Interfacial Reaction of Flux-Free Brazing of Aluminum by Different Heating Methods

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Today, aluminum is a widely used material in applications such as familiar beverage cans and food packaging, portable devices such as smartphones and computers, and transportation infrastructure such as automobiles and bullet trains. The materials used in these products have expanded since the industrial use of aluminum began with the development of alloys with various properties.
High-performance heat exchangers used in automobiles are made of aluminum, which is lightweight and has high thermal conductivity. In recent years, the demand for heat exchangers has further increased with the advent of electric vehicles. The development of the NOCOLOK® brazing method has dramatically improved the productivity and brazing accuracy of these aluminum heat exchangers, and they are now widely used. However, flux brazing has problems such as contamination of the furnace by flux and environmental impact from volatiles and other substances, so there is a need for the practical application of flux-free brazing.
In this study, flux-free aluminum brazing was performed using A6061 alloy as the base metal and A4045 alloy as the brazing filler metal in a rapid heating method. The effects of the rapid heating method and the brazing process on brazeability were evaluated by observing the appearance of the specimens and the microstructure of the brazed area, and by examining the interfacial reaction through elemental analysis.

Keywords: *Aluminum brazing, Flux-free, Brazing process*

1. Introduction

Aluminum brazing today, especially in the manufacture of aluminum heat exchangers, has dramatically improved in productivity with the development of the NOCOLOK® brazing method using flux and brazing sheets clad with brazing material and core material. In addition, aluminum is used as an ideal material for automotive heat exchangers because its thermal conductivity is as high as that of copper, and it is lightweight.

However, products manufactured by flux brazing may not look good due to the time-consuming cleaning process after brazing and the whitening caused by the use of flux. Other issues include flux contamination of the production line and furnace.

On the other hand, flux-free brazing requires a vacuum furnace or inert atmosphere furnace to obtain a good atmosphere in the furnace, and brazing defects due to strong oxide film on aluminum may occur, which may be costly.

Therefore, in order to successfully braze with flux-free brazing, this study evaluated the effects of the rapid heating method and the brazing process on brazeability and the brazing cross-section microstructure by observing the appearance of the specimen and the microstructure of the brazed section using the rapid heating method, and by examining the interfacial reaction by elemental analysis.

2. Experimental procedure

2.1 Base Metal and Brazing Filler Metal

For the base metal, aluminum alloy A6061 was selected for its corrosion resistance, strength, and availability. For the brazing filler metal, aluminum alloy A4045, which is generally used in aluminum brazing, was selected. Brazing sheets are often used in general aluminum brazing, but for this study, a foil form was prepared for workability and ease of adjusting the amount of brazing filler metal. Table 1 show the composition and solidus and liquidus temperatures of each aluminum alloy.

Table 1 Composition of A6061 and A4045 alloy.

Alloy No.	Chemical Composition (mass%)									Temperature (°C)	
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	Solidus	Liquidus
A6061	0.40~0.8	0.7	0.15~0.40	0.15	0.8~1.2	0.04~0.35	0.25	0.15	Bal.	582	652
A4045	9.0~11.0	0.7	0.3	0.05	0.05	-	0.1	0.2	Bal.	577	590

1, 3, 5, 10, and 20 min, and the heating rate was 100, 200, and 300 K/min. In Experiment 2, the heating rate was set to 100 K/min, the brazing temperatures were 575, 580, 585, and 590°C, and the holding time was set as in Experiment 1.

The shape of the specimens was made by overlapping two aluminum plates as shown in Figure 1. The shape of the specimen was a general interview shape, and the interfacial reaction and the brazing zone microstructure were observed.

Table 2 Brazing conditions.

