Development of Aluminum Wiring Harness

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To reduce the amount of CO_2 exhaust, we are required to develop light weight wiring harnesses. Aluminum wiring harness is one of the solutions for weight reduction of automobiles. However, we have to consider some negative points of aluminum wire such as lower conductivity, lower strength, oxide layers generated on a wire surface and galvanic corrosion. To solve these problems we have developed an aluminum alloy for conductor, terminal with unique serrations and anti-corrosion technology. This paper explains each solution in detail.

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

1. Introduction

In the automobile industry the need for weight reduction has increased as CO_2 emission regulations have become more stringent. Resource prices have also increased. To develop a lightweight and low cost wiring harness, we examined the replacement of copper wires with aluminum wires.

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. This paper reports on the development of an aluminum wire, terminal for the aluminum wire and aluminum anti-corrosion technology (**Fig. 1**) aiming at the use in a range where the cross-section area of the conductor is 2.5 mm^2 or smaller, the size frequently used for wiring harnesses.

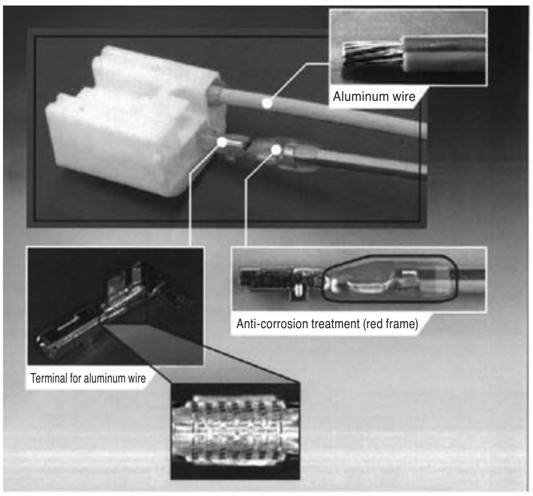

Fig. 1. Development of aluminum wire, terminal and anti-corrosion technology

2. Development of Automobile Aluminum Wire

2-1 Development of aluminum alloy for conductor

(1) Development target

Both tensile strength and electrical conductivity*1 are required for automobile aluminum wires.

The purpose of this development was to achieve tensile strength of 110 MPa or more and conductivity of 58% IACS or more, assuming that the conventional 0.5 mm^2 copper wire generally used in a low-voltage power cable could be replaced by a 0.75 mm^2 aluminum wire.

Electronics & Materials R&D Laboratories in Sumitomo Electric Industries, Ltd. and AutoNetworks Technologies, Ltd. a Sumitomo Electric group company, developed a new aluminum alloy for automobile wires.

(2) Alloy design

Commercially pure aluminum (Ex. AA1060: Purity 99.6%) has good conductivity (62%IACS), but the tensile strength after annealing*2 is pretty low[(1)] (70 MPa). Therefore, the strength must be improved by forming an aluminum alloy that would be suitable for use in automobile wires.

We selected an additive element using the misfit strain[(2)*3] (MS) obtained by the first-principle calculation*4 and the solid solubility at room temperature.

Although the solid solution*5 effectively improves the strength, the conductivity decreases significantly. Meanwhile, MS can be an index of the strength improvement effect, because the strength improvement effect increases as MS becomes large.

To be suitable for automobile wires, the strength must be improved while minimizing the decrease in conductivity. We assumed that an element with small solid solubility and large MS should be effective. After examining the MS and solid solubility of each element, we selected Fe as the best solution for the additive element (**Table 1**).

We then researched the relation between the Fe content and the material property, and found that it was necessary to add 1.5 mass% or more of Fe to satisfy the target performance (**Fig. 2**).

