Investigations on the Capillary Flow of Brazing Filler Metal BNi5

A study is undertaken to determine the paths that filler metal will follow when it must flow against gravity

BY E. LUGSCHEIDER AND K. IVERSEN

Introduction

A valuable help when designing brazing joints is the knowledge of the paths that the filler metal will take under well defined brazing conditions, depending on the clearance. This holds especially true if the filler metal has to flow against gravity—when, in other words, the capillary rise of the filler metal comes into play.

For any specific problem, experimental determination of the capillary rise is necessary wherein experimental and actual application conditions must agree very closely. Nevertheless, it seems to be important to determine how far an exact calculation or estimation of the capillary rise is possible.

In order to simplify experimental conditions as far as possible, a tube-tube geometry was selected, since this leads to a continuously changing gap width. Therefore, the capillary rise can be determined, depending on gap width for a defined temperature in just one experiment. Further, this geometry entails a simple determination of the amount of filler metal required and the amount of silicide phase of the filler metal seam, depending on gap width and capillary rise.

The first step for a comparing calculation was to find out whether the same calculus applies to capillary height and gap width for parallel plates and a tube-tube geometry, and what conditions have to be selected.

Calculation of the Theoretical Capillary Height

The basic condition for the applicability of a certain filler metal-base material combination is sufficient wettability of the solid by the liquid at the specific brazing temperature. As a matter of principle, this depends on whether the two materials can form an intermetallic phase or solid solution at the given temperature.[1]

Wettability can be measured, in terms of the contact angle α of the liquid filler metal in equilibrium on a plane surface. To ensure sufficient wettability, the angle must be smaller than 30 deg and, very often, for high temperature brazing* the angle must be considerably smaller. The angle α is given by a temperature dependent equilibrium of surface tensions according to the equation:

$$\sigma_S - \gamma_{SL} = \sigma_L \cos \alpha \qquad (1)$$

where σ_S is the surface tension of the solid, σ_L of the liquid and γ_{SL} is the surface tension between the solid and liquid respectively. In general σ_S and γ_{SL} cannot be measured, but the difference—also called the wettability tension—can be determined experimentally if certain conditions are given.[2]

The driving force for the filling of capillary gaps is the capillary pressure P_K. This pressure is a function of the wettability tension $\gamma_A = \sigma_L \cdot \cos \alpha$. This demonstrates the importance of γ_A for the filling of a capillary gap when brazing.

According to the new draft of the DIN 8505 (under preparation) brazing where a filler metal with a liquidus temperature above 900 C (1672 F) is used with the exclusion of air (in vacuum or under inert gas cover) and without fluxing aids is to be termed high temperature brazing.

Paper presented at the Eighth International AWS Brazing Conference held in Philadelphia, Pennsylvania, during April 26-28, 1977.

E. LUGSCHEIDER is with the Institut fur Werkstoffkunde, Aachen, and K. IVERSEN is with INTERATOM, Bensberg, West Germany.

According to Young and Laplace, the pressure P_K is given for any geometry:

$$P_K = \gamma_A \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \qquad (2)$$

where R_1 and R_2 denote the main curvature radii of the liquid surface.

If the gap is vertical and both sides run parallel, then P_K equals the hydrostatic pressure of the column of the liquid filler metal. In this case the theoretical limit for the capillary height is given by:

$$H_{theor.} = \frac{\gamma_A}{g\,\delta} \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \qquad (3)$$

where $g = 981$ cm sec^{-2} and δ is the density of the filler metal

In the case of capillary brazing of parallel plates of sufficient extension having a small gap width of C, the theoretical capillary height for a given width C is given by the equation:

$$H_{theor.} = \frac{2\,\gamma_A}{g\,\delta\,C} \qquad (4)$$

since R_1 goes to infinity and R_2 equals C/2. This is half the height as in the case of a vertical circular capillary of radius C/2. The calculus for parallel plates also holds true for a triangular gap enclosing the aperture angle μ. Here the gap is approximated by parallel plates which are not perfectly parallel but enclose a small angle—Fig. 1a.

