Study of a Method for Evaluating the Brazeability of Aluminum Sheet

An evaluation method is proposed that offers a quick and easy means of determining brazeability

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ABSTRACT. An investigation was carried out to evaluate methods for determining the brazeability of aluminum sheet. A joint clearance filling test was selected for the work. To compare the brazeability and to evaluate the adequacy of the test, various brazing experiments with and without flux were conducted using a uniform joint clearance filling test specimen on the same aluminum sheet. The results showed that the joint clearance filling test has some excellent features for evaluating the brazeability of aluminum. Namely, the configuration of the test specimen is simple and easy to assemble, the filled joint clearance can immediately be measured without cutting the specimen, and the flowability of a filler metal can be evaluated by observing the appearance of the specimen after brazing. Furthermore, various values such as flow factor, throat thickness and fillet leg length ratio can be measured by cross-sectional observation.

Introduction

The brazing of aluminum has long been performed with brazing fluxes (Ref. 1). More recently, the vacuum brazing process (Ref. 2) and the VAW brazing process (Ref. 3) have been developed and commercialized. In addition, the Nocolok™ brazing process (Alcan trademark), which uses a small amount of noncorrosive flux has been drawing attention (Ref. 4). All these processes are used to braze sheet for the production of various aluminum heat exchangers, and a variety of testing methods have been proposed to evaluate the brazeability of aluminum. (Refs. 5, 6). Especially in Japan, various unique evaluating methods have been proposed (Refs. 7, 8), but the correlation among these evaluating methods has been unknown. Under these circumstances, the necessity for authoritative evaluating methods to determine the brazeability of aluminum has become apparent from the customer’s viewpoint.

The evaluating factors of the proposed methods can roughly be classified into the following categories:
1) Flowability and wettabiility of filler metal (flow factor, drop test)
2) Ability for fillet formation (length of filled joint clearance, shape of joint)
3) Joint strength (shear strength, tensile strength, static fracture pressure)
4) High-temperature resistance (sag test, deflection at elevated temperature)

As a matter of course, these evaluating methods are correlated with one another. The ultimate aim of evaluating brazeability is to judge whether a uniform and sound filled joint can be formed without a defect. The best way to check the ability of fillet formation with a brazing process appears to be by using brazing sheets.

Taking all these matters into consideration, the Low-Temperature Joint Committee (The Japan Light Metal Welding & Construction Association) examined the various evaluating methods that were reported or proposed. As a result of the examination, the joint clearance filling test originally proposed by Kawase, et al. (Ref. 8), which is one of the joint clearance filling tests, was taken up for further study.

Common test materials were prepared and delivered to each committee member, and brazeability was evaluated using a standard-shaped specimen. The joint work revealed that the joint clearance filling test specimen is quite useful in evaluating brazeability. This paper describes the detailed results of the investigation.

Experimental Method

Materials

The chemical compositions of filler metals used in this investigation are shown in Table 1. Filler Metal 1 was used for flux brazing with the dip, furnace, and Nocolok brazing methods. Filler Metals 2 and 3 were used with vacuum brazing and VAW brazing, respectively.

The core of brazing sheet was A3003 alloy, also indicated in Table 1. Brazing sheets of 1-mm (0.04-in.) thickness were A3003 clad on both sides with the above mentioned filler metals. The thickness of the cladding is 0.1 mm (0.004 in.) on each side. The brazing sheets with a temper of H14 were prepared by common rolling method. The sheet was brazed to an A3003 base metal of 2-mm (0.08-in.) thickness, and the chemical composition of this base metal is identical with the core material indicated in Table 1.

Test Specimens

The shape and size of the joint clearance filling specimen is shown in Fig. 1. The brazing sheet was used as a vertical member and the A3003 base metal was used as a horizontal member. In order to make the clearance (D2), stainless steel wire of 1 to 4 mm (0.04-0.16 in.) in
diameter were used. Brazing sheet and base metal were fastened securely at two locations by a stainless steel wire 0.5 mm (0.02 in.) in diameter. After brazing, the filled joint clearance length \(F_J\) was measured as shown in Fig. 1B.

