Brazing of Stainless Steel to Various Aluminum Alloys in Air

Shuying LIU**, Akio SUZUMURA**, Toshi-Taka IKESHOJI** and Takahisa YAMAZAKI**

Brazing of a stainless steel to various aluminum alloys was carried out using an Al-Si filler metal and a fluoride-active flux in air. The brazeability was remarkably different by the aluminum alloys and the brazing conditions. It was considered that the differences were originated with the compositions of base metals and the filler metal, the solidus temperature and the partially melting behavior of the aluminum alloys, and the behavior of the surface oxide film layers of both base metals. On the other hand, the obstruction of brazeability was identified as the rapid reaction between the aluminum alloys and the brazing filler metal, which makes the molten brazing filler metal disappear at the joining interface before the wetting occurs to the stainless steel. Taking this phenomena into consideration, it was attempted to make previous wetting of the brazing filler to the stainless steel before brazing to the aluminum alloys. This method provided the successful brazed joints for the most combinations of the stainless steel and the aluminum alloys.

Key Words: Brazing, Flux, Filler Metal, Stainless Steel, Aluminum Alloy, Melting Point, Wetting, Dissimilar Metal

1. Introduction

The aluminum alloy possesses excellent corrosion resistance, and its high workability and high recycling efficiency expand its application fields. Especially, in the fields of manufacturing auto vehicles’ parts, demanding for weight saving in recent years, it is expected to establish the joining technology between the aluminum alloys and stainless steels which have higher strength and higher corrosion resistance. However, during the conventional welding process of dissimilar metals between aluminum alloys and stainless steels, the weak intermetallic compounds are generated at the joint interface. Then, the application of brazing methods during which the base metals are not melted, is expected to be developed(1). Up to now, there are many reports on the brazing of stainless steels(2) or aluminum alloys(3) to themselves. On the other hand, there are a few reports of vacuum brazing(4) and furnace brazing(5) of stainless steels to pure aluminum. However, there is almost no report on the brazing of aluminum alloys with lower melting point compared with pure aluminum to stainless steels in air using flux for brazing.

In this research, the brazing of various aluminum alloys and an austenitic stainless steel SUS304 was carried out to make it clear the influence of the brazing conditions on the joining in air. The brazing was conducted with a flux to eliminate the oxide films on both surfaces of aluminum alloys and the stainless steel. The behavior of constituents of aluminum alloys, stainless steel and the flux at the brazing interface was examined. The final aim of this research is to find the suitable brazing conditions between the aluminum alloys and the stainless steel in air(6).

2. Experimental Details

2.1 Materials and brazing method

The supplied materials are austenitic stainless steel, SUS304 and aluminum alloys: A1050, A2024, A5052, A6061, and A7075. The aluminum-base filler metal, BA4045 in JIS and the fluoride active flux, F-19 of Neis Co., Ltd. are used. Their chemical compositions are shown in Tables 1 – 3.

The supplied materials were processed into the plates with a size of 20×40×3 mm. They were cleansed to degrease in acetone by a ultrasonic cleaner. Between the aluminum alloy plate and the stainless steel plate, a sheet of the brazing filler metal, BA4045, was put in the overlapped part. The thickness of the sheet was 150 µm. This assembly was placed in a ceramic tray. In some brazing conditions, the flux was poured in the tray at a certain amount around the joint. The assembly of the specimens
Table 1 Chemical compositions of materials used (mass%)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Al</th>
<th>Mg</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Fe</th>
<th>Melting Temp (K)</th>
</tr>
</thead>
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<tr>
<td>304</td>
<td>0.05</td>
<td>0.46</td>
<td>0.03</td>
<td>0.05</td>
<td>0.03</td>
<td>0.30</td>
<td>18.09</td>
<td>1671–1717</td>
<td></td>
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Table 2 Chemical composition of 4045 filler metal used (mass%)

<table>
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<tr>
<th></th>
<th>Si</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Zn</th>
<th>Al</th>
<th>Melting Temp (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1050</td>
<td>0.25</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>Bal</td>
<td>915–930</td>
</tr>
<tr>
<td>A2024</td>
<td>0.50</td>
<td>5.8–4.9</td>
<td>1.2–1.8</td>
<td>0.25</td>
<td>Bal</td>
<td>775–791</td>
<td></td>
</tr>
<tr>
<td>5083</td>
<td>0.55</td>
<td>0.10</td>
<td>2.2–2.8</td>
<td>0.10</td>
<td>Bal</td>
<td>866–923</td>
<td></td>
</tr>
<tr>
<td>A6061</td>
<td>0.4–0.8</td>
<td>0.15–0.4</td>
<td>0.8–1.2</td>
<td>0.25</td>
<td>Bal</td>
<td>866–925</td>
<td></td>
</tr>
<tr>
<td>A7075</td>
<td>0.40</td>
<td>1.2–2.0</td>
<td>2.1–2.9</td>
<td>5.30</td>
<td>Bal</td>
<td>730–763</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Chemical composition of F19 flux used (mass%)