When the aluminum alloy is produced using the general "billet casting and extrusion" method, coarse Al-Fe compounds crystallize, resulting in brittle material and poor processability. However, Sumitomo Electric Toyama Co., Ltd., another Sumitomo Electric group company, uses the Properzi method*6, where aluminum alloy is cooling rapidly

Table 1. MS and maximum solid solubility of each element

Element	MS	solid solubility (mass%)	Element	MS	solid solubility (mass%)
Fe	**3.9**	**0.03**	Cu	1.6	2.48
Mn	3.5	0.62	Ti	1.0	0.70
Cr	3.2	0.37	**Mg**	**1.0**	**18.60**
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

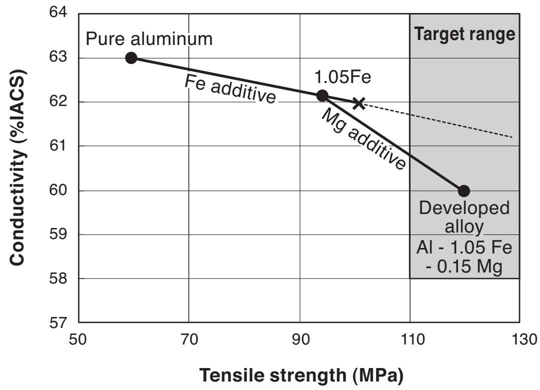

Fig. 3. Component and performance of developed alloy

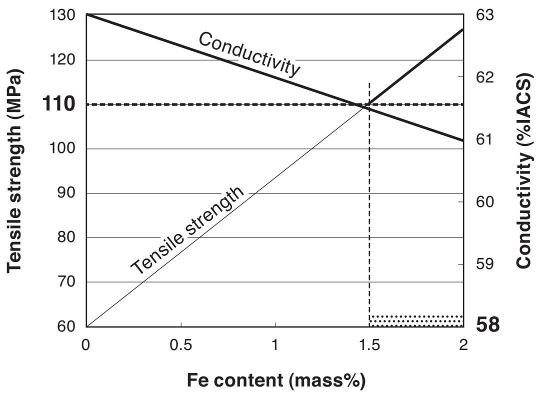

Fig. 2. Relation between Fe content and material property

after casting and sent into hot-rolling process continuously without reheating. This method allows compounds to precipitate in a fine form[(3)], leading to excellent processability.

It was also found, however, that processability of wire drawing or bunching deteriorates when 1.2 mass% of Fe is exceeded, because the diameter of a strand used in an automobile wire is 0.15 to 0.5 mm, which is very thin for an aluminum wire.

Therefore, we searched for a second additive element able to improve the strength by replacing part of the Fe with another element without affecting processability.

As there was sufficient allowance in conductivity relative to the target, some decrease in conductivity may be allowed. We decided to select an element with small MS (because MS affects the decrease of processability) and large solid solubility (which effectively improves strength although conductivity is lowered).

After comparing the elements in **Table 1** again, we determined that Mg would be appropriate, and examined the optimal amount of the Mg additive.

As a result, we found that the composition of Al - 1.05 mass% Fe - 0.15 mass% Mg would satisfy both the ideal processability and performance. Using this composition, the tensile strength of 120 MPa and conductivity of 60% IACS, both of which exceed the preset target, have been obtained (**Fig. 3**).

(3) Establishment of annealing condition

When wiring harness processability and vehicle mountability are considered, flexibility is required for conductors of automobile wires. Therefore, annealed material is generally used.

For the annealing of copper wires, two methods: 'batch annealing' (wire reel is placed in the furnace) and 'continuous annealing' (wire fed from the reel passes through the furnace) are commonly used. The difference in the method does not produce any difference in material property.

However, after treating the newly developed Al-Fe-Mg alloy using each annealing method and then checking performance, conductivity decreased to the lower limit of the target (58% IACS) when treated with continuous annealing. On the other hand, the required performance was obtained when treated with batch annealing.

To identify the cause, we summarized the conditions of batch annealing and continuous annealing as shown in **Table 2**, and confirmed the effect of each item. As a result, we found that the decrease in conductivity was triggered by high temperature and rapid cooling (**Fig. 4**).