The theoretical capillary height is calculated by the equation:

$$\tan \frac{\mu}{2} = \frac{C}{2X} \qquad (5)$$

whereby X is determined according to:

$$H_{theor.} = \frac{\gamma_A}{g\,\delta\,X \tan \mu/2} \qquad (6)$$

This approximation will get less accurate with increasing angles. In other words there is a maximum for the angle μ_{max}, when the applicability of the model of parallel plates for triangular gaps ends.

Similar determinations can be made for the tube-tube geometry. In case of this geometry the angle μ is not just a function of the gap width C and the distance X of the clearance but the radius R as well. The angle is given as a function of these three variables, whereby the radii of both tubes are taken to be identical, by the following expression:

$$\tan \frac{\mu}{2} = 2 \left(\frac{R^2}{C\,R - C^2/4} - 1 \right)^{-1/2} \quad (7)$$

There are two more expressions containing these variables, namely:

$$\tan \frac{\mu}{2} = 2 \left(\frac{R^2}{X^2} - 1 \right)^{-1/2} \quad (8)$$

$$C = 2[R - (R^2 - X^2)^{1/2}] \quad (9)$$

The theoretical limit of the capillary height in case of a tube-tube geometry is given in analogy to the model of parallel plates by the expression:

$$H_{theor.} = \frac{2\,\gamma_A}{C\,g\,\delta} \quad (10)$$

where the equations between gap width clearance radius and angle μ as given above apply.

Like for the triangular gap there is for the tube-tube geometry a maximum angle μ_{max}, when the applicability of the approximation by the model of parallel plates ends. This angle which can be taken of the angle of the tangent at a certain gap width (Fig. 1) is a well defined function of the gap width for a given radius (eq 7). In case of a defined tube geometry it can be referred to a maximum gap width C_{max}, which limits the approximation. These maximum values of the angle and the gap width are reached the sooner, the smaller the tube radii are.

Experimental Procedure and Results

For the experiments, the filler metal-base metal combination of BNi-5 (19Cr, 10Si, balance Ni, wt-%) and the steel X 8 CrNiMoNb 16 16 (WNr. 1.4981, similar to Type 316 stainless steel) was selected. In order to determine the capillary height as a function of the gap width, the tube-tube model was selected.[3] Two tubes with an 8 mm (0.31 in.) diameter, 0.25 mm (0.010 in.) wall thickness and 1000 mm (39.37 in.) length were vertically mounted on a base plate so that they had contact

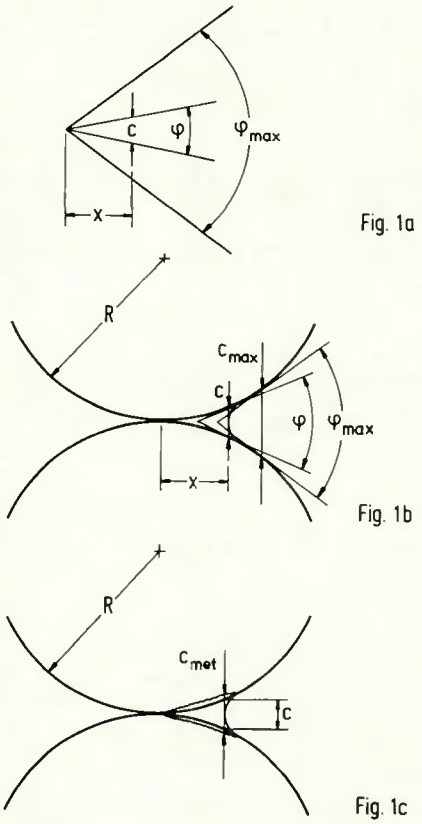

Fig. 1—Schematic representation of triangular gap and tube-tube geometry: C = gap width; $C_{met.}$ = brazing seam width; X = clearance; μ (in text) = φ = aperture angle; R = radius of tubes

all along their length with a gap width of C = 0.

