

Study of Heat Treatment Conditions that Impact Thermal Conductivity of Aluminum Casting Alloy

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ABSTRACT

An approach was studied that sets the heat treatment conditions to increase thermal conductivity after achieving the mechanical properties demanded of aluminum casting alloy parts. The heat treatment conditions that increase thermal conductivity were verified by focusing on the behavior of solute atoms that solid solute in the aluminum metal matrix and obstruct thermal conduction in AC4B, an aluminum casting alloy used as a material for cylinder heads. This study is applicable to heat treatment type aluminum alloy in general, and can also be expanded to aluminum alloy parts with high demand for heat dissipation properties. In addition, the close relationship between thermal conductivity and electrical conductivity indicated the potential for a simple alternative method of measuring thermal conductivity.

1. Introduction

The heat treatment specs of aluminum alloy are known to influence thermal conduction, and Table 1 shows the heat treatment temper designation and thermal conductivity of aluminum wrought products⁽¹⁾. Thermal conductivity is influenced by the amount of solute atoms that are solid soluted (the amount of solid solution) in the aluminum metal matrix. Solute atoms in solid solution are consumed only by room temperature aging precipitation, and T4 treatment that has a high residual amount of solid solution exhibits the lowest thermal conductivity. In T6 treatment, the solute atoms are further consumed by the artificial aging treatment described hereinafter, so thermal conductivity is restored. In O materials, most of the solute atoms are consumed in coarse precipitates, resulting in the highest values. Similar tendencies are present in typical 2000 series alloy that is strengthened by Cu-based precipitates and in typical 6000 series alloy that is strengthened by Mg₂Si precipitates. These results indicate that thermal conductivity is influenced by the amount of solid solution of the residual solute atoms, regardless of the type of solute atom. On the other hand, the heat treatment conditions for aluminum alloy are mainly set for material strength, and in particular with regard to aluminum alloys for castings that are made of recycled materials, there is no known mention of the detailed effect on thermal

Table 1 Thermal conductivity of aluminum alloy with various temper designations

Alloy	Temper designation	Thermal conductivity (20°C) kW/(m·°C)
2014	T4	0.13
	T6	0.15
	O	0.19
2024	T3, T4	0.12
	T6, T81	0.15
	O	0.19
6061	T4	0.15
	T6	0.17
	O	0.18
6051	T4	0.16
	T6	0.17
	O	0.20

conductivity. Parts made of aluminum casting alloy are often used in power units that demand heat dissipation performance, such as internal combustion engines. Thermal load tends to increase as size reduction progresses, so it is thought that the thermal conduction of aluminum casting alloy will become a key functional element in considering future parts development.

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2. Objective

In order to know the influence of heat treatment on thermal conductivity, it is necessary to understand the solid solution and precipitation behavior of solute atoms in aluminum alloy. This study explores the approach of setting heat treatment conditions that increase the thermal conductivity of the AC4B alloy used in the cylinder heads of automobile, motorcycle, and outboard engines after achieving the demanded material properties. An approach is also proposed for control of thermal conductivity including other aluminum alloys.

3. Heat Treatment Conditions that Increase Thermal Conductivity

3.1. Solid Solution and Precipitation Behavior of Solute Atoms in Heat Treatment

First, an overview of the solid solution and precipitation of solute atoms that occur in heat treatment that elicits the material strength of aluminum alloy is explained. Figure 1 shows the typical pattern of T6 and T7⁽¹⁾ heat treatment performed on aluminum alloy. Solution treatment refers to holding at the solution treatment temperature to solid solute the solute atoms in the aluminum matrix and then rapidly

