The Development of the High Strength Aluminum Alloy Wire

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ABSTRACT The development of the high strength aluminum alloy wire, to be used as an industrial wire, was implemented. The development is intended to obtain characteristics that can withstand the practical use even as electrical wires with comparatively small diameter, and additive amounts of Mg and Si were optimized by investigating their effects influencing the electrical conductivity, the tensile strength and the elongation due to the additive amounts of Mn and Si in the Al-Mg- Si alloy. Also, a relation between the additive amount of Mg and a grain-refining effect was investigated and the additive amount of Mn was optimized, then it led to the successful development of the alloy having the high elongation characteristic based on the suppression of a grain coarsening during a high temperature solution heat treatment after a cold wire drawing process. Furthermore, by a Ni addition, we succeeded to suppress the decrease in the elongation characteristic and to improve the tensile strength characteristic, and we found out that a high impact resistance could be achieved. In addition to the above investigation, by examining an age-hardening heat treatment condition, we succeeded in the development of the aluminum alloy wire which is well balanced in the electrical conductivity, the tensile strength and the elongation at a high level.

1. INTRODUCTION

In light of the global situation such as demands in CO_2 emission reduction and soaring copper price, in the field of the industrial electrical cables, the replacement of the copper wire with the light weight and low price aluminum wire is proceeding. Though the electrical conductivity of the pure aluminum is approximately half that of the pure copper, its weight is approximately 1/3, then even a cross sectional area of the aluminum wire is doubled to make the electrical resistance equivalent, there can be an effect of approximately 1/2 in a lighter weight compared to the copper wire. However, the tensile strength of the pure aluminum is 100 MPa, which is inferior to 230 MPa of the pure copper, then there are concerns about wire breakages and usage of the small diameter aluminum wires which are fewer than the copper wires. For example, in our Company, our own aluminum alloy wire named MSAL (Al-0.2Fe-0.2Cu-0.1Si Alloy) which has a higher tensile strength than the pure aluminum, was developed for the automobile wire harness (WH), and this MSAL has been adopted in the circuits with wires with smaller diameter than usual.[1] We believe that the high strength aluminum alloy which can be used even in small diameters will be required in various industrial fields in the future, and we developed the higher strength aluminum alloy without impairing the electrical conductivity and the flexibility, as shown below.

Within the aluminum alloy series, a precipitation-hardened alloy of the Al-Mg-Si alloy series is known as an alloy that can achieve both the high strength and the high electrical conductivity by dissolving Mg and Si through a solution treatment (ST), and forming Mg_2Si chemical compound by an age-hardening heat treatment. This alloy has been used in applications such as overhead transmission lines. Therefore, increasing the Mg and Si concentration and a high processing rate is effective to improve the strength, however there is an issue in the decrease in the elongation. If the elongation is decreased, it causes a concern that the wire breakage may be happen when subjected to an impact load in attaching to an industrial equipment or during use. Also, the increase of the Mg and Si additive amounts may cause a significant decrease in the electrical conductivity.

We developed the aluminum alloy wire having well balanced characteristics in the tensile strength, the elongation and the electrical conductivity, based on the adjustment of the Mg and Si additive amounts and the optimization of the age-hardening heat treatment and the ST with recrystallization. Also, we found out that Mn is effective as an element to suppress the grain coarsening, because the grain coarsening in the ST induces the decrease in the elongation. In addition, we found that the addition of Ni is effective as an element to improve the impact resistance. In this report, we describe the influ-

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ence of the Mg, Si, Mn and Ni amounts on the metal microstructure and the mechanical properties after the ST and the age-hardening heat treatment.

2. THE TEST METHOD

The composition of the alloys in which the amounts of Mg and Si were varied on the basis of a general Al-Mg-Si series alloy (hereinafter Alloy-1), which has been used for the overhead transmission lines, were investigated. And the Mn and Ni added alloys were melt casted, hot and cold rolled, cold drawn, and then, various characteristics (the mechanical properties, the electrical conductivity, the impact resistance and the fatigue life) were investigated after the ST and after the age-hardening heat treatment.

