High-Strength Aluminum Wires for Low-Voltage Automotive Engine Wiring Harnesses

Kinji TAGUCHI*, Takanobu SHIMADA, Jun YOSHIMOTO, Tetsuya KUWABARA and Yasuhiro AKASOFU

The weight of wiring harnesses has been increasing with the growing number of systems used in vehicles in recent years. For the purpose of reducing their weight, aluminum instead of the conventional copper has been getting popular as a wire conductor. Conventional Al alloys, however, cannot be used for small gauge wires (0.35 mm^2 and 0.5 mm^2) or in the engine compartments due to their insufficient conductor strength. For this reason, we have developed a stronger Al alloy that has a conductor strength equivalent to or stronger than that of copper, and successfully manufactured a high-strength Al alloy wire for the first time in the industry. Applying it the 0.35 mm^2 wire used in engine compartment, we started its mass production in April 2015. The target properties of this alloy were a tensile strength of 220 MPa and conductivity of 50%IACS. Based on the age-precipitated 6000 series Al alloy, additive elements and their content were specified. The aging conditions were determined by examining the precipitation status of Mg_2Si intermetallic compounds. With this approach, we achieved a tensile strength of 250 MPa and conductivity of 52%IACS, both of which exceed the targets.

Keywords: aluminum electric wire, engine harness, high-strength aluminum alloy

1. Introduction

Improvements to the safety and comfort of automobiles means an increase in the number of system circuits used in automobiles, and consequently the number of electric wires. There is therefore concern about the increasing weight of wiring harnesses. To reduce the weight of the wiring harness, aluminum wires, which use aluminum as the conductor instead of copper, have been increasingly used for their low specific gravity. The use of aluminum wires is also effective for cost reduction, as the price of copper wires has increased in connection with the recent price hike of raw materials. Due to these advantages, the use of aluminum wires is expected to increase even more. However, since the conductor strength of conventional aluminum wires is insufficient, it is impossible to use them in small sizes such as 0.35 mm^2 or 0.5 mm^2, which are the sizes of conventional copper wires, and cannot be used in engine compartments that are subjected to strong vibration. There were therefore restrictions on how far the weight of wiring harnesses could be reduced.

In response to this, we have developed a high-strength aluminum alloy that has a strength equivalent to or greater than copper and can be used in engine compartments. With the alloy, we have manufactured a high-strength wire with a small size of 0.35 mm^2. We were the first company in the industry to succeed in the application of aluminum wire to engine wiring harnesses. Starting with the 0.35 mm^2 wire, we began producing such wiring harnesses in April 2015.

This paper mainly reports the development of a high-strength aluminum alloy that can be used in small wires and for application in engine compartments.

2. Development of High-Strength Aluminum Alloy

2-1 Development objective

The objective for this alloy development was to achieve an aluminum wire with a minimum size of 0.35 mm^2, which is the size of conventional copper wires. For automotive applications, wires need to have high strength (tensile strength) and good electrical conduction properties (conductivity*[1]) at the same time.

In the development, we aimed to secure a vibration resistance equivalent to or greater than that of conventional copper wires. From past data on terminal crimping strength, we set a target tensile strength of 220 MPa and conductivity of 50%IACS, so that fuse matching would be unchanged even if the wire size is increased by one size in the conventional copper wire ISO line-up. In addition, for the specific material properties, we aimed to satisfy official standards such as ISO.

2-2 Alloy design

The pure aluminum material for general industrial use (1060: purity 99.6%) has a high conductivity of 62%IACS but a low tensile strength of 70 MPa.[(1)] It is therefore necessary to improve the strength for automobile applications.

Strengthening elements are added to aluminum alloys used for conventional wires. However, this only raises the strength to around 120 MPa, which is about half the strength of the copper used in conventional wires, and downsizing the wire to less than 0.75 mm^2 is difficult.[(2)-(4)]

In this new alloy development, we compared the properties of various aluminum alloys (Fig. 1) and selected the 6000 series because its properties were closest to the targets. We thus decided to use magnesium (Mg) and silicon (Si) as the elements to be added to aluminum.

