Contribution to the achievement of SDGs
by Furukawa Electric Group

Development of Conductive Aluminum Wires and Electric Wires/Cables With High Cyclic Durability

Akiyoshi Araki[*1], *Kaho Miyazaki*[*1], *Kaho Imai*[*1], *Yasumichi Cho*[*1],
Hiroshi Kaneko[*1], *Taku Kato*[*2], *Kazuhiro Koseki*[*3], *Ryuichi Hashimoto*[*4]

ABSTRACT We have developed a new metallographic crystal structure control technology and a new manufacturing technology that significantly increases the strength and the fatigue durability of aluminum alloy wire materials while making the wire diameters smaller than those of conventional wires utilizing the technologies acquired in the development and the manufacturing of high-performance copper alloy wires and automotive rectangular magnet wires. The developed aluminum alloy wire material achieves the world's highest strength and a cyclic fatigue life, a high workability, and a high electrical conductivity at the same time, making it suitable for applications that require durability against oscillation, vibration, cyclic motion and manufacturing. Through the development of elemental technologies such as the fine-diameter wire drawing, its twisting, and its coating, we are proceeding with demonstrations of the developed aluminum alloy wire material on its applications in various electric wires and cables. By expanding the range of applications of aluminum electric wires using the developed aluminum alloy wire material, we will contribute to resolving social issues such as energy conservation, decarbonization, resource conservation, labor shortages, and resource exploration.

1. INTRODUCTION

Through the development of the crystal control technology for metallic materials and its application to the products, we are providing copper-based and aluminum-based materials that offer excellent strength, conductivity, workability, and surface functionality. This paper introduces examples of how our company has further developed the metallographic crystal structure control technology and is applying it to the development of new products.

Because aluminum-based materials are one of the lightest metal materials with a specific gravity of 2.7, they are used to reduce weight in a wide range of industries, including transportation equipment and building structures, and contributing to labor and energy conservation. In addition, because aluminum-based materials not only have a low specific gravity, but also have the fourth highest electrical conductivity among metallic materials after silver, copper, and gold, they are being used to reduce the weight of conductive components such as wiring in buildings and automotive wiring harnesses[1), 2)], and their applications are expanding. As the information society continues to become more advanced and vehicles such as automobiles and aircraft continue to become more electrically powered, demand for conductive components will increase. Therefore, making effective use of aluminum-based materials in combination with copper-based materials, which are limited resources, will be important for a sustainable society. On the other hand, compared to copper-based materials, aluminum-based materials have lower tensile strength, bending strength, and fatigue durability, so their application to conductive components is still limited. In particular, cabtyre cables as typified by robot cables, and electric wires used in moving objects are required to be able to follow the equipment during their use and to withstand millions to hundreds of millions of cyclic movements due to oscillation and vibration. Such cables typically use copper wires with a diameter of 100 μm or less, which has a high fatigue durability. However, conventional aluminum-based wire materials have an insufficient fatigue durability and an insufficient workability when processed into small diameters, so their application to the above-mentioned uses has not progressed. Reducing the weight of electric wires and cables by using aluminum-based wire materials that can withstand cyclic motion and vibration is expected to be effective for reducing power consumption and for improving equipment precision, and is thought to be particularly effective in the group of applications shown in Figure 1, for example.

[*1] Material Laboratory, Research and Development Division
[*2] Manufacturing Innovation Department,
NIKKO Copper Rolling Plant,
Copper and High Performance Material Products Division
[*3] Engineering Department,
Electronics Component Material Division
[*4] Facility Innovation Department, Facility Assets Department,
MONOZUKURI Innovation Division

Figure 1 Projected uses of the developed aluminum alloy wires and electric cables.

To improve the tensile and fatigue strength of aluminum-based materials, strengthening technologies such as the solid solution strengthening and the precipitation strengthening, which distort the metal lattice by using solid solution elements or fine second phase particles, have been developed and are used in high-strength aluminum materials for automobile and aircraft structures. In addition, a strengthening technique called the grain refining strengthening, which achieves both the strength and the workability by making crystal grains fine, is also used.

