to allow the direct solid-phase bonding*[5] of their naked surfaces to each other. Ultrasonic welding ensures high-quality connection of element wires by bonding them continuously from their uppermost to the terminal portions. In a crimp connection, the number of element wires that are out of contact with the serration increases as the size of the electric wire increases. As a result, the contact resistance of the electric wire increases. In contrast, ultrasonic welding makes it possible for electric wires to stably maintain very low contact resistance irrespective of their size, as shown in Fig. 8.

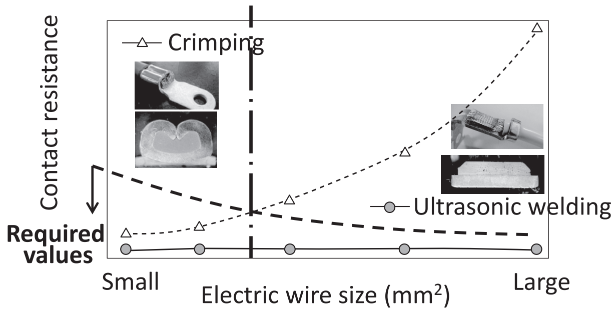


Fig. 8. Relationship between Electric Wire Size and Contact Resistance

The use of large current wiring harnesses comprising aluminum electric wires in battery-driven vehicles for power transmission and other applications has been increasing to reduce the weight of the harnesses. Ultrasonic welding is indispensable to ensure highly reliable electrical connection of the aluminum electric wires used in these harnesses.

3-3 Crimp terminal for splice

Although ultrasonic welding can also be used for splice, crimp terminals are usually used to connect three or fewer copper electric wires. We have developed a crimp terminal that can also be used to connect aluminum electric wires. As shown in Fig. 9, the new crimp terminal has an inner barrel in the center of the wire barrel. When an electric wire is crimped with a new terminal in a conventional way, the wire is compressed strongly at only the central part of the terminal, where the wire and inner barrels overlap one another.

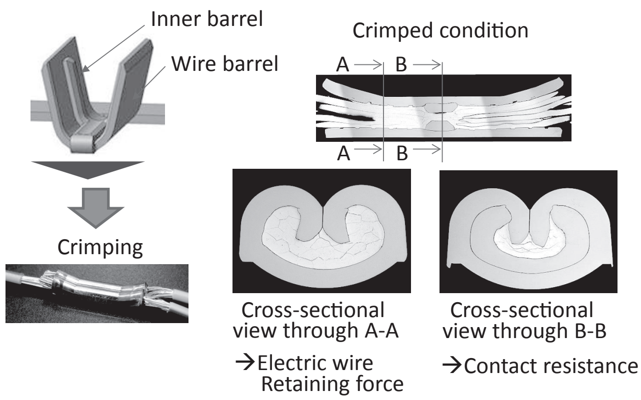


Fig. 9. Splice Terminal for Aluminum Electric Wire

The normally crimped portions on both sides of the terminal ensure the necessary electric wire retaining force. However, the element wires that are out of contact with the serration increase the contact resistance of the electric wire as discussed in Section 3-1. In the highly compressed section of the electric wire, on the other hand, the wire is deformed so excessively as to break the oxide film formed on each wire. The element wires are bonded together in a solid phase as a result of cold pressure welding.*[6] Figure 10 shows a crimp terminal which was dissolved after being used for crimp connection. When an electric wire is crimped with a conventional terminal, the element wires are not bonded to each other and are separated when the terminal is dissolved. We confirmed that the central portion of the new crimp terminal compresses the wire strongly until the element wires are bonded together.

We could dramatically reduce the contact resistance by bonding element wires together in the strongly compressed portion. As a result, as shown in Fig. 11, the newly developed crimp terminal has been confirmed to be able to meet the required contact resistance under a wide range of crimping conditions, which cannot be achieved by conventional terminals.

