Heatproof Aluminum with Excellent Electric Conductivity and Thermal Conductivity

Toru MAEDA*, Hiroka MIYAZAKI, Rui IWASAKI, Ryohei KOBAYASHI, and Miki MIYANAGA

We have developed a new aluminum material that has electrical conductivity and thermal conductivity close to those of pure aluminum, while maintaining strength even at high temperatures. As international regulations on carbon neutrality and CO_2 emissions are being tightened at an accelerating pace, and emphasis is being placed on thermal management of electric devices and communication devices that contain high power semiconductors, aluminum materials are expected to be an alternative solution to copper-based materials for their light weight, high electrical conductivity, and high thermal conductivity. However, their application range is limited due to the decrease in strength at high temperatures above 150°C. Using powdered aluminum obtained by a quenching solidification method as a raw material, we have succeeded in developing a new aluminum material that maintains strength up to a high temperature of around 250°C, while also maintaining electrical conductivity and thermal conductivity close to those of pure aluminum. We are confident that this new material can meet the needs for lightweight conductive parts and heat dissipation products.

Keywords: aluminum alloy, weight reduction, thermal management, heatproof

1. Introduction

Recently, because in every part of the world, CO_2 emissions regulations and carbon neutral-oriented policies are being promoted, there are calls for both materials and systems to be innovated from the perspectives of weight reduction and thermal management. For example, for mobile devices, including smartphones, emphasis is placed on measures used to control heat generated by semiconductor devices, as a result of increasing channel capacity as exemplified by 5G and 6G. Accordingly, thermal management mechanics such as heat pipes and vapor chambers have come into use.

These thermal management mechanics have conventionally used copper-based materials, exhibiting high thermal conductivity*[1] and assuring reliability in terms of strength and heat resistance. Meanwhile, aluminum-based materials are also heat-dissipating materials with about twice the thermal conductivity per unit weight than that of copper-based materials. Taking into account increases in weight, it is highly probable that replacement with aluminum-based materials will increase in importance from the perspectives of energy efficiency and total CO_2 emissions. We have newly developed an aluminum material that, as an alternative to copper-based materials, ensures compatibility between thermal conductivity and reliability in strength and heat resistance. This paper reports on the basic results of the new material development.

2. Challenges to Aluminum-Based Materials and Solutions

Figure 1 summarizes the relationship between strength and thermal conductivity[(1)] of various aluminum alloy materials specified in Japanese Industrial Standard (JIS) H 4000:2014, which refers to ISO 6361-5. ADC12 is a casted aluminum material same to AlSi12 (a), specified in ISO 3522. Pure aluminum (1000-series alloys) exhibits the highest thermal conductivity. However, high-strength alloy materials come with declining thermal conductivity; there is a tradeoff relationship between their strength and thermal conductivity.

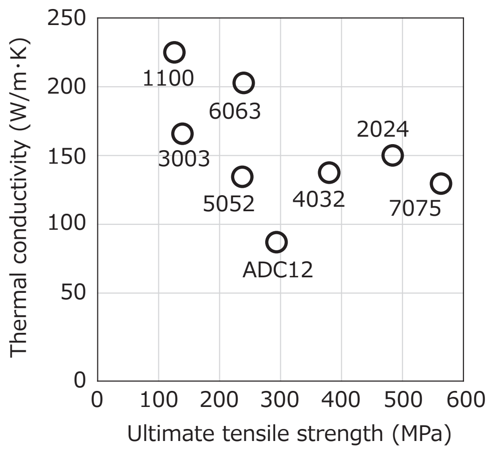


Fig. 1. Tensile strength and thermal conductivity of major aluminum alloys

The ultimate tensile strength of general pure copper materials lies between 250 and 300 MPa. Considering this, expectations are placed on the 6000-series alloys (the Al-Mg-Si series). However, use of these alloys as an alternative material has not spread because their strength decreases by half at 150°C. At present, no such aluminum alloy has been commercialized that is more advantageous than copper materials in terms of weight reduction, electrical and thermal conductivity, and mechanical reliability (high-temperature strength).

The strength of aluminum alloys is enhanced through three representative mechanisms of solid-solution, age, and precipitation hardening, as illustrated in Fig. 2.