To determine the amounts of the Mg and Si additive, we cast alloy materials as prototypes and narrowed down the range in terms of the alloy strength, conductivity, and

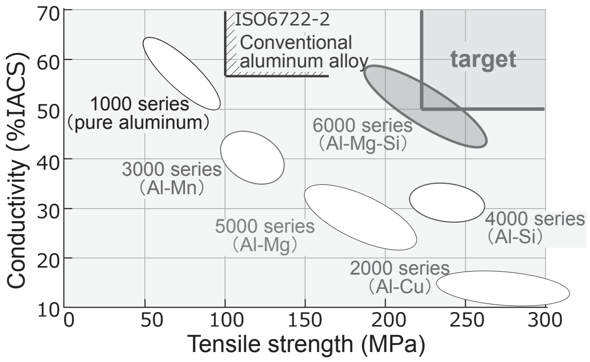


Fig. 1. Characteristics of various aluminum alloys

elongation characteristics, which affect the wire drawability and ease of use.

As a result, we narrowed down the range to where the target characteristics could be satisfied, as shown in Fig. 2, and determined the amounts of additive that would satisfy the target tensile strength of 220 MPa and conductivity of 50%IACS. We also considered the refining methods, as described later, and further narrowed down the range to make production management easy. We thus selected the alloy design values of Al-0.6mass%Mg-0.5mass%Si.

With this composition, we achieved an alloy that has a tensile strength of 250 MPa and conductivity of 52%IACS, which exceeded the targets.

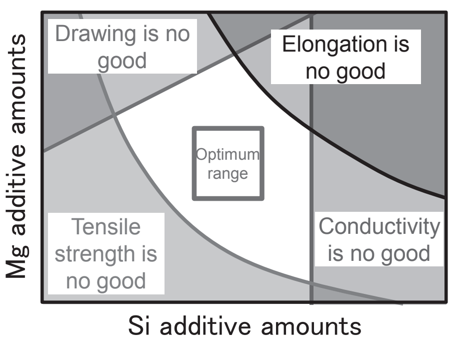


Fig. 2. Results of consideration of amount of Mg and Si addition

2-3 Establishment of refining method

The 6000 series aluminum alloy is a material reinforced by melting the Mg and Si additive into the alloy in a solution heat treatment,*2 followed by an aging heat treatment*3 to precipitate the Mg_2Si compound. In this development, it was necessary to perform the aluminum alloy solutionizing and the aging heat treatment in the wire manufacturing processes. We therefore selected the processes shown in Fig. 3 for efficient wire manufacturing.

After the casting and rolling of the base material with the additive elements included, the additive elements are dissolved into the material during the solution heat treatment. With the elements still dissolved, the alloy is draw

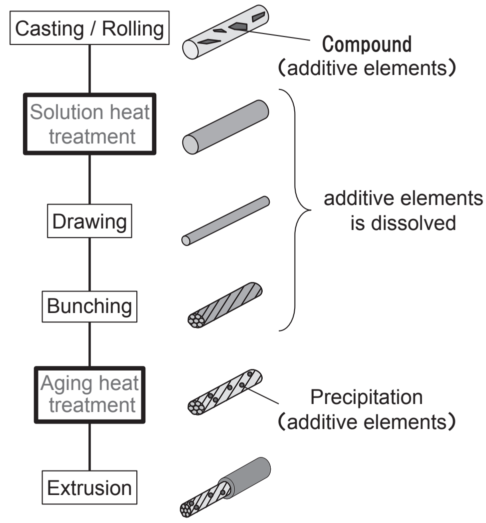


Fig. 3. Manufacturing processes for aluminum wire

and bunched, and then the additive elements are precipitated as intermetallic compounds during the aging heat treatment to finish the conductor. The conductor is then covered in the extrusion process.

During these processes, the additive elements of Mg and Si are dissolved into the aluminum materials by solution heat treatment at 500°C or higher, as shown in the phase diagram in Fig. 4. However, the issue is that the additive elements need to remain dissolved in the material even at room temperature, at which the additive elements generally do not dissolve.

