Understanding Capillary Force

Brazing can be defined as a process in which metals are joined or fused together through the application of heat and a filler metal that melts above 450°C (840°F) but below the melting point of the base metals being fused together. One of the key elements in brazing is the capillary force also known as capillary action. The goal of this article is to analyze the effects of joint clearance on a capillary rise of a molten filler metal. In this article, capillary action is defined in terms of a force that is generated by the combination of adhesive and cohesive forces leading to a displacement of liquid including molten metals within a closely spaced cavity (Ref. 1). In order to give a better understanding of the mechanics behind capillary force, an example of glass tubing submerged in a liquid bath is analyzed. As shown in Fig. 1, a glass tube is submerged into a liquid bath. The change in height of the liquid $H$ in the tube is an unknown variable that must be determined. Some of the variables that affect the change in height $H$ of a liquid pulled upward within the glass tubing are contact angle $\theta$, density of the liquid $\rho$, coefficient of surface tension $Y$, and the radius of the glass tubing $R$. The change in $H$ can be calculated as follows

$$2\pi R Y \cos \theta = \rho g \pi R^2 H \quad (1)$$

Using Equation 1 to solve for $H$

$$H = \frac{2\pi R Y \cos \theta}{\rho g \pi R^2} \quad (2)$$

where $g$ is the force of gravity (Ref. 3). In order for the capillary action to occur, the following factors have to be met: the surface of a solid must be residue free, oxide free, and wettable by a liquid, the contact angle $\theta$ must be less than 90 deg, and most importantly the adhesive forces generated at the solid-liquid interface must be greater than the cohesive forces of a liquid on a molecular level. The adhesive force can be defined as a molecular attraction between bodies in contact. The cohesive force can be defined as an attraction between molecules of a body on the intermolecular level.

As an example, for an ammonia-air-glass interface in 8-mm-diameter glass tubing, the capillary rise was equal to 1.7 mm. It was observed that with larger-diameter glass tubing ($D = 12$ mm) the capillary rise $H$ decreased, as calculated below ($Y$ and $\rho$ values from Ref. 3, Table A.3).

Given $\theta = 0$ deg, $Y = 0.0213$ N/m, $D = 8$ mm, $\rho = 608$ kg/m$^3$, and $R = D/2 = 4$ mm. Using Equation 2:

$$H = \frac{2(\pi)(0.004 \text{ m})(0.0213 \text{ N/m} \cos 0\)}{(608 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(\pi)(0.004 \text{ m})^2}$$

Fig. 1 — A cross-sectional view of a tube inserted in a liquid shows the liquid rises inside the tube to height $H$ due to capillary action. As the diameter of the tube $D$ increases, the height $H$ water rises inside decreases.

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H = 0.0017 m = 1.7 mm (0.067 in.)

Given θ = 0 deg, Y = 0.0213 N/m, D = 12 mm, ρ = 608 kg/m³, R = D/2 = 6 mm. Using Equation 2:

\[ H = 2(e)(0.006 m)(0.0213 N/m)(\cos0°) / (608 kg/m³)(9.81 m/s²)(e)(0.006 m²) \]

\[ H = 0.00012 m = 1.2 mm (0.047 in.) \]

Assuming the variables such as contact angle and surface tension remained constant with the exception of a glass tubing diameter, why did the capillary rise decrease? With an increase in the diameter of glass tubing, the amount of liquid in the tube increased leading to a decrease in the capillary force. This is a very important factor in brazing. Numerous handbooks, including the American Welding Society’s Brazing Handbook, correlate joint clearance to joint strength of a brazed assembly. It is a common standard to see joint clearances fall within a radial range of 0.050 to 0.127 mm (0.002 to 0.005 in.). With reduced clearance, there is less molten alloy within the joint resulting in higher capillary rise. Therefore, it is safe to say that in brazing, less is more. For further evaluation of joint strength and an explanation of the variables affecting joint strength, refer to Lucas-Milhaupt/Handy & Harman Bulletins T-2 through T-5, which are available on the company’s Web site (www.lucasmilhaupt.com).