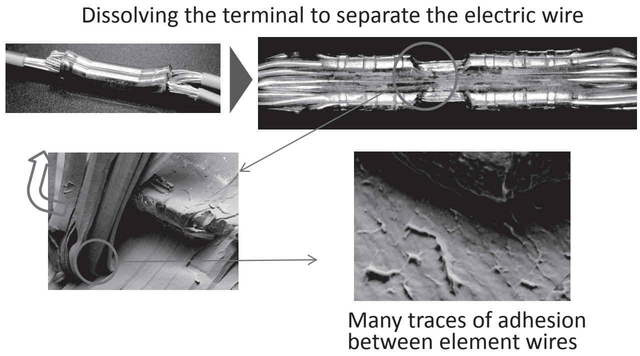


Fig. 10. State of the Wire in the Strongly Compressed Portion

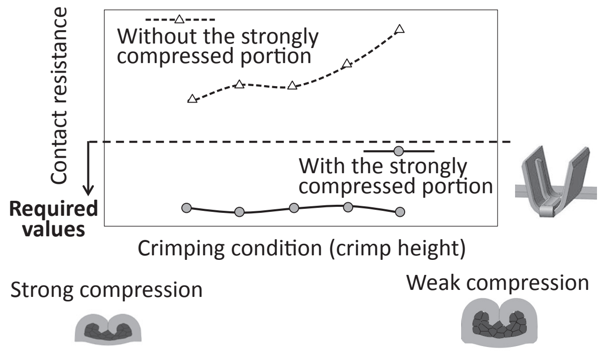


Fig. 11. Effect of the Strong Compressed Portion

3-4 Summary

The newly established ultrasonic welding technology and newly developed special-purpose crimp terminal provided with a strongly compressing member has made it possible to meet every requirement for electric wire connection as shown in Table 4. We will use the technology and terminal effectively to expand the use of aluminum electric wires.

Table 4. Aluminum Electric Wire Connection Method

Type of connection	Terminal connection		Splice connection	
Electric wire	Thin aluminum electric wire	Thick aluminum electric wire	3 or fewer	2 or more
Connection method	Crimping  Improvement by serrating the inner wall of terminal	Ultrasonic welding 	Crimping  Connection by strongly compressing	Ultrasonic welding 

Establishment of wire connection method

4. Anti-corrosion Technology

4-1 Galvanic corrosion between aluminum and copper

If a joint between potentially noble aluminum and potentially base copper is brought into contact with an electrolyte, such as a salt solution, these metals will form a battery with the aluminum serve as anode and the copper serve as cathode. The phenomenon in which aluminum acting as the anode is dissolved in the electrolyte is called "galvanic corrosion" (Fig. 12).(4)

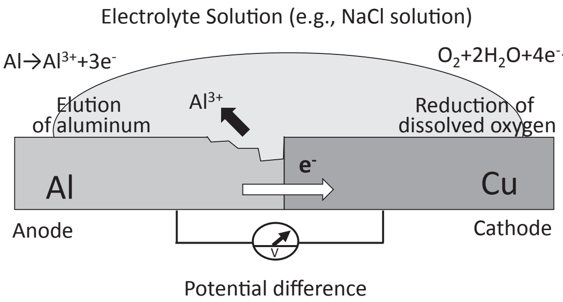


Fig. 12. Galvanic Corrosion between Aluminum and Copper

If an aluminum electric wire-crimped terminal is brought into contact with an electrolyte, the aluminum conductor will be thoroughly dissolved into the electrolyte by the mechanism of galvanic corrosion described above (Fig. 13). Aluminum itself will accelerate corrosion if it is brought into contact with an electrolyte.(4)

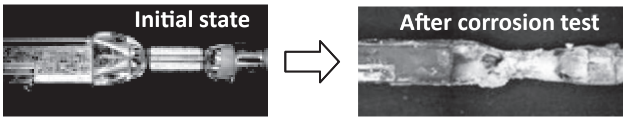
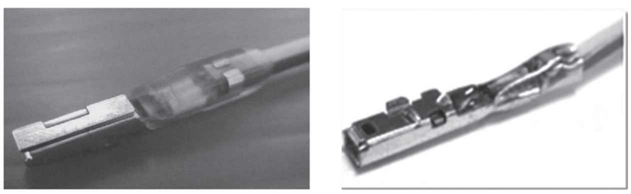


Fig. 13. Corrosion of Aluminum Electric Wire-crimped Terminal

4-2 Conventional anti-corrosion technology for aluminum electric wire and a problem associated with this technology

We developed anti-corrosion technologies for aluminum electric wires, and currently use these technologies for the mass production of aluminum electric wires. These technologies protect crimped joints from exposure to water by coating them with thermosetting resin or ultraviolet curable resin (Fig. 14).

These technologies protect aluminum conductors by coating them with a hard resin and thus prevent their dissolution. However, these technologies have a shortcoming in that they increase the outside dimensions of the crimped terminals compared to the dimensions of the terminals when these technologies are not used. As a result, some wires are left without being crimped when conventional terminals are used. To overcome the above shortcoming, we developed a new anti-corrosion technology that does not affect the shape of the crimped wire or crimp connector.