The ST was performed using a salt bath, and after the heat treatment for a predetermined time, a water cooling was carried out promptly. In the age-hardening heat treatment, the heat treatment was performed in the air at a predetermined temperature and a specified duration. Regarding the mechanical properties, the tensile strength was measured using a sample of 100 mm of gauge length and at a 10 mm/min of crosshead speed. The electrical conductivity was measured with the four terminal method, and the flexural fatigue life was measured with the repetitive alternating bending test method at 0.26% of bending stress on the outer periphery. The microstructure was observed using an optical microscope, and precipitates were observed using a Transmission Electron Microscope (TEM) and a Scanning Electron Microscope (SEM). In the impact resistant investigating test, a device that gives an instantaneous tensile load at a constant initial velocity was built using the wire, and the energy absorbed by the material was comparatively validated.

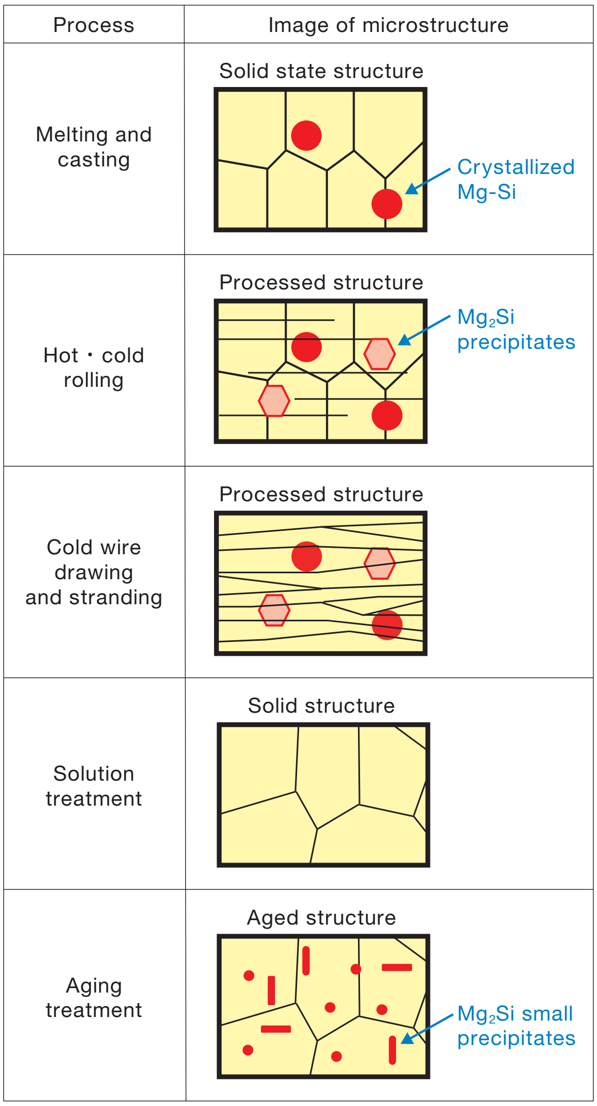


Figure 1 The adopted manufacturing process.

3. THE TEST RESULTS AND CONSIDERATION

3.1 The Optimization of the Mg and Si Additive Amounts

Figure 1 shows the manufacturing process adopted to obtain the high elongation, and the images of the metal microstructure.

In the melting and casting process, the Mg and Si compounds are crystallized and the coarse Mg and Si compounds are precipitated. In the cold rolling process and in the cold wire drawing process, processing strain is generated and the wire becomes hard and brittle. In the ST, by dissolving the crystallized particles and the coarsened precipitates, which do not contribute to high strength, the ductility can be recovered by the recrystallization. After that, the metal structure, in which fine Mg_2Si compounds are precipitated by the age-hardening heat treatment, is obtained.

