Effect of Curvature on Fillet Formation during Aluminum Brazing†

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Abstract

Effect of curvature of convex and concave planes on the fillet size formed after brazing of aluminum was investigated in relation to the brazing method. The fillet size was measured by throat thickness and vertical leg length on the inside (concave plane) and outside (convex) plane of an aluminum pipe braze specimen. Fillet size estimated by the Laplace equation was larger on the inside than that on the outside. In vacuum brazing inside fillet was larger than outside one under limited test conditions, while in dip brazing inside fillet was always larger than outside one, which agreed well with the prediction of the Laplace equation. The discrepancy between the calculation and experimental results in vacuum brazing was attributed to the poor flowability of molten filler metal.

KEY WORDS: (Aluminum Brazing) (Vacuum) (Dip Brazing) (Fillet) (Curvature)

1. Introduction

Aluminum brazing technology has been remarkably developed in recent years, and wide variety of heat exchangers are produced by some brazing methods. Recently, many drawn cup type heat exchangers with relatively enclosed volume are brazed in vacuum. The authors had already reported the effect of degree of enclosure and magnesium content in filler metal on brazeability in vacuum[1),2)]. In brazing of drawn cup type heat exchangers, the fillet forms on curved surface. The curved surface influences the size of fillet and the size could be predicted by Laplace equation[3),4)]. Especially in vacuum brazing, the brazeability is different from that in flux brazing[5)], therefore, the fillet size would be dependent on brazing processes. However, the almost studies on brazing investigated the fillet on planes, accordingly the effect of curvature on brazeability is not discussed. A great variety of braze products with different design and size are developing, therefore, it is expected the cases to braze curved surface become increasing. The present work aimed to reveal the relation between fillet formability on curved surface and its curvature. In this experiment fillet size at inside (concave plane) and that at outside (convex plane) is investigated by the use of aluminum pipe and brazing sheet.

2. Materials and Experimental

Aluminum drawn pipe (A3003TD-H14, thickness of 1.4 mm) and brazing sheet shown in **Table 1** were used for brazing. The brazing sheet is composed of A3003 core material and Al-10Si-(1.5Mg) filler metal as single side cladding. The total thickness of brazing sheet is 1 mm and the proportion of cladding is about 10%. The sheet is used as annealed condition(-O type). BV-2A with magnesium is made for vacuum brazing and BF is used for dip brazing.

Table 1 Chemical composition (mass%) and constitution of brazing sheet.

Brazing sheet	Core material	Cladding			Proportion of clad (%)
		Nominal composition	Main elements (mass%)		
			Si	Mg	
BV-2A	3003	Al-10Si-1.5Mg	9.93	1.44	10.5
BF	3003	Al-10Si	9.36	0.02	9.6

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Figure 1 shows the shape and size of braze specimen, one side clad brazing sheet is placed horizontally with filler metal side up, over the horizontal brazing sheet aluminum pipe was set and wound by a fine stainless steel wire. The effect of spacer diameter (d) degree of opening in pipe (θ) on fillet size at inside and outside of pipe was investigated. Fillet size was measured by throat thickness (d) and height namely vertical leg length (L_V), **Fig. 2**.

Brazing was conducted in vacuum level of 2.67 x 10^{-3} Pa or in molten flux of KCl-NaCl-LiCl-AlF_3 (dip brazing). Brazing condition of 873 K, 3 min was adopted for both brazing methods. In vacuum brazing, the temperature was raised to 803 K in 20 min, after that it was raised to 873 K in 20 min.

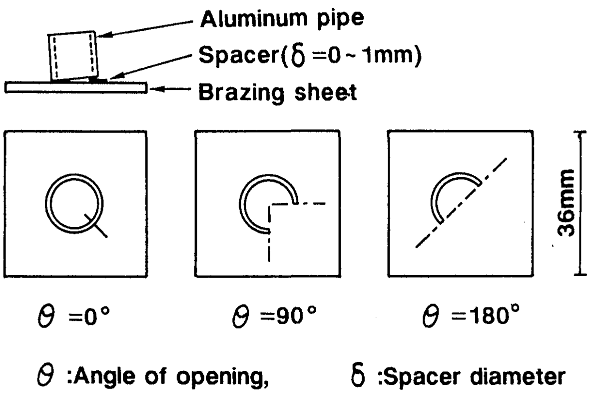

Fig. 1 Shape and size of braze specimen.