Brazing was done at 1100, 1140, 1160, 1180, 1200 and 1240 C (2012, 2084, 2120, 2156, 2192, and 2264 F) in a resistance-heated furnace in a vacuum of less than 5×10^{-4} torr. The amount of filler metal was constant. The heating time averaged 30 min, and the holding time at temperature was 15 min. The temperature was measured at three spots with thermocouples, showing the same temperature all over the length of the tubes.

Capillary Height as a Function of Gap Width

To determine gap width C for a given capillary height $H_{exp.}$, the brazed tubes were cut into 50 mm (2 in.) sections. At the polished faces, the distance X and the metallurgical gap width were measured microscopically.

The metallurgical gap width C_{met} is defined as the width of the brazing seam at a given distance X (Fig. 1c). Because of erosion and diffusion caused by the heat during the brazing, its value is obviously greater than brazing gap width C, which is given by the tube-tube geometry even if the X values are identical. The latter determines the filling of the gap. Therefore, the gap width can be calculated for a given capillary height using equation (9) and the distance as found in the experiment.

Figure 2 shows the brazing gap width (circles) and the brazing seam width (metallurgical gap width, crosses) as a function of the capillary height, at six different temperatures: 1100, 1140, 1160, 1180, 1200 and 1240 C (i.e., corresponding, respectively, to 2012, 2084, 2120, 2156, 2192 and 2264 F). Additionally, the functional dependence of the capillary height calculated by equation (10) is shown as a curve.

The data of Fig. 2 demonstrate that, at brazing temperatures from 1160 to 1240 C (2120 to 2264 F), for a medium range of gap width there is a good agreement between the calculated theoretical capillary height $H_{theor.}$ and the actual values $H_{exp.}$ found after brazing.

At 1100 C (2012 F) there is considerably less agreement between $H_{theor.}$ and $H_{exp.}$. This had to be expected since this temperature is below the liquidus temperature of the filler metal BNi-5, which has a melting range from 1080 C or 1976 F (solidus) to 1135 C or 2075 F (liquidus). When brazing at 1100 C (2012 F) there are solid parts present which cause a basically different flow behavior of the filler metal. This shows up above all for greater gap widths. To give an example, with a gap of 120 microns, only 2/3 of the theoretical capillary height, which was reached at higher temperatures, could be found.

At 1160 to 1240 C (2120 to 2246 F) only for a gap width of more than 150 microns, there was no longer good agreement between experimental and theoretical capillary height. At a gap width of 120 microns there is, in any event, still exact agreement between $H_{exp.}$ and $H_{theor.}$. Taking equation (7) the angles are found to be μ = 38.6 deg (120 microns) and μ = 42.9 deg (150 microns) for the given tube geometry. This means that μ_{max} = 38.6 deg gives the limit above which the model of parallel plates can no longer be taken for the triangular gap and the tube-tube geometry if one wants to be exact.

Figure 2 demonstrates that, when two tubes with a radius of 4 mm are brazed with a gap below 50 microns, the actual capillary height is below the theoretical although the theoretical approach is still valid. The reason is that the filler metal changes by mixing with the base material. The smaller the gap, the more there is diffusion of base metal in the filler metal—and the amount of silicon, which lowers the liquidus temperature, decreases. The consequence is that the melting tem-