Figure 2 shows the relationship between the electrical conductivity and the mechanical properties of the materials, with the various additive amounts of Mg and Si, subjected to the ST and also to the age-hardening heat treatment. The electrical conductivity is decreased as the additive amounts of Mg and Si are increased, and when the additive amounts of Mg and Si are decreased, the tensile strength decreases. The elongation tends to improve within the excess Si region, and the optimum composition was decided in consideration of the relationship between the electrical conductivity and the mechanical properties.

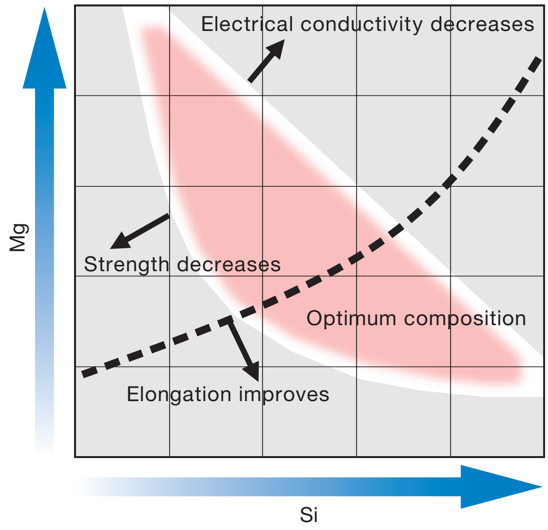


Figure 2 The relationship between the content of Mg, Si and the electrical conductivity or the mechanical properties of the aged Al-Mg-Si alloys.

3.2 The Grain Refining After the ST With Mg Addition

Figure 3 shows the electrical conductivity and the mechanical properties of the Alloy-1 when subjected to 5minutes of the ST at 623 to 893 K. The electrical conductivity decreases as the temperature increases, and shows a tendency to be almost constant at over 793 K, then 793 K is judged to be the solubility temperature. The tensile strength increases with the temperature rise from 623 K to 753 K, and is extremely reduced at over 753 K. The elongation tends to decrease at 623 to 773 K, and tends to increase at over 773 K.

The tensile strength improvement at 623 to 753 K is mainly caused by the solid solution strengthening, and at the temperature over 753 K, we presume that the grain coarsening greatly affects the characteristics. Figure 4 shows the microstructure observation result and the schematic diagram of the S-S curve of the material subjected to the ST at 753 K, 773 K and 853 K. In comparison with the microstructure at 753 K, coarsened large