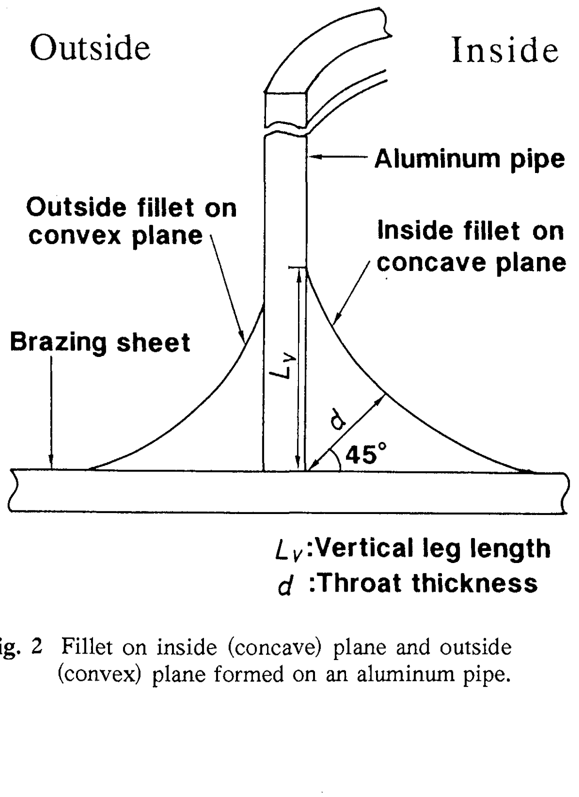

Fig. 2 Fillet on inside (concave) plane and outside (convex) plane formed on an aluminum pipe.

3. Laplace Equation

Laplace equation indicates that pressure difference of liquid surface at inside and outside is related to surface tension of liquid and the curvature of liquid surface (meniscus), Eq. (1).

$\Delta P = \gamma(1/R_1 + 1/R_2)$ (1)

where,

ΔP : pressure difference between meniscus inside and outside

γ : surface tension of liquid

R_1, R_2 : two curvatures of meniscus crossing each other at right angles, (**Fig. 3**)

The curvatures R_1 and R_2 are indicated by positive symbol when the center of curvature located at inside of liquid, whereas it is expressed by negative symbol if the center located at outside of liquid.

On the other hand, the meniscus rise height (h) is given by Eq. (2).

$\Delta P = -\varrho g h$ (2)

g: gravity

From Eqs. (1) and (2),

$h = -(\gamma/\varrho g)\ (1/R_1 + 1/R_2))$ (3)

If liquid wets inside of a pipe with radius r, two curvatures are approximately equivalent, $-R_1=-R_2=r$, then meniscus rise height is given by the following equation.

$h = 2\gamma/\varrho g r$ (4)

This relation is well known by the fact that the meniscus rise height becomes larger in a pipe with smaller radius.

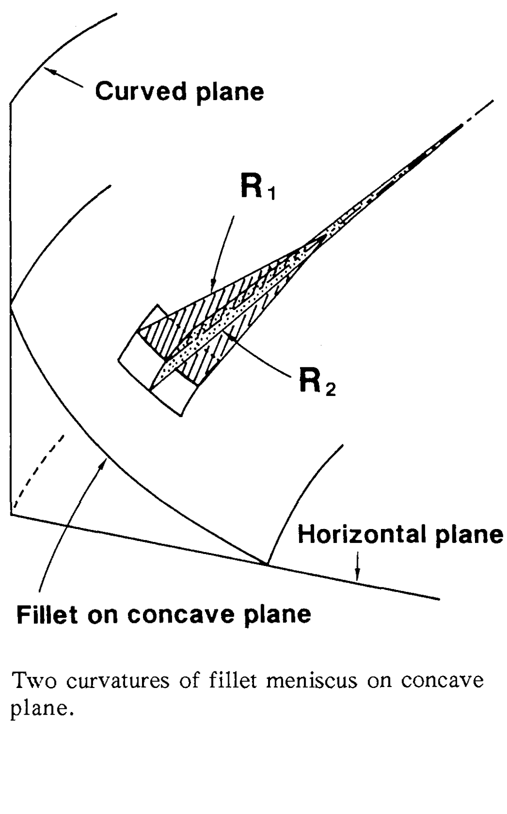

Fig. 3 Two curvatures of fillet meniscus on concave plane.