(Left: thermoplastic resin   Right: ultraviolet curable resin)

Fig. 14. Conventional Anti-corrosion Technologies

4-3 New anti-corrosion technology for aluminum electric wire

We selected a soft, gel-like anti-corrosive that will not increase the force necessary to insert the wire into the crimp connector even if the anti-corrosive interferes with the connector. We also developed a new anti-corrosive by additionally providing our anti-corrosive with a new capability to adsorb to copper. The new anti-corrosive eliminates the need for coating the aluminum conductors, but limits the dissolution of the aluminum conductor by protecting the copper exposed on the surface of the terminal.

To effectively use the new anti-corrosive to protect the copper exposed on the surface of the terminal, it is necessary to elaborately apply the anti-corrosive over the complex surface of the crimp terminal. To meet this need, we have also developed a technology that can elaborately apply the anti-corrosive over all the necessary areas. Thus, we have established a new anti-corrosion system as an alternative to the traditional system (Fig. 15).

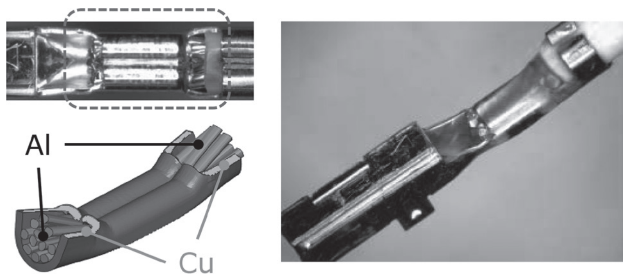


Fig. 15. Schematic Illustration of Aluminum Electric Wire Crimp Terminal and External Appearance of Terminal Coated with New Anti-corrosive

4-4 Summary

We established an anti-corrosion technology that can be used to protect a variety of crimped electric wires for interior use. Our electric wires made by using this technology were first used in vehicles in 2017. Aiming to further expand the use of aluminum wiring harnesses, we have been promoting the development of an innovatively new anti-corrosion technology that makes it possible to locate wiring harnesses in non-watertight area in engine compartments.

5. Conclusion

To make aluminum wiring harnesses available for use in vehicles, we have continuously developed new electric wires, terminals and related technologies. Since 2010 when our aluminum wiring harnesses were first used in vehicles, we have worked to increase the number of wiring harnesses used in each vehicle and, in parallel with this, have expanded our lineup of electric wires.

As of October 2018, 10 vehicle manufacturers (8 Japanese, 2 non-Japanese) use our aluminum wiring harnesses in their total of 50 models.

With the future advancement of self-driving technology and the electrification of drive systems, the number of sensors and ECUs installed in each vehicle will increase. Accordingly, the wiring harnesses for automotive applications will be required to further increase the number of component electric wires. In addition, vehicle manufacturers' demand for higher voltage, large current devices toward the improvement of the performance of the vehicles they manufacture will create new demand for electric wires whose size exceeds the upper limit of the standardized size.

The price of copper is expected to rise continuously even in the future. Replacing all copper electric wires used in a wiring harness with aluminum electric wires reduces the harness weight by more than 25%. Therefore, the demand for aluminum wire harnesses is expected to further increase.

Technical Terms

∗1 Electrical conductivity: The measure of a material's ability to allow the flow of an electric current. The unit of electrical conductivity is %IACS (International Annealed Copper Standard), which represents a value relative to the electrical conductivity of annealed copper, defined as 100%.

∗2 Heat-treatable alloy: An alloy for which heat treatment is required to enhance strength

∗3 Surface oxide film: A film formed on the surface of a metal as a result of its oxidization by oxygen in the air. This film is usually hard and low in electric conductivity, and interferes with electrical connection.

∗4 Serration: Irregularity Grooves formed in the electric wire connection section of a crimp terminal. They break the oxide film formed on the electric wire and also prevent the dislocation of the wire, and thereby enhance the stability of its electrical and mechanical connection to the crimp terminal.

∗5 Solid-phase bonding: A method for bonding metals together. This method is used to bond metals together by bringing their regenerated surfaces in a solid phase into contact without fusing. Ultrasonic welding and cold pressure welding are typical solid-phase bonding methods.

∗6 Cold pressure welding: A solid-phase bonding method in which metals are bonded together without heating. The metals to be bonded together are deformed plastically to remove the surface oxide films and thereby expose their surfaces.

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