<table>
<thead>
<tr>
<th></th>
<th>K</th>
<th>Na</th>
<th>Cl</th>
<th>Mg</th>
<th>Ca</th>
<th>Ba</th>
<th>Li</th>
<th>F</th>
<th>other</th>
<th>Al</th>
<th>Active Temp Range (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15–20</td>
<td>10–15</td>
<td>40–50</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>&lt;1.0</td>
<td>825–973</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1 Assembly of brazing specimens and flux (a), and the movable brazing furnace and the specimen holder (b)

and the supplying methods of flux are shown in Fig. 1 (a).

The brazing was carried in the movable electric furnace shown in Fig. 1 (b). The tray with specimen was placed on the arm inserted from the side of the furnace. The furnace is moved so as not to give the specimens the vibration, and to cool the specimen as soon as possible. The brazing was carried out in air. The brazing temperatures were selected between 858 – 898 K, and the holding times were 30 – 300 s.

As a preliminary experiment, the brazing was conducted with pasting the flux around the joining area. And then various amounts of the flux were poured into the ceramic tray. According to these experiments, the influence of the flux was examined, and the suitable amount of the flux was determined. Then, the brazing temperature and time were changed to find the optimum conditions.

2.2 Wettability test

Besides the brazing experiment, the sessil drop tests of the aluminum brazing filler metal on the stainless steel and the aluminum alloys, were carried out to examine the wettability between those combinations of materials. Whether the filler metal was wet on the base metal was observed, and the duration to become wet was measured. The keeping temperature was almost the same as the brazing process as 868 – 888 K.

2.3 Evaluation methods of joint

After finding the temperature range that the brazing joint can be formed, the microstructure of the obtained joint was observed optically. The cross section of the joint interface was analyzed using EPMA to obtain the distribution of the constituents of the base materials, the brazing filler metal and the flux.

The X-ray diffraction was also measured around the joint interface to identify the intermetallic compounds. The joint was ground parallel to the joint interface from the aluminum alloy’s side until the joint interface was exposed. The aluminum alloy plate was ground little by little, and the X-ray diffraction was measured every time several hundreds micrometer thickness was removed. The formation of the intermetallic compounds and the reaction layer were examined.

On the other hand, for the specimens where the joint was not formed, the surface of the aluminum alloy’s side was analyzed by EDX. The causes that brazing joint was not formed were discussed.

3. Result and Discussions

3.1 Influence of the amount of supplied flux

First of all, as is often a case with the brazing in air, the flux was pasted sufficiently around the joining area of the specimens assembly. The brazed joint was not formed easily except for under some conditions of temperature and time. The results of the brazing under the condition that the brazing time was 30 s with variation of the aluminum alloys and brazing temperature, were tabulated in Table 4. In case of brazing temperature of 858 K, because the filler metal did not melt, the joint was not formed. At the brazing temperature of 868 K, the brazing joints of Al1050, A2024 and A6061 to stainless steel were formed. When the brazing temperature was raised step by step to 898 K, though the good joint was obtained at every temperature for Al1050, the temperature range to form the brazed joint was not simple for other aluminum alloys.

During the brazing process in air, the lack of flux is always concerned. So, the pasting method to supply flux in the previous was abolished, and the flux was supplied by pouring into the ceramic tray to examine the influence
Table 4  The result of brazing in each condition with flux pasted at the brazing interface

<table>
<thead>
<tr>
<th>Base materials</th>
<th>Brazing temperature(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>858</td>
</tr>
<tr>
<td>A1050</td>
<td>▲ΟΟΟΟΟΟΟΟΟ</td>
</tr>
<tr>
<td>A2024</td>
<td>▲ΟΟΟΟΟΟΟΟΟ</td>
</tr>
<tr>
<td>A5052</td>
<td>▲ΟΟΟΟΟΟΟΟΟ</td>
</tr>
<tr>
<td>A6061</td>
<td>▲ΟΟΟΟΟΟΟΟΟ</td>
</tr>
<tr>
<td>A7075</td>
<td>▲ΟΟΟΟΟΟΟΟΟ</td>
</tr>
</tbody>
</table>

▲: filler metal was not melted, the joint was not formed  
Ο: the joint was formed  
□: the joint was formed, but the base metal partially melted  
×: the joint was not formed

of the amount of the supplied flux. When the flux was poured up to the “Full supply of flux” shown in Fig. 1 (a), by which both metals were dipped into the flux, the joint was not formed for most of the combinations. On the other hand, when no flux was supplied, the brazed joint was not formed for all combinations as expected.

