Flow of Aluminum Dip Brazing Filler Metals

Brazing filler metal flow depends on an interrelation among variables that may be adjusted to improve efficiency in high production dip brazing

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ABSTRACT. Flow in aluminum-silicon brazing filler metal has been shown to depend upon the composition and thickness of the brazing sheet cladding layer and upon the temperature of brazing. The interrelationships existing between these parameters are explained in terms of a eutectic melting process. The data are presented in a form which should assist brazing sheet users in selecting appropriate materials and operating temperatures for use in production situations.

Introduction

Dip brazing is a common method of fabricating complex aluminum components. The process, which is very adaptable to mass production, has been widely used in applications such as the production of automotive heat exchangers. In the industry, however, there is a continual effort to make the process more efficient and less costly. One way of achieving this is to reduce the brazing cycle times. In the past, the major difficulty inherent in this approach has been the slower heat-up rates of the thicker components in an assembly. Thus when preheating or dip times are shortened, braze metal flow has been insufficient in some areas and unsatisfactory joints have been formed. Recently, the use of brazing sheet with wider ranges of alloy cladding compositions has been proposed, whereby the silicon content is adjusted to compensate for temperature differences caused by heat-up rate variations. However, at present, this approach is largely empirical.

The present paper presents results of work directed towards establishing a better understanding of aluminum brazing filler metal flow with particular emphasis upon the effects of cladding composition, cladding thickness and brazing temperatures. The results not only clarify some of the fundamental mechanisms governing brazing metal flow, but they provide basic information for predicting the effect of particular sheet specifications, and of proposed changes in brazing schedules or design requirements.

Materials and Experimental Procedures

Experimental brazing sheet was fabricated in the laboratory adhering as closely as possible to standard production practices. The core was 3003 alloy, clad both sides with Al-Si brazing filler metal produced from high purity components. Sheet was produced in a wide range of thickness, cladding thickness and alloy composition, as listed in Table 1. Some commercial sheet 0.020 in. thick, clad 10.2% with a 7.45% silicon alloy, was included in this study as a control material.

The brazing flux composition is listed in Table 2. Although more active fluxes that give greater flow are available for dip brazing aluminum, the flux shown in Table 2 is commonly used in industry because of its relatively low cost. For experimental purposes, the molten flux was contained in a 9 in. deep by 4.5 in. diam alumina crucible which was placed in a resistance heated, vertical crucible furnace. Attached to the top of this furnace was a tall brick collar which helped stabilize the bath temperature. The temperature was monitored by a thermocouple positioned inside the bath giving an accuracy of control of ±2 F.

Drop Formation Test

The testing method selected was a drop formation test, which has been used many times in Kaiser Aluminum's Research Laboratories to evaluate the brazability of commercial sheet. Correlation between these results and production brazing performance of the material has always been good. For this test, brazing sheet samples are cut in the form of strips 2 in. long by 0.5 in. wide. These

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Paper was presented at the 55th AWS Annual Meeting (5th International AWS-WRC Brazing Conference) held at Houston during May 7-9, 1974.

strips are suspended from a rack such that several samples can be dipped into the brazing flux simultaneously. During immersion the brazing metal melts and flows down the sheet to form a drop. The size of this drop gives a measure of the brazability of the sheet. A typical test was performed as follows.

A rack of six specimens was prepared and preheated in an air circulation furnace at 1000 F. After a suitable time, usually five minutes, the rack was quickly transferred to the dip brazing pot. At the end of the required immersion period, the rack was removed from the flux bath and the molten brazing filler metal was allowed to solidify. The specimens were then water quenched and washed to remove adhering flux.

The flow was measured by carefully shearing 1.5 in. from the top of the specimen and weighing the remaining 0.5 in. which contained the drop (Fig. 1). This weight was then compared to known, blank 0.5 in. weights established for undipped sheet. Knowing the specimen dimensions, cladding thicknesses and the average weight of the drops formed, a flow factor (k) could be calculated from the formula:

$$k = V_f / V_a$$

where V_f = volume of filler flowing
V_a = volume of filler available.