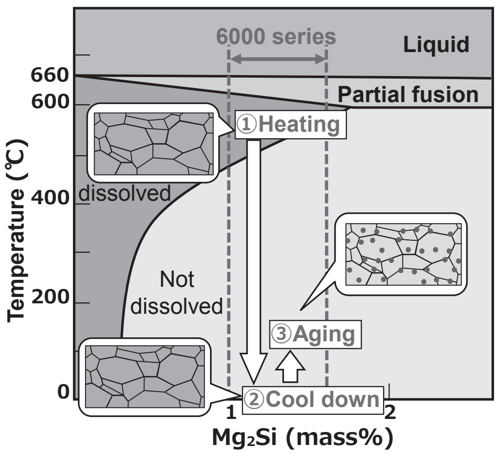
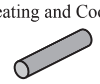
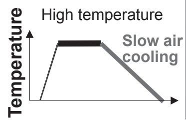
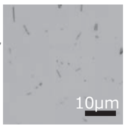
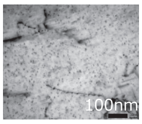
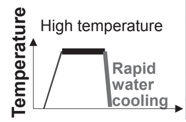
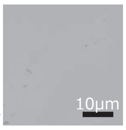
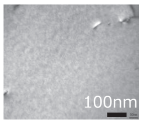


Fig. 4. Pseudo-binary phase diagram for Al-Mg_2Si

For cooling, we compared air cooling, which cools the material slowly, and cold water cooling, which cools the material rapidly by submerging it into water.

As Table 1 shows, the sample cooled rapidly by cold water kept the additive elements dissolved after the bunching process.

Table 1. Comparison of solution heat treatment process conditions

<table>
<tr><th colspan="2">after Heating and Cooling
</th><th>After Bunching
</th><th>Judgment</th></tr>
<tr><td></td><td></td><td></td><td>No good
A compound is not dissolved enough,
They grow up by a bunching process.</td></tr>
<tr><td></td><td></td><td></td><td>Good
A compound is dissolved enough,
A state is maintained.</td></tr>
</table>

Also, in aging heat treatment, by maintaining a low temperature below 200°C, Mg_2Si intermetallic compounds were finely precipitated and dispersed as shown in Photo 1.

As a result, we succeeded in the creation of a high-strength aluminum wire with the target properties.

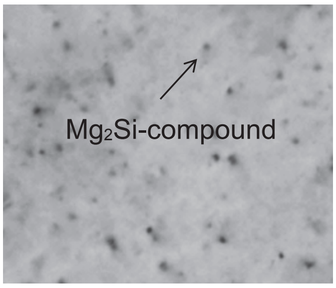
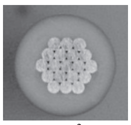


Photo 1. Finely dispersed Mg2Si intermetallic compounds

2-4 Structure of high-strength aluminum wire

Table 2 shows the specifications of the 0.35 mm^2 high-strength aluminum wire that we have developed. The conductor has 19 of the ø0.155 mm strands. Its flexible structure is resistant to engine vibration. These features made it possible to reduce the weight by 53% compared with conventional copper wires of the same size.

Table 2. High-strength aluminum wires

<table>
<tr><th colspan="2">Item</th><th>High strength aluminum wire</th></tr>
<tr><td rowspan="6">Structure</td><td>Cross section</td><td>
0.35 mm^2 Size</td></tr>
<tr><td>Conductor material</td><td>Al-Mg-Si</td></tr>
<tr><td>Element wire diameter</td><td>0.155 mm</td></tr>
<tr><td>Number of strands</td><td>19</td></tr>
<tr><td>Insulation material</td><td>PVC</td></tr>
<tr><td>Insuration thickness</td><td>0.25 mm</td></tr>
<tr><td></td><td>Outer diameter</td><td>1.3 mm</td></tr>
<tr><td rowspan="3">Characteristic</td><td>Tensile strength</td><td>87 N</td></tr>
<tr><td>Elongation</td><td>11%</td></tr>
<tr><td>Conductor resistance</td><td>100 mΩ/m</td></tr>
</table>

2-5 Confirmation of wire characteristics

Figure 5 shows the S-N (strain amplitude and the number of cycles bent) curves of the high-strength aluminum alloy. The strain amplitude is the fluctuation of the change rate in the conductor length on the surface during bending.

It suggests that the high-strength aluminum alloy has a greatly improved life span at low strain compared to conventional aluminum alloys.

It is also superior to conventional copper wire in engine vibration strain, which was the target of this development. Under low strain, the stronger a material is, the longer its life span will be, and therefore we can say that this displays the effect of raising strength to a higher value than that of copper.

The high-strength aluminum alloy also exceeds copper in bending tolerance for opening and closing the door. This can be described as the optimal conductor for bending tolerance and vibration tolerance.