Furthermore, the appearance of the test specimen was checked. After that, the longitudinal center of the fillet (a location indicated as \(F_J/2\), Fig. 1B) was cut perpendicular to the longitudinal direction. After polishing, and if necessary, etching in 3% HF or 10% NaOH solution, various parameters (Fig. 2) were measured by an optical microscope or an enlarged projector. The parameters for evaluation of fillet formability were flow factor \(k = (t_0 - t)/(l_0 + l_2)\), fillet leg length \(L_v\): vertical leg length, \(L_H\): horizontal leg length), fillet leg-length ratio \(L_v/L_H\), and throat thickness \(d\).

**Brazing Methods**

As this research work aimed to examine the joint clearance filling test as an evaluating method for brazing sheet, seven different methods were used: dip brazing, furnace brazing, dry air brazing, Nocolok brazing, vacuum brazing, carrier gas brazing and VAW brazing.

Each committee member took charge of a portion of these brazing processes. In each test, a specimen was degreased by a regular organic solvent and brazed. Test pieces for furnace and dry air brazing were degreased by a weak alkaline solvent. The brazing condition of 600°C (1112°F) for 3 min was specified as a basic condition, but the heating rate was left up to each group member of the testing consortium, as each had different brazing equipment. The heating curves for the furnaces of each member are shown in Fig. 3 together with brazing processes. Figure 3 also indicates the members of the Low Temperature Joining Committee who conducted the experiments.

**Experimental Results and Discussion**

**Dip Brazing**

Dip brazing was carried out by K and S. From the heating curves of dip brazing shown in Fig. 3, it requires about 125 min to reach the brazing temperature in the case of S. The reason for the slow heating rate is that S used the actual production furnace for the experiment.

On the other hand, in the case of K, a specimen was immersed directly into a laboratory salt bath kept at 600°C (1112°F) without preheating. The curve shows that the temperature of the specimen rose to the required temperature in approximately 2 min.

Figure 4 illustrates the appearance of samples brazed by S. They show uniform flowability and good fillet formation at the joint clearance between horizontal and vertical members.

Figure 5 shows the changes in the filled joint clearance length \(F_J\) and throat thickness \(d\) with joint clearance \(D_0\). At clearances of \(D_0 = 0 \text{ and } 1 \text{ mm, the filler metal filled the whole length of the joint clearance. At clearances of } D_0 \geq 2 \text{ mm or more, the } F_J \text{ tended to shorten as } D_0 \text{ became larger. The tendency to reduce } F_J \text{ was slightly less in K than that in S. The flow factor } k \text{ was not influenced by } D_0, \text{ and the values of } k \text{ in S and K were 0.96 and 0.93, respectively, showing similar values, with each mean value having only a narrow scatter.}

In general, longer preheating time would tend to deteriorate the flowability of filler metal and fillet formation ability as Si in the filler metal diffuses into the core material (Ref. 5); however, in this experiment, the influence of preheating time was not significant.

The relationship between throat thickness \(d\) and \(D_0\) is also shown in Fig. 5. As \(D_0\) grew larger as \(D_0\) became larger. In
principle, the flow factor $k$ is not influenced by $D_0$. The reason for the increase in $d$ by the increment of $D_0$ is attributable to the fact that $F_L$ becomes small with the increase in $D_0$ (Fig. 5), and this increases the fillet volume per unit of filled joint length.

From the reasons mentioned above, the throat thickness ($d$) and the filled joint length ($F_L$) behave inversely with each other. The leg length ratio ($L_v/L_h$) in these specimens was nearly 1, independent of $D_0$, showing the ideal results.

The results confirm that the dip brazing gave good results in joint clearance filling capability and flow factor.

**Furnace Brazing**

In furnace brazing, the flux was applied uniformly on the surface of the test specimens by immersion into an aqueous solution containing 20 or 60 wt-% chloride-fluoride flux as shown in Fig. 3. After withdrawal from the solution, specimens were dried in an oven prior to brazing.

Figure 6 shows the effect of flux concentration and brazing atmosphere on $F_L$ in furnace brazing. The brazing with a flux of 60% concentration gave better joint filling capability than the 20% concentration. When the brazing atmosphere was adjusted by dry air (dew point: less than $-28^\circ C/-18^\circ F$), the length of filled joint was longer than in the open-air atmosphere without a dew point adjustment. The improvement was prominent under the brazing condition with the lower flux concentration (20%). The moisture in the atmosphere reacts with aluminum and tends to form adherent oxide films that often prevent brazability. Therefore, the brazing of aluminum in a low dew point atmosphere is beneficial to prevent the oxidation by moisture.