During the present work, each sample on the rack was from sheet of a different composition or thickness so that some degree of randomization in testing was achieved. At least three, and usually six or more, samples were run for each condition, changing sample position on the rack each time. Consistency was maintained by always including one sample of control material on each rack. If the result for this was outside control limits of a three standard deviation range established in preliminary tests under the same conditions, results of that particular batch were disregarded. Consistently low control results indicated that the flux had deteriorated and should be replaced.

Results

Trials were run to more precisely establish the correlation between results of the drop formation tests and

Table 2 — Composition of Brazing Flux

Element	Wt %
Na	10.4
K	26.0
Ca	7.4
Li	0.6
Cl	51.2
F	2.7

Table 1 — Variations in Test Materials

	Sheet thickness, in.	Cladding, %	Silicon content, wt %
Variable cladding composition	0.065	4.1	6.45, 7.65, 8.58, 10.50, 11.50
Variable sheet and cladding thickness	0.021	4.7, 9.4, 14.1	7.65
	0.065	4.7, 8.9, 13.9	7.65
	0.120	4.6, 8.2, 13.5	7.65

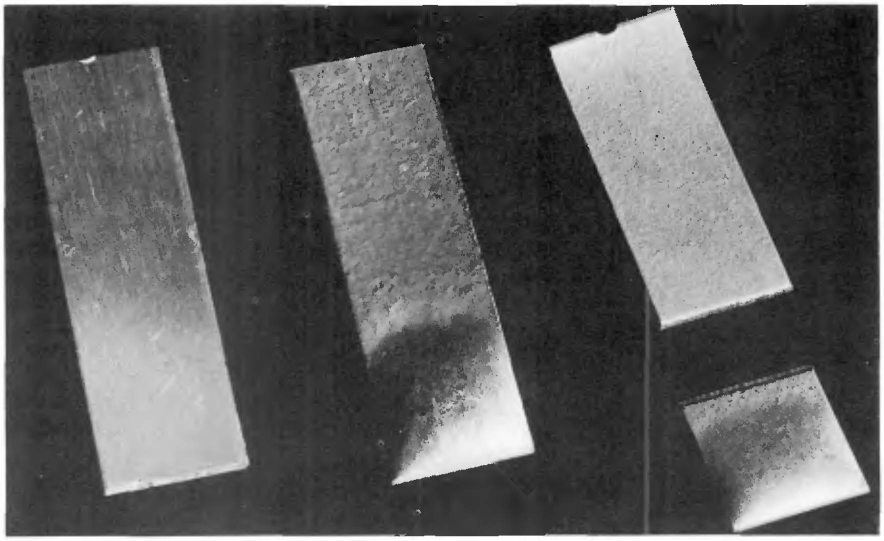

Fig. 1 — Undipped, dipped and sheared flow test samples

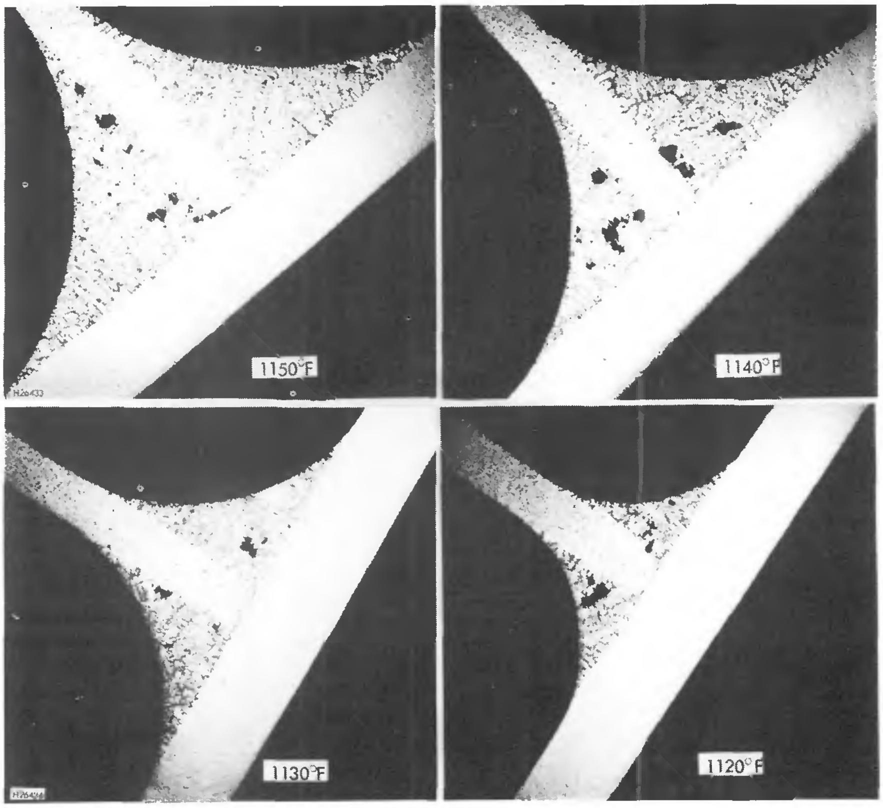

Fig. 2 — Fillet joints formed from 7.65% brazing filler alloy in the temperature range 1120-1150 F

joint formation properties of the cladding. Simple inverted "T" joints were formed between a 2 × 0.5 in. vertical strip of brazing sheet and a similarly sized strip of 1100 aluminum alloy. The brazing sheet was 0.020 in. thick, clad 9.4% with 7.65% Si alloy. Fillet brazed joints were then produced at 10 F intervals over the range 1120-1150 F (Fig. 2). The volume of filler metal flowing into the joint was calculated from the radius of the fillet according to the formula given by Miller (Ref. 1):

$$A = 0.215\, y^2$$

where A = cross-sectional area of the fillet

