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ABSTRACT

Controlled atmosphere brazing (CAB) is a state-of-the-art joining technology associated with high production rates of many products, including microchannel aluminum heat exchangers. The complex designs of highly augmented compact heat transfer surfaces impose very difficult requirements for a brazing process. Regardless of the fact that brazing is a highly developed engineering art, many state-of-the-art manufacturing operations lack predictability and clear description of the phenomena involved. The related phenomena are to a large extent only partially explored, owing the progress mostly to the lack of a detailed knowledge of involved physical-chemical processes.

This paper elaborates on the comprehensive research and development activities involved in manufacturing new generation Al heat exchangers using brazing technology. Our current activities are aimed at a set of goals that significantly contribute to the optimization of bonding processes, including material selection and process conditions. In this paper, an overview of the CAB aluminum brazing process will be introduced first. Transport phenomena related to molten metal flow behavior and joint formation during microchannel heat exchanger brazing process is the major objective of this study. The *in-situ* real time monitoring facilities in our brazing lab are used for direct observation of wetting kinetics of surface tension governed reactive flows of molten aluminum filler metal during brazing. Interesting phenomena such as flow of liquid metal through capillary grooves and its relation with Al heat exchanger brazing will be explored. Examples of in-house designed and brazed Al compact heat exchangers will be illustrated. The examination of brazing results using metallographic procedure will also be elaborated.

1. INTRODUCTION

All aluminum microchannel heat exchangers are used increasingly in the HVAC &R industry. Compare to conventional round tube/fin unit, the microchannel coil has the advantages such as reduced weight, high thermal performance, low refrigerant charge, and enhanced corrosion resistance. Key components of a microchannel coil, i.e., flat microchannel tube, fins between tubes, and header manifolds, are joined together by brazing. Controlled Atmosphere Brazing (CAB) technology is the state-of-the-art technology for manufacturing the aluminum heat exchangers. Many factors can influence the quality of a CAB brazed products, e.g., both inherent temperature non-uniformities and possible alterations of background atmosphere can severely hamper the flow of molten filler metal. The current tight requirements for more compact and highly thermally augmented heat transfer surfaces, as well as the intricate designs of manifold/header areas of modern compact heat exchangers (Shah and Sekulic, 2003) impose very difficult requirements for a brazing process. Regardless of the fact that brazing is a highly developed engineering art, the manufacturing operations lack predictability and clear description of the phenomena involved.

Therefore, it is important to take into considerations the challenges may be faced in manufacturing process when designing new generation of aluminum heat exchangers for HVAC&R systems.

This paper presents a series of research and development activities involved in fabricating of compact aluminum heat exchangers using CAB technology. The focus is to use modern experimental techniques, including hot stage microscopy and transparent CAB glass furnace for real time *in-situ* monitoring of filler metal melting, spreading, and solidification process, and to improve fundamental understandings of the transport phenomena during the aluminum brazing process. The work presented has been directed primarily to the: (1) Surface tension governed wetting behavior of Al-Si alloy on Al substrate; (2) Molten metal flow behavior through micro-scale capillary grooves; which is closely related to surface morphology influence on wetting and other important issues, such as microchannel blockage, during manufacturing process; and (3) Joint formation at intricate geometry such as the bonding between microchannel tube and header tubes with small diameters. A 2-D simulation of brazed joint configuration using Surface Evolver software will be presented to illustrate importance of proper selection of filler metal amount. The overall goal is to contribute to the optimization of brazing processes for fabricating small scale aluminum heat exchangers, including material selection and process conditions, especially with respect to handle materials diversity, geometry complexities, and innovative joining concepts.

2. FUNDAMENTAL OF CAB BRAZING PROCESS

Brazing is a joining technique by using molten filler metal. The liquid braze alloy or filler is drawn into the gap between materials to be joined (parent materials) by capillary forces. A metallurgical bond is formed on solidification of the filler metal. For aluminum brazing, before melting of the filler metal, the native oxide film present on all aluminum surfaces must be destroyed to allow the free flow of molten clad during brazing. For a controlled atmosphere Al brazing process (CAB process), this task is accomplished by a deposition of flux on aluminum surface to be joined (Swidersky, 2001). A tightly controlled inert gas (N_2) atmosphere prevents the reformation of oxide layer on aluminum surface, and reduces the formation of HF generated by reaction between flux and moisture during heating process. For the CAB Al brazing, the inert gas atmosphere is monitored by measuring dew point, which is normally controlled at the level of -40 °C or lower.