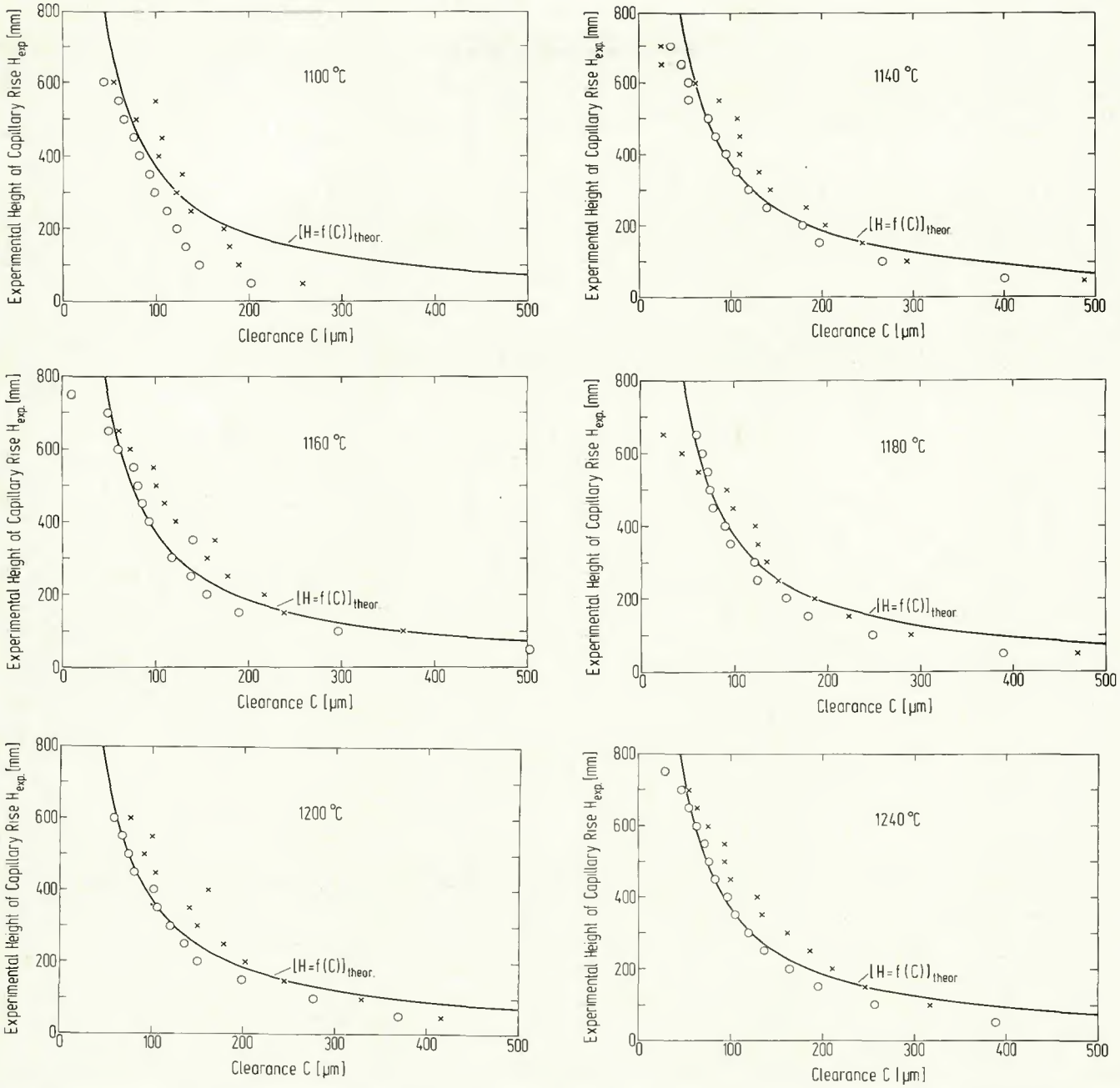

Fig. 2—Experimentally found capillary height of BNi-5 as a function of the gap width at six different temperatures and plot of calculated function $[H = f(C)]_{theor.}$ *with* o = *gap width (C) and* x = *brazing seam width* ($C_{met.}$)

perature of the filler metal close to the brazing seam rises relative to the selected brazing temperature. With decreasing gap width, the latter gets below the liquidus temperature of the now changed filler metal. If the steadily increasing solidus temperature finally reaches the value of the brazing temperature, the filler metal solidifies and the maximum of all possible capillary heights ($H_{exp.}^{max.}$) is reached. Therefore, capillary height can be calculated for a triangular gap and a tube-tube geometry up to angles of $\mu_{max.} = 38.6$ deg.