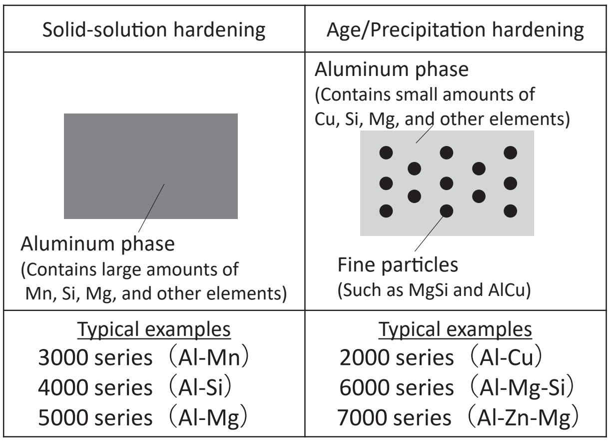


Fig. 2. Principal hardening mechanisms of aluminum alloys

Solid-solution hardening is the phenomenon of an aluminum phase increasing in strength due to an impurity element dissolving into it. Representative examples include the 3000-series alloys that use manganese (Mn) as the impurity element, the 4000-series alloys that use silicon (Si) as the impurity element, and the 5000-series alloys that use magnesium (Mg) as the impurity element.

In contrast, age or precipitation hardening involves heat treatment of aluminum containing impurity elements in a solid solution state. The treatment causes the phenomenon of improved strength, as the impurity elements separate from the aluminum phase and occur in a dispersed manner in the aluminum phase as fine particles nanometers (nm) to micrometers (µm) in size. Typical examples include the 2000 series alloys using copper (Cu) as the impurity element, the 6000 series alloys using magnesium (Mg) and silicon (Si), and the 7000 series alloys using zinc (Zn) and magnesium (Mg).

Both hardening mechanisms occur by dissolving impurity elements, such as silicon, magnesium, manganese, and copper with high solubility, into the aluminum phase in the manufacturing process. Therefore, the final product retains a significant amount of impurity elements in the aluminum phase. Thus, the hardening mechanisms reduce thermal and electrical conductivity*2 substantially from those of pure aluminum.

Sumitomo Electric Industries, Ltd. strived to work out a solution to this challenge by delving into its technologies used to manufacture sintered iron powder materials (Lubrite)[2] and extruded aluminum powder materials (SUMI ALTOUGH).[3] As an impurity element, iron was selected, which has low solubility to aluminum and can be procured at low cost. The intent behind the use of an impurity element with low solubility was to avoid decreases in thermal and electrical conductivity by reducing the amount of the impurity element remaining in the aluminum phase. The result was the development of an aluminum material with: twice the strength of the previous material at 200°C and better electrical and thermal conductivity per unit weight than copper materials. This aluminum material offers the features described below.

3. Features of the Newly Developed Aluminum Material

3-1 Manufacturing process and workability

One notable feature of the newly developed aluminum alloy is the amount of iron added as the impurity element, which is as high as 10 mass% at the maximum, while the conventional limit of the amount of iron in aluminum alloys was 1.5 mass%. To manufacture this material, first, a liquid quenching method is used to produce an aluminum material in the form of powder or ribbons with a prescribed amount of the element iron added, then the material is fine-structured through a powder extrusion process*3 and formed into a round bar or strip, as pictured in Photo 1.

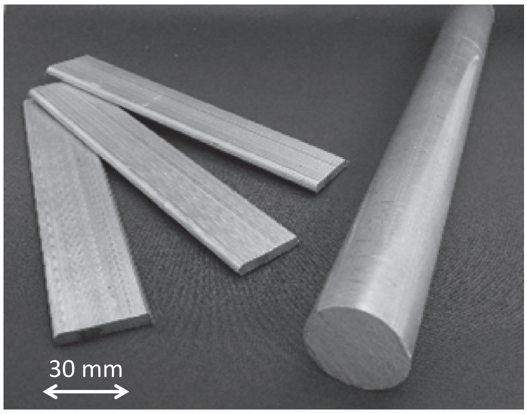


Photo 1. Newly developed material, extruded

The liquid quenching method employs a technique such as jetting out prescribed molten metal (e.g. aluminum and iron) onto a copper roll (melt spinning process) or spraying a cooling gas or a mist of cooling water (atomization process) onto molten metal. The method allows the metal to solidify in a short amount of time 1/100 to 1/10,000 of that required by the conventional technique involving pouring metal into a mold followed by cooling. The amount of iron that can be added increases with the shorter cooling time. Consequently, it is necessary to select a suitable quenching technique for the amount of iron added. This report describes a material prepared through the melt spinning process.