y = radius of curvature of the fillet

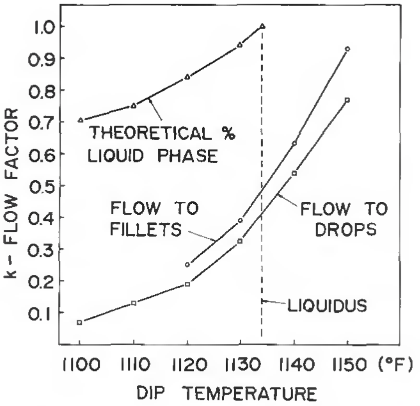

Fig. 3 — Comparative flow results in fillet and drop formation tests

Drop formation tests were run simultaneously using samples of the same brazing sheet, and the results are shown in Fig. 3.

The flow factors obtained from the fillet measurements were some 20% higher than those calculated from the drops. This was due mainly to a difference in the method of suspension. The net effect was that in the drop formation tests some filler was lost in forming a joint with the aluminum suspending wire. When nickel wires were substituted, results from the two tests became identical. Therefore, it was concluded that results of the simpler drop formation test would provide a reliable guide to the comparative brazabilities of the various brazing filler metal and sheet systems.

Since filler flow is known to be time dependent, tests were next run to establish the effect of dip time upon flow. Two sheet types were used in this investigation: (1) 0.021 in. thick, clad 9.4%, containing 7.65% Si and (2) 0.050 in. thick, clad 10.0%, containing 7.45% Si.

Strip samples were preheated for five minutes at 1000 F and flux dipped at 1130 F. The results (Fig. 4) showed that flow was very rapid, with most occurring in the first minute after the sheet reached brazing temperature. In the thicker sheet, which took longer to heat up, no flow occurred for the first 20 seconds of the dip cycle. Since flow was substantially complete in all samples after an immersion time of two minutes, this was chosen as the dip time for use in most of the subsequent work.

The effects of dip temperature and cladding composition upon flow were investigated simultaneously. Data were obtained over the cladding composition range of 6.45-11.5% silicon for sheet 0.065 in. thick, clad 4.1%. A preheat of 5 min at 1000 F and a 2 min dip were employed at temperatures from 1120 F to 1150 F. The flow results are presented in Fig. 5.