The value of flow factor ($k$) should not depend on $D_0$, and it might show a certain fixed value irrespective of $D_0$, as observed in dip brazing. However, in furnace brazing, the flow factors were ranging between 0.4-0.7 (average was about 0.55), depending on brazing condi-
ions such as atmosphere and flux concentration. This scattering is caused by the uneven fillet formed in low flux concentration conditions, because the measurement of k was taken only on one location at $D_0/2$.

Figure 7 shows the changes of leg length ratio ($L_V/L_H$) with $D_0$. The $L_V/L_H$ tended to deteriorate as $D_0$ grew larger. This tendency was prominent in a low flux concentration and in an open-air atmosphere. One of the reasons that $L_V/L_H$ became smaller than 1 when $D_0$ became large is the effect of gravity. A large amount of molten filler metal gathered at the short end of the joint clearance, and therefore, filler metal spread onto the surface of the horizontal base metal. Of course, this is not desirable from the standpoint of uniform fillet formation.

From the results mentioned above, brazeability was found to be dependent on the flux concentration and braze atmosphere (dew point) in the case of furnace brazing.

**Nocolok Brazing**

In Nocolok brazing, a mixture of potassium fluoroaluminates flux shown in Fig. 3 was dissolved in water, and after stirring sufficiently, the flux was applied with a brush to the brazing sheet surface of the specimen. After drying, the weight of the applied flux was calculated by measuring the weight of brazing sheet before and after applying the flux. Nocolok brazing was performed in a $N_2$ gas atmosphere, maintaining the dew point at less than $-40^\circ C$ ($-40^\circ F$).

Figure 8 shows the change of $F_1$ and $L_V/L_H$ for the specimen with flux of 10 g/m$^2$ on the brazing sheet. At $D_0 = 2$ mm, the $F_1$ of R showed a slightly longer length than that for N. However, $F_1$ with other joint clearances showed almost the same values. Accordingly, there is little difference between these two results. So within the range of this work, the difference in heating rate had no significant influence on $F_1$ in Nocolok brazing.

Figure 9 shows the appearance of specimens brazed at N. The formation of the fillet was sound and uniform. The flow factor (k) showed the fixed value ranging between 0.70 to 0.75, irrespective of $D_0$. The changes of $L_V/L_H$ with $D_0$ was also indicated in Fig. 8. The values were almost 1.0 irrespective of $D_0$ and showed relatively few deviations, indicating that the formation of a fillet was sound and uniform.

Figure 10 shows the effect of the amount of flux on the brazing sheet on $F_1$ and k at $D_0 = 2$ mm. This figure shows that $F_1$ increased slightly as the amount of flux increased, but k became considerably higher. At the level of 30 g/m$^2$ of flux, k reached 0.95. This is the same level as in dip brazing. Since in general furnace brazing the value of k would not exceed 0.8 at this heating cycle even if the amount of flux is increased to some extent (70% solution or more than 100 g/m$^2$), the flux for the Nocolok process is considered to be highly effective.

Upon comparing the three types of flux brazing methods mentioned above, the relationship between $D_0$ and $F_1$ showed a similar tendency. In addition, there was not much difference in these values if the amount of flux used was appropriate. That is, at $D_0 = 0$ and 1 mm, the full joint length (50 mm) was filled; at $D_0 = 2$ mm, $F_1$ was 37-43 mm (1.5-1.7 in.); and at $D_0 = 4$ mm, $F_1$ was 24-29 mm (1.0-1.1 in.), irrespective of brazing methods. All values were within the difference range of 5 mm (0.2 in.).

The filled length of the joint ($F_1$) showed little variation with the different brazing processes; however, the flow factor (k) showed a distinct difference as indicated in Fig. 11. This result provided evidence that dip brazing gave better brazeability compared to the other brazing processes. However, the increase of k only slightly influenced $F_1$, as shown in Fig. 10. Considering the measured values of the flow factor (k), the Nocolok process would be one of the most suitable brazing processes.
The joint clearance filling test made it possible to easily evaluate brazeability by checking the appearance and the filled length of the joint \( F_L \). Furthermore, in order to evaluate brazeability more precisely, it would be more effective to measure the flow factor \( k \) and leg length ratio \( \frac{L_V}{L_H} \) by sectioning at the location \( F_L/2 \).