We checked the effect of the thermal history (high temperature and rapid cooling) on the metallic structure using a transmission electron microscope (TEM), and found that substantial precipitation of Al-Fe compounds was observed in the material after batch annealing, but was hardly observed in the material after continuous annealing (**Fig. 5**).

It was assumed that Al-Fe compounds were precipitated in a fine form in batch annealing, whereas in continuous annealing, where the alloy is heated to high temperature and then rapidly cooled, the Fe became supersaturated, exceeding the solid solubility, and causing a decrease in conductivity.

Therefore, we decided to use only batch annealing for the newly developed aluminum alloy to obtain properties appropriate for automobile wires.

Table 2. Difference in annealing conditions

	Annealing temp.	Annealing time	Cooling
Batch annealing	350°C	4 hours	Slow cooling (several hours)
Continuous annealing	500°C or higher	1 second or shorter	Rapid cooling (instantaneous)

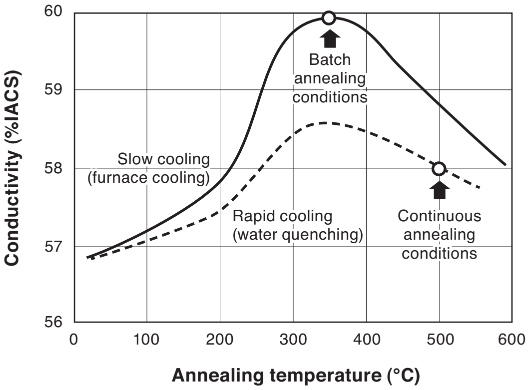

Fig. 4. Effect of annealing conditions on conductivity

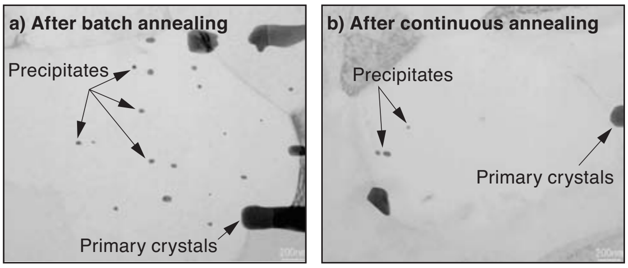

Fig. 5. Difference in precipitation due to different annealing methods

2-2 Establishment of aluminum wire manufacturing technology

(1) Aluminum wire manufacturing problems and solutions

Figure 6 shows the aluminum wire manufacturing processes and manufacturing problems in each process.

At the initial examination phase, wire breakage frequently occurred in each process, and therefore productivity was low. Improvement measures were implemented in each process at Sumitomo Electric Toyama Co., Ltd. and Sumitomo Wiring Systems. As a result, the breakage rate was reduced tremendously, achieving productivity equal to that of copper wire manufacturing processes.

Process	Problem	Improvement details
Casting, rolling	–	• Prevent mixture of inclusion. • Search for flaws over entire wire length and remove them.
Drawing	Wire breakage	• Optimize viscosity of lubricant. • Optimize reduction. • Develop special drawing machine.
Bunching	Surface flaws, wire breakage	• Develop low tension control machine. • Develop guide surface treatment.
Annealing	–	–
Extruding	Wire breakage	• Develop low pressure resin jig. • Develop low friction wire feeder.

Fig. 6. Manufacturing problems and solutions

(2) Aluminum wires currently available

Table 3 shows aluminum wires that can be manufactured and the effects of replacing copper wires by them.

Copper wires can be replaced by aluminum wires one size larger.

