

# Aluminum Wiring Harness

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As the demand for the reduction of CO<sub>2</sub> emissions from automobiles 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, low tensile strength, and poor workability, as well as a strong insulating oxide film on the surface and galvanic corrosion. To solve these problems, we have developed an aluminum alloy conductor with improved electrical conductivity, tensile strength, and workability. We also developed a unique serration terminal structure that maintains low contact resistance and sufficient wire retention force even under a thick oxide layer. We also established an anti-corrosion technology that prevents galvanic corrosion by molding the crimped joint of the terminal. This paper explains respective solutions in detail.

Keywords: aluminum wire, crimping, wiring harness, automobile, anti-corrosion

## 1. Introduction

In the automobile industry the need for weight reduction has increased as CO<sub>2</sub> emission regulations have become more stringent. Moreover, partly due to soaring copper prices, we began studying aluminum wiring harnesses, changing electrical conductors in wiring harnesses from copper to aluminum to reduce both weight and price<sup>(1)</sup>.

Aluminum wires have been used mainly in overhead power lines and automobile battery cables, where the cross-section area of the conductor is large to support high current. Meanwhile, conductor cross-section area of wiring harness is usually not more than 2.5 mm<sup>2</sup>. We have developed an aluminum wiring harness in this class for automobile applications. **Figure 1** shows the wire, terminal and

anti-corrosion of the aluminum wiring harness. This paper reports on the techniques used in their development.

## 2. Automobile Aluminum Wires

Aluminum alloys used to fabricate automobile aluminum wires are required to exhibit high tensile strength and high electrical conductivity<sup>\*1</sup>.

The development project aimed to achieve material property goals of tensile strength of 110 MPa and electrical conductivity of 58% IACS. These values were required in order to replace 0.5 mm<sup>2</sup> copper wires, conventionally widely used in low-voltage power supply cables, with 0.75 mm<sup>2</sup> aluminum wires<sup>(2), (3)</sup>.

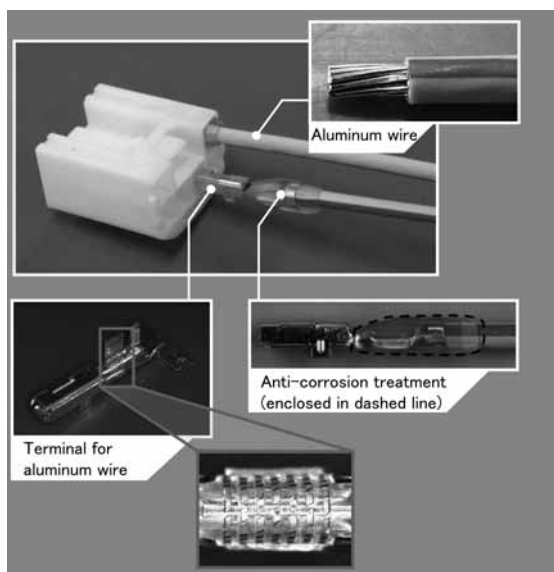
Therefore, Sumitomo Electric's Electronics & Materials R&D Laboratories and AutoNetworks Technologies, Ltd., a member of the Sumitomo Electric Group, together worked on the development of an aluminum alloy for automobile wires.

### 2-1 Alloy design

Pure aluminum (1060: 99.6% purity) for general industrial uses has high electrical conductivity of 62% IACS. However, after annealing, it exhibits low tensile strength of 70 MPa<sup>(4)</sup>. For automobile wire applications, it is necessary to improve its tensile strength through alloying.

Solid solution<sup>\*2</sup> strengthening is effective for improving the tensile strength of metal. However, this method results in a noticeable decrease in electrical conductivity. Meanwhile, greater misfit strain (MS)<sup>\*3 (5)</sup> is also expected to improve the tensile strength of metal.