**Vacuum Brazing**

Since the flow factor \( k \) in this experiment was measured by the amount of filler metal dripped from a brazing sheet, \( k \) should relate to brazing temperature, time and the composition of filler metal, but not be influenced by the clearance \( D_0 \). In fact, the value of \( k \) remained a constant value, irrespective of \( D_0 \), in every test conducted in this investigation.

However, a great difference in the absolute value of \( k \) was observed. The average values of \( k \) for each experiment were 0.7 for Sk, 0.5 for Os and Or, and 0.065 for K.

Figure 12 indicates the relationships between filled clearance length \( F_L \) and

\[
\text{Flux (g/m}^2\text{)}
\]

\begin{align*}
0 & \quad 10 & \quad 20 & \quad 30 & \quad 40 & \quad 50 \\
0 & \quad 0.2 & \quad 0.4 & \quad 0.6 & \quad 0.8 & \quad 1.0 \\
\end{align*}

\[
\text{Flow factor, } k
\]

\[
\text{Clearance: } D_0 = 2 \text{ mm} \\
\text{Temperature: } 600 \text{ °C} \\
\text{Brazing time: } 3 \text{ min}
\]

**Fig. 10** — Effect of amount of flux on the length of filled joint clearance \( F_L \) and flow factor \( k \) using Nocolok brazing

\[
\text{Flow factor, } k
\]

\[
\text{Clearance, } D_0 (\text{mm})
\]

\[
\text{Dip brazing} \\
\text{Nocolok brazing at } D_0 = 2 \text{ mm (Flux 30 g/m}^2\text{)} \\
\text{Nocolok brazing (Flux 10 g/m}^2\text{)} \\
\text{Furnace brazing (Flux 60% soln.)}
\]

**Fig. 11** — Flow factors obtained in various flux brazing processes

\[
\text{Flux (g/m}^2\text{)}
\]

\[
0 & \quad 1.0 & \quad 0.8 & \quad 0.6 & \quad 0.4 & \quad 0.2 & \quad 0.0 \\
\end{align*}

\[
\text{Flow factor, } k
\]

\[
\text{Clearance, } D_0 (\text{mm})
\]

\[
\text{Dip brazing} \\
\text{Nocolok brazing at } D_0 = 2 \text{ mm (Flux 30 g/m}^2\text{)} \\
\text{Nocolok brazing (Flux 10 g/m}^2\text{)} \\
\text{Furnace brazing (Flux 60% soln.)}
\]

**Fig. 9** — Appearance of specimens brazed with Nocolok process at N

**Fig. 10** — Effect of amount of flux on the length of filled joint clearance \( F_L \) and flow factor \( k \) using Nocolok brazing

**Fig. 11** — Flow factors obtained in various flux brazing processes
The full length (50 mm/2 in.) of a test piece was filled in the case of $D_0 = 0$ mm. Although some deviations existed among the experiments, the trend indicated the same tendency, and the lines did not cross each other. The length of $F_L$ became short as $D_0$ increased. The deviation became smaller in the case of $D_0 = 4$ mm; yet, as shown in Table 2, the ratio of the standard deviation ($\sigma$) to average value of all experiments ($F_L$) $\sigma/F_L$ did not change greatly with $D_0$.

Since the difference of $F_L$ in each experiment became greater with a small $D_0$, the clearance of 1 mm is convenient for the detection of differences in brazability. Furthermore, upon comparing Or with Os, the length of $F_L$ was longer in the preheated Os than in Or without preheating.

Throat thickness (d) showed the similar tendency in the case of furnace brazing, as shown in Fig. 5. That is, d also increased as $D_0$ increased.

Since $k$ kept a constant value unaffected by $D_0$, the reason for the increase in d with the increase of $D_0$ is attributable to $F_L$ getting smaller as $D_0$ increases (Fig. 12), resulting in much fillet metal at the end of the filled joint length.

The vertical leg length ($L_V$) of the fillet grew longer as $D_0$ grew larger, which is the same tendency with d. In the preheated process $F_L$ got longer; therefore, $L_V$ became smaller even with the same flow factor in the preheated and without preheated processes. Despite deviations, the leg length ratio ($L_V/L_H$) tended to become smaller with the increase of $D_0$.