Photo 2 compares the internal structure of an aluminum material—prepared through this technique with the amount of iron added equal to 5 mass% (Al 5 mass% Fe)—with that of a conventional aluminum ingot. The region of aluminum matrix phase (grey portions) consists of aluminum at a proportion of 99 mass% or more. The region of precipitation (white portions) contains iron at a proportion of 10 mass% or more. By making the material of the precipitation region harder and higher in melting point than pure aluminum, the high-temperature strength of the aluminum material increases. The size of the precipitation region should be noted. While it is coarse in the ingot at a few micrometers, it is fine, on a submicron scale, in the material produced through the melt spinning process. With coarse precipitation, the material is of little practical use because cracks develop when it is bent or rolled. In contrast, one feature of materials produced through the liquid quenching method is that this issue can be avoided.

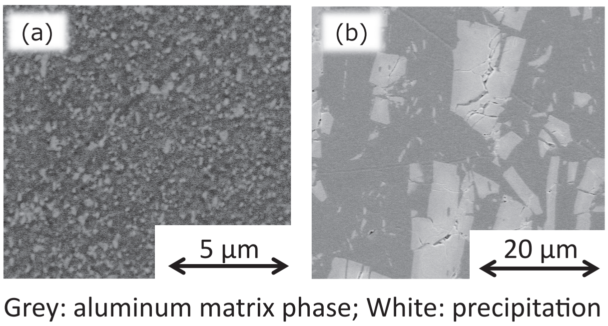


Photo 2. Internal structures of the newly developed material (a) and conventional ingot (b)

Photo 3 shows the results of a cold compression test as an example of workability. Even after undergoing substantial deformation at a degree of processing of 60%, the material remained in a healthy state with no cracks developing in the surface.

This material is expected to be suitable for cold bending and drawing. It is thought to be a potential substitute for many currently used heat dissipating parts and conductors made of a copper-based material.

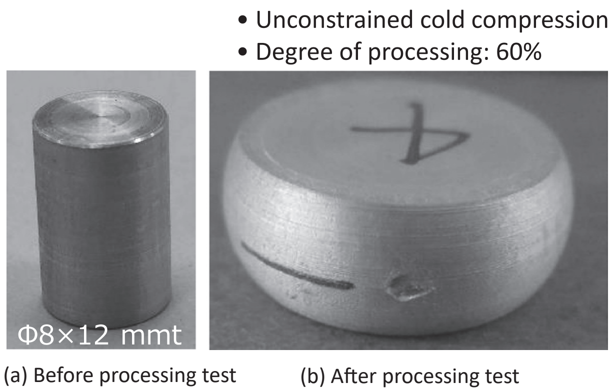


Photo 3. Cold compression test on the newly development material

3-2 Properties of the newly developed material

This section describes the properties of the newly developed material. Figure 3 shows the relationships between thermal conductivity and ultimate tensile strength at room temperature, and between electrical conductivity and ultimate tensile strength at room temperature of the newly developed material in a comparison with various aluminum alloys[1] specified in JIS H 4000:2014. Codes such as 1100 shown in the figure are JIS alloy codes. These are a group of heat-treated materials that exhibit elongation at break of 10% or more when subjected to a tensile test at room temperature.

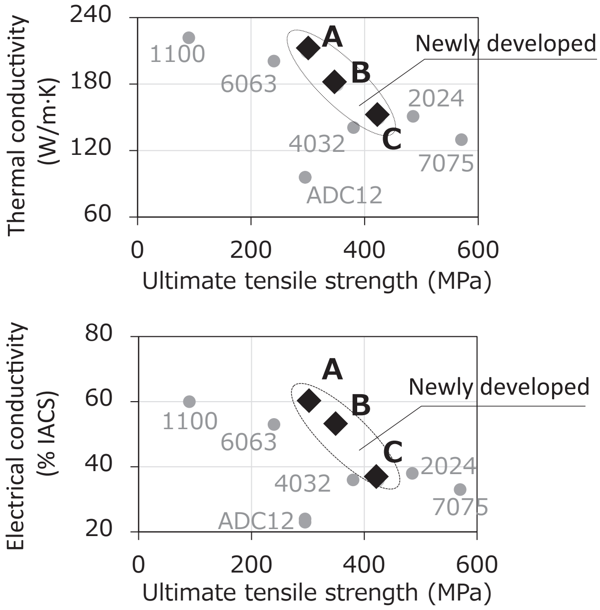


Fig. 3. Thermal/electrical conductivity vs. tensile strength

The graphs show the results for pieces A, B, and C of the newly developed material, which differed in quality depending on the amount of iron added. One major feature of them is that they are stronger than JIS materials in regions of high electrical and thermal conductivity. Notably, material A exhibited a comparable strength level to pure copper (approx. 250 MPa), while maintaining similar levels of thermal and electrical conductivity to those of pure aluminum (1100). It is a better balanced material than the 6000-series alloys (6063). Consequently, the structure with a fine precipitation phase produced by melt spinning, as shown in Photo 2 (a), was effective for strength improvements. Meanwhile, materials B and C contained larger amounts of iron added than material A. They exhibited increased strength, but tended to decline in thermal and electrical conductivity. Thus, it is important to fine-tune the amount of the precipitation phase.