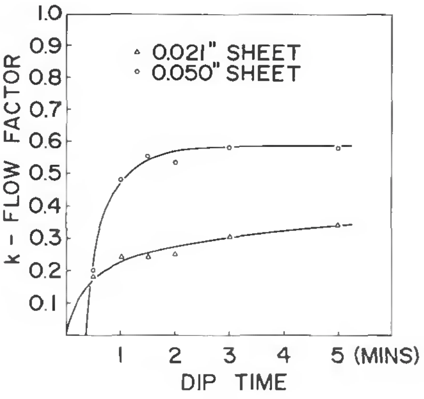

Fig. 4 — The variation in filler metal flow with dipping time at 1130 F

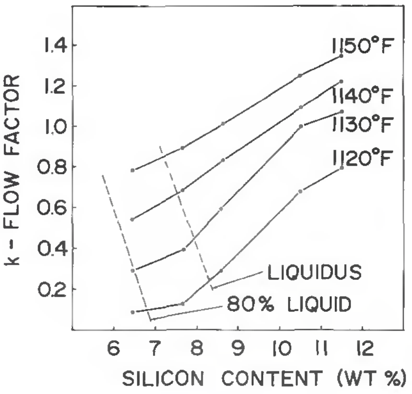

Fig. 5 — Filler flow as a function of cladding composition and dip temperature

Increased flow was obtained as both dip temperature and cladding silicon content were raised. The changes with temperature and composition were quite regular, although there was evidence of some increase in flow as the liquidus was approached, especially at low temperatures. Flow factors greater than unity were obtained when the molten cladding began dissolving some of the core. At higher temperatures there was no major discontinuity in the flow curves after 100% flow had been reached. This indicates that core solution increased at a relatively uniform rate. Solution of the core was greatest where the drop attained maximum thickness (Fig. 6). Measurements of this are given in Figs. 7a, b and c, where it is shown that solution increases as increases are made in brazing temperature, cladding silicon content and the volume of filler metal flowing to the drop. The solution factor (S) was calculated from the formula:

$$S = (t - t_1)/t$$

where t_1 = thickness of eroded core at thinnest point

t = original thickness of the core.

Fig. 6 — Solution of the 3003 alloy core in the drop area, ½% HF etch; X 9, reduced 52%

The effects of core solution were also observed in spectrographic analyses of the braze metal drops. For example, brazing a 6.45% Si sample at temperatures from 1120 to 1150 F produced the silicon content changes in the drop shown in Fig. 8. At 1120 F, where flow was low, the silicon content of the drop was virtually the same as the original cladding. However, at 1130 F where

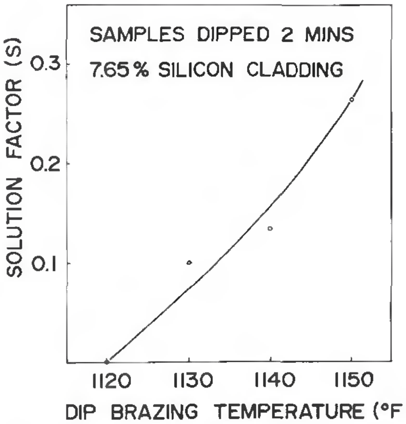

Fig. 7a — Core solution increases as dip brazing temperature increases

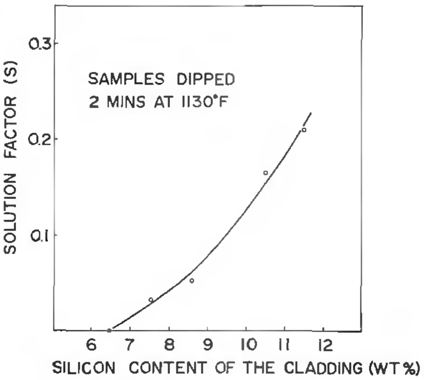

Fig. 7b — Core solution increases as the silicon content of the cladding is increased

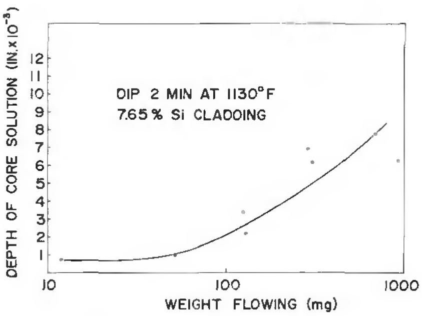

Fig. 7c — The depth of core solution increases as the volume of braze metal flowing increases

flow was considerably higher, the silicon content of the drop increased to 7.12% Si. At 1150 F where the drop contained 5.50% Si, considerable core solution had diluted the flowing filler metal. Core solution also contributed to the lowering in composition to 3.2% Si of the retained, non-flowing cladding layer on the shaft.