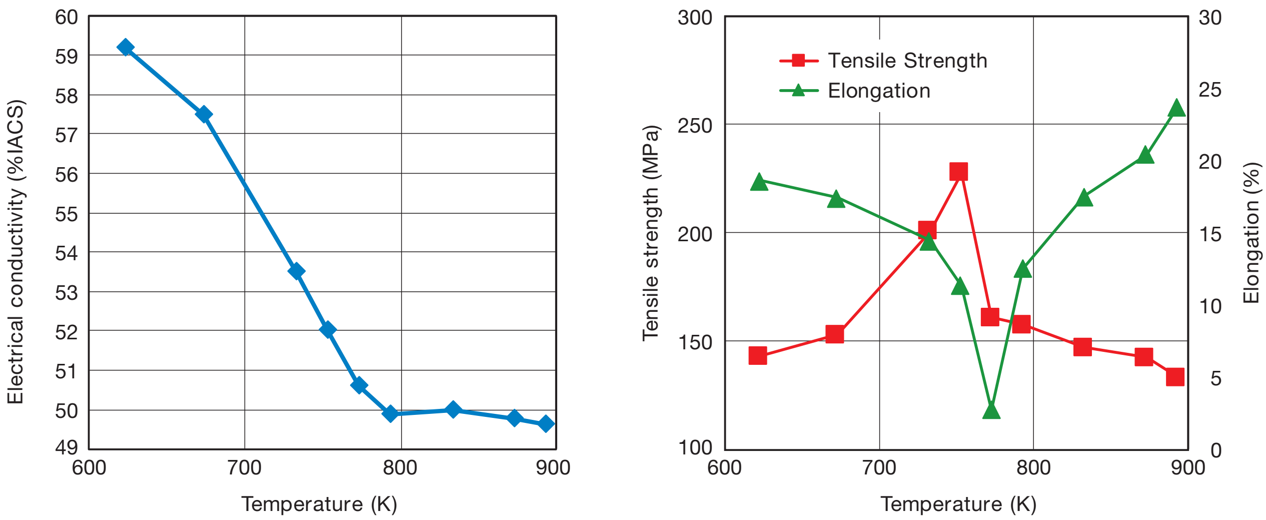
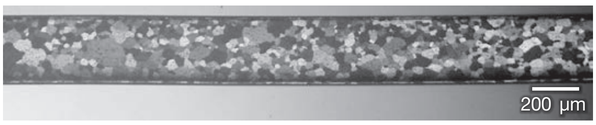
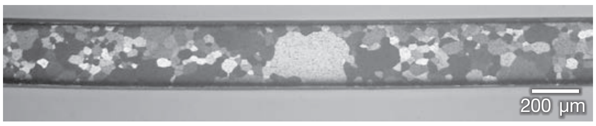
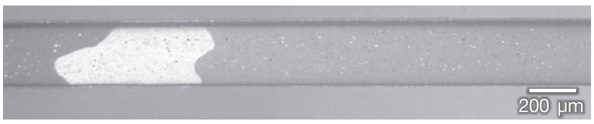
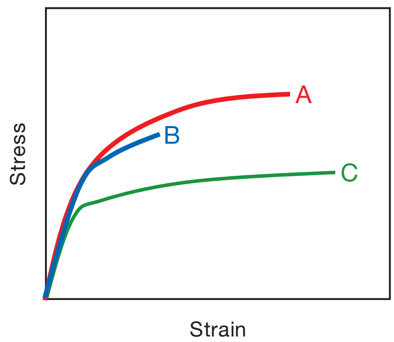


Figure 3 The relationship between the solution treatment temperature and the electrical conductivity, the mechanical properties of the Alloy-1.

	ST temp. K	T.S. MPa	El %	Microstructure
A	753	228	11	
B	773	161	3	
C	853	138	18	



ST temp.: Solution Treatment temperature
T.S.: Tensile Strength
El: Elongation

Figure 4 The relationship between the microstructure and the mechanical properties after the ST of Alloy-1.

crystals can be seen at the broken part of the material treated at 773 K.

The cause of the low tensile strength and the elongation is considered as follow. The grain coarsening part was not fully process hardened due to the local deformation. As the coarsened grains widely existed along the longitudinal direction in the material treated at 853 K, although the coarsened grains were preferentially deformed, a uniform deformation was caused over a relatively wide range, and the high elongation was shown, so far we presume. On the other hand, we presume that the transition was difficult to be accumulated as the grains were coarsened, and the processing hardening amount was reduced so the tensile strength was reduced. Although the improvement in the tensile strength can be expected in the subsequent process of the age-hardening heat treatment, Mg and Si dissolve as the elongation tends to decrease, and it is difficult for Alloy-1 to achieve both the tensile strength and the elongation, then the suppression of the grain coarsening is necessary at the solubility temperature. The result of the investigation for the refinement effect by adding Mn is reported in here.

Figure 5 shows the relationship, between the Mn additive amount and the elongation and the grain structure, of the solution treated Al-Mg-Si series alloy materials which are added with varied Mn amounts. The elongation reduction is suppressed by the addition of over 0.05 mass%, from the microstructure observation result, it can be confirmed that the grain coarsening is suppressed by the Mn addition and the fine and uniform structure can be obtained.