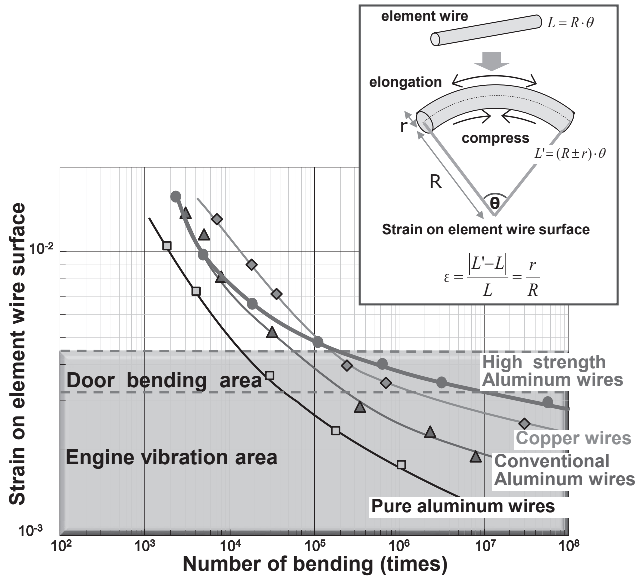


Fig. 5. S-N characteristics of various conductors

We tested the high-strength aluminum wire at simulated engine vibration in the condition where the wire is actually used in a harness (Photo 2).

In the results, good characteristics were obtained as shown in Fig. 6. The developed wire showed greatly improved strength compared to conventional aluminum wires, and withstood a larger number of cycles than conventional copper electric wires.

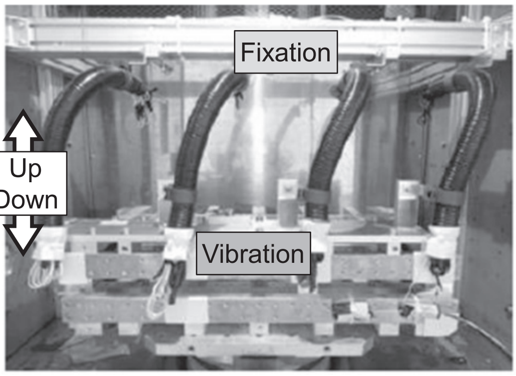


Photo 2. Situation of tests simulating engine vibration

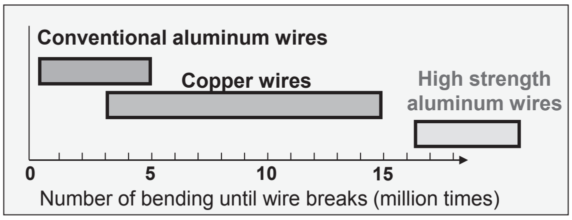


Fig. 6. Results of tests simulating engine vibration

Assuming the environment of an engine compartment, we investigated the conductor strength during and after being exposed to a high temperature of 125°C. The results were as shown in Figs. 7 and 8.

The developed aluminum alloy is stronger than conventional aluminum alloy, and although the strength declines as the temperature gets higher, it does not fall below the strength of copper. Even at 125°C, the strength was higher than that of copper. In addition, although the strength declines at room temperature, the wire tested at 125°C maintains the strength more than copper.

In this way, the high-strength aluminum wire can secure at least the same level of strength as conventional copper wire in engine compartments.