As the size of fillet (shown as d and $L_V$) grows larger as $D_0$ increases, the shape of a fillet is significantly influenced by the gravity (Ref. 9). Therefore, the length of $L_V$ becomes shorter than $L_H$, and as a result, it was supposed that $L_V/L_H$ becomes smaller.

The Comparison of Fluxless Brazing

Brazing tests were conducted by means of a carrier gas ($10^{-1}$ torr with $N_2$ gas) and the VAW process ($N_2$ gas with a dew point less than $-68^\circ\text{C}/-90^\circ\text{F}$, 760 torr), and the results were compared with the vacuum brazing process. Carrier gas brazing was conducted without preheating (Or), while VAW brazing was performed under a preheated condition (Os).

As observed in the vacuum brazing process, the flow factor ($k$) was not significantly affected by $D_0$. In the carrier gas process, Al-1050-1.5Mg filler metal (the same as that for vacuum brazing) was used, and the flow factor ($k$) was 0.5, irrespective of $D_0$, which is about the same as for the vacuum brazing process. On the other hand, $k$ in the VAW process using Al-1050-0.1Bi filler metal was slightly larger, 0.64.

Figure 13 shows the relationship between $F_L$ and $D_0$ in various fluxless brazing processes. The VAW process had the largest $F_L$ since it had a larger $k$. Although there was a large deviation in the $F_L$ with the carrier gas process, it displayed the same tendency as in vacuum brazing without preheating. This confirms that no distinct difference was found in $F_L$ between two the processes as long as the heating rate and filler metal were the same.

Throat thickness (d) in the carrier gas process deviated widely, as did $F_L$; however, the average value was almost the same as in vacuum brazing with the same heating rate. In the VAW process, the mean value of $d$ was small due to the extensive spreading of filler metal on the horizontal material, which left a smaller $L_V$ and a larger $L_H$ since the brazing atmosphere was not so favorable.

As a whole, the value of $d$ increased according to the increment of $D_0$, which is the same as shown in Fig. 5.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Clearance (mm)</th>
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<tbody>
<tr>
<td>$F_L$</td>
<td>1</td>
</tr>
<tr>
<td>$\overline{F}_L$</td>
<td>37.65</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>5.57</td>
</tr>
<tr>
<td>$\sigma/F_L$</td>
<td>0.148</td>
</tr>
</tbody>
</table>


**Table 2—Mean Values of Filled Length of Joint Clearance ($F_L$), Standard Deviation ($\sigma$) and the Ratio ($\sigma/F_L$) for Each Clearance in Vacuum Brazing**
Such irregularity or lack of smoothness in fillet formation (nonuniform fillet formation) would be difficult in the case of \( D_0 = 0 \) mm (a conventional tee joint specimen). Since the frequency of occurrence of the nonuniform fillet is expected to correspond with the possibility of developing a joint defect and improper fillet formation, the use of the specimen with a joint clearance of a certain value (\( D_0 = 1-3 \) mm) is more effective and practical in evaluating brazability than the use of a simple tee joint (\( D_0 = 0 \) mm).

The common feature of specimens with nonuniform fillets was the difference in fillet size on both sides of the brazing sheet. However, different fillet size on both sides was not a sufficient factor to cause improper appearance of the filled joint. In the case of the difference of \( L_V/L_H \) on the left and right side, an improperly filled joint clearance was observed. But this did not serve as a clear indication of something wrong, because improper filling of a test specimen was not clearly detected by the evaluating parameters (\( F_L, k, d, L_V, L_H \)). But, the joint clearance filling test specimen with \( D_0 \) is easy to check for appearance, and this is one of the excellent features of this type of test.

Table 3 shows the comparison of mean throat thickness (\( d \)) for vacuum brazing to that of carrier gas brazing without preheating, respectively. The values of \( d_c \), theoretical throat thickness, were calculated by assuming a uniform fillet formation. In this instance, \( d_c \) was obtained in the following manner.