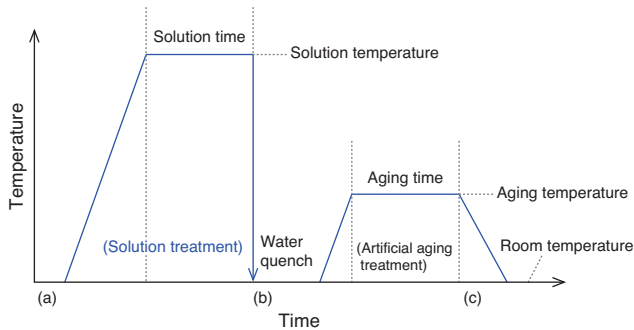


Fig. 1 Typical pattern of T6 and T7 heat treatments for aluminum alloy

cooling such as by water quench to achieve a solute atom supersaturation state. Artificial aging treatment (hereinafter, aging treatment) refers to holding at the aging treatment temperature to artificially precipitate the supersaturated solute atoms and obstruct the movement of dislocations of the aluminum metal matrix after that in order to suppress the deformation behavior of the metal and increase the material strength.

Figure 2 shows a schematic diagram of each state of the solute atoms in the aluminum metal matrix in process stages (a), (b), and (c) in Fig. 1. Figure 2(a) is a simplified model of a coarse precipitate formed in the initial stage due to the slow solidification rate in aluminum alloy casting raw materials. (b) is the state in which the solute atoms undergo solid solution into the aluminum matrix by solution treatment, and (c) is the state in which the solute atoms are formed as precipitates that contribute to enhancement of material strength by aging treatment.

The age hardening characteristic that occurs due to the movement and precipitation of solute atoms is known to be influenced not by the amount of solid solution of solute atoms that changes according to the solution holding time, but rather by the atomic vacancy density formed in the aluminum matrix based on the solution treatment temperature⁽²⁾. Equation (1) expresses the atomic vacancy density $C_v^{(3), (4)}$. Here, A is a constant (2 to 5), H_F is the atomic vacancy formation energy, k is Boltzmann's constant, and T is the absolute temperature.

$$C_v = A \cdot \exp[-H_F / (k \cdot T)] \quad (1)$$

As the atomic vacancy density is a function of temperature, it is determined by the holding temperature of the solution treatment, and those atomic vacancies are fixed in the aluminum matrix by water quench. Figure 3 shows a schematic diagram of how solute atoms move due to atomic vacancies. With regard to the movement of atoms, the energy barrier is lowered by passing through atomic vacancies, and thus the amount of aluminum atom and solute atom movement per unit time depends on the atomic vacancy density⁽⁵⁾.