Table 3. Available aluminum wires

Copper wire				Aluminum wire			
Type	Size (mm^2)	Weight (g/m)		Type	Size (mm^2)	Weight (g/m)	**Weight reduction (g/m)**
Ultra-thin wall	0.5	5.4	➡	Ultra-thin wall	0.75	3.1	**▲2.3**
	0.75	7.6			1.25	5	**▲2.6**
	1.25	13.1		Thin wall	2	9.1	**▲4.0**
Thin wall	2	21.2			2.5	11.7	**▲9.5**

3. Development of Terminal for Aluminum Wire

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

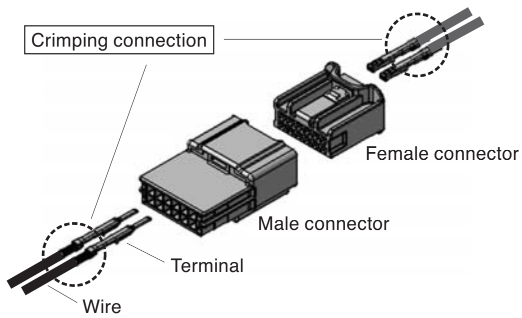

Fig. 7. Connectors and crimped wires

For the mass-production of aluminum harnesses, it is necessary to enable the crimping*7 connection (a general method in harness manufacturing) for connecting the aluminum wire to the terminal.

As shown in **Fig. 8**, crimping is a connecting method where wire with the stripped insulation is crimped in the U-shaped section called the 'wire barrel' on the terminal, to ensure the electrical connection and retention force of wire.

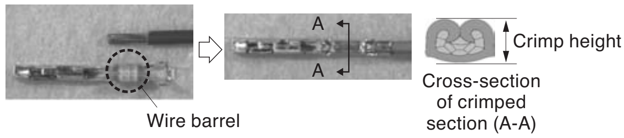

Fig. 8. Crimping connection

It is known that these properties vary depending on the crimping condition (crimping strength). That is, crimping conditions for harness manufacturing must be in the range where both the required electrical connection and wire retention force can be obtained. Sumitomo Electric developed new crimping technology to enable connection of aluminum wires and terminals in automobile harnesses.

3-1 Development challenges

Table 4 shows the copper and aluminum properties and effects on crimping connection of aluminum wires.

Table 4. Copper and aluminum properties and effects on crimping

	Copper	Aluminum	Effects on crimping
Surface oxide film	Cu_2O Conductivity 10 s/cm	Al_2O_3 Conductivity 10-7 S/cm ⇒ Insulating performance	Insulating oxide film ⇒ Increase in contact resistance
Conductivity (base material)	100%IACS	60%IACS	Increase in constriction resistance component
Coefficient of thermal expansion	17.7 × 10^{-6}/°C	23.6 × 10^{-6}/°C	Large variation in contact load relative to variation in temperature ⇒ Decrease in contact load, particularly on low temperature side

Among these properties, the surface oxide film may have the largest effect because the aluminum surface is covered with a robust insulating oxide film. Therefore, we assumed that breaking this insulating oxide film would be the greatest challenge in the crimping process to ensure effective electrical connection.

In the baseline assessment, we conducted an experiment where a wire conductor is pushed against the terminal and load is applied while measuring the contact resistance[*9]. We confirmed that aluminum requires a larger load than copper to stabilize the contact resistance.

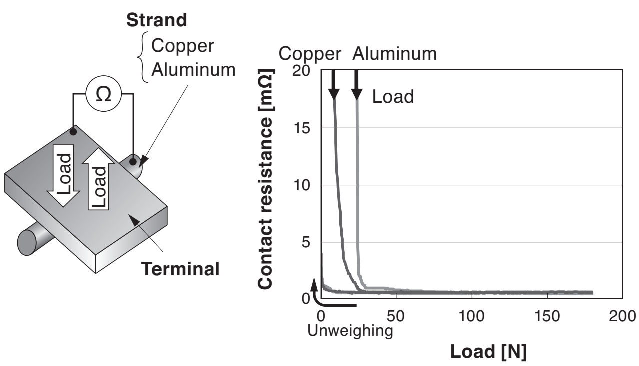

Fig. 9. Load and contact resistance

We then verified the crimping property by crimping a copper wire and an aluminum wire to a terminal for copper wire. **Figure 10** shows the result. The X-axis indicates crimping conditions (crimping force is larger to the left of the axis). Generally, as the crimping force increases, the electrical connection stabilizes, but the wire retention force lowers. Therefore, crimping conditions in harness manufacturing must be set in the range where both properties satisfy the standard.