As the silicon content of the cladding was raised, the silicon content of the braze metal flowing at a constant temperature became slightly lower (Fig. 9). Corresponding increases in manganese content were detected, showing that the reduction in silicon content was largely due to core solution. This effect became more pronounced as the volume of braze metal flowing down the specimen increased. The same decreasing trend in silicon content was shown by the specimens at constant silicon composition (7.65%) and brazing temperature where cladding thickness was varied (Fig. 10).

The flow results corresponding to the various cladding thicknesses are shown in Fig. 11 for the range of brazing temperatures 1120-1150 F. The standard treatment was a 5 min preheat at 1000 F followed by a 2 min dip. All the samples, with varying core and cladding thicknesses, were from sheet clad with a 7.65% silicon alloy. Since the data at each brazing temperature fell on relatively smooth curves, it was concluded that flow was independent of core thickness. At constant temperature, the flow factor first increased sharply with increasing cladding thickness, tending eventually towards a limiting value. This limit became progressively higher as the brazing temperature was raised. At the lower end of the flow scale, there appeared to be a limit of about 0.0006 in. on the cladding thickness below which no flow would occur, whatever the brazing temperature. In physical terms, the increasing flow factor meant that as either temperature or cladding thickness was increased, the proportion of flowing over non-flowing cladding alloy also increased.

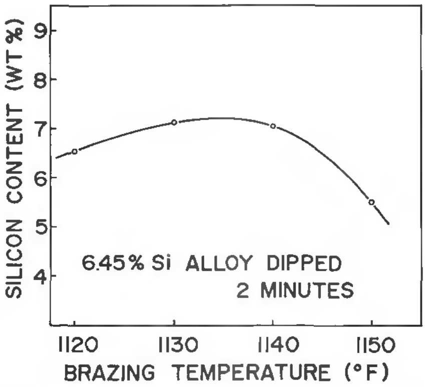

Fig. 8 — The composition of the braze filler metal flowing changes with brazing temperature

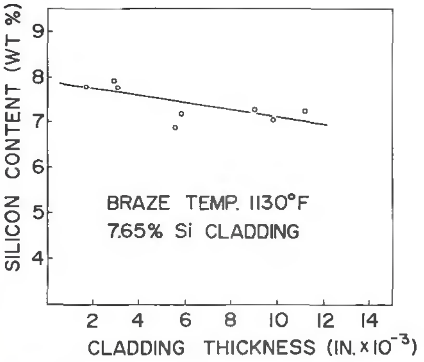

Fig. 10 — The silicon content of the brazing filler metal flowing decreases as the cladding thickness increases

Since preheating is an essential part of the dip brazing process, its effect upon flow at 1130 F was determined. Samples of material 0.020 in. thick, clad 9.4% with a 7.65% Si alloy were preheated for between 5 and 2285 min at 1000 F. Resulting microstructures are shown in Fig. 12, and flow after a 2 min dip is shown in Fig. 13. Results showed that flow rapidly decreased after only short preheat periods, ceasing altogether after approximately 500 min.

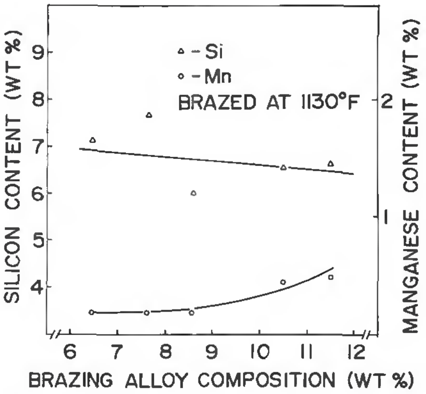

Fig. 9 — Brazing filler metal composition changes with changes in cladding alloy composition