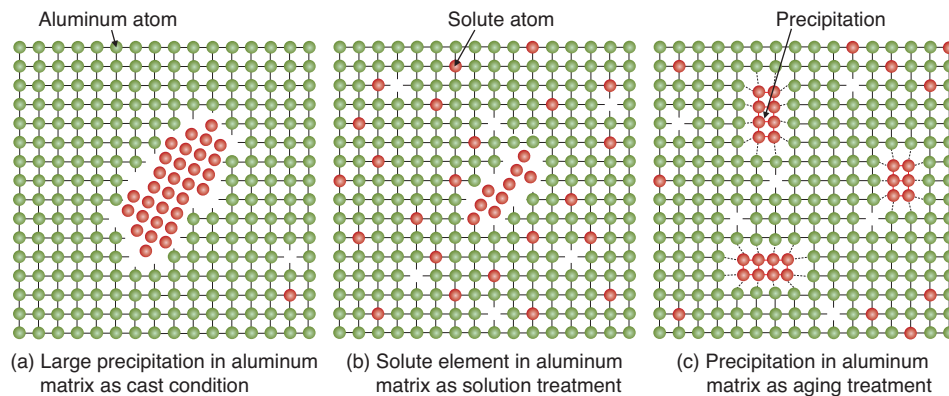


Fig. 2 Diagram of solid solution and precipitation in aluminum alloy

This section will verify that the age hardening characteristic depends only on the atomic vacancy density formed in the aluminum matrix based on the solution treatment temperature and not on the amount of solid solution of solute atoms determined by the solution holding time. Figure 4 shows the relationship between the solution holding time and the mechanical properties of the AC4CH alloy used in cast wheels. The solution treatment temperature was standardized at 540°C and the aging treatment condition was standardized at 140°C × 150 minutes. Precipitation hardening of the AC4CH alloy is due to Mg₂Si precipitates. As the solution holding time increases, solid solution of the solute atoms progresses and the amount of solid solution increases, but there is little effect on the mechanical properties even if the solution holding time is extended. This indicates that the age hardening characteristic is influenced by the atomic vacancy density, which is determined by the solution treatment temperature. Figure 5 shows the relationship between the solution holding time and elongation under the same heat treatment conditions as in Fig. 4. The reason why elongation increases together with the solution holding time is that spheroidization of eutectic silicon progresses and the crack propagation speed decreases. The objective of Sr addition in cast wheels is to increase the fineness of the eutectic silicon in order to stabilize the elongation characteristic and help achieve the demanded shock absorption characteristics. Sr addition helps to enhance production efficiency by shortening the solution holding time within the range that can help achieve the elongation value that is important in terms of the part requirement characteristics. As such, it is used as an effective method in materials for cast wheels.

3.2. Age Hardening Characteristic and Thermal Conductivity of AC4B Alloy

AC4B alloy for aluminum castings has a good balance of castability, mechanical properties, and high temperature characteristics, and is widely used as a material for cylinder heads. Table 2 shows the composition of the AC4B alloy test sample used in this study.

Figure 6 shows the age hardening characteristic due to aging treatment temperature of AC4B alloy after solution treatment at 500°C × 360 minutes. In order to remove the

Table 2 Chemical composition of AC4B alloy test sample

	(wt%)					
	Si	Cu	Mg	Fe	Zn	Mn
AC4B sample	8.2	2.7	0.34	0.76	0.67	0.24

influence of room temperature aging that occurs between solution treatment and aging treatment, all test pieces were stored at -20°C from immediately after solution treatment by water cooling until loading into the aging treatment furnace. In addition, a hot air circulation type drying furnace was used to keep a constant temperature in aging treatment. The main precipitation hardening of AC4B alloy is due to Cu-based precipitates.

With aging at 150°C to 180°C, the hardness is initially around HRB 60 due to metastable precipitates called the GP(1) zone and then increases due to the formation of an intermediate phase called the GP(2) zone⁽⁶⁾⁻⁽⁹⁾. With aging at 200°C to 235°C, hardening due to precipitation of the intermediate phase progresses from the initial stage, resulting in hardness of about HRB 75. Then, as the aging time increases, the intermediate phase coarsens and becomes the stable phase, and softening occurs.

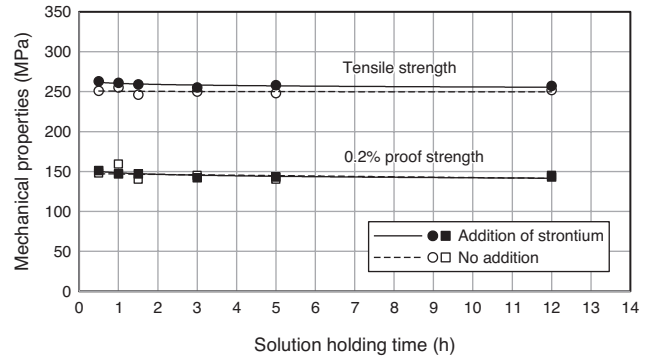


Fig. 4 Effect of solution temperature holding time on mechanical properties of AC4CH-T6