For the aluminum wire, as the contact resistance does not stabilize unless it is crimped at higher compression than the copper wire (see **Fig. 10**), the wire retention force lowers, reducing the possible crimping condition range where both properties satisfy the standard. Therefore, it was necessary to improve the contact resistance at lower compression or the wire retention force at higher compression to enable the crimping connection of aluminum wires.

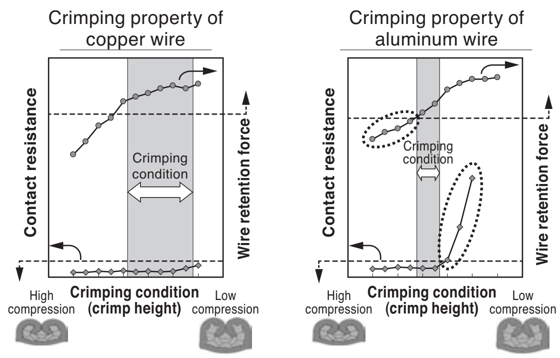

Fig. 10. Crimping strength, contact resistance and wire retention force

3-2 Improvement of crimping performance

(1) Improvement of electrical connection

To enable the crimping connection of aluminum wires, we used the cause and effect diagram to narrow contributing factors, and focused on the serration[*8] on the terminal (**Fig. 11**). 'Serration' is an asperity formed on the terminal wire barrel. The typical serration found on existing copper wire terminals is formed by three grooves.

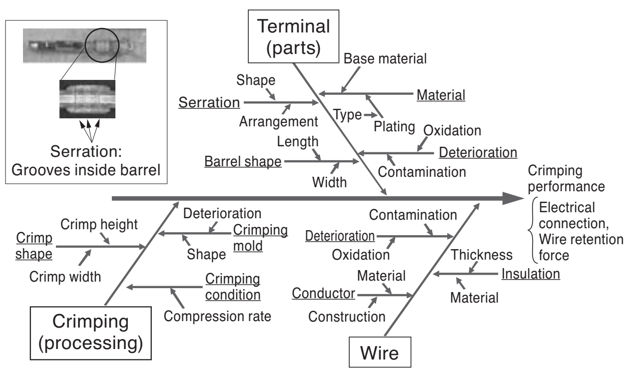

Fig. 11. Cause and effect diagram regarding crimping properties

We evaluated crimping properties of a terminal with serration and a terminal without serration. As shown in **Fig. 12**, the contact resistance of a terminal without serration does not stabilize regardless of the crimping condition, indicating that the ideal serration greatly contributes to acquiring the electrical connection.

Then we verified the connection mechanism near the serration. As the observation of the aluminum oxide film is difficult, we conducted simulation tests using clay to observe the effects on the aluminum oxide film. As shown in **Fig. 13**, we coated the clay with paint to represent the oxide film. Regarding this clay as a wire, we pushed a terminal onto the clay. It was confirmed that the clay near the serration was largely deformed, causing the film to break. We estimated that this large deformation near the serration would contribute to breaking the oxide film.

