High-Strength and High-Heat-Resistant Aluminum Alloy Wires for Lightweight Automotive Components

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In the automotive industry, with the goal of reducing CO_2 emissions by improving fuel efficiency, there is a need for high-performance aluminum materials that can contribute to reducing the weight of automotive components. We have been working to improve the strength and heat resistance of aluminum alloys for forged automotive components. By improving the alloy composition and processing methods, we have developed two aluminum alloy wires with higher strength and higher heat resistance than widely used 6000 series aluminum alloys. This paper introduces the development of the aluminum alloy wires and the characteristics of the developed aluminum alloys.

Keywords: forged automotive component, weight reduction, 6,000 series aluminum alloys, high-strength aluminum alloy wire, high-heat-resistant aluminum alloy wire

1. Introduction

In recent years, efforts to achieve carbon neutrality have accelerated in all fields. In the automotive industry, there is a growing need to reduce component weight to reduce CO_2 emissions by improving fuel efficiency. Under such conditions, aluminum is increasingly used as a component material due to its characteristics of being lightweight, strong, and excellent in electrical conductivity and corrosion resistance.

Sumitomo Electric Toyama Co., Ltd., (hereinafter called Sumitomo Electric Toyama) a member of the Sumitomo Electric Group, manufactures a wide variety of high-quality aluminum wire rods, including those for overhead power transmission wires, aluminum alloy wires for automotive components, and high purity aluminum wires for electronic devices.

Sumitomo Electric Toyama and Sumitomo Electric Industries, Ltd. have jointly developed aluminum alloy wires for automotive components, which are excellent in workability, strength, and heat resistance, in order to meet the needs for component weight reduction in the automotive field. This paper reports the details of the technological development and the characteristics of the developed materials.

Table 1. Aluminum alloys manufactured by Sumitomo Electric Toyama

Alloy series	Variety	Feature
Pure aluminum series	99.92%AL 1050 1070 1100	Pure aluminum wires with an impurity content of one percent or less. They are excellent in electrical conductivity, workability, corrosion resistance, and weldability.
Al-Cu series	2014 2017	Alloys made by adding Cu to Al, known as "duralumin." They are excellent in strength and hardness.
Al-Mn series	3003	Alloys made by adding Mn (1.5%) to pure aluminum to increase strength by approximately 20% compared to pure aluminum. They are excellent in corrosion resistance and workability.
Al-Si series	4043	Alloys made by adding Si (4–12%) to pure aluminum. Due to their lower melting point and good flowability, they are used as welding wires and soldering materials. They have a low coefficient of thermal expansion.
Al-Mg series	5052 5056 5356 5154 5183	Alloys made by adding Mg (0.3–5%) to pure aluminum. They have high strength and excellent seawater resistance. Among aluminum alloys, Al-Mg series alloys are used most widely for welded structures. These alloys have good anodic oxidation treatability and stainability.
Al-Mg-Si series	6061 6063 6151 6110 6056	Heat-treatable alloys with high strength, excellent workability, and high corrosion resistance. They also exhibit high anodic oxidation treatability and stainability.
Al-Zn series	7075	A high strength aging alloy known as super-duralumin

2. Aluminum Wire Rods Manufactured by Sumitomo Electric Toyama

The aluminum wire rod lineup of Sumitomo Electric Toyama is shown in Table 1. The company manufactures these wire rods using a Properzi method-based continuous casting and rolling machine (Fig. 1).[(1)]

This machine quickly solidifies the molten aluminum when casting it and does not reheat the wire rod when rolling it, exhibiting the following features: (1) Solute elements rapidly form a solid solution*[1]; (2) Crystallized substances*[2] that embrittle metals are finely dispersed; and (3) Metallurgical structures are refined. Therefore, the

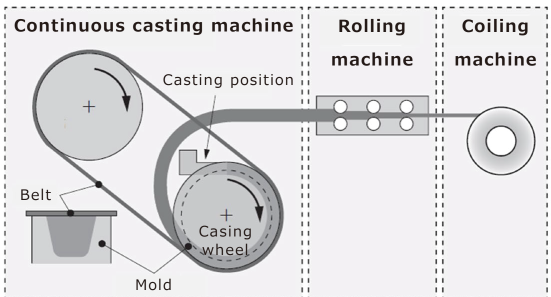

Fig. 1. Schematic illustration of the Properzi method

manufactured alloy wires are not only excellent in strength, but also provide a workability superior to those manufactured by "billet casting and extrusion," a widely used manufacturing method. The Sumitomo Electric Toyama's system is also excellent in productivity and enables the manufacture of long, seamless coils of a maximum unit weight of two tons (Fig. 2).