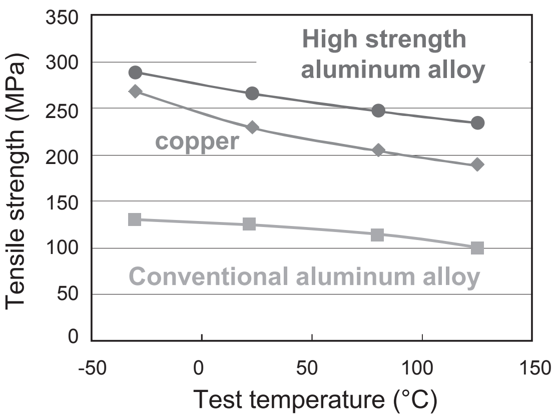


Fig. 7. Temperature characteristics of strength

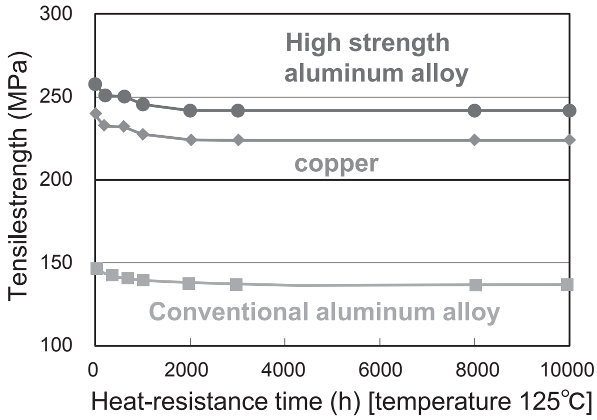


Fig. 8. Strength after high temperature storage

3. Development of Terminals for High-Strength Aluminum Wire

The structure used generally for the connection part on automotive wiring harnesses is as shown in Fig. 9. A terminal connected to the wire by a method called crimping*4) is inserted into a connector and the connectors are fitted together.[(3),(4)]

In order to expand the use of these aluminum harnesses, we use terminals specifically for conventional aluminum wires that can be connected by crimping, which is commonly used in harness manufacturing. We developed technology to connect the newly developed wires to the terminals.

Crimping is a manufacturing method in which the cladded wire is stripped off and swaged with a U-shaped barrel on the terminal so that the contact resistance and retention force are obtained.

As the surface of aluminum is covered with a strong

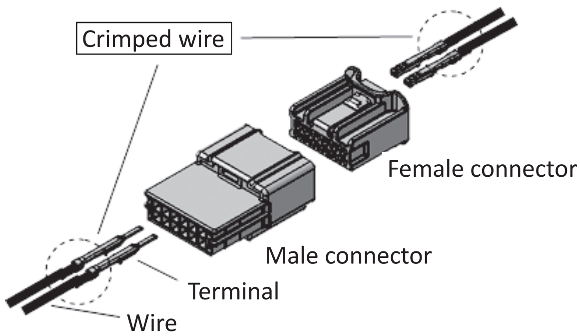


Fig. 9. Connectors and crimped wire

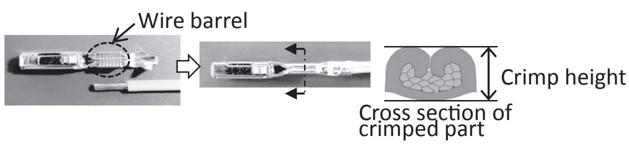


Fig. 10. Crimping method

insulating oxide film, it needs to be swaged stronger than copper to obtain stable contact resistance. We investigated the physical properties of the high-strength aluminum wire conductor in terms of connection performance and verified whether the crimping method used for conventional aluminum wire can also be used for the developed wire. The results are shown in Table 3.

Table 3. Physical properties of wire conductor

Item		High strength aluminum wire	Conventional aluminum wire
Strength		250 MPa	130 MPa
Surface oxide film	Volume resistivity	10^{13} Ω•m	10^{13} Ω•m
	Thickness	approx. 50 nm	approx. 50 nm

The investigation found that the physical properties of the oxide film on the developed wire conductor and the conventional aluminum wire conductor were quite similar. As the conventional crimping method was likely to be used for the developed wire, we evaluated the crimping characteristics. As shown in Fig. 11, the crimping conditions that satisfy the standards for both contact resistance and retention force were obtained.

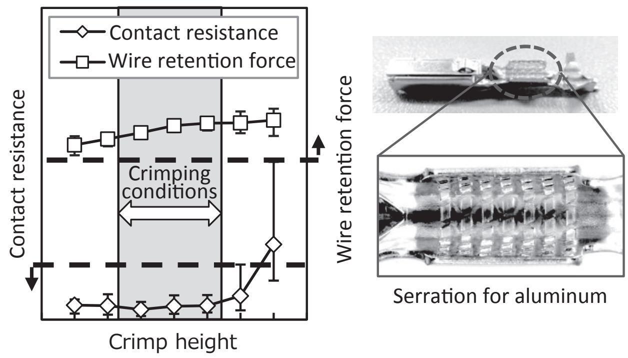


Fig. 11. Crimping characteristics of terminals for high-strength aluminum wires

4. Engine Wiring Harness Using Aluminum Wire and Future Product Lineup

We began manufacturing high-strength aluminum wires in April 2015, starting with 0.35 mm^2 wire. The wire and engine wiring harness we have launched are shown in Photos 3 and 4. The high-strength aluminum wires account for about 20% of the harness shown in Photo 4.