Taking into consideration to braze inside and out side of a pipe, the pressure difference of meniscus at inside and outside for both concave plane and convex plane is introduced by Laplace equation.

On concave fillet at inside of a pipe the following relation holds.

$$\Delta P^{In} = \gamma(-1/R_1{}^{In}-1/R_2{}^{In})<0 \qquad (5)$$

On convex fillet at outside the following relation holds.

$$\Delta P^{Out} = \gamma(-1/R_1{}^{Out}-1/R_2{}^{Out}) \qquad (6)$$

In this case, under the hypothesis that $R_1{}^{In}=R_1{}^{Out}$ (suffix at top means at inside or outside), the following relation is derived.

$$\Delta P^{In} < \Delta P^{Out} < 0$$

The relation is valid under the condition of $R_1<R_2$. Accordingly, it is expected fillet rise height at inside becomes higher than that at outside.

The relations between meniscus rise height on aluminum pipe inside and outside and pipe diameter derived by numerical calculations[6)7)] are shown in **Fig. 4**. The precise method will be presented in a separate report. The used constants of aluminum filler metal for calculation are as follows; density ϱ=2500kg/m^3 [8)], surface tension γ=0.69N/m[8)], contact angle θ=0 . In Fig. 4, as described above, it is shown the fillet height at inside is higher than outside. In case that the radius of a pipe is infinite, the meniscus height coincides with the height on the infinite vertical plane, vertical leg length, $\gamma/\varrho g$=7.51mm, g: gravity.

4. Experimental Results

4.1 Spacer diameter

Under a constant brazing sheet size, fractional area of brazing sheet between inside of a pipe and outside becomes smaller except the pipe diameter of 30 mm.

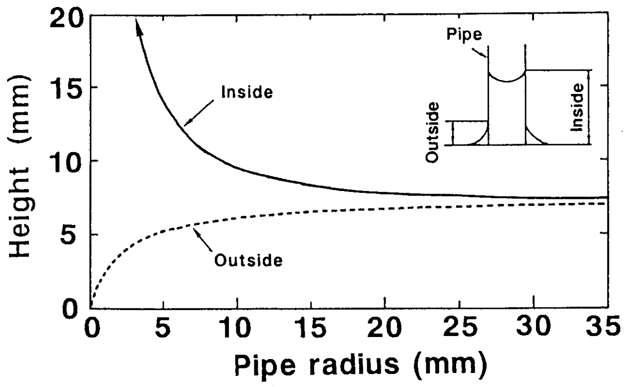

Fig. 4 Calculated fillet height of aluminum filler metal formed on the inside and outside of an aluminum pipe.

Therefore, the amount of molten filler metal becomes less at inside of a pipe, this might cause the difference of fillet size between inside and outside. Then at the first stage of the experiment, the relation between diameter of spacer rod set between brazing sheet and aluminum pipe shown in Fig. 1 and throat thickness of fillet is obtained in vacuum brazing, **Fig. 5**. Inside fillet size did not exceed the outside fillet size up to the spacer diameter, δ, of mm. At δ=0 mm, outside fillet was larger than inside fillet. Similar results were obtained in vertical leg length, L_V. Laplace equation predicted that inside fillet is larger than outside fillet, however, the results in vacuum brazing did not coincided with the prediction.

On the other hand, the results of dip brazing coincided with the prediction by Laplace equation under the same brazing condition in vacuum, **Fig. 6**. Inside fillet was always larger than outside one irrespective of magnesium addition to clad filler metal. The difference of fillet size between inside and outside became larger with decreasing spacer diameter. Throat thickness in BF for dip brazing was smaller than BV-2A, the main reason is attributable to large flow factor in BV-2A with magnesium bearing filler metal. Magnesium bearing filler metal has lower melting point, solidus of 824-832 K[9)10)] than binary Al-Si filler metal with solidus of 850 K. At brazing temperature of 873 K[11)], the more liquid could appear in magnesium bearing low melting point filler metal. The reason that larger fillet obtained in dip is attributable to the high flowability under the effective fluxing action[5)].