The 38.6 deg angle corresponds to 120 microns for tubes with a 4 mm radius. With 40 mm (1.57 in.) radii the capillary height can be calculated for a gap width of up to 1.2 mm—equation (7). These values will never be used for high temperature brazing; they simply show the limits of the formal usefulness of the model of parallel plates for such a tube-tube geometry. Therefore, there is no need to discuss to what extent the conditions, which had been set up in the beginning for the two main curvature radii of the liquid filler metal, can be realized for so great a gap width.

With a high gap width limit for radii of 40 mm (1.57 in.), it becomes evident that the geometry dependence of the upper limit for the calculation has only to be considered for a very small tube-tube geometry. The lower limit is, as previously mentioned, given by metallurgical reactions between filler metal and base material. The term upper and lower limit for the calculation refers to the value of the gap width for which the capillary height is to be calculated. Within these limits the capillary height calculated for a tube-tube geometry is in any case identical to those reached when parallel plates are brazed with identical gap width.

For a gap width below 50 microns, the relation between experimental and calculated capillary height for the material combination BNi-5 Ni-Cr-steel can be found by the experimental results. It amounts to:

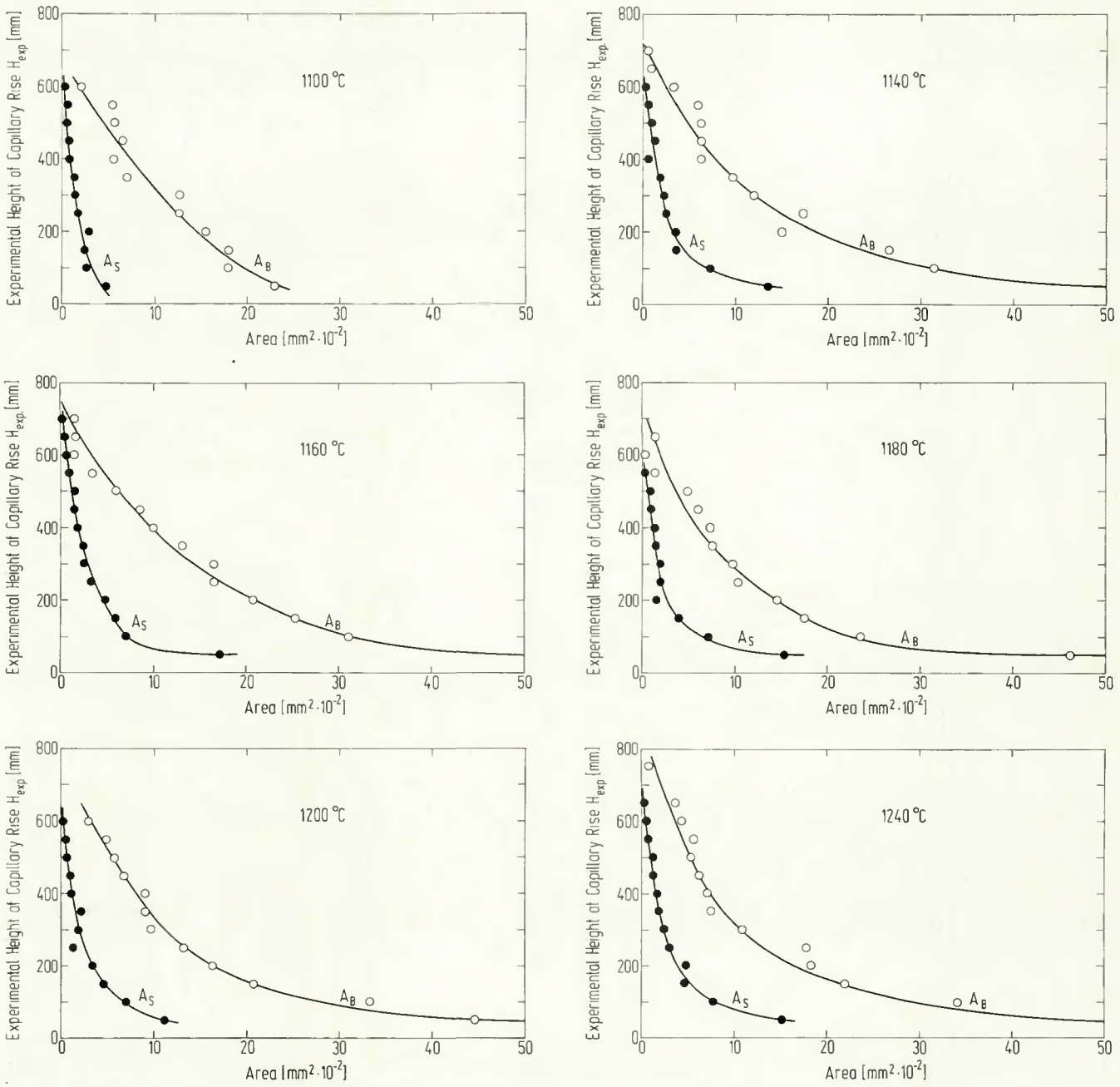

Fig. 3—Brazing area (A_B) and area of silicide phase in the brazing seam (A_S) as a function of the capillary rise at six different temperatures

$$\left(\frac{H_{exp.}}{H_{theor.}}\right)_{15\ microns} \sim 0.3$$

and:

$$\left(\frac{H_{exp.}}{H_{theor.}}\right)_{25\ microns} \sim 0.5$$