Next, Fig. 4 plots the test temperature dependence of ultimate tensile strength. JIS materials, except for ADC12 alloys with poor thermal conductivity, sharply declined in strength at test temperatures above 100°C, and, at around 150°C, became less strong than their room-temperature strength by a factor of 50% or more.

This is likely the cause of the difficulty in using them as electric parts in locations where high reliability requirements need to be fulfilled for strength. In this respect, the newly developed material is advantageous, because it does not exhibit any sharp decrease in strength up to around 250°C, maintaining its strength higher than 50%. Regarding this advantage, the key to the strength imparted in the newly developed material is that the precipitation consisting of aluminum containing a large amount of iron is a substance that is stable at high temperatures. The contributing factor is the absence of changes that reduce strength—such as the size of the precipitation becoming coarse—up to around 400°C. Thus, the newly developed material is expected to be adapted to uses, for which aluminum materials have been avoided due to their decreasing strength at high temperatures.

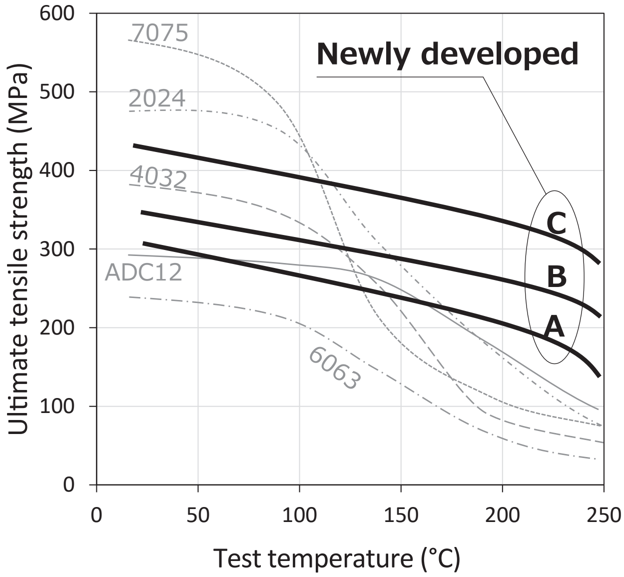


Fig. 4. Temperature dependence of ultimate tensile strength

Photo 4 presents the results of a salt spray test conducted on newly developed material A and JIS materials. The salt spray test was conducted under the condition of spraying a 5% sodium chloride (NaCl) solution for 240 h. The newly developed material exhibited comparable corrosion resistance to the 1000 and 5000 series of high-corrosion-resistant aluminum alloys, at a low-level weight change of 0.03%. If the additive element iron is present as a coarse precipitation phase, it is predicted that galvanic corrosion*4 progresses between the dissimilar metals of the precipitation and the aluminum phase. However, the precipitation comprising a stable compound of aluminum and iron is very finely dispersed in the newly developed material. Therefore, it is highly probable that galvanic corrosion occurred only in limited areas of fine precipitation, delaying the rate of corrosion development in the depthwise direction.