4.2 Degree of opening

Figure 7 shows the results of vacuum brazing on specimens with opening in aluminum pipe. At degree

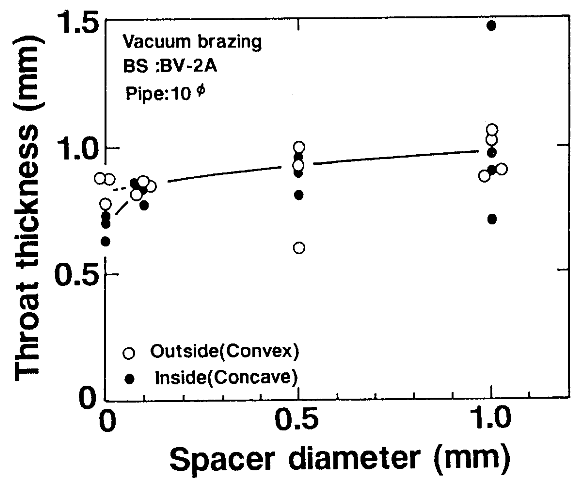

Fig. 5 Relation between spacer rod diameter and throat thickness after vacuum brazing.

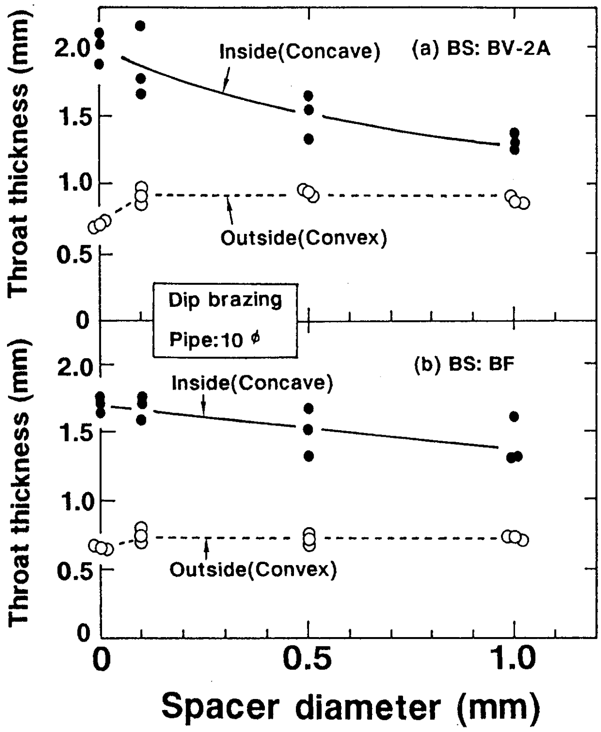

Fig. 6 Relation between spacer rod diameter and throat thickness after dip brazing, (a) BV-2A, (b) BF.

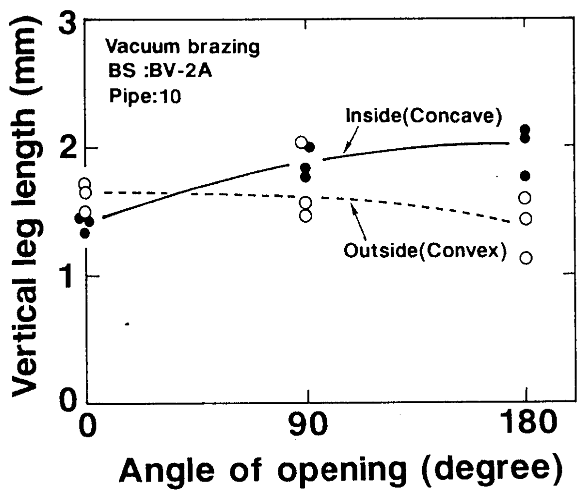

Fig. 7 Effect of degree of opening on vertical leg length after vacuum brazing.

of opening is zero, $\theta=0$, outside fillet was larger, however, at $\theta=90$ or more, inside fillet became larger, the results coincided with the prediction of Laplace equation. In dip brazing, inside fillet was always larger than outside fillet irrespective of degree of opening, **Fig. 8**. The difference in size became larger with increasing the degree of opening. In the following experiment, specimens with $\theta=180$ were mainly used.