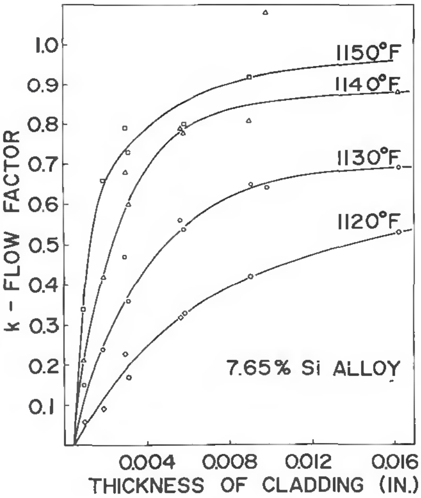

Fig. 11 — Filler metal flow as a function of cladding thickness and temperature

The thickness of the silicon depleted zone in the cladding was calculated from data supplied in Ref. 2 and compared to that measured in the heat treated samples. As shown in Table 3, agreement between the two sets of data was good. Using the experimental values, an expected reduction in flow was calculated assuming that flow decreased in

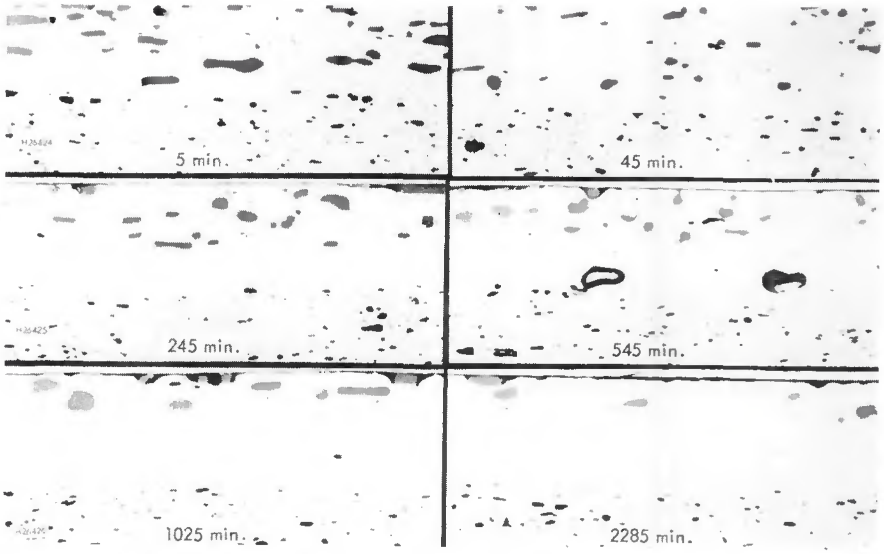

Fig. 12 — The effect of progressively longer preheats at 1000 F on the silicon particle distribution in brazing sheet claddings 0.0019 in. thick; ½% HF; X 750, reduced 51%

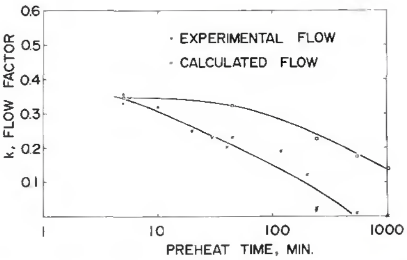

Fig. 13 — Filler metal flow in brazing sheet subjected to extended preheating periods

Table 3 — Calculated and Measured Depleted Zone Thicknesses[a]

Preheat Time, min	Depleted zone thickness, in.×10^{-4}	
	Calculated	Measured
5	0	0
45	2	2
245	5	6.5
545	7.5	9.4
1025	10	11.3
2285	15	13.7

(a) All samples 0.020 in. sheet clad 9.4% with 7.65% Si alloy and preheated at 1000 F.

direct proportion to the increase in depleted zone thickness. Results of this calculation, which are also given in Fig. 13, show that flow decreased much more rapidly than predicted from a simple consideration of the depleted zone thickness. One reason for this discrepancy was apparent from earlier results where it was shown that as the cladding thickness decreased, flow factors decreased (Fig. 11).

Another important consideration was revealed by an electron microprobe investigation of compositional changes. It was shown that during the early stages of preheat, a general solution of silicon particles occurred within the cladding. After about a 45 min preheat, this raised the cladding solid solution level from 0.28% Si — which was typical for annealed material — to slightly over 1% Si, which is the equilibrium solid solution level expected at 1000 F.