A typical aluminum heat exchanger may be manufactured using the brazing sheets and other aluminum parts. The brazing sheet core is made of an aluminum alloy, such as AA3003 with cladding consisting of Si rich alloys such as AA4343, AA4045, or AA4047. Figure 1 presented microscopy images of cross sections of louver fin and microchannel tube before brazing (Fig. 1(a)) and after brazing with joint formation (Fig.1(b)&(c)). The fin material was double sided brazing sheet that contains a thin layer of clad alloy on core alloy, as illustrated in Fig. 1(a). The core aluminum alloy would melt at about 640°C (Schuster *et al*., 2007), while the clad may melt in the temperature range between 577°C and 613°C (Swidersky, 2001). Therefore, the ideal CAB furnace temperature range for the peak brazing temperature must be within the indicated melting range of the cladding material and well below the core melting point. The samples illustrated in Fig. 1 were brazed at peak temperature level around 605 °C. Heating ramp during brazing cycle was controlled around 20 °C /min to maintain the proper uniformity of temperature distribution on the brazed object and to prevent Si depletion from filler metal due to diffusion (Gao *et al*., 2002).

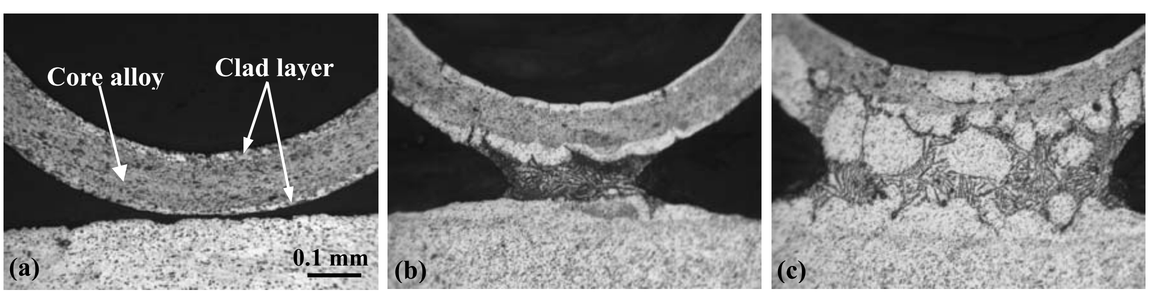

Figure 1 CAB brazed joint between fin and tube (a) Fin and tube before brazing; (b)(c) examples of joints after brazing

3. EXPERIMENTAL FACILITIES

For the purpose of understanding transport phenomena during brazing processes, especially during clad melting, spreading and solidification, visualization in a real time manner is often desired but difficult to realize because the CAB brazing requires a closed hot zone with tightly controlled inert gas atmosphere. An in-house designed transparent furnace was developed for the purpose of *in-situ* monitoring of brazing process. In addition, a hot stage microscopy system was used to observe the flow behavior of flux and molten filler metal under large magnification.

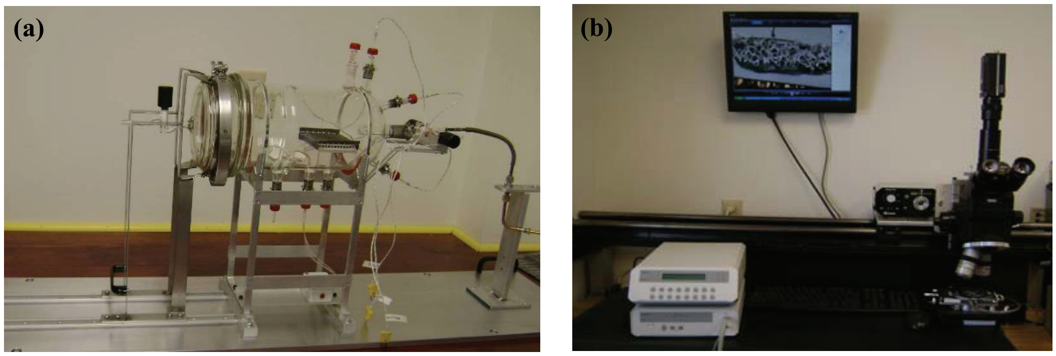

Figure 2 Visualization facilities (a) Hot zone of transparent glass furnace; (b) Hot stage microscopy system