We have reduced the crystal grain size of conductive aluminum materials to about 100 nm by applying the metallographic crystal structure control technology that we have acquired in the development and the manufacturing of high-performance copper materials to aluminum alloy wires. It enabled the development of a new conductive aluminum alloy wire material that significantly improves a fatigue life and a tensile strength, has an excellent workability, and maintains an electrical conductivity at the same time, making it suitable for use in electric wires that are subject to vibration and cyclic motion. We also processed them into electric wires and cables, and have succeeded in developing electric wires and cables that exhibit strength properties equal to or greater than those of copper-based materials. In this paper, we report on the metallographic crystal structure and the strength properties of the newly developed conductive aluminum alloy wire material, as well as the future outlook.

2. CRYSTAL GRAIN REFINEMENT METHOD

Metallic materials, including aluminum-based materials, are composed of an aggregate of small crystals called crystal grains, and by refining the crystal grains, it is possible to improve mechanical properties such as strength, toughness, and fatigue durability. In recent years, research has been conducted into methods for significantly increasing the strength of structural aluminum materials by subjecting the material to severe processing that imparts high processing strain to make the crystal grains finer than before[3)-5)]. Figure 2 shows the results of plotting the relationship between the material strength and the crystal grain size of aluminum-based materials that had been subjected to severe processing, quoted from the references. As can be seen from the so-called Hall-Petch empirical formula, the strength of the material increases in proportion to the -1/2 power of the crystal grain size, and by refining the grain size to the order of 100 nm, it is possible to obtain a strength several times higher than that of conventional materials. Therefore, in this study, we aimed to improve the strength and the fatigue durability by refining the crystal grains.

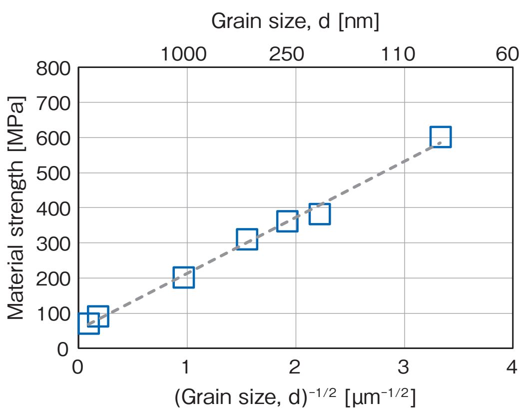

Figure 2 Grain refinement strengthening by Equal Channel Angular Pressing (ECAP) method for a structural aluminum alloy[3)].

Furthermore, a wire drawing process is generally used to manufacture wire materials. Figure 3 shows a schematic diagram of a wire drawing process[6)]. Each time a wire passes through a die, the wire diameter becomes smaller and processing strain is imparted to the material. For example, by processing a wire material with a diameter of 10 mm down to a diameter of 0.1 mm, the cross-sectional area reduction ratio becomes as high as 99.99%, making it possible to impart extremely high processing strain. In this study, we aimed to refine the crystal grains by using the processing strain caused by drawing processing.

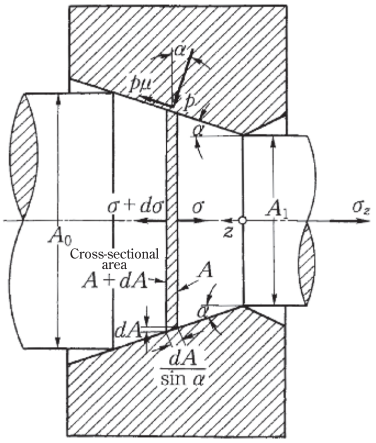

Figure 3 **Schematic of a die drawing processing[6].**

3. CRYSTAL GRAIN REFINEMENT IN VARIOUS ALUMINUM MATERIALS

In this study, a wire of pure aluminum-based material and aluminum alloy materials A, B, and C with different alloy compositions were prepared and processed by drawing to a cross-sectional reduction ratio of about 99.99%. Figure 4 shows the crystal grain structures observed from the transverse cross section of each wire material after drawing. The areas with different gray contrast correspond to individual crystal grains. This figure shows that while the crystal grain size of the pure aluminum material is about 1 µm, the aluminum alloy materials A and B can achieve fine crystal grain sizes of about 100 to 500 nm. In the case of the aluminum alloy C, the wire broke during the drawing processing, and it was impossible to achieve a cross-sectional area reduction ratio of 99.99%.