For automobile wire applications, it is necessary to suppress reductions in electrical conductivity and improve tensile strength. Accordingly, if an element provides great MS at a low amount of solid solution, it is considered effective as an alloying element. The MS values and maximum amounts of room-temperature solid solution of various elements alloyed with aluminum were determined through first-prin-



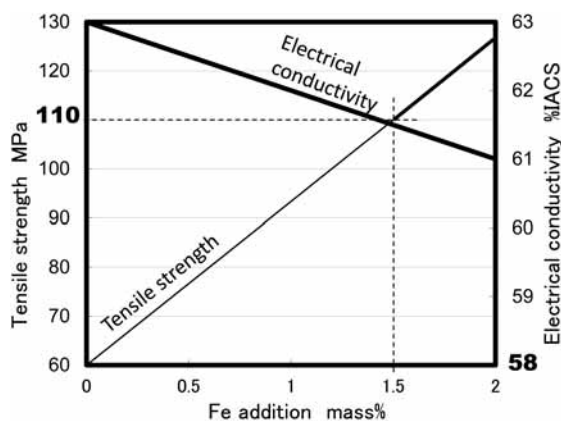
**Fig. 1.** Development of aluminum wires, terminal and anti-corrosion technology

ciple calculation<sup>4</sup>. After analyzing the calculation results, Fe was selected as an alloying element (**Table 1**).

Further study of the relationship between the amount of alloying Fe and material properties of Al-Fe alloys revealed that the performance goals would be achieved if the mass percentage of alloying Fe was 1.5% or higher (**Fig. 2**).

**Table 1.** MS and maximum amounts of solid solution of aluminum alloyed with various elements

Element	MS	Max. amount of solid solution mass%	Element	MS	Max. amount of solid solution mass%
<b>Fe</b>	<b>3.9</b>	<b>0.03</b>	Cu	1.6	2.48
Mn	3.5	0.62	Ti	1.0	0.70
Cr	3.2	0.37	<b>Mg</b>	<b>1.0</b>	<b>18.60</b>
Ni	2.9	0.11	Li	0.7	14.00
Sn	2.2	0.00	Si	0.6	1.50
W	2.0	0.05	Zn	0.4	67.00
Mo	2.0	0.06	Au	0.3	0.60
Pt	1.8	0.00	Ag	0.2	23.50

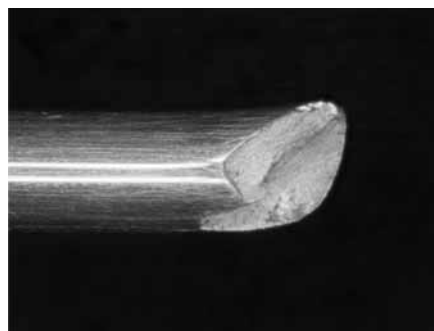


**Fig. 2.** Fe addition versus material properties

Wire rods fabricated by conventional billet casting and extrusion crystallize<sup>5</sup> coarse Al-Fe compounds. They are poor in ductility and workability. In contrast, wire rods manufactured by Sumitomo Electric Toyama Co., Ltd., a Sumitomo Electric Group company, have excellent workability. These wire rods are produced through the Properzi method<sup>6</sup>, using a high cooling rate during casting and rolling without reheating. This process controls the compound in a fine state and maintains the high ductility of the alloy<sup>(6)</sup>.

Nonetheless, strand diameters of automobile wires are very small for aluminum wires, ranging from 0.15 to 0.5 mm. When the mass percentage of Fe exceeded 1.2%, the wire's workability decreased, with the wire breaking during the drawing and stranding processes due to machining limits, as shown in **Photo 1**.

As a solution to this problem, we searched for a second alloying element that would partially replace Fe in order



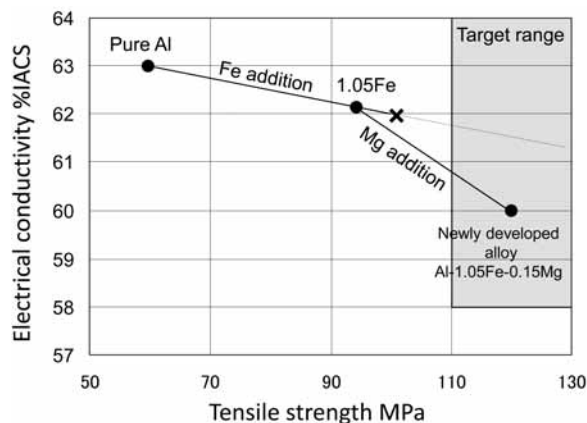
**Photo 1.** Broken aluminum strand

to provide improved tensile strength without compromising workability.

Since the Al-Fe alloy met the electrical conductivity goal with a relatively large margin, it was permissible to reduce the alloy's electrical conductivity to some extent. Consequently, for use as a second alloying element, we selected an element that is low in MS (which adversely affects workability), yet is high in the maximum amount of solid solution, despite some decrease in electrical conductivity.