The photograph of the in-house built glass furnace hot zone is given in Fig. 2(a). The size of glass cylinder chamber is about 130 mm in diameter and 300 mm in length. The heating source is an electrical heater plate. In the CAB mode, the furnace operates with a high purity N_2 gas. Tightly controlled furnace atmosphere provides optimum brazing conditions. Two thermocouples can be attached to the sample. The heater temperature, sample surface temperatures, chamber pressure, dew point and other parameters were monitored in real time. A data acquisition system and a computer feedback control loop guided the experiment automatically after the pre-set input data were imported through a control program. The furnace can also work in a mode with vacuum hot zone when application needed. The hot stage microscope system used for this study was a THMS600 stage system manufactured by Linkam Corp, UK. The system set-up is given in Fig. 2(b). The hot stage has a temperature range of –196° C to 600° C. The heating element inside the chamber is cast into a silver block, to form an integral heater and sensor assembly. The CI94 (Linkam) programmer is run by Linksys software for both heating and cooling routines. Nitrogen gas was supplied to the stage chamber with a fixed flow rate. A Mitutoyo microscope was used to observe sample inside the hot stage chamber under variable magnifications. A Sony XC57 video camera is attached to the microscope through a C-mount to capture real time images.

4. RESULTS AND DISCUSSION

4.1 Wettability tests by glass furnace

A successful brazing process depends upon subsequent bonding between parent metals and the filler metal, which occurs only if the filler metal wets the surface of the parent metals. The bonding can be inhibited by many factors involving various metallurgical issues (alloy composition, morphology of the structure, diffusion processes, etc.), system control (temperature-time history, background atmosphere), and mechanical stress-strain related issues (initial state of the structure, fixturing, cool-down conditions). A clearance filability test can be used to evaluate the wettability of selected filler metal on Al substrate. Figure 3(a) illustrates experimental set-up. Basically, a vertical Al plate was placed such that the bottom left corner touches the horizontal Al plate, and the bottom right corner was raised to have some distance from the horizontal plate. Upon melting of the filler metal, the liquid will flow through the clearance between the two Al plates due to capillary action. When such test is performed using the transparent glass furnace, both the final wetting distance and flow speed of the liquid metal under certain brazing conditions can be measured for quantitative evaluation of the filler wettability. An example of the clearance filiability test performed using glass furnace was illustrated in Figs. 3(b)-(d), which contain a series still images extracted from the captured video. In this test, both vertical and horizontal plates are AA3003 alloy, the filler metal is Al-12Si alloy.