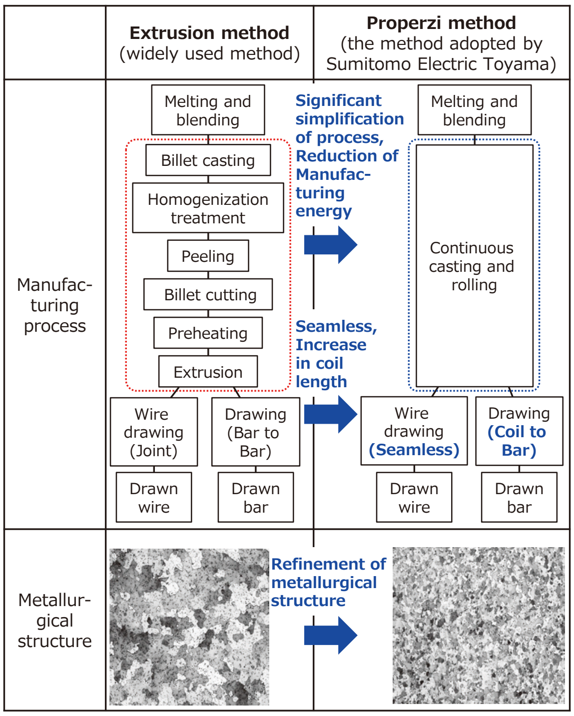

Fig. 2. Features of products manufactured by the Properzi method

3. Requirements for Automotive Components and Their Material

3-1 Growing need for weight reduction of automotive components

With the aim of achieving carbon neutrality, CO_2 emission regulations have been globally imposed on automobiles, and the regulatory values are expected to be tightened in the future. To this end, automakers and automotive component suppliers are making strenuous efforts to develop technologies that can improve fuel economy, and as part of these efforts, they are actively replacing the material of components with aluminum to reduce vehicle weight.

3-2 Requirements for aluminum materials

With the increasing use of aluminum automotive components, efforts are being made to reduce their wall thickness without reducing their strength in order to further reduce the weight of components made by forging.*3 In particular, two types of aluminum materials are required: 1) a high-strength alloy that combines high forge formability with high mechanical properties (tensile strength and 0.2% yield strength) in the room temperature range, and 2) a high-heat-resistant alloy that can maintain high mechanical properties in the range of room temperature to high temperature (150°C) while maintaining the required forge formability.

4. Development of High-Performance Aluminum Alloys

4-1 Development targets

In light of the above-described growing demand for high-strength and high-heat-resistant aluminum materials, we began to develop high-strength and high-heat-resistant alloys. As the base materials, we selected aluminum-magnesium (Mg)-silicon (Si) alloys (6,000 series alloys), which were increasingly used for various forged automotive components.

Table 2 shows the development targets. For the high-strength alloy, the target was to increase the strength by 15% or more while maintaining the same workability (critical compressibility*4 of the H12 material*5) as that of A6061 alloy, a general-purpose material generally used for forged components. For the high-heat-resistant alloy, the target was to improve heat resistance (residual tensile strength after heat treatment at 150°C for 1,000 h) by 5% or more compared to that of general-purpose A6056 alloy, which is generally used in environments where retention of strength at high temperatures is required.

Table 2. Target properties of the alloys to be developed

Evaluation item		Workability	Strength		Heat resistance
Property		Critical compressibility of H12 material	Tensile strength at room temperature	0.2% yield strength at room temperature	Tensile strength†1 after heat treatment at 150°C
		%	MPa	MPa	MPa
General purpose material	A6061	88	370	320	365
	A6056	85	420	375	380
Material to be developed	High-strength alloy	**88 min.**	**430 min.**	**370 min.**	365 min.
	High- heat-resistant alloy	80 min.	420 min.	375 min.	**400 min.**

†1: Residual tensile strength after heat treatment at 150°C for 1,000 h

4-2 Development policy

In this section, the mechanism of increasing the strength of an aluminum alloy is described first, followed by the development policy for high-strength and high-heat-resistant alloys.

(1) Mechanism of increasing the strength of aluminum alloy

When a metallic material such as aluminum receives an external force above a certain level, atoms slide along a specific crystal plane, causing the material to deform. This slide is caused by the movement of "dislocation", which is a region where atomic arrangement is disturbed (Fig. 3). In general, the key to increasing the strength of a metallic material, i.e., making it less susceptible to deformation, is to inhibit the movement of dislocation in some way and thus to prevent atoms from slipping along a crystal plane.