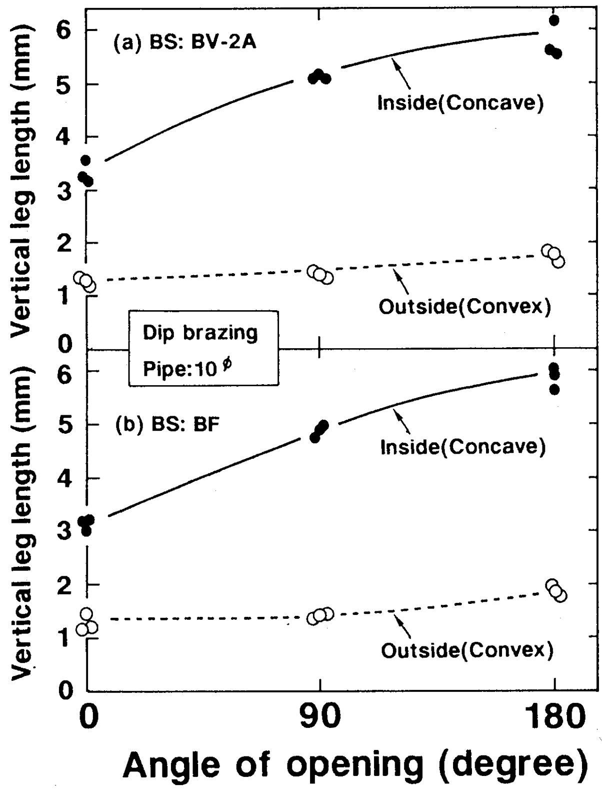

Fig. 8 Effect of degree of opening on vertical leg length after dip brazing, (a) BV-2A, (b) BF.

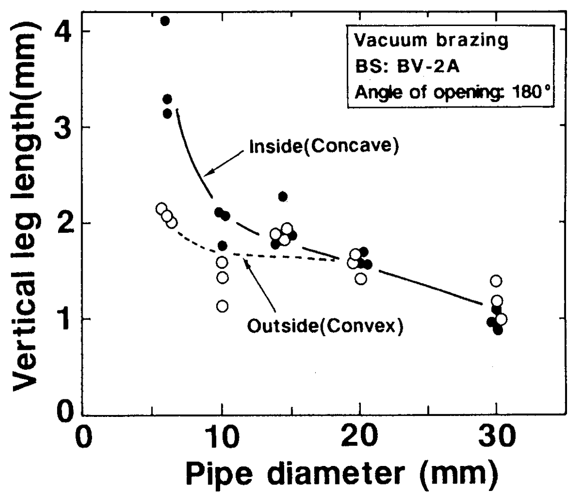

Fig. 9 Effect of pipe diameter on vertical leg length at inside and outside fillet after vacuum brazing, BV-2A.

4.3 Pipe diameter

Figure 9 indicates the results of vacuum brazing on specimens with $\theta=180$ which investigated the effect of pipe diameter on vertical leg length, L_V. The size maintained nearly the same at both sides up to pipe diameter of 30-14 mm, however, at the diameter less than 14 mm, L_V at inside became larger than at outside.

The relation between d and pipe diameter showed similar inclination to Fig. 9. In vacuum brazing, it is found that the fillet size is greatly dependent on its curvature and direction of curve toward meniscus, convex or concave in case that the curvature of curved plane became under 7 mm.