Base Metal	Brazing Metal	Atmosphere	Brazing Metal Thickness (μm)	Hold Time (min)
A6061	A4045	Argon (Ar)	100	1
				3
				5
				10
				20

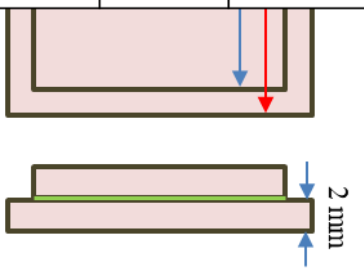

Fig 1 Specimen schematic

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2.3 X-ray CT Analysis

Brazed specimens were subjected to X-ray CT analysis in order to investigate voids and defects inside the brazed surface. The void ratio, size, distribution, etc. of the brazed surface were examined from the CT images obtained.

2.4 Cross-sectional observation, EPMA analysis

After X-ray CT analysis, the specimens were cut and mirror-polished in cross-section for microstructural observation of the brazed area. Microstructural observation using an optical microscope and elemental analysis using EPMA were conducted to discuss the interfacial reaction.

3. Results and Discussion

3.1 Experiment 1

Figures 2, 3, and 4 show representative cross-sectional microstructures for each heating rate in Experiment 1. 100 K/min and 200 K/min at a holding time of 1 min resulted in a clean brazed joint with few voids. However, as the holding time increased, the number and size of voids increased, and the joint appeared to be defective. At 1 min, the brazing filler metal did not melt completely, and the brazed part was brazed, but as the holding time increased, the brazing filler metal melted, and an interfacial reaction occurred.

Next, Figures 5 show X-ray CT images at a heating rate of 100 K/min. At 1 min, there were almost no noticeable voids, but at 20 min, voids could be clearly seen in the center. From the cross-sectional microstructure and CT images, it was found that the distribution of voids was more pronounced in the center of the specimen with longer holding time, and that there were relatively few voids in the outer periphery, resulting in a well-sealed brazed part.

Figure 6 shows the results of EPMA analysis of the brazed area at each heating rate for a holding time of 1 minute. As seen in the cross-sectional microstructure, at 100 K/min, silicon (Si) remained as brazing filler metal crystals, confirming that the brazing was brazed without completely melting. At 300 K/min, no Si crystals remained, showing that the brazing filler metal was completely melted. This indicates that the brazing filler metal has completely melted. The thickness of the brazing filler metal layer was considerably thinner than at 100 K/min and 200 K/min, indicating that the molten brazing filler metal was pushed out by pressure or other factors. The oxygen (O) analysis results for the oxide film on the aluminum surface show that the oxide film is distributed at the base metal interface, although only slightly.

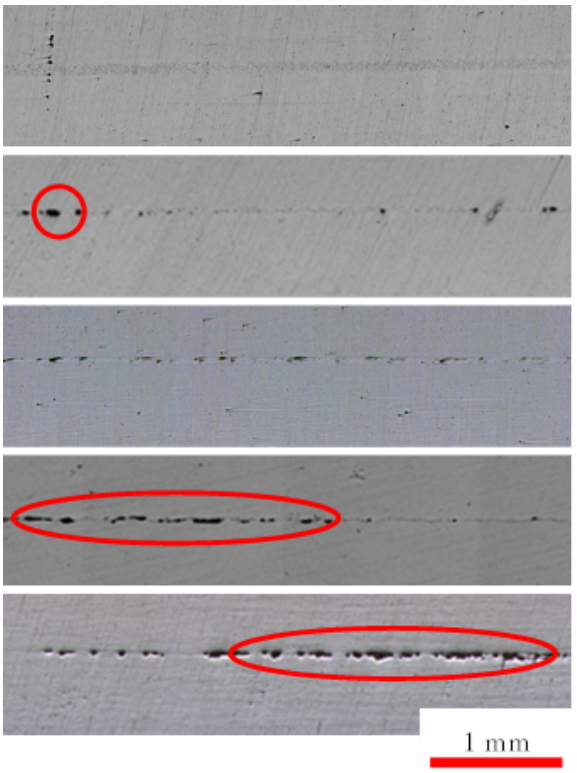


Fig 2 Cross-sectional microstructure at a temperature increase rate of 100 K/min
Holding times from top to bottom: 1min, 3min, 5min, 10min, 20min.