Tongjai et al. organized the ease of obtaining stable fine crystal grains in terms of the ease of segregation of alloying additional elements to grain boundaries[7]. We consider that because the amount of added elements in the pure aluminum-based material was small, and fine crystals couldn't exist stably, recovery and recrystallization occurred during processing with a cross-sectional area reduction ratio of 99.99%, and therefore fine crystal grains of 1 µm or less could not be obtained.

In the observation of the fracture surface of the broken aluminum alloy C, in which breaks occurred during processing, the causes of break were found to be precipitates, cracks at grain boundaries, surface defects, etc. In addition, wire break also occurred when the manufacturing process (manufacturing conditions) such as the melting and casting conditions of the aluminum alloy A were changed, and the same causes of wire break as those of the aluminum alloy C were confirmed. For this reason, in order to achieve crystal grain refinement by drawing processing with a cross-sectional area reduction ratio of 99.99%, it is important to select an appropriate alloy material and to design a process from melting/casting to drawing.

The following sections show the results of various evaluations carried out using aluminum alloy A wire material (hereinafter referred to as the developed aluminum alloy).

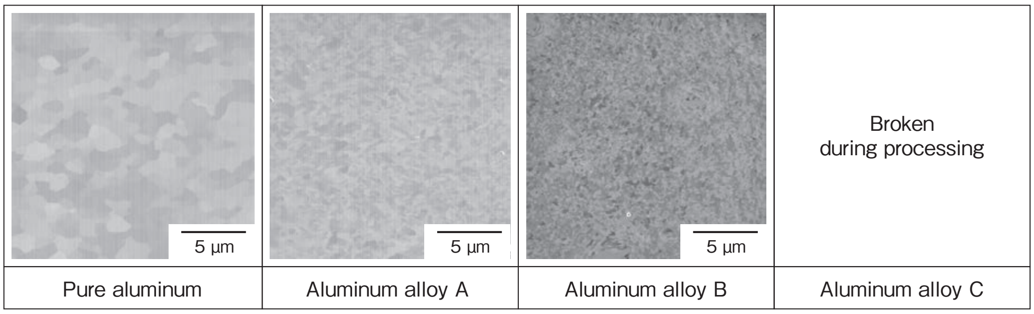

Figure 4 **Microstructures of various aluminum alloys after wire drawing with an area reduction ratio of 99.99%.**

4. CYCLIC DEFORMATION DURABILITY AND ELECTRICAL CONDUCTIVITY

4.1 Cyclic Deformation Durability

As mentioned at the beginning, the cyclic fatigue durability is important for cabtyre cables and electric wires used in moving objects that are subjected to vibration and oscillation. In this study, to evaluate the fatigue durability, we carried out an alternating bending fatigue test using a cyclic bending tester shown in Figure 5 (a), and a vibration test using a cyclic tensile tester shown in Figure 5 (b).

The cyclic bending durability of the developed aluminum alloy with a cross-sectional area reduction ratio of 99.99% produced in this study is shown in Figure 6, and the cyclic tensile durability is shown in Figure 7. As comparative materials, a pure aluminum wire and a pure copper wire were also evaluated. Electric wires that are subject to vibration, oscillation, and cyclic bending are required to be able to withstand cyclic motions of 10^6 to 10^9 times. Comparing the cyclic bending life at a bending strain of 0.17%, as shown in Figure 6, the fatigue life of the conventional pure aluminum wire is about 1/5 that of the pure copper wire, whereas the fatigue life of the developed aluminum alloy wire is more than 10 times or more that of the pure copper wire, demonstrating a significant improvement in fatigue life compared to convention-