Inside fillet was always larger in dip brazing irrespective of brazing sheet clad composition and pipe diameter, **Fig. 10**, but the difference is small at pipe diameter of 30 mm, where the amount of filler metal per unit length of pipe is small. The difference in fillet size at inside and outside could not be appeared at small amount of filler metal. In fact, large degree of opening under the same brazing sheet size results in the increase of amount of filler metal per unit length of pipe circumference. This increment makes remarkable difference between inside and outside fillet even in vacuum brazing. Then, the following brazing tests were conducted in vacuum. The effect of pipe diameter on fillet size at inside and outside was measured by changing the degree of opening to obtain same amount of filler metal per unit circumference of pipe of different diameter under the fixed length of brazing sheet side. The results are shown in **Fig. 11**. At all pipe diameters, inside fillets were larger than outside ones; larger inside fillets were obtained even at 30 mm diameter because of large amount of filler metals compared by experimental condition in Fig. 9. The amount of filler metal for smaller pipe diameters was smaller than in Fig. 9, however, inside fillets were always maintained larger than outside.

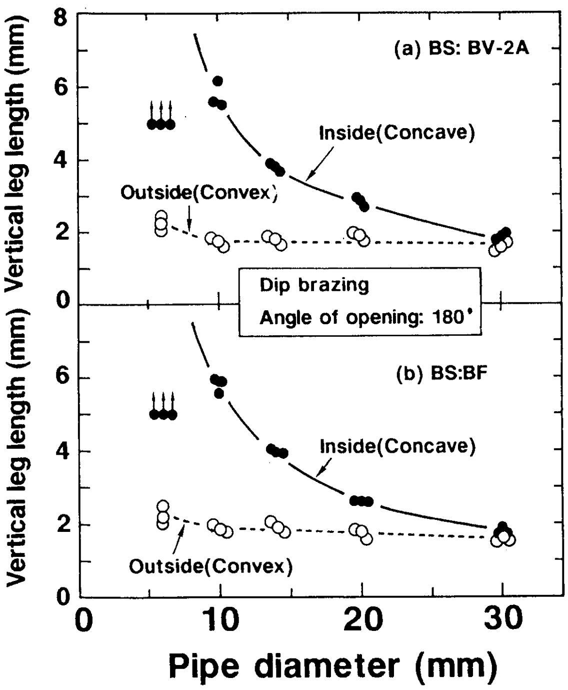

Fig. 10 Effect of pipe diameter on vertical leg length at inside and outside fillet after dip brazing, (a) BV-2A, (b) BF.

Figure 12 compares the cross section of pipe brazed in vacuum and dip. It is clear that inside fillet is larger than outside especially at small pipe diameter and in dip brazing. The inside fillet for dip brazing at pipe diameter of 6 mm showed convex meniscus partially, this is due to the low pipe height of 5 mm.

Figure 13 also shows the results on specimens with constant amount of filler metal per unit circumference of pipe by changing the side length of brazing sheet. Similar to Figs. 9 and 10, inside fillet became larger than outside at small pipe diameter in both brazing methods.

From the above results, inside fillet was larger in dip brazing irrespective of brazing conditions, this is correspondent to the prediction by Laplace equation, however, it was found inside fillet became large under certain test condition in vacuum brazing, i.e., with opening or small pipe diameter less than 14 mm.

5. Discussions

It is rather hard to get different fillet size at inside and outside in vacuum brazing, however, in dip brazing inside fillet was always larger or at least not smaller than outside as predicted by Laplace equation. The reason that the difference could hardly be obtained by vacuum brazing is discussed. In general, the flowability of molten filler metal is considered to be low in vacuum brazing, because the flow factor in vacuum process is remarkably lower than in dip process. It is confirmed that the difference could be easily obtained in sufficient amount of filler metal, however, in dip brazing large difference appeared even under the small amount of filler

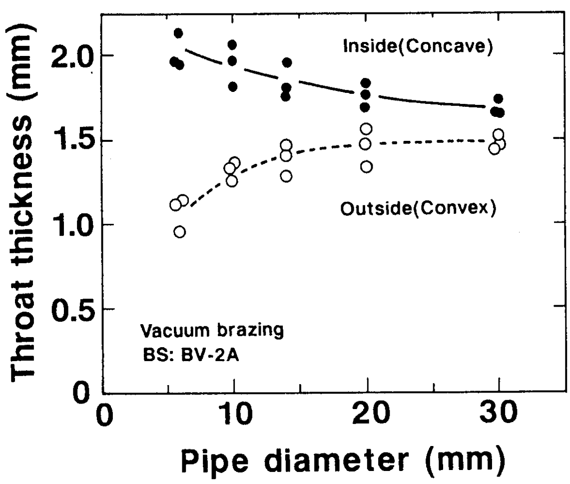

Fig. 11 Throat thickness at inside and outside fillet after vacuum brazing. Circumference length of pipe was constant.