Under the assumption that the total volume of the formed fillet equals the volume of filler metal dripped from the brazing sheet, the equation below holds true. It is based on the assumption: cross-sectional area of a fillet on one side, \( S \times \) filled length of the joint clearance \( F_L = \) surface area of the brazing sheet on one side \( (55 \times 25 \text{ mm}) \times \) average value of filler metal thickness, \( (t_1 + t_2)/2 \times \) flow factor, \( k \),

\[
S \times F_L = 55 \times 25 \times [(t_1 + t_2)/2] \times k \quad (1)
\]

Assuming that a cross-section of fillet is \( \frac{1}{4} \) of a circle (radius, \( r \)),

\[
S = \pi r^2 (1 - \pi/4) \quad (2)
\]

\[
d_c = r (\sqrt{2} - 1) \quad (3)
\]
From Equations 1, 2 and 3, \( d_c \) can be obtained as follows:

\[
d_c = \sqrt{\left(\frac{55 \times 25 \times k \times (l_1 + l_2)}{1 - \pi/4}\right) \times \left(h + l_1 + l_2\right) / 2}
\]

As shown in Table 3, \( d_c \) was larger in the carrier gas process than in the vacuum brazing process, while \( d_c \) remained almost the same value, and \( k \) and \( F_l \) were not very different with both processes. For this reason, \( d/d_c \) in the carrier gas process was larger than that in the vacuum brazing process. Therefore, it was confirmed that the carrier gas process had produced a larger filler metal volume at the central portion of the brazement in the longitudinal direction. On the other hand, the vacuum brazing process tends to produce a more uniform fillet deposition rather than the carrier gas process.

In this experiment, filler metal containing 1.5% Mg was used in both processes. Accordingly, the amount of evaporation of Mg would be less in the carrier gas process than in vacuum brazing because the pressure is high in the carrier process. Therefore, the difference in fluidity of filler metal due to the differential residual amount of Mg, or the difference in the surface cleanliness caused by the difference in Mg vaporization rate might have influenced the distribution of filler metal (Ref. 10).

As a result of the test specimens used in this test, some differences were observed in the absolute values of various parameters obtained from the respective experiments, but significant change was not observed in the relationship between various parameters and joint clearance. The test specimen enables easy inspection to determine the proper filling of the joint clearance. In addition, a test specimen of this type (joint clearance filling test specimen) is easy to prepare and assemble, and also, it is possible to measure the filled length without cutting the brazed specimen. It is easy to check appearance, and the various brazeable parameters can be measured by observing the cross-sectional fillet at the position of \( F_l / 2 \). Thus, it can be concluded that the shape of this test specimen is excellent for the evaluation of brazeability.

**Conclusions**

The joint clearance filling test specimen adopted in this investigation had the following features:

1. The configuration of the test specimen is simple and easy to assemble.
2. The filled joint clearance length can be measured immediately after brazing without cutting.
3. The flowability of a filler metal can be determined by visual inspection after brazing.
4. Furthermore, various evaluation parameters such as flow factor (\( k \)), throat thickness (\( d \)) and fillet leg length ratio \( (L_v/L_d) \) can be measured by cross-sectional observation of vertically cut test specimens in the transverse direction of the fillet.
5. It is also possible to observe erosion, penetration and diffusion of molten filler metal into the core material and the base metal. Furthermore, the experiments showed that, as commonly claimed, a flux brazing system is superior to a fluxless brazing system from the viewpoint of reproducibility and stability in joint quality i.e., a better joint filling property and better flowability.
6. The dip brazing process is the most stable and reproducible brazing process. The Nocolok process also yields equally stable brazing results if a suitable amount of flux is used. On the other hand, there still remains a number of items to be clarified. In vacuum brazing, there has been a considerable difference in the measured values of test parameters among the experiments performed.

Since the type of furnace and evacuating systems were different, the difference in the leak speed, absorption contents of moisture, gas amount and evacuating capacity may have caused the difference in brazeability with each experiment. But, in flux brazing, there was less deviation in test data with each experiment, because the factors caused by the equipment or brazing condition were eliminated by sufficient fluxing action.

As the size of test specimens adopted in the present work was relatively small, test results may not exactly reflect on the brazeability of larger pieces on a production scale. But, these data are considered to be reliable for conducting basic evaluation of brazeability of materials and equipment.

The Japan Light Metal Welding and Construction Association is now making an authorized standard for evaluation of brazeability of aluminum using the joint clearance filling test specimen.

**Acknowledgments**

The authors express sincere thanks to the members of the Low-Temperature Joining Committee (The Japan Light Metal Welding and Construction Association for experimental works).

**References**