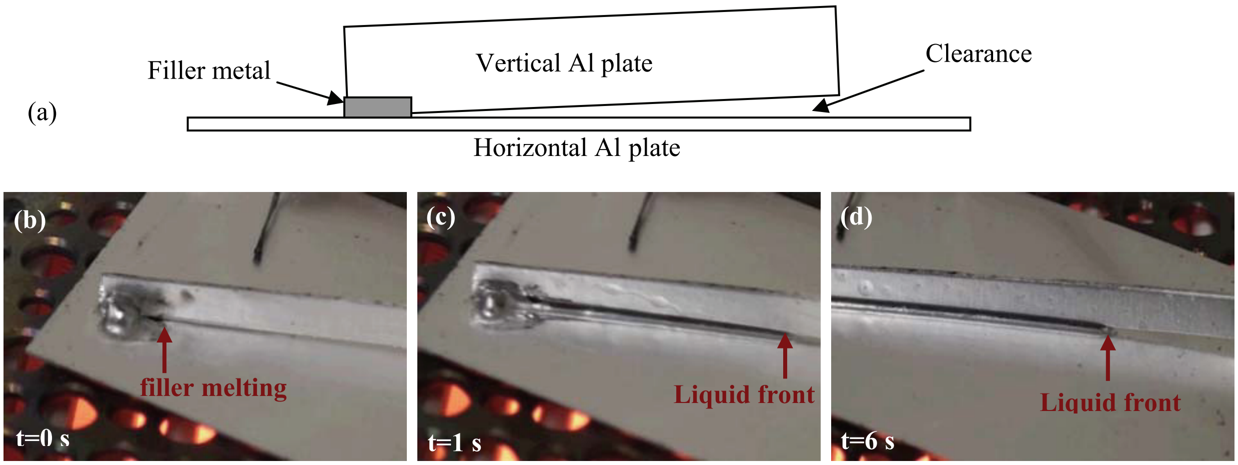

Figure 3 : *In-situ* monitoring of liquid filler metal filling the joint clearance (a) experiment set-up; (b)-(d) still images extracted from real-time video of brazing process.

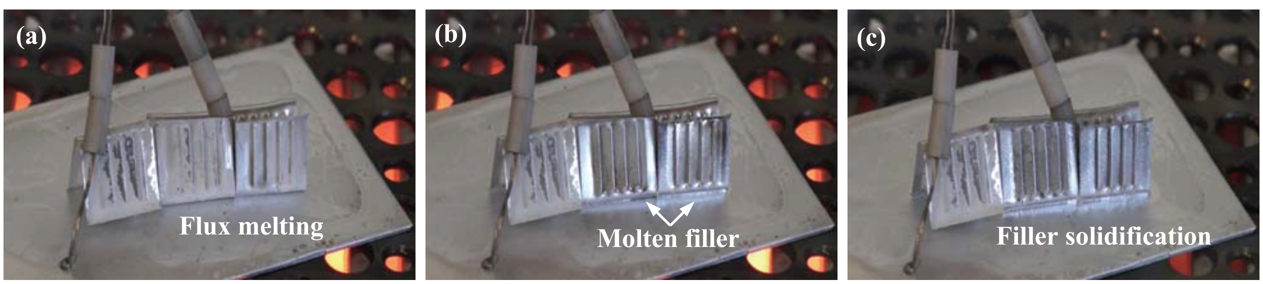

Figure 4: *In-situ* monitoring of fin/tube joint formation (a) flux melting; (b) joint formation;(c) solidification

Using the transparent furnace, the bonding process between cladded fin and Al substrate was monitored *in-situ*. The cross section image of the double-sided clad fin was presented in Fig. 1(a). The experimental sample set-up is illustrated in Fig. 4(a), Nocolok® flux was applied on both fin and substrate surfaces to effectively destroy the oxide layer. Both heating ramp and brazing peak temperature were controlled according to industrial production process. Figure 4 shows a series of extract images from real-time video that captures joint formation process. As the thermocouple embedded in the fin structure shows a temperature approaching 580 ºC, shiny appearance of the fin surface and starting of joint formation were observed. The molten clad gradually fill the gap between fin and the substrate as illustrated in Fig. 4(b). It was also noted that there was no joint formed between the fin at left side and the substrate due to the fact that this particular fin was not touching the substrate at any point. The molten filler metal does not jump; there must be some contact point to initiate the capillary flow, as illustrated in the clearance filability test (Fig. 3). From the real-time monitoring of brazing process using the transparent glass furnace, the process parameters can be precisely recorded and correlated with quality of brazed joint, such as joint integrity and erosion levels, when combined with metallurgical study and other examination methods on brazed samples.

4.2 Study of molten filler capillary flow using hot stage microscopy

Hot stage microcopy system has the advantage of offering a microscopic real-time observation of phenomena involved in the process of filler metal melting, spreading and solidification. Figure 5 illustrates an example of the dynamic wetting behavior of Al-12Si alloy on a flat AA3003 substrate. The Al-12Si filler is characterized as more flowable than other Al-Si alloys because of its close to eutectic composition. It is observed that upon melting, the liquid metal spread on the substrate initially with a close to circular contact line shape, see Figs. 5(a), the molten filler front (triple line) advances fast and was eventually beyond the filed of view of microscope objective (X50).