Consequently, there was a reduced volume of silicon particles available for melting throughout the cladding, which would also lead to a reduction in flow factor. With the cladding at an equilibrium solid solution level, the only silicon losses thereafter are by diffusion into the core. Once the silicon particles at the core/cladding interface have been dissolved, the diffusion depleted zone begins to widen. Therefore, throughout the preheat process, diffusion reactions are occurring which lead to progressively lower values of the flow factor. Because of the short range nature of diffusion within the cladding, changes in flow factor may be especially marked after short preheat times and any predictions of flow must take this into account.

Discussion

Examination of the aluminum-silicon phase diagram (Ref. 3) shows that at the brazing temperatures used in the present work, various proportions of solid and liquid phases should be present. Terrill (Ref. 2) has shown that the proportion of liquid flowing is considerably less than the theoretical percentage of fluid present — a finding which was confirmed in the present work. This behavior is especially surprising at brazing temperatures above the alloy liquidus where the whole of the cladding should be molten and available to flow.

At temperatures just below the liquidus, the solid phase would not be expected to flow unless washed along by a much greater volume of liquid. At still lower temperatures, the solid phase network might become complete enough to retard flow by capillary action. Thus, it would be expected that the flow should be lower than predicted by the phase diagram at low temperatures, becoming higher than predicted near the liquidus and 100% or more above the liquidus as core solution becomes significant. The fact that the experimental pattern of flow behavior deviates so much from that predicted above leads to the conclusion that equilibrium melting is not occurring.

As a model of the melting process, it is proposed that the silicon particles in the cladding first react with the surrounding aluminum to form molten pools of approximately eutectic composition. This liquid, which at first is silicon-rich, is the first to flow. The remaining non-flowing portion of the cladding is therefore quickly silicon-depleted and so its tendency to flow is reduced. Following this concept, an increase in cladding silicon content would be expected to cause a directly proportionate increase in volume of liquid formed by the eutectic reaction. Flow factors would become correspondingly higher and recovery greater.

This pattern of behavior was found in the experimental work. At a given brazing temperature, flow increased almost linearly with increasing silicon content. It was also found that when the bath temperature was raised using sheet of a constant silicon content, increased flow again resulted. In this situation, as the temperature is raised, the initial eutectic melting occurs as before, but dissolution of the aluminum matrix proceeds further. Thus, the volume of liquid formed and the volume flowing increases and the overall silicon content of the flowed portion decreases — an effect which was confirmed by spectrographic analyses of the drops.

Once the initial burst of melting and flow of silicon-rich material has occurred, the cladding is depleted to such an extent that no further eutectic reaction or flow can take place. This is consistent with the observation that all flow took place in a very short time at the beginning of the dip. Longer dipping periods produced no extra flow, although a considerable weight of cladding still remained on the sample. Spectrographic studies showed that this retained cladding still contained some

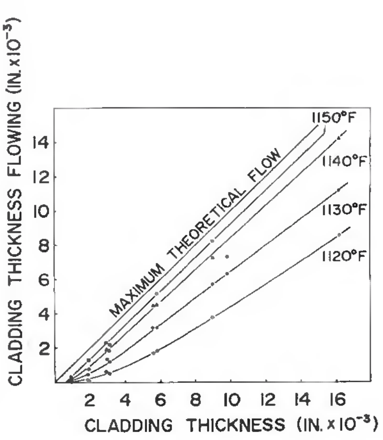

Fig. 14 — Cladding flow relationships over the temperature range 1120-1150 F

silicon but at a level much below the initial sheet composition.

Generally, as the cladding thickness increased, the volume of braze metal flowing increased as did the thickness of the retained non-flowing layer. The flow curves presented earlier were generally parabolic in form; however, when these data are expressed to show the cladding thickness flowing as a function of the total cladding thickness, the relationships shown in Fig. 14 are obtained. At a dip temperature of 1150 F, the relation was linear. The non-flowing portion of the cladding was 6×10^{-4} in. thick at all cladding thicknesses. This represents a boundary layer of liquid adhering to the specimen shaft. Therefore, any increases in thickness of the brazing sheet will, at this temperature, cause flow to increase by the same volume. At lower temperatures the flow increase was always somewhat less than the corresponding thickness increase. Thus, at 1130 F approximately 78% of any thickness increase appeared as extra flow, and at 1120 F this was reduced to 66%.