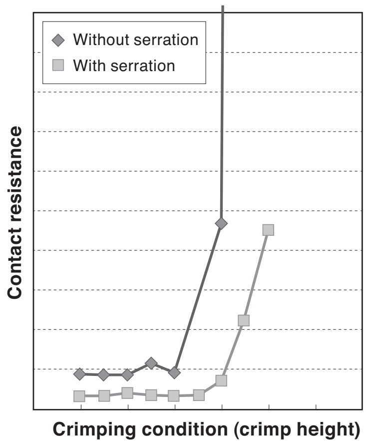

Fig. 12. Crimping properties of terminal with and without serration

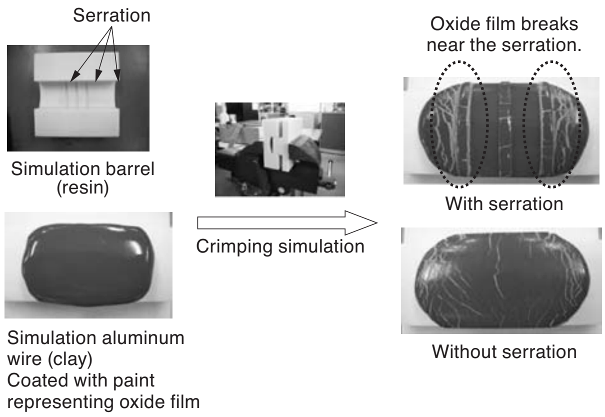

Fig. 13. Simulation test using clay

Meanwhile, we implemented crimping CAE[*10] to analyze load applied to the crimped wire. As shown in **Fig. 14**, it was found that load particularly around serration is quite large. Based on this, we assumed that the oxide film on the wire would likely break near the serration.

Then we disassembled the terminal with the aluminum crimped wire, and analyzed the surface of the aluminum wire. We found that tin (terminal plating material) has adhered to the serration edges (**Fig. 15**), the same section as that where the simulated oxide film broke in the clay experiment.

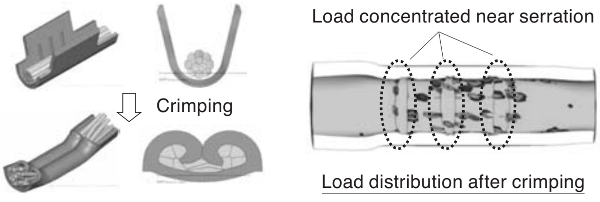

Fig. 14. Crimping simulation using CAE

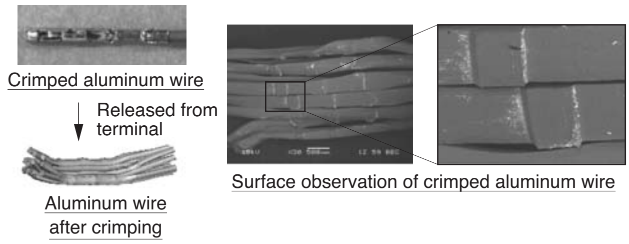

Fig. 15. Crimped wire surface observation

Based on the above data, the aluminum wire crimping connection mechanism can be considered as below. The robust insulating oxide film on the aluminum surface breaks when the wire is largely deformed at the serration on the terminal during crimping. When further load is applied to this section, the newly-formed surfaces of the wire and the terminal are bonded (tin adheres to aluminum wire), and the electrical connection is established. Therefore, we specified in the terminal development guideline to increase the volume of serration edges (bonding section of terminal and wire).

(2) Improvement of wire retention force

To enable the crimping connection of aluminum wires, it is also effective to improve the wire retention force when the wire is crimped at higher compression (**Fig. 10**).

As a result of examining the wire retention force based on the cause and effect diagram as we did to improve the electrical connection, we found that the wire retention force could be also improved by modifying the serration so that the fine asperity is spread over a broad range.

3-3 Crimping terminal for aluminum wires

Figure 16 shows the newly developed crimping terminal for the aluminum wire. The connection performance has been ensured simply by modifying the serration. We regarded the following as the design requirements: (1) to secure sufficient serration edges to improve the electrical connection and (2) to spread fine asperity over a broad range to improve the wire retention force. Considering the terminal manufacturing restrictions and performance mar-

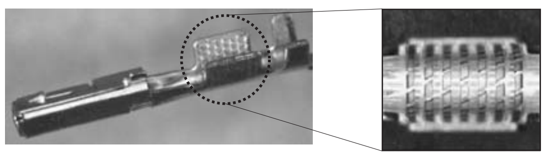

Fig. 16. Crimping terminal for aluminum wires

gins, the terminal shape was optimized based on experimental evaluation and CAE analysis.