According to the results, the braseability of the aluminum alloys to the stainless steel is influenced not only by the amount of supplied flux but also the constituents of the base metals and the brazing filler metals. The aluminum alloys’ solidus temperature restricts the upper bound of the brazing temperature range, and the disruption of the oxide film layer and the partial melting induced by the constituents of the alloys might affect the brazing temperature range. The melting and solidification behavior by the reaction among those constituents is also probably interacted.

3.2 Macroscopic observation

The macroscopic observation of the crosse section of the SUS304/A1050 joint obtained by brazing at the brazing temperature of 888 K for 30 s is shown in Fig. 2. The well-wetted large fillets around the brazed joint indicated the formation of good brazing joint. This joint suggests the possibility to make joint for this combination of the pure aluminum and the stainless steel in air under the suitable brazing conditions. The SUS304/A2024 assembly was however, failed to be brazed at the brazing temperature of 888 K for 30 s. Figure 3 (a) and (b) show the appearance of the surfaces of the brazing part of the A2024 alloy and the stainless steel. Though it is not easy to observe from this photograph, no marks of the brazing filler metal to have adhered on the stainless steel surface was observed, despite that the discoloration at several parts was seen on the surface of stainless steel. On the contrary, on the surface of the aluminum alloy, the traces of the reaction between the brazing filler metal and the base metal, and those of the absorption of the brazing filler metal into the base metal are observed.

3.3 Elemental analysis and intermetallic compounds

Table 5 shows the results of EDX analysis on the brazing filler metal layer of the SUS304/A1050 joint formed at the brazing temperature of 888 K for 30 s. It also shows the results on the surface of the A2024 side of SUS304/A2024 assembly which was failed to join at the brazing temperature of 888 K for 30 s. In the result of the SUS304/A1050 joint, Si and Zn are detected besides the
constituent elements which had diffused from both of the aluminum alloy side and the stainless steel side into the joint interface layer. The Zn is considered as a constituent element from the flux. It should be mentioned that a large amount of Si still exists in the brazing filler metal layer.

On the other hand, the composition on the surface of A2024 side of the SUS304/A2024 assembly was almost the same as that of the base metal except the amount of Zn. It is considered that the A2024 alloy absorbed all the brazing filler metal to be evacuated from the brazing interface, which disturbed the joining of the assembly. In other words, the brazing between the aluminum alloys and stainless steel requires the existence of the molten brazing filler metal at the joint interface until the stainless steel is wetted.

These results suggest that the behavior of the aluminum brazing filler metal with both the base metals at the brazing interface is closely linked with the brazability, especially, with the time to make both of the base metals wetted. Then, the sessil drop wetting tests were carried out to measure the time for the base metals to be wetted by the aluminum brazing filler metal. The elemental analysis on the surface of wetted area was also conducted.

### 3.4 Time for base metals to be wetted

The macrostructure of the aluminum brazing filler wetting to the SUS304 stainless steel is shown in Fig. 4. The temperature of the sessil drop test was 868 K and the keeping time was 10 s. It is observed that the stainless steel was well wetted by the keeping time of 10 s. On the other hand, the aluminum alloys of A1050 and A2024 were wetted by 5 – 8 s at the same temperature.

Table 6 shows the results of the elemental analysis using EDX on the surface of the sessil drop test specimens of A2024 alloy, which was kept at 888 K for 15 s, 30 s, 60 s. For the specimen kept for 15 s, a lot of Si was detected adding to the composition of the base metal. A2024 alloy. It indicates that the brazing filler metal’s composition had still remained. The amount of Si, however, decreased remarkably by heating the specimen for 30 s. The composition of the specimen became almost the same as that of the base alloy. The longer heating time makes the tendency progressed.

These result shows that because the molten brazing filler metal was absorbed into the aluminum alloy, and solidified isothermally before the wetting of the stainless steel, the SUS304/A2024 brazing joint could not obtained under the brazing condition of the brazing temperature 888 K for 30 s as shown in Table 4.

Taking into account the above results, the brazing method was attempted by making the stainless steel wetted in the first place followed by the aluminum alloys’ brazing afterwards. For most of the combinations of the aluminum alloys and the stainless steel, which were unable to make joint with usual brazing method, the brazed joints were confirmed to be obtained.

### 3.5 Microstructure at the brazing interface

Figure 5 shows the backscattered electron image (BEI) and the elemental distribution maps by EPMA analysis (EPMA map) for the SUS304/A1050 joint brazed at the brazing temperature of 868 K for 30 s (The arrows in the figure indicate the interface between the SUS304 base metal and the brazing filler metal layer). These figures indicate that the thickness of the brazing layer, where the aluminum brazing filler metal had been dissolved into the aluminum alloy, is about 300 µm. It is twice as thick as the initial thickness, 150 µm of the filler metal.