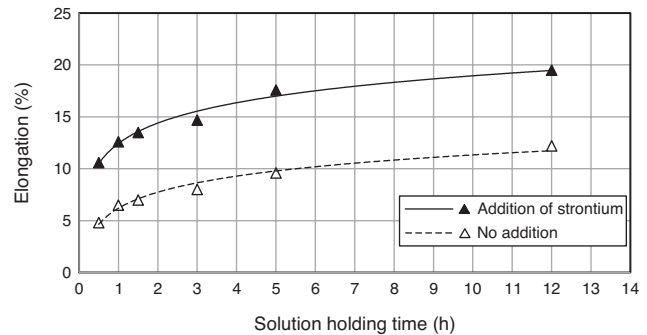


Fig. 5 Effect of solution temperature holding time on elongation of AC4CH-T6

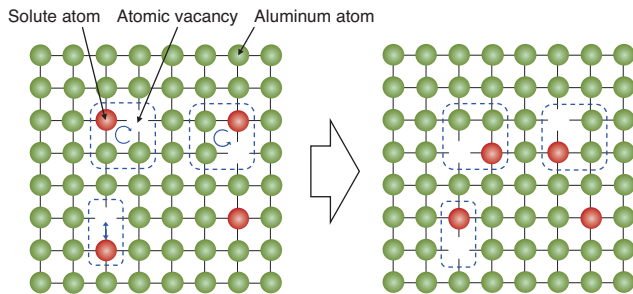


Fig. 3 Diagram of atomic vacancy and atomic diffusion

This section will verify how the thermal conductivity changes as solute atoms in solid solution are consumed by aging precipitation. Figure 7 shows the change in aging time and thermal conductivity at 160°C, 180°C, and 220°C, which exhibit a different age hardening characteristic, when solution treatment is performed under the same conditions as in Fig. 6. The thermal conductivity λ was calculated by measuring the thermal diffusivity α by the laser flash method and multiplying it by the density ρ at room temperature and the specific heat Cp measured by the DSC method. Equation (2) shows the thermal conductivity λ .

$$\lambda = \rho \cdot \alpha \cdot Cp \quad (2)$$

λ : Thermal conductivity [W/(m·K)]

ρ : Density [g/cm³]

α : Thermal diffusivity [m²/s]

Cp : Specific heat [J/(g·K)]

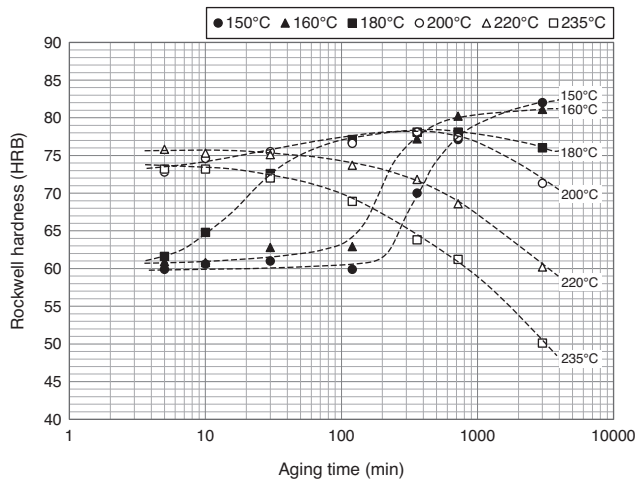


Fig. 6 Aging curve of AC4B alloy

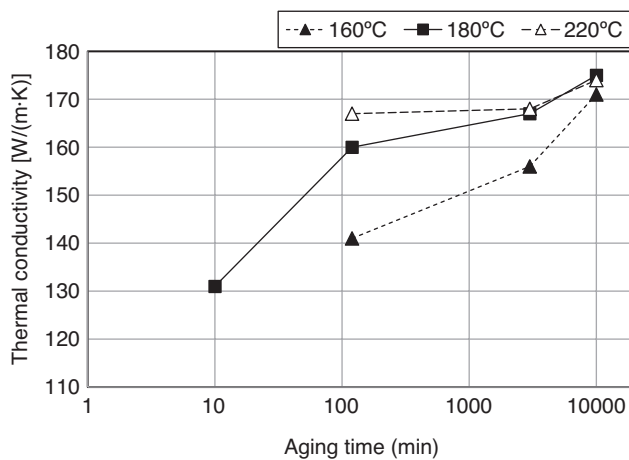


Fig. 7 Thermal conductivity with various aging treatments

It was confirmed that the solute atoms in solid solution are consumed by precipitation over time, and that thermal conductivity is enhanced accordingly. Precipitation tends to progress faster at higher aging temperatures, and thermal conductivity tends to be higher as more solute atoms are consumed. In addition, the thermal conductivity continues to increase even in the over aging area where hardness decreases, and thus it is presumed that the residual solute atoms obstruct thermal conduction.