This behavior was consistent with our earlier melting model in that at any particular temperature, the silicon particles and aluminum matrix in the cladding would be expected to react to produce a given proportion of liquid which is available to flow. Thickness increases alone would not be expected to change the solid/liquid ratio. Also, following the patterns of earlier results, the ratio of liquid to solid at all thicknesses would be expected to increase as the brazing temperatures were increased. Thus recovery should follow a corresponding increasing trend. At the lower end of the dip brazing temperature range and at lower cladding thicknesses, the recovery relationship was not linear. In fact, recovery with thin claddings was higher than expected by extrapolation of the linear portion of the data.

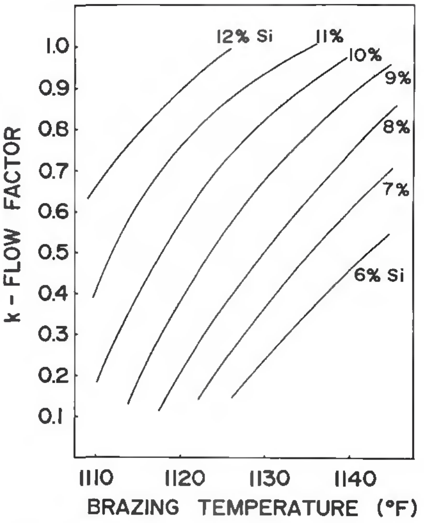

Fig. 15 — The flow interrelationship between dip brazing temperature and filler metal composition

From a practical standpoint, large quantities of today's brazing sheet are produced in sheet 0.020 in. thick, clad 10%, and are brazed at temperatures of the order of 1130 F. This is in a region of non-linear behavior where small thickness variations can make a large difference to percentage change in flow. However, as a general principle, filler metal flow can be increased by increasing the cladding thickness. But it should be noted that only a portion of the added cladding may flow — an amount which depends upon the particular cladding thickness and temperature involved. The data presented in Fig. 14 can be used to predict the increased flow resulting from specific changes in cladding thickness.

In addition to improved flow resulting from cladding thickness increases, flow can also be enhanced by increasing either the silicon content of the alloy or the brazing temperature. A diagram, constructed from the present data, defines the flow interdependence of temperature and composition and may be helpful in determining relationships for fillet formation (Fig. 15).

Consider a situation in which experience has established that satisfactory fillet formation is obtained with a cladding composition of 7.5% silicon and a dip brazing temperature of 1130 F. This corresponds to a flow factor of just over 0.4 from the data sheet. Assume next that it becomes desirable to reduce the operating temperature of the dip brazing bath to 1120 F without sacrificing joint quality. This can be achieved by maintaining the same relative flow factor (i.e., just over 0.4). Therefore, by determining where the required flow percentage line intersects the new operating temperature, the cladding silicon content necessary to achieve the desired flow can be predicted.

Conversely, the diagram could be used to predict the progressively higher brazing temperatures which would be necessary to maintain joint quality if a decrease in the silicon content of the cladding were desirable. In general, it appears that a change of some 6 F in brazing temperature necessitates a corresponding change of 1% silicon in the dip brazing sheet composition. On the basis of the core solution measurements obtained in the present work, no adverse erosive effects would be expected by making changes such as those outlined above, since flow factors are not appreciably changed.

Conclusions

1. Flow of aluminum-silicon brazing alloys is governed by a mechanism of local eutectic melting.
2. Flow changes brought about by adjusting either cladding alloy compositions or brazing temperature are mutually interdependent. In general, a change of 6 F in dip brazing temperature is equivalent to a change of 1% silicon in the cladding.
3. Brazing metal flow can be increased by increasing the thickness of the cladding layer. However, not all the additional filler metal becomes available for flow. Other factors such as the brazing temperature and cladding thickness are influential in determining the increase in flow factor.
4. Silicon diffusion, both within the cladding and into the core of the sheet, causes rapid losses in brazability with extended preheat times.
5. Core solution increases with an increase in volume of braze metal flow, silicon content or brazing temperature.

Acknowledgement

The authors would like to thank Kaiser Aluminum and Chemical Corporation for permission to publish this study and in particular thank F. L. Thach, who performed much of the experimental work.

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