Comparison of the elements shown in **Table 1** suggested that Mg would be most appropriate. The next step was to find the optimum amount of element addition.

The result was the following composition (mass %): Al-1.05%Fe-0.15%Mg. This composition improved both workability and performance and achieved 120 MPa tensile strength and 60% IACS conductivity, well exceeding the goals (**Fig. 3**).



**Fig. 3.** Components and performance of newly developed alloy

## 2-2 Aluminum wire lineup

**Table 2** shows the lineup of currently manufacturable aluminum wires and the effects of replacing conventional copper wires with aluminum wires. Conventional copper wires can reasonably be replaced with aluminum wires one size larger than copper.

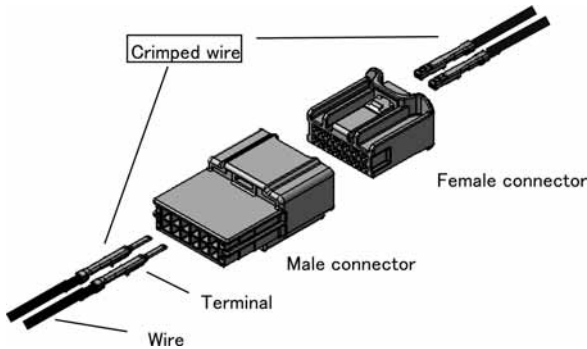
**Table 2.** Aluminum wire lineup

Copper wire			Aluminum wire			
Type	Size (mm <sup>2</sup> )	Weight (g/m)	Type	Size (mm <sup>2</sup> )	Weight (g/m)	Weight reduction effect(g/m)
CIVUS	0.5	5.4	ALVUS	0.75	3.1	▲2.3
	0.75	7.6		1.25	5.0	▲2.6
AVSS	0.85	10		1.5	5.8	▲4.2
CIVUS	1.25	13.1	ALVSS	2	9.1	▲4.0
AVSS	2	22		2.5	11.7	▲10.3

### 3. Terminals for Aluminum Wires

As shown in Fig. 4, most connecting sections in automobile harnesses use a structure where a terminal with a crimped wire is inserted into a connector<sup>7</sup>.

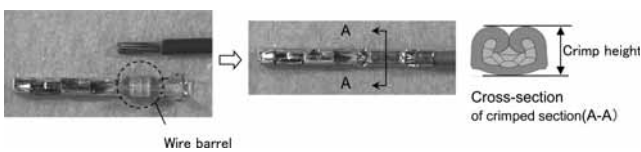
To apply aluminum wiring harnesses widely, Sumitomo Electric has developed a special terminal that can be connected with an aluminum wire by crimping<sup>(7)</sup>.



**Fig. 4.** Connectors and crimped wires

#### 3-1 Development challenges

Crimping is a connecting method where wires with the stripped insulation are crimped in the U-shaped section called the “wire barrel” on the terminal, to ensure the electrical connection and retention force of wires, as shown in Fig. 5.

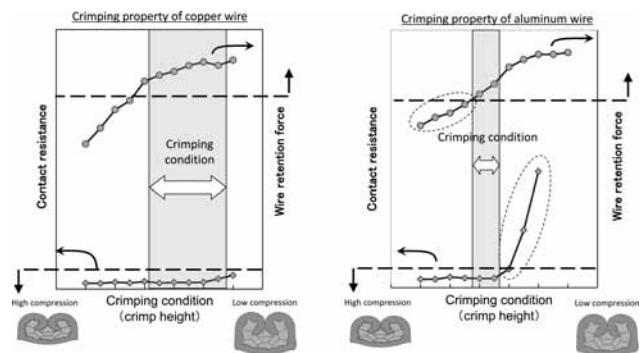


**Fig. 5.** Crimping connection

Figure 6 shows crimping properties of copper and aluminum wires with which the conventional copper terminal is used. Crimp condition is plotted on the X-axis, with

crimping stronger toward the left (high compression). Higher compression generally leads to a more stable electrical connection. However, the wire retention force decreases in the excessively high compression range. Therefore the crimp condition in harness manufacture is set in a range where both properties satisfy the specification.