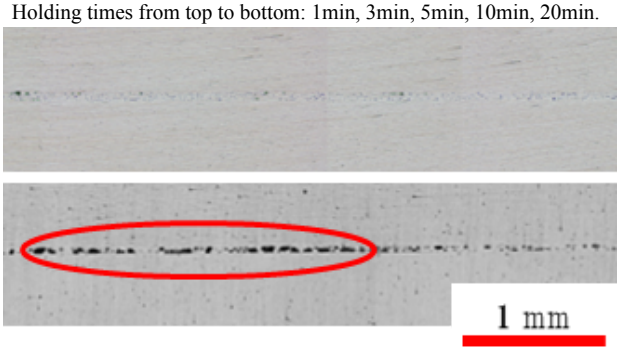


Fig 3 Cross-sectional microstructure at a temperature increase rate of 200 K/min
Holding time from top to bottom: 1 min, 20 min.

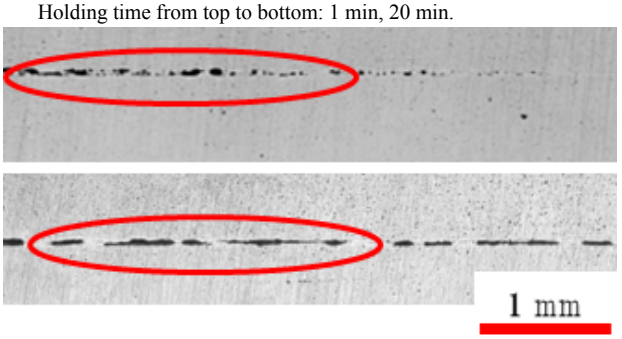
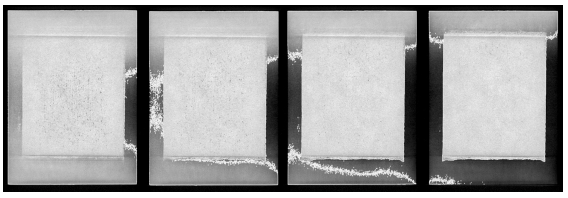


Fig 4 Cross-sectional microstructure at a temperature increase rate of 300 K/min
Holding time from top to bottom: 1 min, 20 min.



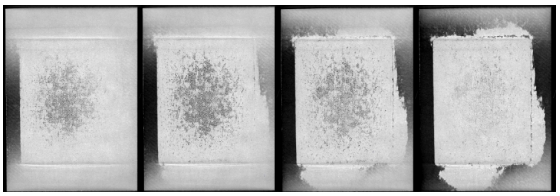


Fig 5 X-ray CT with a temperature increase rate of 100 K/min and a retention time of 1 and 20 min.

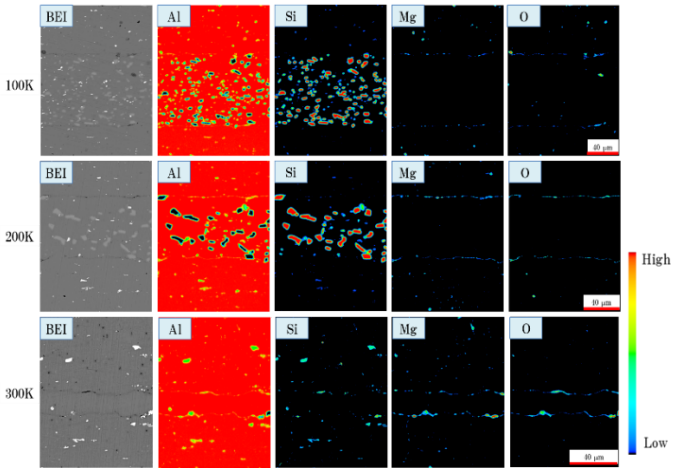


Fig 6 Results of EPMA analysis of joints at each temperature rise rate and holding time of 1 min.