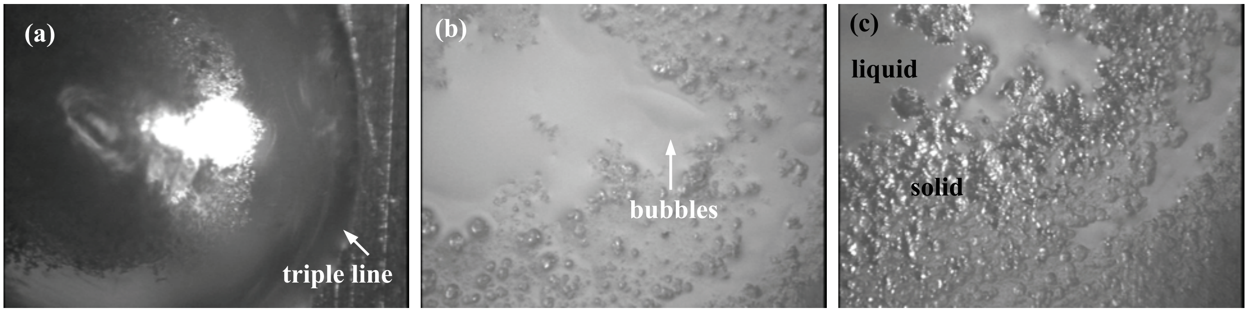

Figure 5 A sequence of frames extracted from a real-time monitoring of molten filler spreading using hot stage microscopy (a) spreading; (b) liquid surface features bubbles; (c) solidification.

Some interesting phenomena were observed during the dynamic wetting and phase change processes. In Fig. 5(b), the extract frames captures bubble-like formations at random locations on liquid surface. It was speculated that these formations might be indication of gas phases generated at the liquid/solid interface due to interactions at interface. Studying the bubble formation mechanism and its correlation with the defect voids often found in brazed joints may provide useful information on how to improve joint quality. Figure 5(c) shows a still image during molten liquid solidification process. It is often assumed that the effect of solidification on joint topology can be neglected (Zellmer *et al*., 2001); the liquid free surface shape is determined by minimal energy principle. While such an assumption may hold for the joint configuration in a macro scale, it is found microscopically that the joint surface morphology may be significantly altered during the solidification process. The real time observation using the microscope clearly shows that during solidification Al-12Si filler alloy, local deformation of the liquid free surface occurs and leads to a bumpy surface morphology of the resolidified joint. It was also observed that coverage of the substrate surface by filler metal as a thin film at the triple line location can be further extended during solidification.

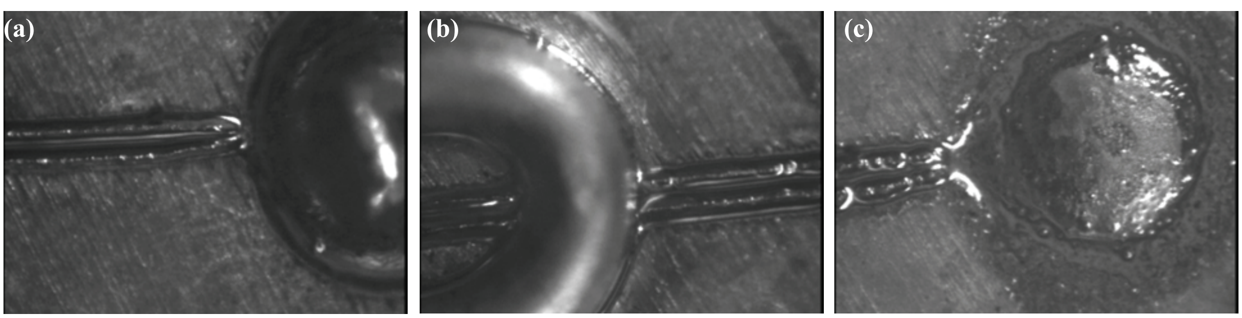

Figure 6 A sequence of frames extracted from molten filler spreading through groove (a) capillary flow through groove; (b) joint formation between U-shape wire and substrate; (c) filler metal residue.