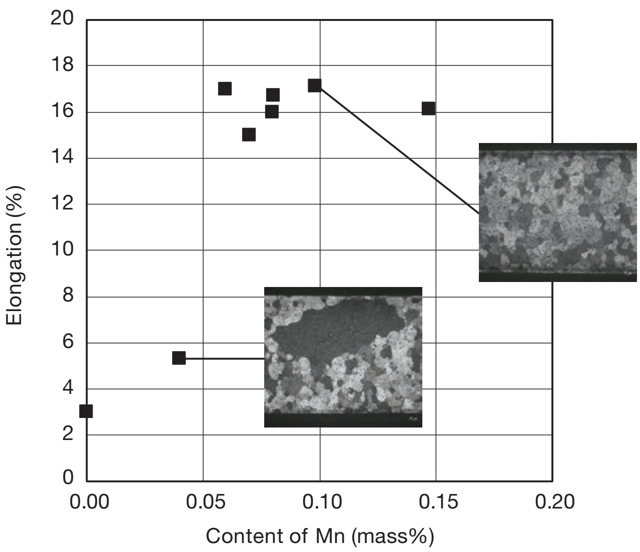


Figure 5 **The relationship between the content of Mn and the elongation of the Al-Mg-Si alloys after the ST.**

Figure 6 shows the SEM image of the Al-Mg-Si alloy after the ST. The presence of many compounds containing Mn are confirmed near the grain boundary, and it seems to contribute to the suppression of the grain coarsening. By optimizing the Mn amount, the ST becomes available at the temperature over the solubility curve, and we succeeded in achieving both the grain refining and the dissolving of Mg and Si.

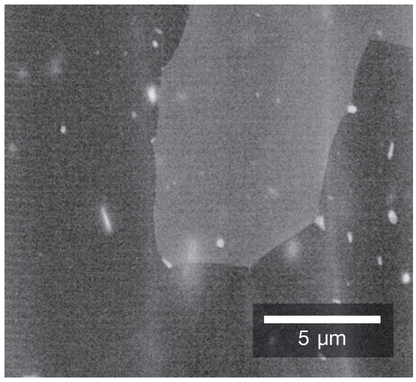


Figure 6 **The SEM image of the Al-Mg-Si alloy to which manganese is added.**

3.3 The Optimization of the Age-hardening Heat Treatment Condition

Figure 7 shows the electrical conductivity, the tensile strength and the elongation of the material subjected to the ST at 733 K and then subjected to the age-hardening heat treatment from 373 to 448 K for 1 to 45 hr. The electrical conductivity and the elongation showed a tendency to increase with the age-hardening heat treatment at a high temperature for a long time, and the fine precipitation of Mg_2Si seems to be in progress. On the other hand, the elongation is rapidly decreasing with the long duration of the high temperature of the age-hardening heat treatment, differing from the tensile strength, where the low temperature short duration of the age-hardening heat treatment is effective to keep the high elongation.

Figure 8 shows the TEM image of the material after the age-hardening heat treatment. The clear contrast of the precipitates are confirmed and these are presumed to be Mg_2Si consistent with the crystalline structure of the aluminum. It is considered that these precipitates contribute to the strengthening of this alloy.