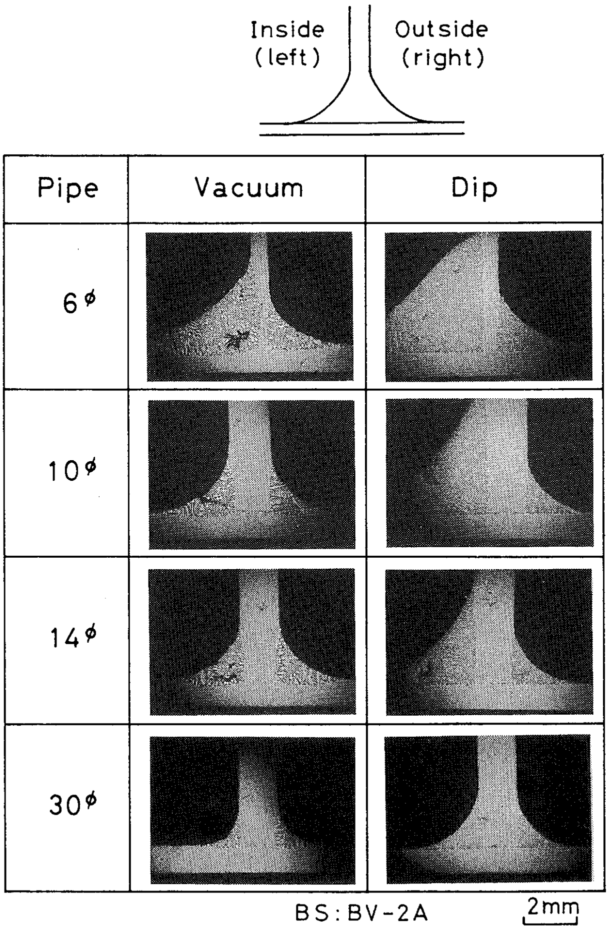

Fig. 12 Cross section of brazed aluminum pipe with different diameter.

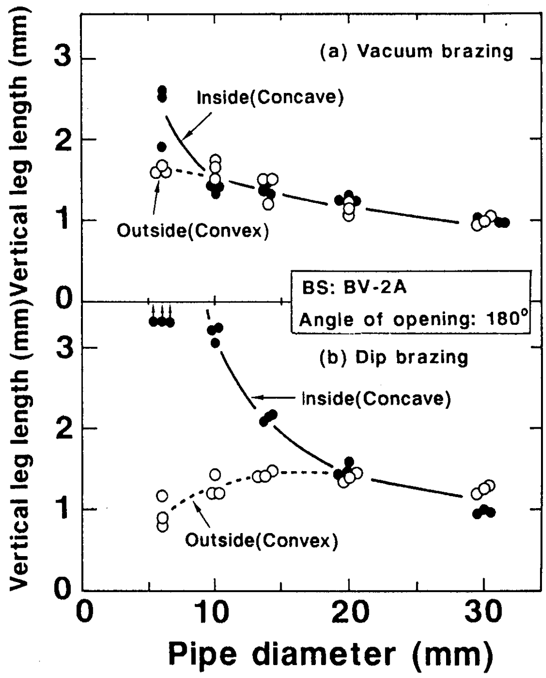

Fig. 13 Vertical leg length at inside and outside fillet after vacuum brazing (a) and dip brazing (b). The length of a side of brazing sheet was changed corresponding to the pipe diameter to keep the volume of molten filler metal per unit circumference length of pipe at a constant value.

metal. Therefore, the reason that the difference was hardly obtained in vacuum brazing was not considered only to the small amount of filler metal available in vacuum brazing.