To increase the strength of 6,000 series aluminum alloys, a solution treatment and aging treatment are conducted. In the former treatment, additive elements of

Mg and Si are solid-dissolved in the aluminum matrix until they are supersaturated, while in the latter treatment, the supersaturated Mg and Si in the solid solution are precipitated*[6] as an Mg-Si compound (β” phase). A series of the above treatments is called “T6 treatment.” The β” phase precipitated by this heat treatment is finely dispersed in the aluminum matrix and inhibits the movement of dislocation, thereby increasing the strength of the alloy (Fig. 4).

Another method of increasing the strength of an alloy is to use the solid solution phenomenon. This method utilizes the fact that when an additive element is solid-dissolved in aluminum, a strain field is generated in the crystal lattice due to the radial difference between aluminum atoms and solute atoms. The strain field attracts the dislocation and prevents it from moving around the solute atoms. As a result, the strength of the alloy is increased (Fig. 5).

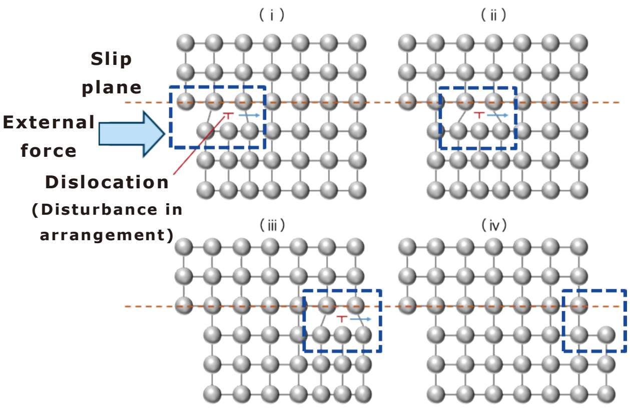

Fig. 3. Deformation of metal due to the movement of dislocation

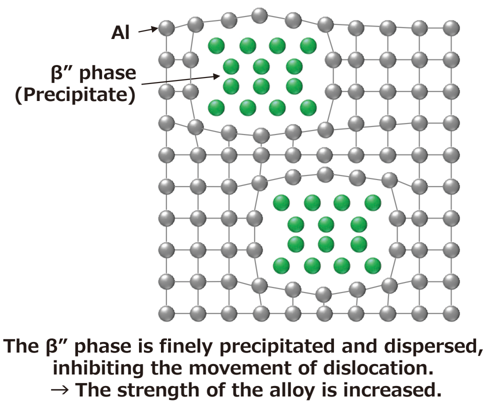

Fig. 4. Increasing the strength of the alloy by T6 treatment

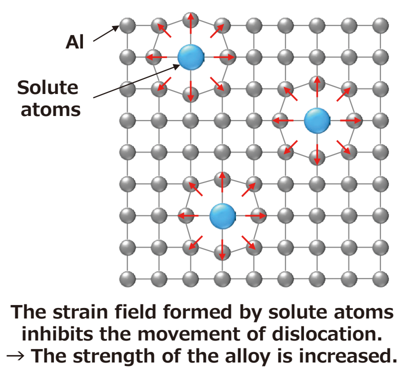

Fig. 5. Increasing the strength of metal by solute atoms

(2) Development policy for high-strength alloy and high-heat-resistant alloy

Sumitomo Electric Toyama uses a Properzi method-based continuous casting and rolling machine. This machine 1) casts aluminum with a relatively small cross-sectional area of 5,000 mm^2 or less and rapidly quenches the molten metal in a water-cooled copper mold, and 2) uses the residual heat from casting for hot working, eliminating the need to reheat the metal. These features provide the wire rod manufacturing process with the following advantages: 1) it is easy for elements with a low equilibrium solid solubility to maintain a supersaturated solid solution state, and 2) even when the concentration of additive elements is increased, the formation of coarse crystallized substances due to segregation during casting can be suppressed and high workability can be obtained.

In light of the above features of the Properzi method, we reviewed the possibility of 1) increasing the strength and 2) improving the heat resistance of aluminum alloys by actively utilizing the strengthening mechanism by solid solution elements described in the preceding section, in addition to precipitation strengthening which is widely used for 6,000 series aluminum alloys.