This means that, for temperatures in the range 1160 to 1240 C (2120 to 2264 F), the experimental capillary height can be approximated to half the theoretical for a gap width of 25 microns and about 30% of the theoretical for a width of 15 microns.

To calculate the theoretical capillary height according to equation (10) the wettability tension γ_Λ and the density δ of the filler metal must be known. BNi-5 has a density of 7.65 g · cm^{-3}; the values of γ_Λ, however, are not known for high temperature filler metals. Therefore γ_Λ has been estimated to be 1400 dyn · cm^{-1} for BNi-5, based on the surface tension of the materials contained in BNi-5 (nickel, chromium and silicon) since the surface tension is practically equal to the wettability tension for small angles. Taking the gravitational acceleration as 981 cm · sec^{-2} the following hyperbolic function for capillary height and gap width follows:

$$H_{theor.} = \frac{2\gamma_\Lambda}{g\,\delta\,C} = \frac{2 \cdot 1400}{981 \cdot 7.65\ C} = \frac{0.373}{C} = \frac{K}{C}$$

Changing the value of the constant K to 0.37, complete agreement within the expected gap width range was found between the hyperbolic curve $H_{theor.} = f(C)$ and the experimental data. From $K = 0.37$ a wettability tension $\gamma_\Lambda = 1388$ dyn · cm^{-1} follows for BNi-5. As shown in Fig. 2, this value is independent of temperatures in the range 1160 to 1240 C (2120 to 2264 F).

It has been known for quite some time that tension γ_Λ can be determined using the experimental data of the hyperbolic function of capillary height and gap width.[2] A geometry of

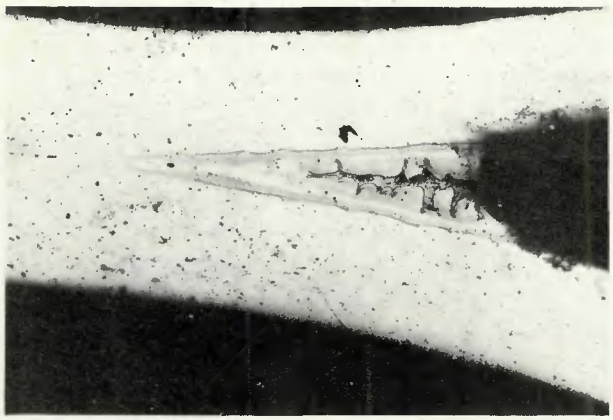

Fig. 4—Tube-tube geometry (R = 4 mm) of stainless steel brazed with BNi-5 at 1180 C. Micrograph of a cut edge at a height of capillary rise of 300 mm (C = 120 microns). M = 100:1