It has been known that the capillary attraction is small in vacuum brazing of aluminum[12,13], therefore, the filling ability of aluminum filler metal was extremely lower in vacuum than in dip process. **Figure 14** confirms this fact by braze tests. A3003

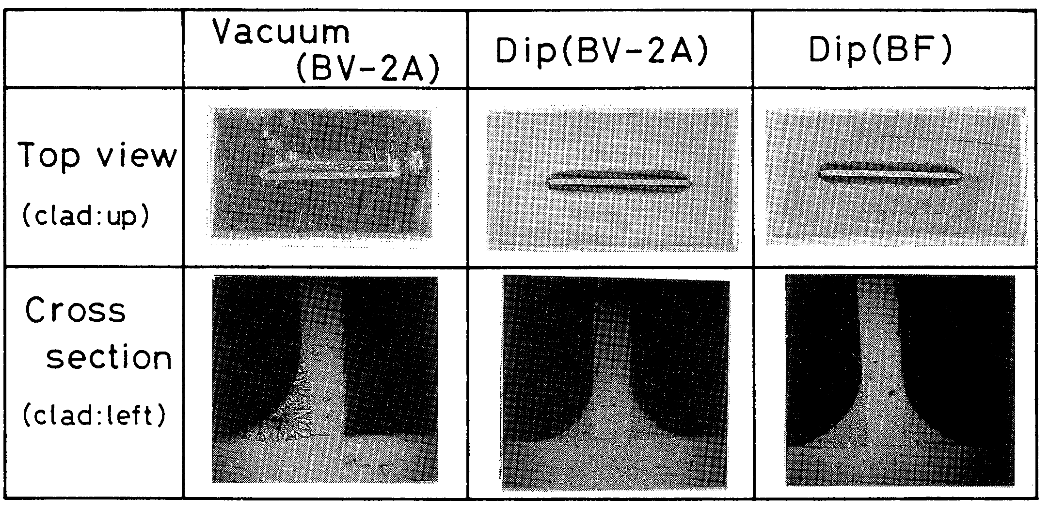

Fig. 14 Appearance and cross section of tee type brazed specimen.

aluminum alloy base metal of horizontal member was brazed with a vertical brazing sheet. Fillet was formed only on clad side but no fillet on opposite side in vacuum brazing, whereas sound fillet was formed on both sides in dip brazing irrespective of the clad material of brazing sheet. Accordingly, magnesium in clad material of brazing sheet has no effect on fillet formability or flowability of filler metal in dip brazing.

The excellent brazeability is brought by the getter action of magnesium added into filler metal[14]. The magnesium getter reacts with oxygen and water in vacuum furnace, but it will not reduce the surface oxide film on base metal that does not come into contact with molten filler metal. On the other hand, surface oxide films on both base and filler metals are covered and chemically removed by flux in dip and other flux brazing processes. Therefore, the surface tension of filler metal should be smaller in flux process than in vacuum process. It is understood by Young relation that the spreadability in vacuum brazing became low if only the surface tension of base metal is decreased. In vacuum brazing, the spreadability of filler metal is low, this seems to be the main reason of low flowability and filling ability of clearance.

6. Conclusions

The effect of curvature of curved surface on braze fillet size was investigated in relations to brazing method and shape of test specimen. It is estimated that inside fillet on concave plane becomes larger than the outside fillet on convex plane by the Laplace equation, and the meniscus rise height on both planes were obtained by calculation. The main results obtained are summarized as follows.

(1) The effect of curvature (pipe diameter) on fillet size was depended on brazing method. In vacuum brazing the effect of curvature appeared only in pipe specimen with small diameter, at large diameter the difference could not be obtained clearly. In dip brazing, inside fillet was always larger than outside ones irrespective of pipe diameter, this is coincided with the estimation by Laplace equation. Of course the difference becomes dominant in small diameter.

(2) The disagreement of the experimental results with the prediction by Laplace equation is estimated by the low flowability of filler metal in vacuum brazing.

(3) Magnesium in clad filler metal did not affect the fillet formation on pipe inside and outside in dip brazing process.

(4) Inside fillet becomes larger, which means the size difference between inside and outside became dominant, with increasing the amount of filler metal.

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