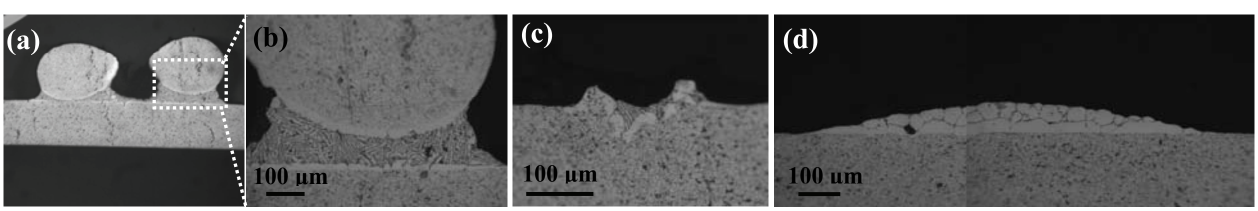

Figure 7 Cross section images of re-solidified sample: (a)(b) Joint formed between U-shape wire and substrate; (c) re-solidified filler residue in the micro-groove; (d) re-solidified filler residue at original location

Manufacturing of compact Al heat exchanger involves brazing of microchannel tubes with other components, the possibility of molten filler flowing into microchannels by capillary action may leads to serious consequence such as blocking refrigerant passage, and deplete the amount of filler needed at joining locations. Closely related phenomena can also be identified in a number of other applications (Zhao *et al*., 2006). Hot stage microscopy can be used to study capillary driven liquid metal flow through micro channels. A test was arranged to illustrate the wetting behavior of molten filler when a micro-channel is present on Al plate (AA3003) surface. A piece of Al-12Si alloy was placed on the plate close to one end of the groove. A U-shape Al wire was placed on the other end of groove. Figures 6(a)-(c) shows a series of images extracted from the captured video on the molten metal behaviors. It is found that the molten filler is attracted into the micro channel instantaneously when the liquid front is in contact with the groove entrances (Fig. 6(a)), and then rapidly flows through the groove. The liquid metal is delivered to the other end of groove and fills the capillary gap between U-Shape wire and substrate surface (Fig. 6(b)). The residue of filler metal left at the original source location was mainly the solid portion, i.e., α-Al phase, of the semi-solid mixture of molten filler; see Fig. 6(c). The re-solidified sample was metallurgically cut and examined, microscope images of sample cross sections at different locations were presented in Fig.7. It is confirmed that good bonding was formed between the U-shape wire and substrate by the liquid filler delivered through the capillary groove. The test illustrates the capability of micro-scale channels on attracting liquid filler metal due to capillary action, a phenomena that should be prevented or utilized depending on application requirements during brazing process.

4.3 Joint formation at intricate geometry during CAB brazing

In application such as a mini-cooling system, small scale heat exchangers are often needed. The design of intricate geometries can impose challenges on the fabrication process. Figures 8(a)&(b) illustrates prototypes of small-scale serpentine condensers brazed using a batch CAB furnace. The design of header, as illustrated in Figs. 8(c)&(d), eliminates the need of using an extra connector with the microchannel tube. For the brazing process, the following issues need to be considered: (1) The surfaces of microchannel tube and header tube are not coated with clad layer, additional filler metal must be supplied to the joining location. Proper selection of filler material is essential to a successful bonding; (2) The inner diameter of the header tube is very small, in some case the header inner diameter is only slightly larger than the microchannel tube thickness, see Fig. 8(d). When the microchannel tube is inserted into the header tube, it is important to control the proper length of the insertion. If the tube is inserted too deep and/or touches the inner wall of header, as illustrated in Fig. 9(a), flow of refrigerant into the microchannels will be hampered; if the tube insertion length is too short, see Fig. 9(b), excessive molten filler may flow extensively to the edge of the tube and further attracted into the microchannels by capillary force.

Figure 8 Serpentine condenser fabricated using CAB brazing (a) louver fin condenser ; (b) foam condenser; (c) 6.4mm OD header/tube joint; (d) 3.2mm OD header/tube joint.