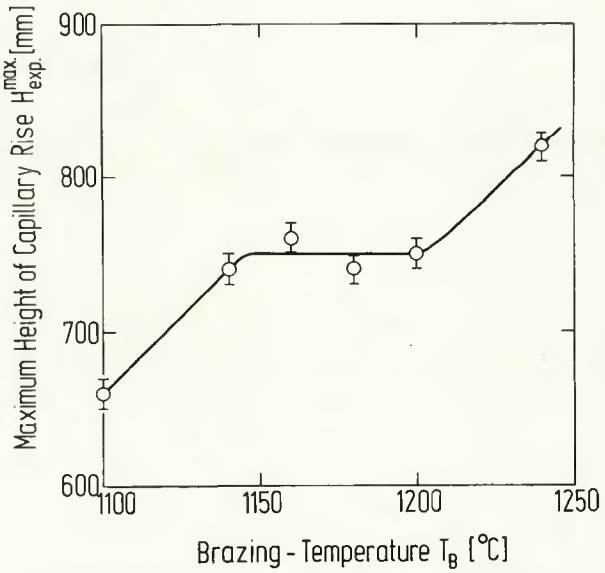

Fig. 5—Upper limit of experimentally determined capillary height of BNi-5 as a function of brazing temperature

plates at a certain angle has to be used which corresponds to a triangular gap with small aperture angle. The experiments, as reported here, demonstrate that this also holds true with sufficient accuracy in the case of a tube-tube geometry, although only a relatively small part of the hyperbolic function could be used.

Taking the wetting angles as $\alpha = 6.7$ deg at 1183 C (2161 F) and 5.1 deg at 1233 C (2251 F) for the filler metal-base metal combinations, as reported in the literature,[4] then a surface tension for BNi-5 in the recommended temperature range is about 1400 dyn • cm^{-1}.

The surface tension and the wettability tension of nickel base high temperature filler metals on high alloy steel can be approximately taken as 1400 dyn • cm^{-1}. This is considerably higher than for other filler metals. For example, for steel and Ag-Cu-Zn-filler metal (LAg 45) γ_Λ is taken as 500 dyn • cm^{-1} and for copper-filler metal γ_Λ is about 1000 dyn • cm^{-1}.[5] The capillary pressure of high temperature filler metal is correspondingly higher. For a gap of 50 microns the pressure for a nickel base filler metal amounts to 0.56 atmospheres, and for LAg 45 it only amounts to about 0.2 atmospheres.[5]

Area of Filler metal and Area of Secondary (Silicide) Phase as a Function of the Capillary Height

As mentioned previously, the area of the filler metal (A_B) and the silicide phase (A_S) was determined and set into relation to the corresponding capillary height. Figure 3 shows this dependence for temperatures of 1100, 1140, 1160, 1180, 1200 and 1240 C, i.e., the temperatures of Fig. 2. By integrating the product of area and capillary height, the mass of filler metal transported up to a certain height, and the amount of silicide phase as well, can be calculated.

For the upper limit of capillary height, the total filler metal mass was calculated for every temperature. It was found to be well below the offered quantity of filler metal.

The ratios of the areas A_S/A_B for a given capillary height are of prime importance. This is especially true when parallel vertical plates are brazed and the ratio of areas equals the ratio of volumes. Using the data of Fig. 2 for any capillary height $H_{exp.}$, the corresponding gap width C can be found without ambiguity and thus it becomes possible to discuss the ratio of areas as a function of the gap width.

As can be seen from Table 1, no silicide phase was found at all temperatures for gap widths of 15 and 25 microns. The same applies to a width of 50 microns for temperatures of 1180 to 1240 C (2156 to 2264 F). This result confirms the fact as previously discussed, namely that the experimental and theoretical heights differ for a gap width below 50 microns. The amount of silicide phase at 50 microns width was, at 6%, relatively small for temperatures from 1100 to 1160 C (2012 to 2120 F). This demonstrates the fact that a relatively short diffusional anneal suffices to eliminate the silicide phase after the brazing for comparable gap width. For temperatures from 1100 to 1240 C (2012 to 2264 F) and a gap width of 100 microns an average of 18% brittle phase was observed—Fig. 4.