Aluminum differs from copper in that it is covered with a strong insulating oxide film. Its contact resistance remains unstable unless it is crimped more strongly than copper. Strong crimping results in a reduced wire retention force. Consequently, an aluminum wire crimp condition that ensures both properties is tighter than the copper wire crimp condition. Thus, for aluminum wires to be reliably connected by crimping, it is necessary to either stabilize their contact resistance in the low compression range or improve the wire retention force in the high compression range.



**Fig. 6.** Crimping strength, contact resistance and wire retention force

#### 3-2 Crimp performance improvements

##### (1) Improved electrical connection performance

For a study to improve the electrical connection performance of crimped aluminum wires, we selected factors from a cause-and-effect diagram, and focused on the serration<sup>8</sup> on the terminal. The serration refers to asperities formed in the wire barrel of the terminal. Terminals for copper wires commonly have three grooves. Figure 7 shows crimp properties of terminals without serration. With such terminals, the contact resistance<sup>9</sup> remains unstable regardless of the crimp condition. This proves the effectiveness of the serration.

Aluminum wires were removed from crimp terminals for surface observation in order to check terminal-wire connection conditions. Adhesion of the terminal plating material, tin, was observed at locations corresponding to serration edges, as shown in Fig. 8.

Furthermore, using CAE, we analyzed loads applied to the wire during crimping. Loads were specifically high in areas close to the serration, as shown in Fig. 9. From this observation, the serration was believed to facilitate oxide film breakage in locations close to the serration.

From the above-mentioned observation results, the mechanism of aluminum wire crimp connection was surmised as follows: the insulating oxide film on aluminum is

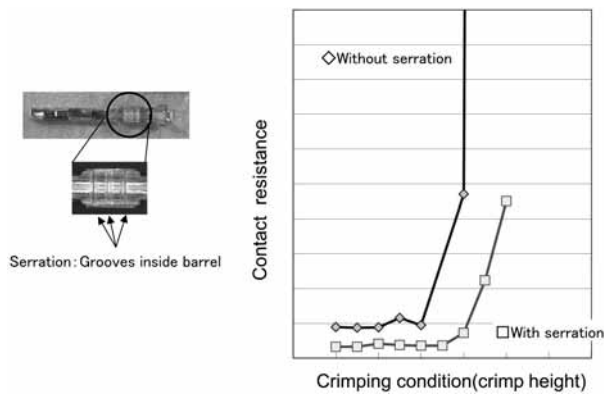


Fig. 7. Effects of serration on electrical connection performance

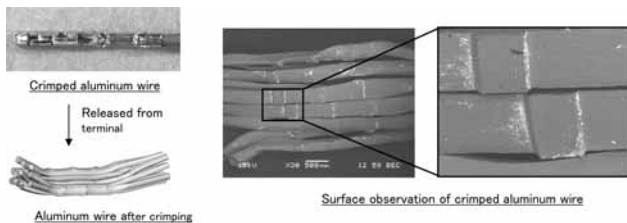


Fig. 8. Crimped wire surface observation

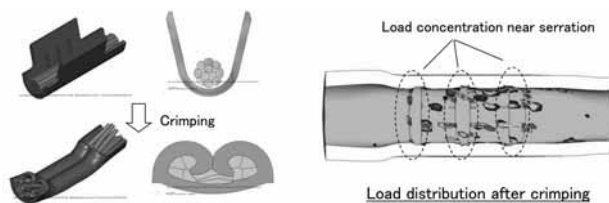


Fig. 9. Crimping simulation using CAE

broken when the wire is substantially deformed by the serration on the terminal during the crimping process; and as loads are additionally applied to the serration edges, newly exposed surfaces of the wire and terminal are connected (with tin adhering onto the aluminum wire), thereby ensuring electrical connection. Therefore, we specified in the terminal development guideline to increase the volume of serration edges (bonding section of terminal and wire).

#### (2) Improved wire retention force

To achieve aluminum wire connection by crimping, it is also effective to improve the wire retention force in the high compression range, as one of the crimp properties shown in Fig. 6.

Cause-and-effect diagram analysis results, as with electrical connections, showed that it would be possible to improve the wire retention force by redesigning the serration. The fine asperities in a wider range turned out to be effective.

### 3-3 Crimp terminals for aluminum wires

Figure 10 shows the newly developed crimp terminal designed for aluminum wires. This terminal ensures connection performance simply by serration modification. Design requirements were: (1) a number of serration edges enough to improve electrical connection performance, and (2) fine asperity placed in a wider range for improved wire retention force. The shape was optimized considering manufacturing and performance margin.