3.3. Heat Treatment Condition Settings that Increase Thermal Conductivity of AC4B Alloy

This section will verify the approach to setting conditions that increase the thermal conductivity by reducing the residual amount of solid solution. Figure 8 shows the effect of solution holding time at 500°C on the age hardening characteristic of AC4B alloy at 200°C. Within the observed period, the age hardening characteristic at 200°C has an under aging area where the hardness increases and an over aging area where the hardness decreases, and this change was selected as an easy-to-understand condition. In the under aging area where the hardness increases, no difference in hardness was observed between the solution holding times of 10 minutes, 180 minutes, and 360 minutes. This lack of difference in hardness, which is closely correlated with yield strength, confirmed a similar situation to the results in Fig. 4 where solution holding time had no effect on the mechanical properties of AC4CH alloy. In the over aging area where the hardness decreases, a solution holding time of 10 minutes resulted in lower hardness compared with 180 minutes and 360 minutes. The reason for this is thought to be that the solute atoms needed for precipitation were depleted due to the small amount of solid solution.

Figure 9 shows the results of measuring the thermal conductivity of test pieces immediately after solution treatment held at 500°C for 10 minutes, 180 minutes, and 360

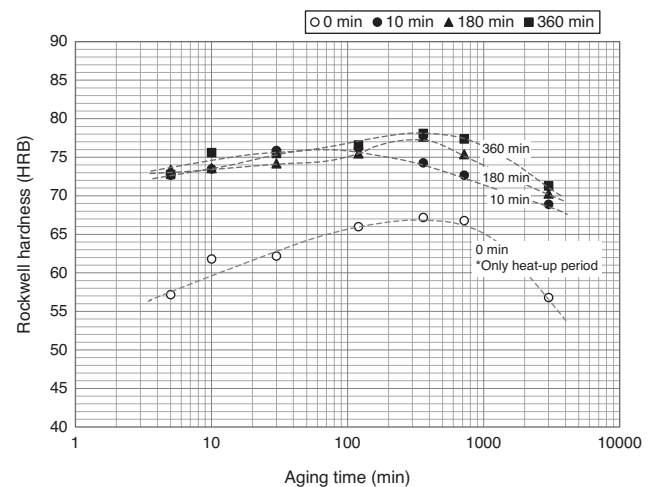


Fig. 8 200°C aging curve of AC4B alloy with various solution holding times

minutes, and of test pieces with equal hardness after addition of aging treatment at $200^{\circ}\text{C} \times 120$ minutes. All test pieces were stored at -20°C so that the amount of solid solution immediately after solution treatment did not decrease due to room temperature aging. In addition to storage at -20°C , the test pieces used to measure the state immediately after solution treatment were further treated to help prevent the advance of room temperature aging. This consisted of loading into a 100°C furnace for 10 minutes for exposure to higher than room temperature in order to help prevent consumption of solute atoms in solid solution by room temperature aging until the measurement of thermal conductivity.

The results show that immediately after solution treatment, the thermal conductivity decreases and the amount of solid solution of solute atoms increases in accordance with the increase in the solution holding time. After aging treatment at $200^{\circ}\text{C} \times 120$ minutes, the solute

atoms are consumed by the aging treatment and the thermal conductivity is restored in each case. However, even after aging treatment, longer solution holding times resulted in lower thermal conductivity, and thus it is assumed that the amount of solid solution of the residual solute atoms is higher at longer solution holding times. From this, it is thought that the solute atoms in solid solution in excess of the amount consumed by aging treatment remain even after aging treatment and become a factor obstructing thermal conduction.