3.2 Experiment 2

Next, Figures 7, 8, 9, and 10 show representative cross-sectional microstructure images of Experiment 2. The heating rates were all 100 K/min. At 575°C and 580°C, where the brazing temperatures were low, the brazing filler metal was not melted and many voids were observed, but at 585°C, a relatively clean brazed part appeared to have been obtained. On the other hand, at 590°C, the solidus temperature of the base metal was considerably exceeded, so melting of the base metal was observed from around 5 min of brazing time, and by 10 min, it had completely melted.

4. Conclusions

The results of this study on interfacial reactions in aluminum brazing without flux,

(1) When brazing on a surface with well adhered brazed parts, sufficient brazing can be obtained without using flux.

(2) Extremely high heating rate and long holding time cause different progress of the interfacial reaction between the outer and inner surfaces, which may lead to bonding defects.

(3) The base metal and brazing filler metal do not bond well.

(4) The presence of an oxide film does not necessarily cause brazing defects and may be negligible under certain conditions.

The above were found.

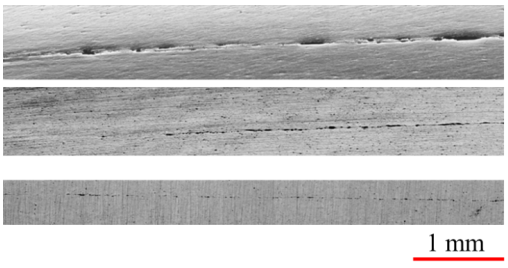


Fig 7 Cross-sectional microstructure at brazing temperature of 575°C and holding time of 1, 3, and 5 min.

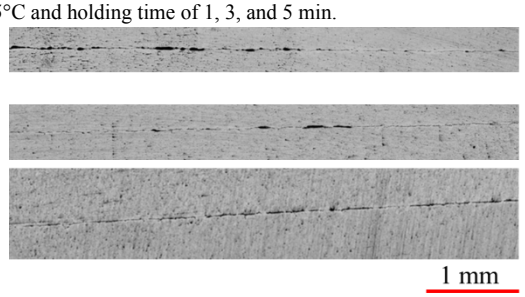


Fig 8 Cross-sectional microstructure at brazing temperature of 580°C and holding time of 1, 3, and 5 min.

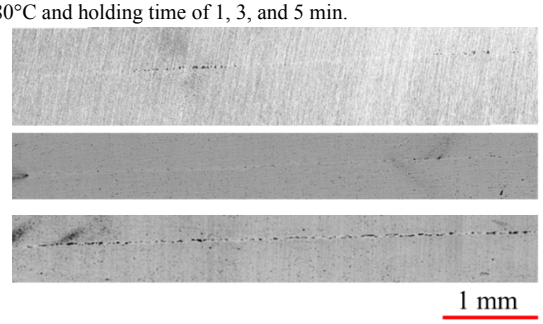


Fig 9 Cross-sectional microstructure at brazing temperature of 585°C and holding time of 1, 3, and 5 min.

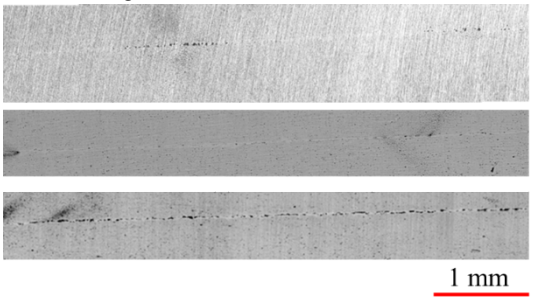


Fig 10 Cross-sectional microstructure at brazing temperature of 590°C and holding time of 1, 3, and 5 min.

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