A case study was performed using Al-12Si wire (0.76 mm gauge) as filler metal for header brazing. Cross section views of the preplaced filler wire at the joining location before brazing were illustrated in Figs. 9(a)&(b). Header tubes with outside diameters (OD) of 6.4mm and 3.2 mm are used for the study. A public available software "Surface Evolver" is used to predict the brazed joint topology (Brakke, 2008) based on the following assumptions: (1) The filler wire melts completely during brazing and forms the joint between header inner wall and microchannel tube surface; (2) the liquid filler metal distribution is uniform along the periphery of the microchannel tube, so the string model of the software can be used to simulate the 2-d configuration of joint cross section; (3) the brazed joint size is small so that gravity influence on joint surface topology can be neglected. Based on the 2-D assumption, cross section area of the filler wire is used as an estimated amount of liquid metal that will form the joint between header tube inner wall and microchannel tube surface. The "Surface Evolver" software selects the membrane shape that corresponds to the minimal potential energy of the molten metal surface (Sekulic *et al*., 2004). Since the gravity influence is neglected, the potential energy of the membrane is given by:

$$E_p = E_s + E_w \tag{1}$$

Where $E_s = \int_l \sigma dl$, $E_w = \int_l -\sigma \cos\theta dl$ represents the membrane surface potential energy, potential energy along the bonding surfaces, respectively. σ and θ represents surface tension and contact angle, respectively. The minimization of the potential energy, i.e., $\min(E_p) = \min(E_s + E_w)$, determines the joint topology.

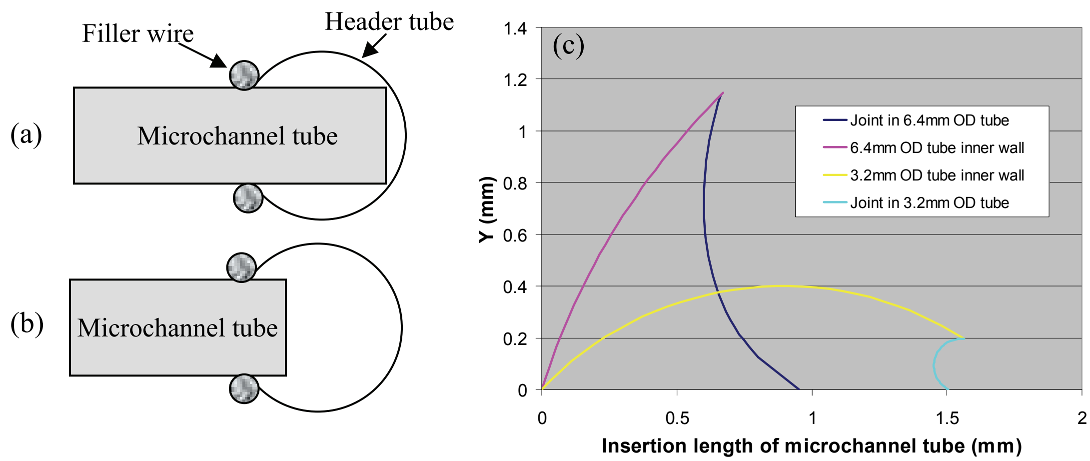

Figure 9 Influence of bonding surface geometry on joint topology: (a) a sketch illustrating too deep tube insertion to header; (b) a sketch illustrating too short tube insertion to header; (c) prediction of brazed joint topology using Surface Evolver software

The prediction results of joint topologies are illustrated in Fig. 9(c). For given amount of filler metal, when a 6.4mm OD tube was used as the header, the joint dimension on the microchannel tube surface is less than 1mm, in other words, if the inserted length of microchannel tube is sufficiently longer than 1 mm, the molten filler may not over flow to the edge of the tube. When the 3.2mm OD header tube is used, the space between header inner wall and microchannel tube becomes relatively narrow, the predicted joint dimension on the microchannel tube surface is around 1.5 mm, the maximum length of the microchannel tube that can be inserted into the header, as illustrated in Fig. 9(a)), is around 1.8 mm. These numbers indicate that the proper insertion of the microchannel tube is very difficult to manage to satisfy both requirements of: (1) being long enough to prevent over flow of liquid to the tube edge; (2) leaving sufficient space for refrigerant entering the microchannels. The applied filler wire maybe oversized for the joining of 3.2mm OD header tube. The amount of filler metal should be reduced or alternative method needed to be considered.