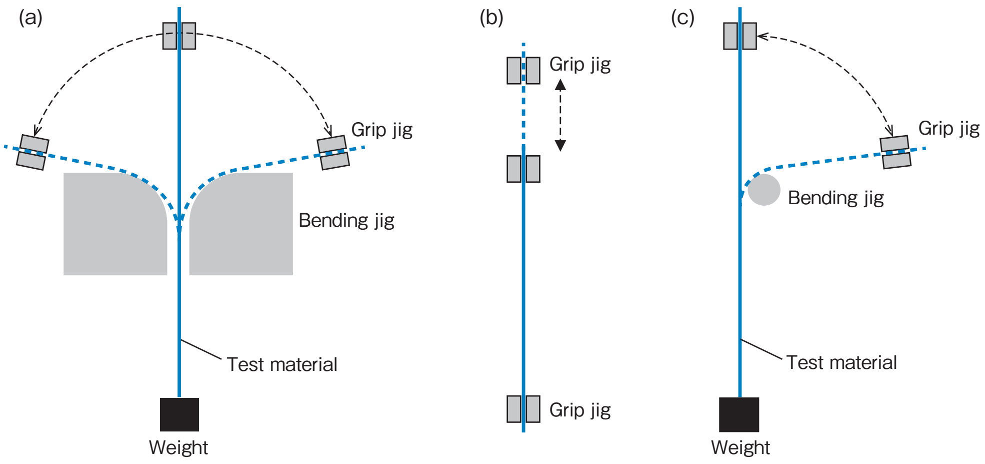

Figure 5 Schematics of (a) bending fatigue test, (b) tensile vibration fatigue test, and (c) severe bending fatigue test.

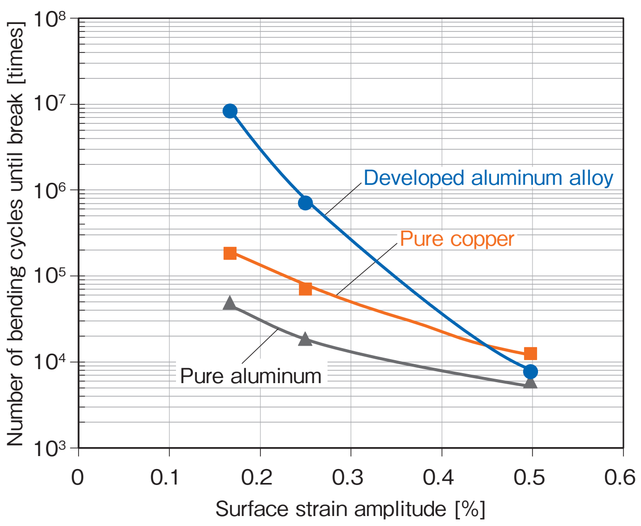

Figure 6 Bending fatigue life of the developed aluminum alloy, pure aluminum, and pure copper.

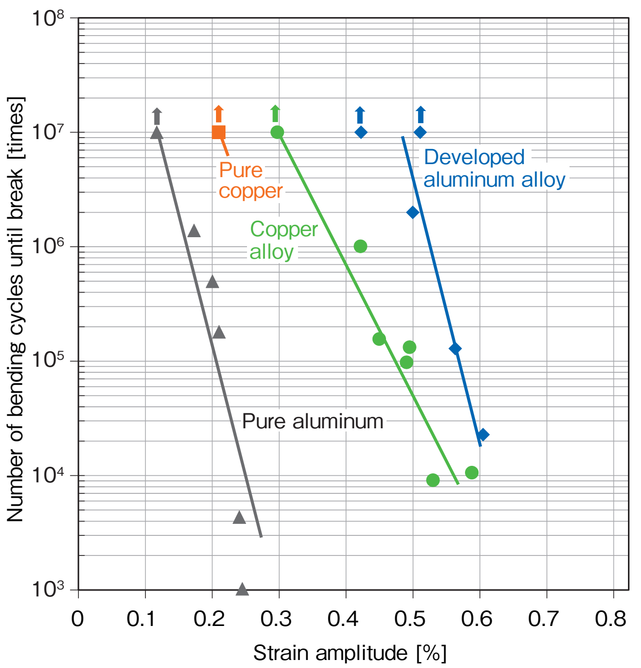

Figure 7 Tensile vibration fatigue life of the developed aluminum alloy, pure aluminum, pure copper and the copper alloy wire.

al materials. In addition, as Figure 7 shows, the vibration durability is higher than that of the pure copper wire and is equivalent to that of the copper alloy wire, and it indicates that the developed aluminum alloy has significantly improved fatigue durability compared to conventional materials due to its fine crystals. Therefore, we believe that customers can use this product with confidence in terms of fatigue durability.