This means that in order to increase thermal conductivity after achieving the demanded material properties, it is necessary to reduce the amount of solid solution of the residual solute atoms after aging treatment. The key to achieving this is to set solution treatment conditions that result in the amount of solid solution that is necessary and sufficient for aging precipitation. The necessary and sufficient amount of solid solution of solute atoms can be understood by performing verification with different solution holding times under aging conditions defined as shown in Fig. 8. This type of approach enables verification with a test piece cut from a part, and is useful in setting solution treatment conditions that increase thermal conductivity.

4. Examination

4.1. Application to Other Alloys

This section will verify that the approach of setting heat treatment conditions that increase thermal conductivity is also applicable to Al-Si-Mg-based alloy that is strengthened by precipitation of Mg_2Si in the same manner as AC4B alloy that undergoes precipitation hardening by Cu-based precipitates. Figure 10 compares the aging characteristic when solution treatment is performed at the standard temperatures of 535°C and 500°C in an Al-5%Si-0.3%Mg aluminum casting alloy, of which impact resistance is demanded like AC4CH. Age hardening results in higher

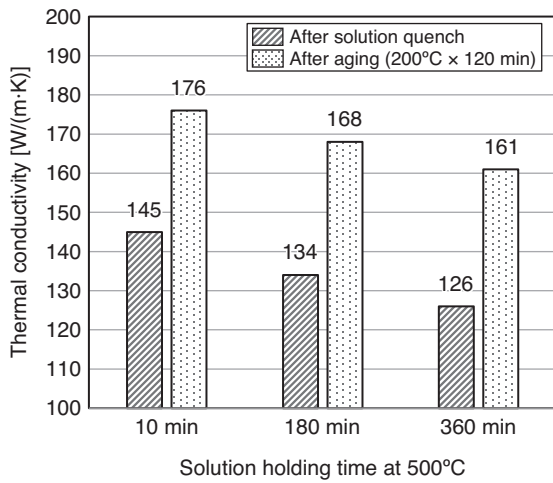


Fig. 9 Thermal conductivity with various solution holding times

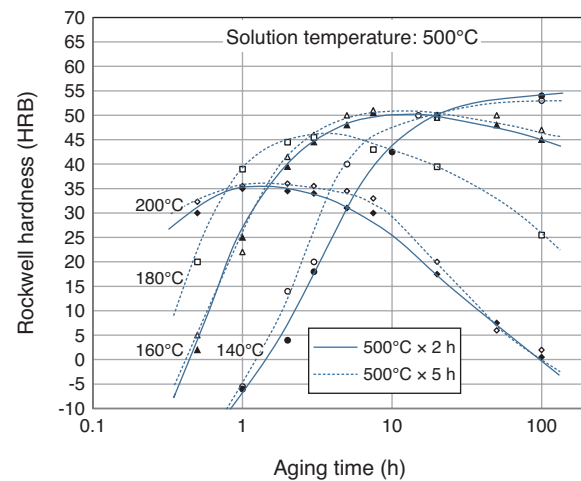
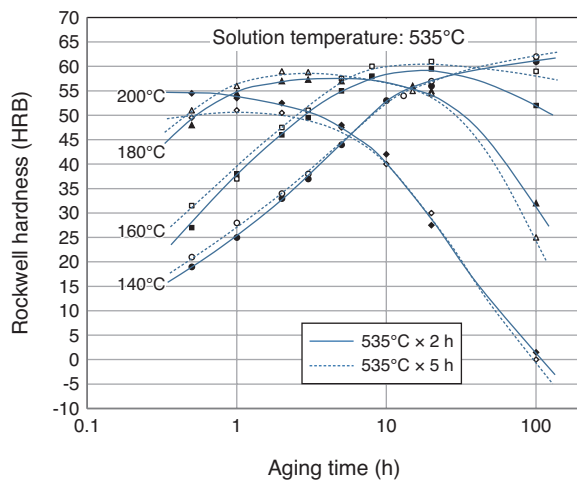