Table 1—Ratio of Areas of the Silicide Phase (A_S) and Filler Metal (A_B) for Different Gap Widths and Temperatures

Gap width C, microns	Temperature, C	Ratio of areas, $\frac{A_S}{A_B}$
15	1100-1240	0
25	1100-1240	0
50	1100-1160	~ 6
50	1180-1240	0
100	1100-1240	~ 18

If the maximum experimental capillary height $H_{exp.}^{max.}$ has to be found, then this can be done more accurately by extrapolating the amount of filler metal to zero rather than the gap width. The results for different temperatures are shown in Fig. 5. A perfect condition of the areas to be brazed is the basic condition in order to reach the maximum values. Our experiments show that, with defective surfaces, the capillary height can be up to 100 mm below the values given in Fig. 5. Figure 5 shows that brazing above the liquidus temperature of BNi-5 up to 1200 C (2192 F) leads to fairly constant maximum values of about 750 mm. If the brazing is done within the solidus-liquidus range, the $H_{exp.}^{max.}$ is lowered to values as were observed under faulty surface conditions.

It is interesting to note that with temperatures above 1200 C (2192 F) the capillary height rises and reaches 820 mm at 1240 C (2264 F). This indicates that, at higher temperatures, the higher liquidus temperature (caused by mixing with the base material) is surpassed again shortly and flow is again possible. This should be further investigated as it seems to be possible to eliminate brazing defects in this way.

Summary

It has been shown that the model of parallel plates and the general Laplace approach can be used for the calculation of the theoretical capillary height

of brazing vertical triangular gaps and tube-tube geometries up to a limiting angle. For the materials BNi-5 and X 8 CrNiMoNb 16 16 this angle was found to be 38.6 deg. This corresponds to a maximum gap width ($C_{max.}$) of 120 microns. When 4 mm radius tubes are brazed up to this value, the calculated $H_{theor.}$ and experimental $H_{exp.}$ capillary height coincide as long as the brazing temperature is above the liquidus temperature of the filler metal.

With increasing tube radius, the upper limit for the calculations shifts to higher gap clearances. The lower limit for the calculations is at about 50 microns due to metallurgical reactions between filler metal and base material. The dependence of experimental capillary height on the gap clearance for temperatures between 1100 to 1240 C (2012 to 2264 F) shows that for clearances between 15 and 25 microns only 30 to 50% of the theoretical rise is attainable.

By microscopical analysis of the areas, the ratios of silicide phase to the total amount of filler metal as a function of the capillary height and gap clearance could be determined.

Under consideration of the brazing temperature and the total heat treatment upon brazing, it becomes possible to find the general conditions for a diffusional annealing treatment to eliminate the brittle silicide phase.

The maximum values of the capillary height $H_{exp.}^{max.}$ (found by extrapolation as a function of temperature) showed that nearly constant values of about 750 mm are reached when BNi-5 is brazed above the liquidus temperature up to 1200 C (2192 F).

Indications of a short overshooting of the remelting temperature at brazing temperatures above 1240 C (2264 F) are to be further investigated since they could be helpful for the elimination of brazing defects.

References

1. Ailey, G. L., and Watkins, H. C., *J. Inst. Metals*, 80 (1951/52), p. 57.
2. Wolf, K. L., *Physik und Chemie der Grenzflächen*, Vol. 1, Springer, Berlin, Göttingen, Heidelberg, 1957.
3. Iversen, K., and Lohe, H., *DVS-Ber.*, No. 15 (1970), p. 175.
4. Feduska, W., "High-Temperature Brazing Alloy—Base Metal Wetting Reaction," *Welding Journal*, 38 (3), March 1959, Res. Suppl., pp. 122-s to 131-s.
5. Schatz, J., *Schweissen und Schneiden*, 9 (1957), p. 522.