In the process of manufacturing electric wires by processing element wires and in the process of routing the electric wires in designated locations, the element wires and covered wires may be severely bent in order to pass them through limited spaces, and it is required that the element wire conductors do not break during such processing. In general, it is expected that workability will improve by refining the crystals, and the fine-grained aluminum alloy achieved in this study is also expected to have a good bending workability. Therefore, the cyclic severe bending durability of the developed aluminum alloy wire to the small bending diameter was evaluated using the test method shown in Figure 5 (c). In this test, because the bending strain was large, and the wire would plastically deform and develop a bending habit, a pulsating test was performed.

Figure 8 shows the evaluation results at a bending strain of 7%. Although the developed material is inferior to a pure copper wire, which is a soft material, it has a bending durability that is more than twice that of a conventional aluminum wires and is equivalent to that of a copper alloy wire. The achievement of fine crystals makes the material less likely to break even when subjected to a severe bending processing during the manufacture and the installation of electric wires.

4.2 Electrical Conductivity

In addition, when applied to conductive components, the electrical conductivity is also important. In this developed aluminum alloy, the effect of grain refinement to about 100 nm on electrical resistance was small, which was at 1%IACS or less. Therefore, this material can also be applied to conductive components.

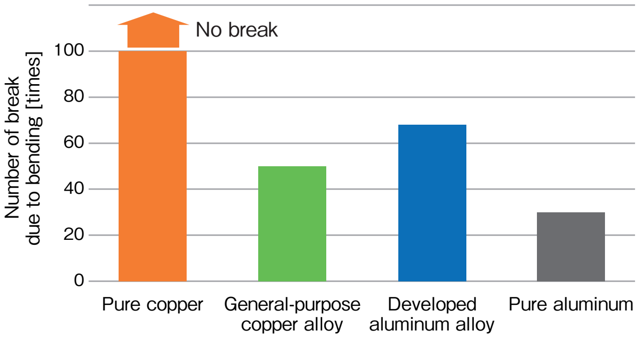

Figure 8 Severe bending fatigue life of the developed aluminum alloy, pure aluminum, pure copper, and general-purpose copper alloy.

5. PROPERTIES AFTER WIRE PROCESSING

In this study, in addition to the evaluation of the element wires described above, we also evaluated the electric wires and cables which the element wires were stranded and coated. The stranded wire structure and the coating material were selected according to the applications.

Table 1 shows the result of the U-type cyclic bending test on a flat elevator cable made of 30 element wires with a wire diameter of 0.18 mm, which were then twisted together to form a 36-stranded cable. As Table 1 shows, even under the test condition where a copper cable would break after about 1.5 million bending cycles with a U-type bending radius of 60 mm, the developed aluminum alloy cable had a lifespan of 9.5 million times or more bending cycles. In addition, while the copper cable reached the end of its life due to break of the conductor, the developed aluminum alloy cable reached the end of its life due to destruction of the cable coating. Table 2 shows the result of the cyclic bending test on a LAN cable that uses 64 element wires with a diameter of 0.1 mm as a horizontal wound shielding conductor. The bending radius was 30 mm. When the coating was stripped off after three million cycles and the state of the break in the shielding conductor was investigated, it was found that multiple wires had broken in the conventional copper alloy shielding conductor, whereas not a single wire had broken in the developed aluminum wire. In addition, a severe bending durability test was conducted on an electric wire made of 19 strands of element wire with a wire diameter of 0.127 mm, with a bending radius of twice the diameter of the electric wire. The pure aluminum wire broke after about 10 times of bending, whereas the developed aluminum alloy wire withstood 90 times or more of bending. As described above, the high fatigue durability, which is a property of the developed aluminum wire material, is fully demonstrated even when it is implemented into electric wires and cables.