Table 4 shows the lineup of high-strength aluminum wires that we are planning to release from now onwards. In addition to the 100°C heat-resistance grade 0.35f type with a flexible stranded conductor structure that we have already mass produced, we are also preparing items for engine harnesses (100°C heat-resistance grade) and internal harnesses (80°C heat-resistance grade) as in the copper wire lineup.

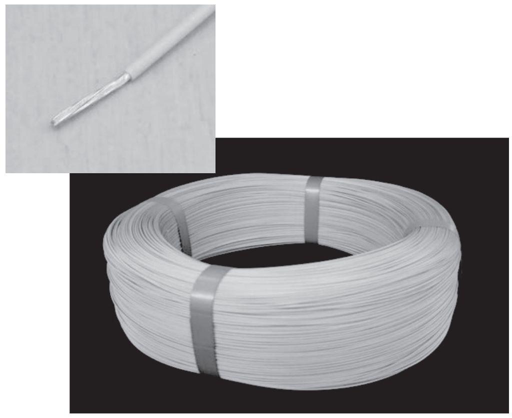


Photo 3. 0.35 mm^2 high-strength aluminum wire for which mass production has started

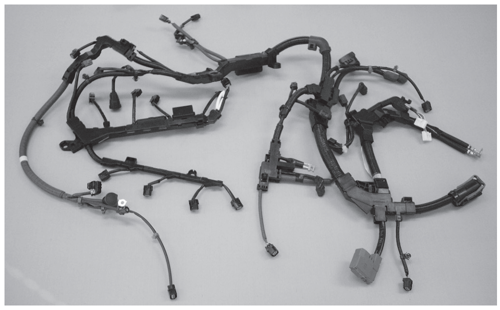


Photo 4. Engine wiring harness using high strength-aluminum wire

Table 4. Lineup of high-strength aluminum wire products

Heat resistance grade	conductor construction				Insulation		Outer diameter (mm)	Weight (g/m)
	type	Size	construction	diameter (mm)	material	thickness (mm)		
80°C	Compressed	0.35	7/SB	0.70	PVC	0.20	1.10	1.8
		0.50	7/SB	0.85		0.20	1.25	2.3
100°C	Standard	0.35	7/0.250	0.75	PVC	0.25	1.25	2.1
		0.50	7/0.300	0.90		0.28	1.46	2.9
100°C	Flexible	0.35f	19/0.155	0.80	PVC	0.25	1.30	2.2
		0.5f	19/0.185	0.95		0.28	1.51	3.0
		0.75f	19/0.225	1.15		0.30	1.75	4.2
		1.25f	37/0.210	1.50		0.30	2.10	6.2
		2.0f	37/0.260	1.85		0.35	2.55	9.3
		2.5f	37/0.285	2.05		0.375	2.80	11.1

5. Conclusion

We have developed a high-strength aluminum wire for automotive wiring harnesses with the aim of reducing their weight and costs. The wire uses a high-strength aluminum alloy conductor with a strength equivalent to or greater than that of copper. These features make the wire applicable to engine compartments and allow it to reduce in the size to 0.35 mm^2.

Using the aluminum alloy of Al-0.6mass%Mg-0.5mass%Si and effective refining treatment conditions, we produced the high-strength aluminum wire, which has a high resistance to engine vibration and a reduced weight by 53% compared to conventional copper wire of the same size. We commenced the production of high-strength aluminum wires in April 2015, starting with 0.35 mm^2.

From now onwards, we will work to expand the size variation of the aluminum wires and find new applications such as aluminum braiding and shielding wires.

Technical Terms

∗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 Solution heat treatment: A heat treatment in which a material is heated at a comparatively high temperature and then rapidly cooled to have the additive elements evenly dissolved throughout the aluminum alloy.

∗3 Aging heat treatment: A heat treatment in which a material is heated at a comparatively low temperature and have the dissolved additive elements precipitated as compounds over time.

∗4 Crimping: A method of electrical and mechanical connection performed by swaging the terminal and wire.

References

(1) Japan Aluminium Association, Aluminum Handbook Ver. 7 (2007)

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