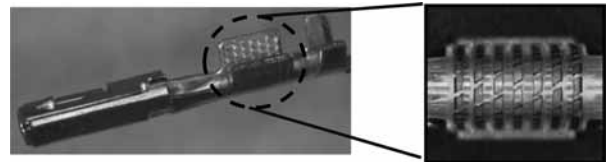


Fig. 10. Crimping terminal for aluminum wires

Figure 11 shows the crimp properties of the newly developed terminal. Both the electrical connection and the wire retention force have been improved, and crimping conditions equivalent to that of conventional copper wires have been secured. Connection reliability equivalent to that of copper wires was also confirmed in various endurance evaluations based on severe vehicle environments.

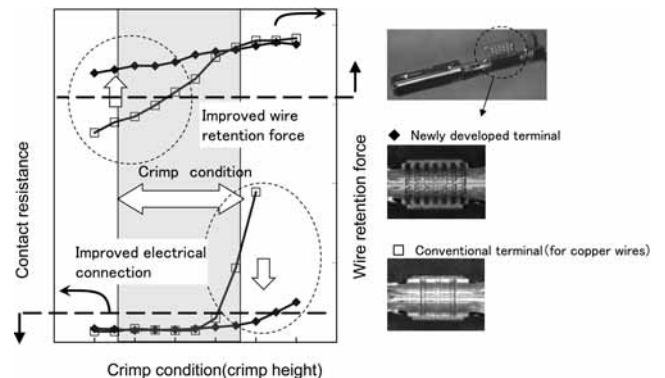


Fig. 11. Crimping properties of terminal designed for aluminum wires

### 3-4 Summary

A special terminal has been developed for the development of aluminum wiring harnesses. This terminal enables connecting aluminum wires by crimping, which is a general-purpose technique used to manufacture wiring harnesses. This terminal can be used in the same harness manufacturing process as used for conventional copper wiring harnesses.

Moreover, this terminal can be used with copper wires and is expected to improve the reliability of copper wire connection. As a result of vehicles' functional sophistica-

tion and increased use of electronic components, connectors and crimped wires are envisioned to be placed under a severe environment. The newly developed technique is believed to be effective as a reliability improvement technique viable for the above-mentioned environment.

#### 4. Anti-Corrosion Technology

##### 4.1 Bimetallic corrosion of aluminum

When an electrolysis solution, such as salt water, contacts the section where the copper (high natural electrode potential) and the aluminum (low natural electrode potential) make contact, a local battery is formed as the copper serves as a cathode and the aluminum serves as an anode, causing bimetallic corrosion (galvanic corrosion), resulting in heavy elution of aluminum (Fig. 12).

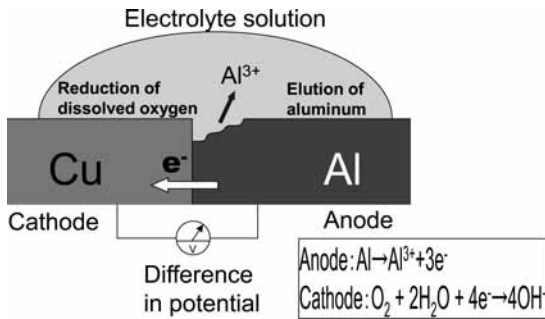


Fig. 12. Bimetallic corrosion of copper and aluminum

##### 4.2 Anti-corrosion technology for aluminum

We checked the progress of corrosion when electrolysis solution contacts the crimped section of the terminal of the aluminum wire.

Figure 13 shows the state when 5% salt water is applied to the aluminum conductor and this conductor is left for a certain period in hot and humid conditions.

Aluminum has been eluted completely, showing that contact with even a slight amount of electrolysis solution causes a deep corrosion.

Therefore, we assumed that anti-corrosion is possible by preventing the electrolysis solution from coming into contact with the crimped sections, that is, by preventing moisture from entering crimped sections.