Figure 6 shows an example of the manufacturing process of forged aluminum alloy components, together with the development concept of new alloys. In the development of new alloys, we formulated a policy of manufacturing wire rods while maintaining a high solid solubility of the elements and suppressing the degradation of workability that would result from an increase in the concentration of additive elements. In practice, the additive amount of specific elements other than Mg and Si was increased during melting and blending, and the conditions for the Properzi method-based continuous casting and rolling were optimized (Fig. 7). When component manufacturers complete the T6 treatment, they would thus be able to

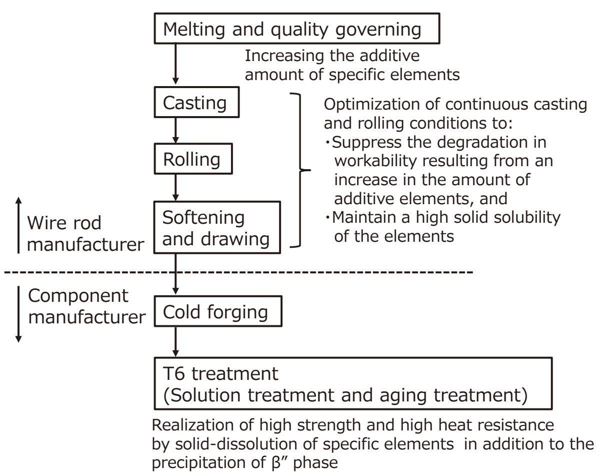

Fig. 6. An example of a manufacturing process of forged components and the concept of alloy development

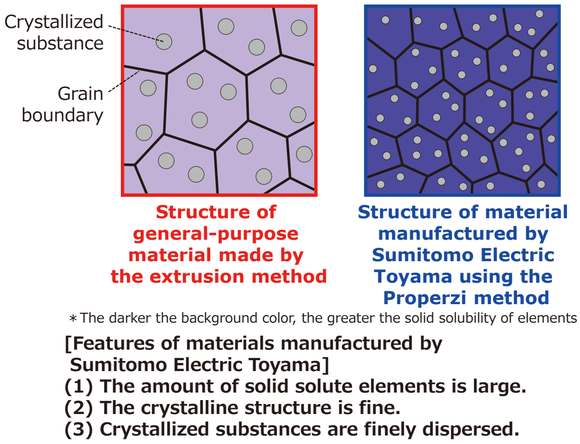

Fig. 7. Comparison in metallic structure between a general-purpose material and Sumitomo Electric Toyama's material

achieve 1) high strength and 2) high heat resistance due to the solid solution phenomenon of the specific elements.

4-3 Selection of an additive element for the development of a high-strength alloy

We focused on iron (Fe) as the element to be solid-dissolved to produce a high-strength alloy. Table 3 shows examples of the magnitude of lattice distortion when each element was added to aluminum and the maximum thermodynamic solid-solubility of each element, which were estimated by first-principles calculation.(2) Fe is an element with extremely high lattice distortion, and we considered that if Fe could be solid-dissolved in aluminum, the resulting high dislocation movement inhibition effect would increase the strength of the aluminum alloy.

Table 3. Lattice distortion and the maximum amount of solid solute in each element

Element	Lattice distortion (%)	Maximum amount of solid solute (at%)	Element	Lattice distortion (%)	Maximum amount of solid solute (at%)
Li	0.7	14	Fe	3.9	0.03
Mg	1.0	18.6	Ni	2.9	0.11
Si	0.6	1.5	Cu	1.6	2.48
Sc	1.0	0.2	Zn	0.4	67
Ti	1.0	0.7	Ga	0.6	9
V	2.5	0.3	Ge	0.2	2
Cr	3.2	0.37	Se	1.8	0.003
Mn	3.5	0.62	Zr	1.0	0.09

4-4 Selection of additive elements for the development of a high-heat-resistant alloy

In 6,000 series aluminum alloys, the β" phase precipitated by the T6 treatment transits to coarser phases such as the β' and β phases when it is exposed to a high temperature of 150°C, and the dispersion interval of the precipitates increases. As a result, the dislocation movement inhibition effect of the precipitates decreases and the strength is lowered. Such a strength reduction phenomenon is generally known as "over-aging."

In the development of a high-heat-resistant alloy, we considered that solid-dissolving in aluminum such as 1) elements that do not easily diffuse in the aluminum matrix and 2) elements that form a large strain field would form a stable strain field that does not easily move even at high temperatures. As a result, it would be possible to improve the heat resistance of aluminum alloy while maintaining its strength by preventing the above-described strength reduction due to over-aging. Then, we focused on chromium (Cr) and manganese (Mn) as the elements that satisfy both 1) and 2) above. Figure 8 shows the temperature dependence of the diffusion coefficient of each element in an aluminum matrix.(3) Cr and Mn are elements that exhibit a small diffusion coefficient in the aluminum matrix and are expected to generate a large lattice strain, as shown in Table 3. Based on the above consideration, we decided to add both Cr and Mn to improve the heat resistance of the aluminum alloys.