### Estimating Joint Clearances

The tensile strength of joints decreases with increasing joint thickness or joint clearance — Fig. 2. Therefore, it is very important to calculate joint clearances at braze temperatures to obtain the maximum strength out of the brazed assembly. This is especially important when brazing dissimilar metals because each metal expands and contracts at different rates.

### Effects of Joint Thickness on Tensile Strength

One approach to determine the joint clearances at braze temperatures is to use a linear expansion theory as presented in Equation 3 (Ref. 2). The change in diametric clearance is \( \Delta DC \)

\[ \Delta DC = (T_2 – T_1)(D_2\alpha_2 – D_1\alpha_1) \]  

Where \( T_1 \) = room temperature, \( T_2 \) = solidus temperature of the brazing filler metal, \( D_1 \) = OD of the male part at room temperature, \( \alpha_1 \) = coefficient of thermal expansion of the male part, \( D_2 \) = ID of the female part at room temperature, and \( \alpha_2 \) = coefficient of thermal expansion of the female part.

Consider the joint design shown in Fig. 3 where a brass male component with \( D_1 = 12.57 \text{ mm} \) and \( \alpha_1 = 20.5 \times 10^{-6} \text{ m/m/°C} \) is to be brazed to a steel female component with \( D_2 = 12.70 \text{ mm} \) and \( \alpha_2 = 12.8 \times 10^{-6} \text{ m/m/°C} \). The joint clearance was originally designed for 0.127 mm total joint clearances at room temperature. How much will the joint clearance change if this assembly is brazed with Braze™ 505 (AWS BAg-24) alloy with a solidus temperature of 660°C?

Given \( T_1 = 20°C \), \( T_2 = 660°C \), \( D_1 = 0.01257 \text{ m} \), \( \alpha_1 = 20.5 \times 10^{-6} \text{ m/m/°C} \), \( D_2 = 0.0127 \text{ m} \), \( \alpha_2 = 12.8 \times 10^{-6} \text{ m/m/°C} \).

Inserting these data into Equation 3:

\[ \Delta DC = (660° – 20°C)(0.0127 \text{ m})(12.8 \times 10^{-6} \text{ m/m/°C}) – (0.01257 \text{ m})(20.5 \times 10^{-6} \text{ m/m/°C}) \]  

\[ \Delta DC = -0.061 \text{ mm} \]  

The joint clearance at brazing temperature will decrease by -0.061 mm (0.002 in.). The negative sign (–) indicates a decrease in joint clearance; whereas a
positive sign (+) would indicate an increase in joint clearance.

Although there are several factors that affect the success of a brazed assembly, one of the key elements in proper joint design is to obtain a proper fitup.

The reduction in joint clearance at braze temperature from room temperature may lead to voids within the joint due to lack of sufficient alloy content within the joint due to increased volume of the joint. Therefore, it is recommended to calculate joint clearances at braze temperatures—not room temperature—especially when brazing dissimilar metals. When brazing similar grades of alloys, the issue of thermal expansion is not as critical.

How to Estimate the Amount of Alloy in the Joint

Generally, once the joint clearance is established at the braze temperature, a theoretical amount of filler metal can be calculated. Consider the example where two base metals of the same grade are being brazed as shown in Fig. 4. Using the basic formula for volume, \( V = \pi R^2 L \), the volume of the joint can be determined. The volume should be calculated at the largest possible joint clearance.

Given ID plate = 12.70 ± 0.127 mm, OD tube = 12.57 ± 0.051 mm, shear depth (overlap distance) = 12.70 mm

\[
V = \left(\pi \times \left(\frac{12.83 \text{ mm}}{2}\right)^2\right) - \left(\pi \times \left(\frac{12.52 \text{ mm}}{2}\right)^2\right) \times 12.70 \text{ mm} = 76.2 \text{ mm}^3.
\]

After interpolation of the data, the minimum wire diameter necessary to fill the joint is equal to 1.57 mm (0.062 in.) as shown in Table 1. Generally, an additional 20% of alloy is added to the total weight of the preform to compensate for potential alloy losses during fillet formation or alloy shrinkage during solidification process.

References