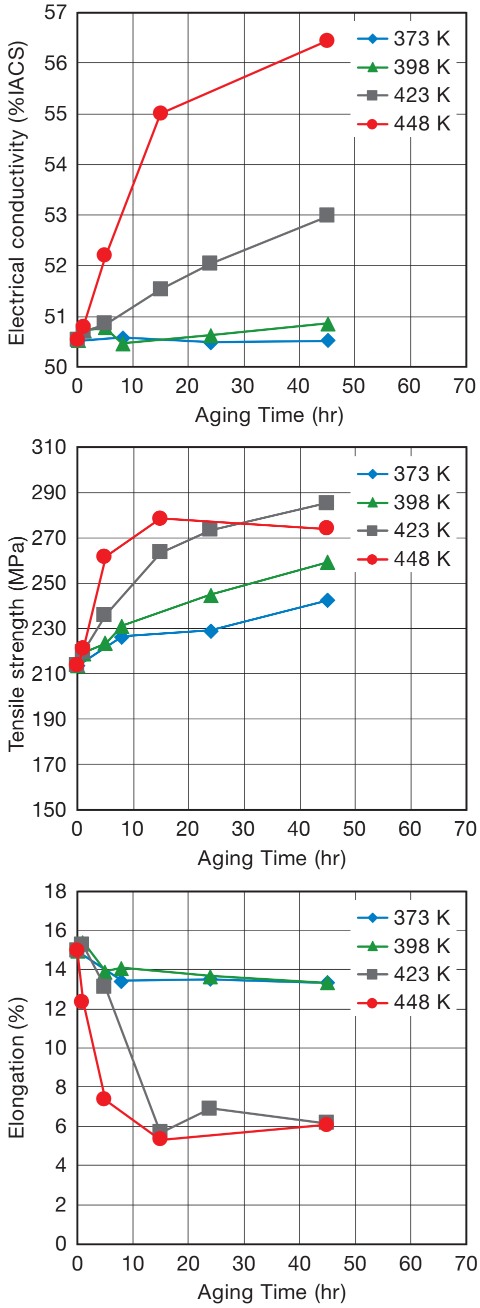


Figure 7 The relationship between the aging condition and the electrical conductivity, the mechanical properties of the Alloy.

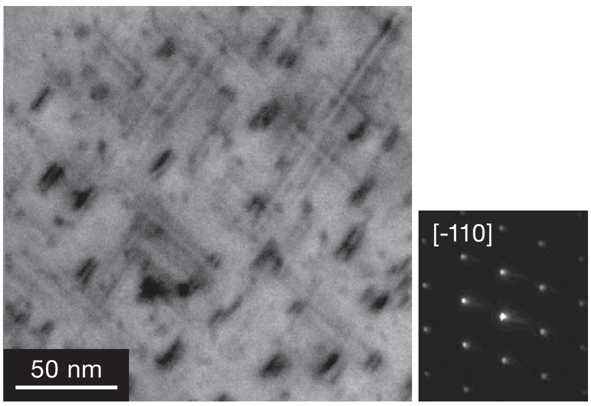


Figure 8 The TEM blight field images of the aged Al-Mg-Si alloy.

3.4 The Improvement of the Impact Resistance by the Ni Addition

In order to improve the impact resistance which is a concern when installing in an equipment, a study for a sub additive element was made. The impact resistance is strongly correlated to the elongation and the tensile strength, then it is effective to make them compatible. In this report, the effect of the Ni addition is reported. Figure 9 shows the relation between the Ni addition amount and the tensile strength, the elongation and the impact resistance. An improvement is shown from approximately 0.05 mass%, and a tendency to increase in tensile strength is shown along with the increase of the Ni amount. On the other hand, the elongation stays at a high level without showing a significant decrease. It is shown that the impact resistance also increases along with the tensile strength. It is presumed that Ni has a large mismatch with the crystal lattice in the mother phase and contributes to the improvement of the tensile strength and the impact resistance mainly by the solid solution strengthening.

3.5 The Flexural Fatigue Test and Confirmation of the Wire Characteristics

Based on the result of the study, up to this point, for the additive elements and the manufacturing process, the flexural fatigue test was carried out on the developed products. Two types of the developed products, with only the age-hardening heat treatment conditions changing, were prepared. The developed product Ⅰ is a material excellent in the balance between the tensile strength and the elongation, and the developed product Ⅱ is the material that further improved the tensile strength by the high temperature age-hardening heat treatment. As comparative materials, a pure aluminum wire and a conventional Cu wire were also evaluated. Figure 10 shows the test result of the alternating bending test using the ϕ0.3 mm of wire under the condition that the surface strain amplitude becomes 0.26%. The developed product Ⅰ has a fatigue life equal to or higher than that of the conventional Cu wire, and the developed product Ⅱ shows a very high flexibility, then both of them can be considered to replace the conventional Cu wire.