Figure 17 shows the crimping properties. Both the electrical connection and the wire retention force have been improved, and crimping conditions equivalent to that of conventional copper wires has been secured. Connection reliability equivalent to that of copper wires was also confirmed in various endurance evaluations based on severe vehicle environments.

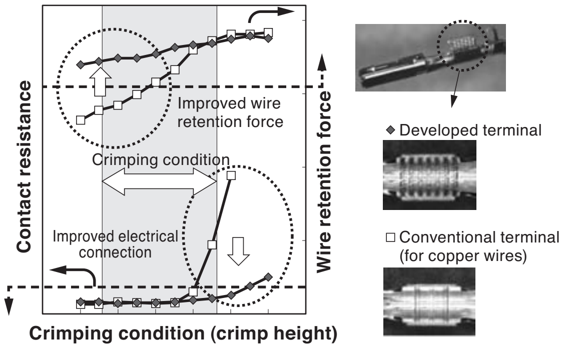

Fig. 17. Crimping properties of terminal for aluminum wire

3-4 Summary

To develop aluminum wiring harness, we improved crimping technology (general method in wiring harness manufacturing) to ensure connection between wire and terminal. As this connection technology ensures the same quality as that in the copper harness manufacturing process, future expansion of aluminum harnesses can be expected.

As this technology can also be applied to copper wire crimping, the connection reliability of copper wires may be further improved. It is assumed that wiring harnesses will be subject to more severe environments as vehicles become more sophisticated and computerized. We believe that this technology will also effectively improve reliability in response to these situations.

4. Development of Aluminum 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. 18**).

Therefore, we decided to investigate the corrosive environment of wiring harnesses, especially at the crimped section, used in older vehicles.

4-2 Survey of older vehicles

As it is obvious that contact with an electrolysis solution, such as salt water, causes the aluminum to corrode, we tried to obtain older vehicles in the region where electrolysis solution easily attached to the vehicles. The most characteristic regions are, the Middle East, where it is known that contact with chloride is often found in vehicles, because chloride was found in the radiator and the subsequent water quality survey report(4), the North America, where significant vehicle corrosion problems have been found due to contact with snowmelt salt(5), and the South-East Asia, where vehicles may be frequently inundated due to squalls.

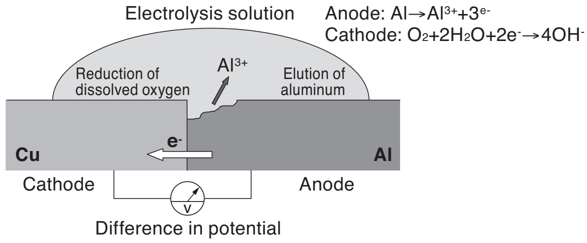

Fig. 18. Bimetallic corrosion of copper and aluminum

As a result of older vehicles investigation, we found that a large amount of dust had entered the cabin in the vehicles used in hot and humid coastal desert areas. And as the worst example, we found that the terminals had drastically corroded (**Fig. 19**).

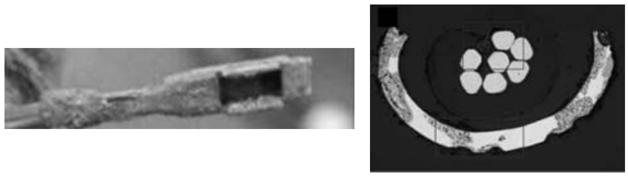

Fig. 19. Corroded terminal found in older vehicle

The results of this investigation showed that the crimped section of the terminal may corrode, we developed an anti-corrosion technology to protect the crimped section of the terminal of the aluminum wire.

4-3 Development of anti-corrosion technology

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

Figure 20 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

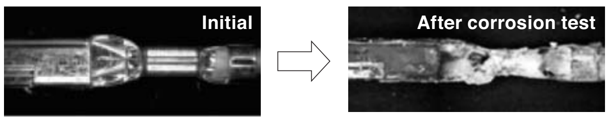

Fig. 20. Corrosion of aluminum wire crimped section

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.