Fig. 10 Aging curve with solution temperatures of 535°C and 500°C of Al-5%Si-0.3%Mg alloy

hardness when solution treatment is performed at 535°C compared with 500°C, and there is no difference between solution holding times of 2 hours and 5 hours. This shows that like AC4B, the atomic vacancy density is the dominant factor for the age hardening characteristic. Therefore, the amount of solid solution of solute atoms that is necessary and sufficient for aging precipitation can be understood in the same manner as for AC4B alloy. The approach of changing the thermal conductivity by controlling the amount of solid solution of the residual solute atoms is applicable to heat treatment type aluminum alloy in general, regardless of the type of solute atom. Furthermore, application can also conceivably be expanded to aluminum alloy parts that demand heat dissipation properties, and conversely to parts that demand thermal insulation properties.

4.2. Issue for Practical Application

At present, measurement of thermal conductivity calls for dedicated equipment and skilled operators, and a simpler method is demanded to achieve thermal conductivity as a requirement characteristic. This section considers an alternative direction using electrical conductivity that is correlated with thermal conductivity. Figure 11 shows the correlation between thermal conductivity and electrical conductivity in various aluminum wrought product alloys⁽¹⁾.

It is known that in the thermal conduction of metals, the contribution of electrons is more dominant than thermal conduction due to lattice vibration (phonon), and a correlation appears because electrons are responsible for both electrical conduction and thermal conduction⁽¹⁰⁾.

Equation (3) shows the relationship between the electrical conductivity and thermal conductivity of metals, generally referred to as the Wiedemann–Franz rule. Here, λ is the thermal conductivity, σ is the electrical conductivity, L is the Lorentz number, and T is temperature.

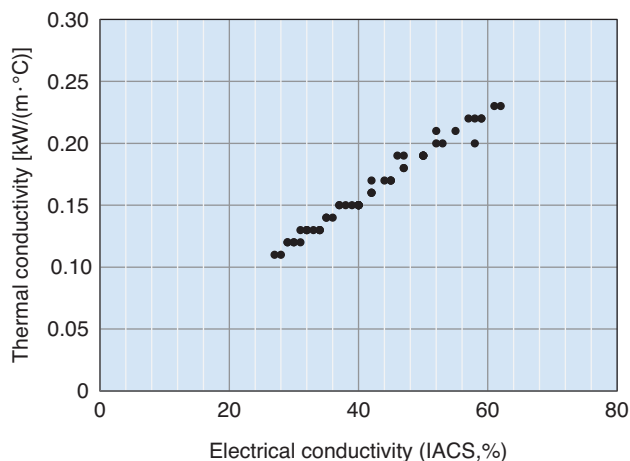


Fig. 11 Relation between thermal conductivity and electrical conductivity

$$\lambda / \sigma = L \cdot T \quad (3)$$

This indicates that if the temperature is the same, the ratio of thermal conductivity to electrical conductivity is nearly the same even for different types of metals. This presents future potential for replacing measurement of thermal conductivity with relatively simple measurement of electrical conductivity, and may be useful in both practical application of thermal conductivity as a requirement characteristic and in verification of more detailed changes in thermal conductivity.

Aluminum alloy has an established resource recycling environment, and many recycled materials including AC4B alloy are used and have facets as sustainable materials. The addition of thermal conductivity control technology is expected to enhance performance and expand the applications of existing products.

5. Conclusion

The following conclusions were obtained by verification and examination of thermal conductivity using the aluminum alloy AC4B.

- (1) In order to increase thermal conductivity after achieving the demanded material characteristics, it is necessary to reduce the amount of solid solution of the residual solute atoms after aging treatment. The key to achieving this is to set solution treatment conditions that result in the amount of solid solution that is necessary and sufficient for aging precipitation.
- (2) The approach of understanding the amount of solid solution that is necessary and sufficient for aging precipitation and changing the thermal conductivity by controlling the amount of solid solution of the residual solute atoms is applicable to heat treatment type aluminum alloy in general, regardless of the type of solute atom.
- (3) The measurement method is an issue for future practical application of thermal conductivity, but potential was shown for replacement by relatively simple measurement of electrical conductivity.

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