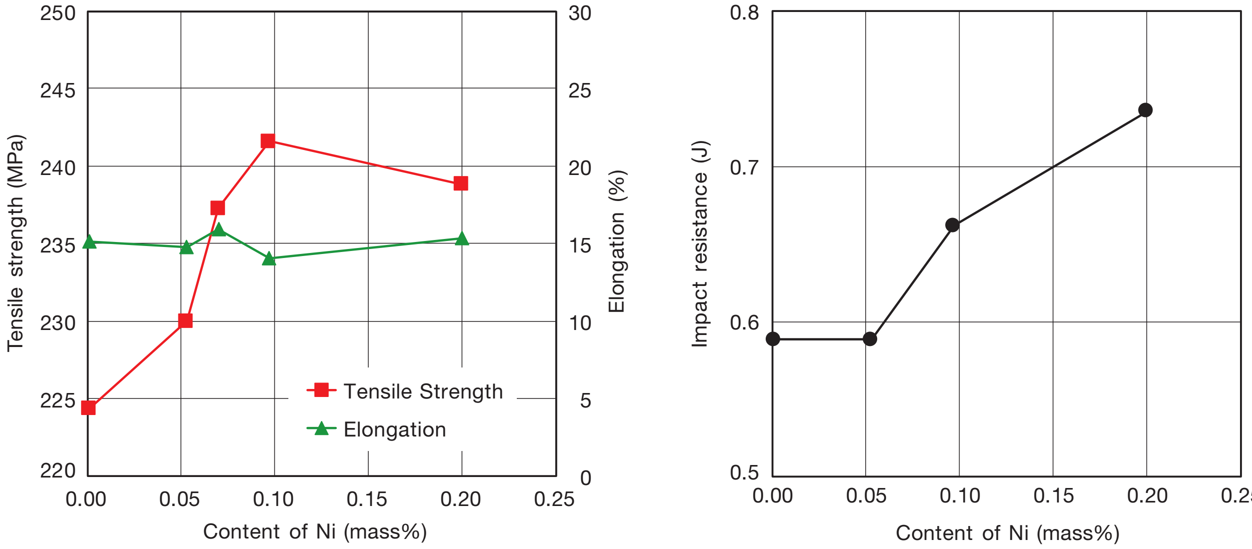


Figure 9 The relationship between the content of Ni and the tensile strength, the elongation and the impact resistance of the Al-Mg-Si alloy subjected to the age-hardening heat treatment.