Table 1 Fatigue life of 36-wire flat elevator cable after U-type cyclic bending test of 3 x 10^6.

	Fatigue life
Made of developed aluminum	Pass (> 9.5 million)
Made of conventional pure copper	Fail (1.5 million)

Table 2 Fatigue life of LAN cable shielding conductor after cyclic bending tests of 3 x 10^6.

	Evaluation condition No break after three million times
Made of developed aluminum	Pass (No break)
Made of conventional pure copper	Fail (Multiple broken wires)

Crimping is used for jointing electric wires for many applications. Figure 9 shows the crimped tensile strength and the crimped resistance of the wires using a pure aluminum wire material and the developed aluminum wire when using commercially available conventional crimp terminals for copper wires. The horizontal axis is the crimp height after crimping, with the crimping being stronger on the left side. The surface of aluminum-based materials is covered with a strong, insulating oxide film, and in order to ensure electrical conductivity, it is necessary to crimp the material strongly to increase the amount of deformation and then destroy the oxide film. The pure aluminum wire has a low material strength, so if the deformation amount is increased, the strength range will deviate from the required level. On the other hand, the developed aluminum alloy wire has a high material strength, so it retains sufficient strength properties even when the deformation amount is large. In addition, because the material strength is high and the contact pressure at the crimped part can be increased, the electrical conductivity is stable even under crimping conditions of small deformation, making the wire easy to joint.

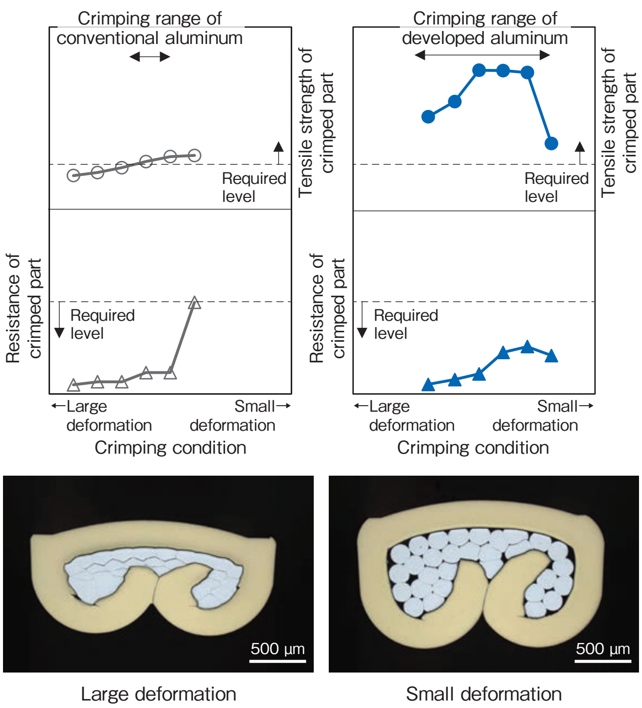

Figure 9 Relation between the resistance and the strength of the crimped part, and the crimping condition.

6. CONCLUSION

We have developed a new metallographic crystal structure control technology and its manufacturing technology to refine crystals of metal materials to the nanometer order, and by applying them to various aluminum alloy materials, we have developed an aluminum alloy wire material with an extraordinarily long fatigue life compared to conventional ones.

(1) By refining the crystal grain size to the order of 100 nm, we have developed an aluminum alloy wire material that achieves both an extraordinary high-cycle fatigue life and a good low-cycle fatigue life compared to conventional ones.

(2) By processing the developed aluminum alloy wire material into electric wires, we have developed aluminum electric wires and cables that achieve a better fatigue durability than copper electric wires, a good bendability, a good crimp strength, and a good electrical conductivity at the same time.

The developed aluminum alloy wire material, and electric wires and cables have been offered to customers for testing, and have been highly evaluated for their features, such as a cyclic bending life greater than that of copper, their lighter weight than a copper wire, and their ability to withstand severe bending during manufacturing and installation. In the future, we will continue to contribute to energy conservation, labor savings, and automation through these highly durable and lightweight aluminum electric wires and cables.

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