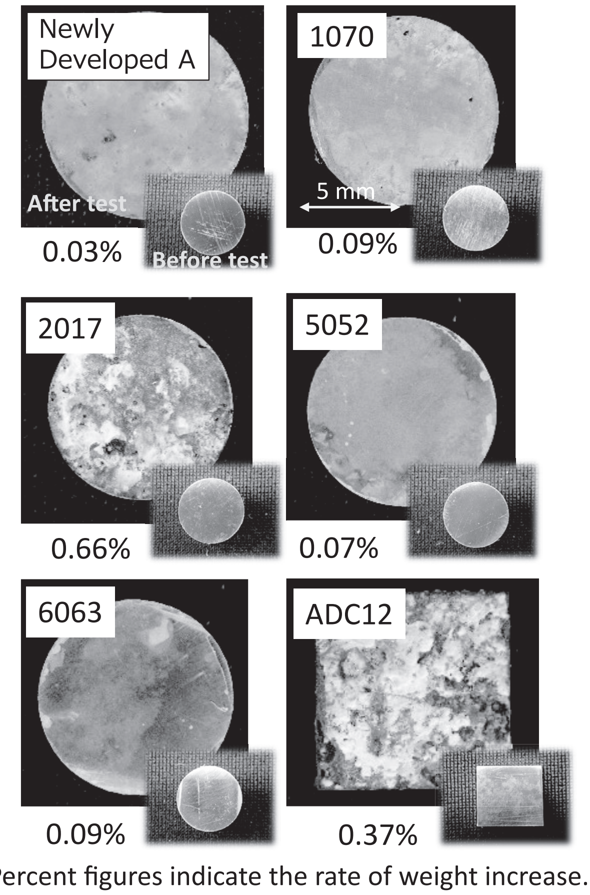


Photo 4. Salt spray test results

Tables 1 and 2 compare the newly developed material A, the 6000 series, and pure copper in thermal conductivity, electrical conductivity, and tensile strength. Property values are shown on the left side of each performance column, while the material weights required to achieve comparable performance to pure copper are shown on the right side of each performance column. The expected weight reduction benefits of the newly developed material against pure copper are substantial at more than 40% in terms of thermal and electrical conductivity and at 60% in terms of tensile strength at 120°C. Consequently, high expectations are placed on the material's use as an alternative to copper.

Table 1. Thermal and Electrical Conductivity Comparison

	Thermal conductivity		Electrical conductivity	
	W/mK	Weight/ Thermal conductivity (Cu = 1)	%IACS	Weight/ Electrical conductivity (Cu = 1)
Al alloy (Newly developed material A)	210	0.59	60	0.52
Al alloy (6063)	201	0.59	53	0.57
Pure Cu (1020)	394	1	101	1

Table 2. Comparison in Ultimate tensile strength

	Ultimate tensile strength (Room temperature)		Ultimate tensile strength (120°C)	
	MPa	Weight/ Strength (Cu = 1)	MPa	Weight/ Strength (Cu = 1)
Al alloy (Newly developed material A)	300	0.33	270	0.34
Al alloy (6063)	240	0.40	200	0.45
Pure Cu (1020)	320	1	300	1

4. Summary

Using a liquid quenching method, we developed an aluminum alloy with a high level of workability that achieves compatibility between electrical and thermal conductivity, corrosion resistance and high-temperature strength. The material is expected to meet the need for lightweight conductors and heat-dissipating parts.

5. Acknowledgments

We are grateful to Professor Katsuyoshi Kondoh at the Joining and Welding Research Institute, Osaka University for his invaluable support to our prototype extrusion of powdered aluminum.

Technical Terms

∗1 Powder extrusion process: An engineering method of simultaneously imparting a fine structure and a shape to powdered aluminum or similar material by consolidating the material to between 70 and 95 volume%, heating it from 300°C to 500°C to make it soft, and passing it with pressure through a die opening formed to the prescribed shape.

∗2 Thermal conductivity: An indicator of how much heat a material can conduct. With a higher thermal conductivity, the material conducts heat better and is useful as a heat-dissipating material.

∗3 Electrical conductivity: An indicator of how much electricity a material can conduct. As a reference, standard annealed copper (volume resistivity = 1.7241×10^{-2} μΩ·m) has a conductivity of 100% IACS.

∗4 Galvanic corrosion: A corrosion phenomenon in which, when the contacting surfaces of dissimilar metals are in contact with moisture or other electrolyte, the metal with a relatively high solubility dissolves in an accelerated manner.

References

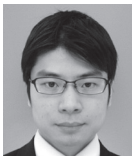
(1) The Japan Institute of Light Metals, 1991, “Aruminiumu no soshiki to seishitsu (in Japanese)”
(2) D. Harimoto, et al., “Progressed Sinter Brazing Technology Enables the Production of Complex Shaped Parts,” SEI TECHNICAL REVIEW, No.82 (April 2016)
(3) T. Tokuoka, et al., “Development of High-Strength, Heat-Resistant Aluminum Alloy Made by Powder Forging Process,” SEI TECHNICAL REVIEW, No.61 (January 2006)

Contributors The lead author is indicated by an asterisk (∗).

T. MAEDA*
• D. eng
Senior Assistant Manager, Advanced & Materials Laboratories

H. MIYAZAKI
• Assistant Manager, Advanced & Materials Laboratories

R. IWASAKI
• IoT R&D Center



R. KOBAYASHI
• Advanced & Materials Laboratories

M. MIYANAGA
• Group Manager, Senior Assistant Manager, Advanced & Materials Laboratories