The more precise EPMA maps at the interface between the stainless steel and the brazing layer observed in Fig. 5 are shown in Fig. 6. The sight of the EPMA maps is the squared area indicated in the BEI. On the EPMA maps for Cr, Fe and Si, the thin reacted layer can be distinguished apparently between the stainless steel base metal and the brazing layer. The average constituent of 2 points in the reacted layer is shown in Table 7. The Zn originated from the flux is detected in the reacted layer. The formation of the thick intermetallic compound phase causing the brittleness of the interface was at least not recognized.

### 3.6 X-ray diffractometry for the reacted layer

The aluminum alloy side of the SUS304/A1050 joint specimen brazed at 878 K for 30 s was polished to remove it little by little. The exposed surface near the interface between A1050 base metal and the brazing filler was analyzed. The surface was further polished and the exposed brazing interface of the stainless steel side was also analyzed. The X-ray diffraction patterns are shown in Fig. 7 (a) and (b), respectively. In the interface vicinity of the

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**Table 6** EDX analyses on the surface of sessile drops of aluminum brazing filler on A2024 after keeping at 888 K

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
<th>Cu</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 s</td>
<td>75.55</td>
<td>14.32</td>
<td>0.46</td>
<td>0.16</td>
<td>2.11</td>
<td>7.31</td>
</tr>
<tr>
<td>30 s</td>
<td>94.49</td>
<td>0.62</td>
<td>0.51</td>
<td>0.09</td>
<td>2.29</td>
<td>2.01</td>
</tr>
<tr>
<td>60 s</td>
<td>93.84</td>
<td>0.39</td>
<td>0.48</td>
<td>0.05</td>
<td>1.64</td>
<td>3.61</td>
</tr>
</tbody>
</table>

**Table 7** The point analysis result of a reaction layer shown in Fig. 6 (mass%)

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Al</th>
<th>Ni</th>
<th>Zn</th>
<th>O</th>
<th>Cr</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25</td>
<td>60.7</td>
<td>0.3</td>
<td>11.85</td>
<td>23.35</td>
<td>0.85</td>
<td>2.05</td>
</tr>
</tbody>
</table>
Fig. 5  Results of SEM(BEI) and EPMA for SUS304/A1050 brazing joints (Brazing temperature: 868 K, Brazing time: 30 s)

Fig. 6  Results of EPMA for SUS304/A1050 brazing joints (Brazing temperature: 868 K, Brazing time: 30 s)

Fig. 7  Comparison of X-ray diffraction patterns for the joints of SUS304/A1050 brazed
   (Brazing temperature: 878 K, Brazing time: 30 s)

(a) In the vicinity of the brazing interface of Al side  (b) At the brazing interface of SUS304 side
aluminum side, the intermetallic compounds except for $\text{Al}_{76.8}\text{Fe}_{24}$ were not detected. On the other hand, the result on the stainless steel side interface indicates the existence of the intermetallic compounds of $\text{Al}_{76.8}\text{Fe}_{24}$, $\text{Fe}_{0.42}\text{Si}_{2.67}$, and $\text{CrO}_{0.87}$, and the Al and Zn were also detected.

For this joint and the joint in Table 7, though the difference of the brazing temperature was 10 K, under the assumption that both of the joints have the similar reacted layer, the following might be derived. The aluminum detected in Table 7 is considered to be originated from the aluminum in the Al-Si brazing filler metal. Some parts of it might form the Al-Fe compound, and some parts of Si originally contained in the brazing filler metal may form the Fe-Si compound on the surface of the stainless steel. Some part of Cr in the stainless steel may become the oxide. But, the intermetallic compound phase formed on the stainless steel side interface has only several $\mu$m thickness, and it is thought that the possibility for it to embrittle the brazing interface is very small$^{(6)}$.

Though the strength test for the brazed joint is waited for, the above microstructure observation and the elemental analysis results are considered to show that the sufficiently strong brazed joint of the aluminum alloys to the stainless steel can be formed when the stainless steel surface is wetted before brazing to the aluminum alloys.

4. Conclusions

(1) The brazing of various aluminum alloys to a stainless steel was conducted in air using flux for brazing. The brazing properties changed remarkably with kinds of aluminum alloys and brazing conditions. It was possible to obtain the joint only within the narrow range of brazing temperature of 868–898 K for the brazing time of 30 s.

(2) The obstacles for the brazing was identified to the rapid reaction between the aluminum alloys and the aluminum brazing filler metal before wetting of the brazing filler metal to the stainless steel. As the result of the reaction, the molten brazing filler metal was disappeared from the brazing interface.

(3) For brazing of dissimilar metals of the aluminum alloys to the stainless steel, it is necessary to make the stainless steel surface wet with the brazing filler metal in the first place, and then, the aluminum alloys should be brazed. This process provided the brazed joints for the most of the combinations of the aluminum alloys and the stainless steel.

References