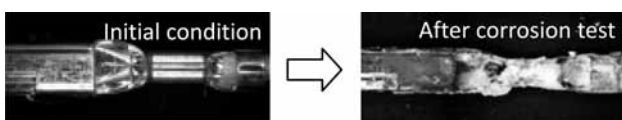


Fig. 13. Corrosion of aluminum wire crimped section

Moisture can reach the crimp through the paths shown in Fig. 14. Path 1 is the aluminum conductor exposed at the forward end of the wire barrel. Path 2 is the aluminum conductor exposed between wire barrels. These paths involve aluminum conductor sections not covered with the terminal. In addition, moisture can enter through the clearance between wire and terminal, which is Path 3.

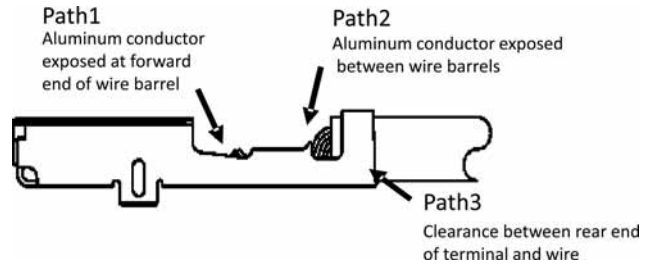


Fig. 14. Paths through which moisture reaches an aluminum wire crimp

Consequently, we considered that it would be necessary to tightly protect the rear end of the terminal as well as the exposed sections of the aluminum conductor.

With the above-mentioned factors in mind, we decided to cover the crimping section and the rear end of the terminal entirely with resin, as an anti-corrosion technique.

Resin material optimization was made from the perspectives of adhesion with the terminal, filling performance, and heat resistance. The resin was evaluated by durability and severe tests for the goal of practical onboard installation.

Finally, a mold structure shown in Fig. 15 was devised to establish an anti-corrosion technology for aluminum.

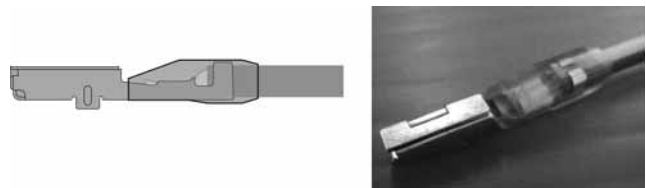


Fig. 15. Mold structure of aluminum wire crimping section

#### 5. Conclusion

Aluminum wires, terminals and an anti-corrosion technology were developed to use aluminum wiring harnesses in vehicles.

Copper prices are expected to increase or to remain high. If all copper wires used in wiring harnesses are replaced with aluminum wires, wiring harnesses will be approximately 25% lighter. Demand for aluminum wiring harnesses is expected to increase due to these factors.

\*This article is the revised edition of "Development of Aluminum Wiring Harness," SEI TECHNICAL REVIEW No.73, pp.73-80.

### Technical Terms

- \*1 Electrical conductivity: Ability of a substance to conduct electricity. It is expressed by a ratio where annealed copper is regarded as 100. The unit is %IACS (international annealed copper standard).
- \*2 Solid solution: The phenomenon in which atoms of added element(s) are dissolved in the parent metal. In this paper, solid solution refers to the dissolution of Fe or Mg atoms into the parent metal of aluminum.
- \*3 Misfit strain (MS): A quantitative value that indicates the degree of distortion of rows of parent metal atoms resulting from the solid solution of an element. Misfit strain serves as an indicator of tensile strength improvement effects.
- \*4 First-principle calculation: Method to directly calculate physical properties based on the basic law of quantum mechanics, etc. or basic physical quantity, without relying on a rule of thumb.
- \*5 Crystallization: Precipitation, due to decreased solvent temperature, of crystals from a solution in which a crystalline material is dissolved.
- \*6 Properzi method: Refers to the continuous casting and rolling system manufactured by Continuus-Properzi in Italy. This system comprises a belt wheel type continuous casting machine and a triaxial multistage rolling machine in a tandem configuration.
- \*7 Crimping: Method to electrically and mechanically connect a terminal and a wire by physical pressure.
- \*8 Serration: Asperities formed on the terminal wire barrel. The oxide film covered on the wire surface is broken at the serration, and the wire is caught in the serration after crimping to prevent the wire coming off, contributing to the stability of electrical and mechanical connection of terminals and wire.
- \*9 Contact resistance: Electrical resistance at the interface between two conductors in contact with each other. For application to automobile harnesses, connection reliability is required to ensure that contact resistance remains stable even in severe vehicle environments.

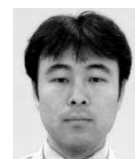
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