Moisture may enter through the paths shown in **Fig. 21**. Path (1) is the section where the aluminum conductor is exposed at the tip of the wire barrel, path (2) is the section where the aluminum conductor is exposed between barrels, and path (3) is the clearance between the wire and the terminal.

Therefore, we thought it was necessary to protect the rear end of the terminal to prevent any clearance, in addition to the exposed section of aluminum conductor.

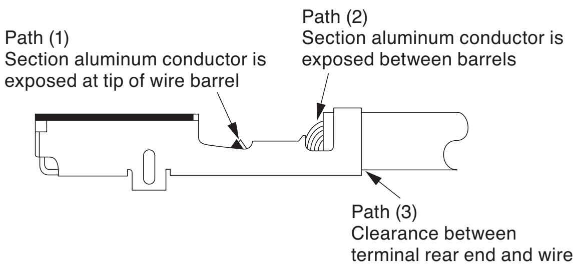

Fig. 21. Moisture intrusion paths into crimped section of aluminum wire

Based on the above data, we decided to use an anti-corrosion technique to cover the entire crimped section, including the terminal rear end, with resin.

We optimized the resin material in terms of adhesion to the terminal, filling performance, heat resistance etc., and conducted endurance evaluations and abuse tests, assuming actual use in vehicles.

Finally, we created the mold structure shown in **Fig. 22**, and established an aluminum anti-corrosion technology.

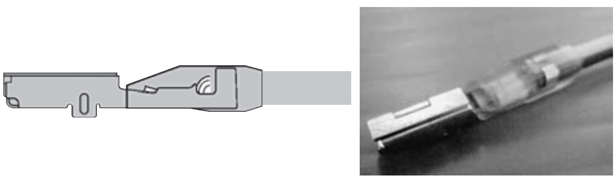

Fig. 22. Mold structure of aluminum wire crimping section

5. Conclusion

We developed three new technologies to produce aluminum wiring harnesses, and succeeded in mounting these harnesses in the Toyota Ractis on a mass production basis.

As it is predicted that the price of copper will continue to rise and remain high, we believe that the demand for aluminum wiring harnesses will further increase.

6. Acknowledgments

In the development of the aluminum wiring harness, we received cooperation from many people in the Western Customers Group – Division 1, Production Engineering Development Group, and Quality Management Group of Sumitomo Wiring Systems, Ltd., where the Aluminum Project has been promoted to achieve mass production of aluminum wiring harnesses.

We also received an award for the vehicle development project from Toyota Motor Corporation. This commendation generated great motivation for all persons involved in this project to contribute to future development.

We express our sincere gratitude to all people involved in the Aluminum Project.

Technical Term

*1 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 Annealing: Heating treatment to soften a metal from work hardening condition. Although the strength decreases, elongation and conductivity increases.

*3 Misfit strain (MS): Index that quantitatively indicates the degree of deformation of atomic arrangement in the base metal due to solid solution of an element.

*4 First-principles 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 Solid solution: State where an element is melted in a base metal in an atomic state. In this document, the state where Fe or Mg is melted in the aluminum in an atomic state.

*6 Properzi method: Continuous casting and rolling system developed by CONTINUUS-PROPERZI in Italy, where a belt wheel type continuous caster and a triaxial multistage rolling mill are arranged in tandem.

*7 Crimping: Method to electrically and mechanically connect a terminal and a wire by physical pressure. Although there are various crimping forms, F-type crimping is generally used for automobile harnesses.

*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 wires.

*9 Contact resistance: Electrical resistance generated at the interface where two conductors make contact. For application to automobile harnesses, connection reliability is required to ensure that contact resistance remains stable even in severe vehicle environments.

*10 Crimping CAE (Computer Aided Engineering): Computer simulation for the crimping process. Load size and distribution in the crimping process can be analyzed, allowing you to estimate the connection performance against the crimping conditions.

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