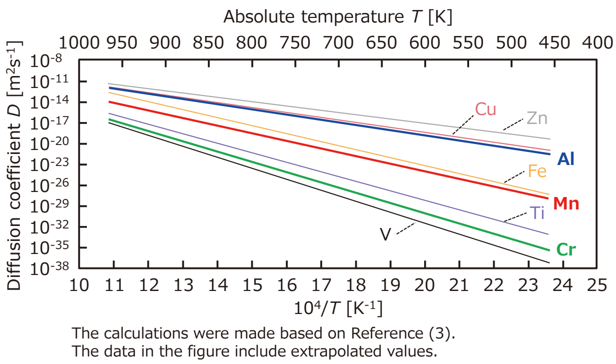

Fig. 8. Diffusion coefficient of each element in aluminum

4-5 Optimization of casting and rolling process

As described above, alloys with a high additive element concentration tend to segregate the components during casting. As a result, we were concerned about the possibility that crystallized substances would become coarse and reduce workability. In general, coarse crystallized substances are less likely to occur at high cooling rates during casting. Therefore, we optimized the casting conditions and further increased the cooling rate to minimize coarse crystallized substances. In particular, we optimized the mold shape, pouring method, cooling water injection method, etc. by making full use of simulation (Fig. 9), and succeeded in casting a high-concentration alloy with a little generation of coarse crystallized substances.

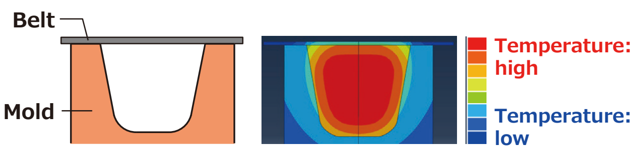

Fig. 9. Schematic illustration of the simulation for optimization of casting conditions

4-6 Properties of the developed materials

Table 4 shows the evaluation results for the workability, strength, and heat resistance of the newly developed high-strength alloy and high-heat-resistant alloy. This table also includes the properties of the general-purpose A6061, A6056, and A7075 alloys.

Table 4. Properties of developed materials

Values given in parentheses () represent development target values.

Evaluation item		Workability	Strength		Heat resistance
Property		Critical compressibility of H12 material	Tensile strength at room temperature	0.2% yield strength at room temperature	Tensile strength[†1] after heat treatment at 150°C
		%	MPa	MPa	MPa
General purpose material	A6061	88	370	320	365
	A6056	85	420	375	380
	A7075	60	550	490	285
Developed material	High-strength alloy	**88** (88 min.)	**440** (430 min.)	**400** (370 min.)	365 (365 min.)
	High-heat-resistant alloy	84 (80 min.)	430 (420 min.)	380 (375 min.)	**410** (400 min.)

†1: Residual tensile strength after heat treatment at 150°C for 1,000 h

The high-strength alloy has been confirmed to have the same workability and 15% or more higher-strength when compared to general-purpose A6061 alloy. Replacing general-purpose A6061 alloy with the newly developed high-strength alloy will make it possible to reduce the wall thickness of conventional components by 15% without degrading their workability and strength, and thus contribute to weight reduction of automotive components and car bodies.

The high-heat-resistant alloy has been confirmed to exceed the heat resistance of A6056 alloy, a general-purpose material widely used in environments requiring high-temperature strength, by more than 5%. Replacing general-purpose A6056 alloy with the newly developed high-heat-resistant alloy will make it possible to assure high strength in high-temperature environments and to save material when manufacturing components, thereby contributing to the weight reduction of automotive components and car bodies.

5. Conclusion

Sumitomo Electric and Sumitomo Electric Toyama have jointly developed a high-strength aluminum alloy wire and high heat-resistant aluminum wire, which are in increasing demand as materials for forged automotive components.

Effective use of the newly developed 6,000 series aluminum alloys for automotive components is expected to contribute to weight reduction of the components and car bodies.

In the future, we will make full use of our component design technology and casting processing technology to develop further high-strength and high-heat-resistant 6,000 series aluminum alloys.

Technical Terms

*1 Solid solution: A state in which additive elements are uniformly dissolved in the solid base metal at an atomic level.

*2 Crystallized substance: A compound different from the matrix metal, which is formed from additive elements dissolved in the molten metal.

*3 Forging: The process of forming metal into a required shape by hammering.

*4 Critical compressibility: The maximum compression ratio at which a wire rod can be processed without generating cracks or other defects when deformed by compressing in the longitudinal direction.

*5 H12 material: A wire rod made by drawing the original material so that its hardness becomes one-fourth with a few percent decrease in cross-sectional area after softening.

*6 Precipitation: A phenomenon in which an additive element dissolved in a solid metal in an atomic state forms a compound different from the matrix metal.

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