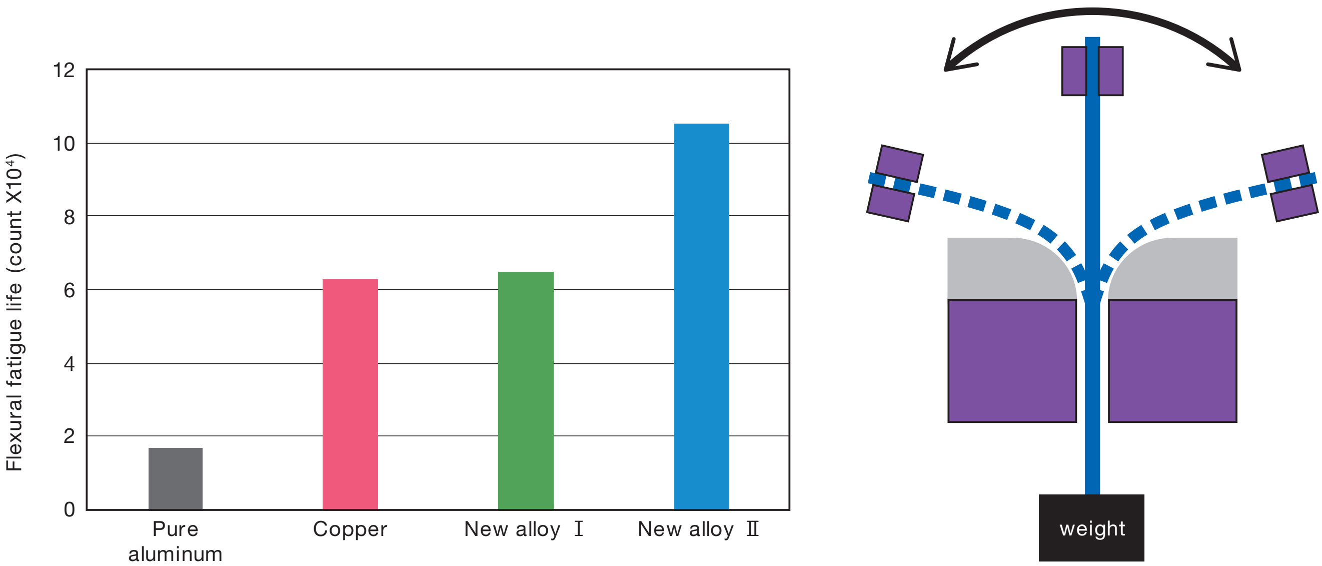


Figure 10 The comparison of the flexural fatigue life between the new aluminum alloy and the pure aluminum and the copper wire.

An actual equipment test of the wires, reflecting the contents of the study in this report, was carried out. The tentative obtained values are shown in Table 1. The wires with 0.35 sq. and 0.5 sq. of cross sectional area have the tensile strength of 250 MPa and the elongation of 15%, showing higher values for the tensile strength of 130 MPa of the pure aluminum wire. The electrical resistance of the 0.35 sq. wire and the 0.5 sq. wire was each approximately 100 mΩ/m and 70 mΩ/m. As a result of this study, we succeeded in the development of the aluminum alloy wire, with a high impact resistance, having a higher tensile strength and a higher elongation than the conventional aluminum wire. We believe that the application range of the aluminum wire can be expanded.

Table 1 The characteristics of the developed wire.

	Tensile strength	Elongation	Conductor resistance
Wire cross sectional area	MPa	%	mΩ/m
0.35 sq.	250	15	100
0.5 sq.	250	15	70

4. CONCLUSION

For the purpose of the development of the aluminum wire which is compatible with the electrical conductivity, the tensile strength and the elongation, based on the Al-Mg-Si series alloy, the manufacturing process and the influence of the additive elements of Mg, Si, Mn and Ni, influencing the mechanical property and the electrical conductivity were investigated. As a result, we obtained the following conclusion.

(1) The effect of Mg and Si additive amounts on the electrical conductivity and the mechanical properties were investigated and we found out the region satisfying the necessary characteristics for the small diameter wire.

(2) The relation between the Mn additive amount and the grain refining effect were investigated, and we succeeded in developing the alloy with the high elongation by optimizing the Mn additive amount, because of the suppression of a grain coarsening during a high temperature solution heat treatment after a cold wire drawing process.

(3) The low temperature aging treatment was adopted and succeeded in balancing the tensile strength and the elongation at the high level.

(4) By adding Ni, the decrease in the elongation was suppressed also the tensile strength was improved, and a high impact resistance was obtained.

We have succeeded in suppressing extreme decrease in the electrical conductivity and the elongation and in improving the tensile strength compared with those of the conventional aluminum wire. The aluminum alloy wire is possible to be adopted in narrow parts of the industrial equipment where a wire with relatively small diameter is required in the industrial wire field. And we anticipate that demands will become increasingly stronger in the future, and that we can contribute to the weight reduction and the cost saving.

REFERENCE

1) S. Sekiya et al., Proceedings of the 60th IWCS Conference (2011), 445.