Figure 10: *In-situ* monitoring of liquid filler metal blocking microchannels using glass furnace: (a) molten filler formed joint between header and tube; (b)&(c) microchannels being blocked by molten filler

Brazing tests for header joining with microchannel tube was arranged using glass furnace. One example is illustrated in Fig. 10. The 3.2mm OD header tube was cut partially open for the purpose of direct observation of molten metal flow inside the header. The filler wire was pre-placed at joining location. It was found that when filler wire starts to melt, liquid metal first fills the clearance between tube and header as desired, see Fig. 10(a). However, the over flow of liquid metal into the microchannels occurs after a prolonged time while heating temperature is still increasing, see Figs. 10(b)&(c). It is speculated that the viscosity of molten alloy decreases as heating temperature increases because the alloy melts completely instead of being a semi-solid mixture. Liquid flows more freely to extended range, eventually touches the entrance of microchannel and flows into the channels by capillary force. It is demonstrated that careful control of brazing conditions such as peak brazing temperature and soak time are also important on preventing the filler metal overflow, especially in the situation when it is difficult to reduce filler metal amount.

Two samples of the header/tube joints brazed with 0.76mm gauge filler wire were metallurgically cut and examined. The microscopy images of joint cross sections are presented in Fig. 11. Figure 11(a) shows the joint formed between 6.4mm OD header and microchannel tube. Filler metal is maintained in the wedge area between header inner wall and tube surface without overflowing to the microchannels. Certain level of erosion, i.e., substrate dissolution into filler metal, can be identified, indicating a high brazing temperature and/or longer dwell time. The white dot lines represents original substrate surface before brazing. Figure 11(b) illustrates the brazing results of 3.2mm OD header tube and the microchannel tube. Apparently, excessive molten filler metal overflows into microchannels and blocked refrigerant passage. Substrate erosion was indicated by reduction of tube wall thickness at joint location.

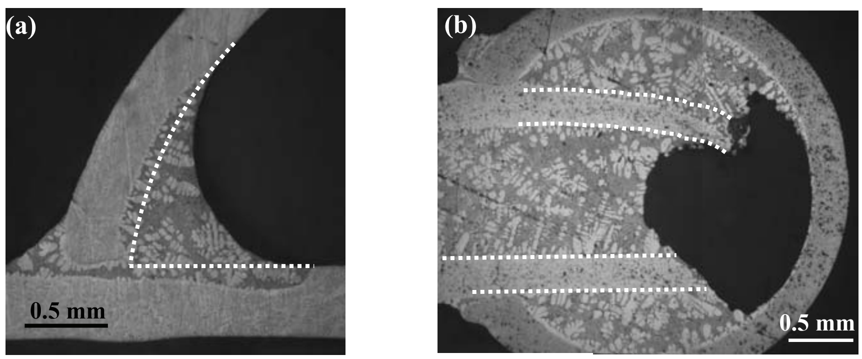

Figure 11 Cross sections of re-solidified joints between microchannel tube and header tubes with: (a) 6.4mm OD diameter; (b) 3.2mm OD diameter.

5. Conclusion

The main characteristic of illustrated fabrication issues is that a state-of-the-art CAB technology may face many challenges during manufacturing process. This is mostly due to a still highly empirical nature of the involved knowledge about brazing process. When approaching the peak brazing temperature, brazing phenomena are characterized with complicated transient processes. Many related phenomena are to not fully explored. It has been shown that detailed study using the visualization facilities provided valuable information on understanding the transport phenomena involved in the CAB aluminum joining process, therefore greatly enhanced the capability on in-house fabrication of high quality novel heat exchangers designed for modern refrigeration and cooling system. It has been demonstrated that both brazing condition control and joint design optimization are essential in the brazing process of object with intricate geometry, such as small scale heat exchangers. Modern computer simulation tools can greatly assist the joint design and brazing material selections.

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