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Influence of Surface Morphology on Wetting Behaviors of Liquid Metal during Aluminum Heat Exchanger Fabrication

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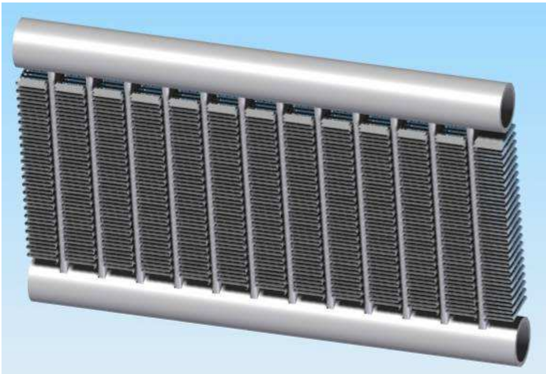
ABSTRACT

The market demand for aluminum brazed exchangers in air conditioning and refrigeration industry is continually growing owing mostly to the cost and weight savings of aluminum materials, with undisputed compactness and low charge. Manufacturing of aluminum heat exchangers requires reliable metal bonding technology to join together various components, such as tubes, fins and header manifolds. Controlled atmosphere brazing (CAB) of aluminum is the state-of-the-art technology for mass production of compact aluminum heat exchangers. Traditionally, the development of a brazing process relies on trial and error in practice. However, modern manufacturing process requires good understanding of scientific principles involved in the brazing operations. It is well known that a brazing process is assisted by the capillary flow of liquid filler metal on the base surfaces of various heat exchanger components. Therefore a good understanding of the molten flow behavior on aluminum surfaces is critical in quality assurance of the brazed heat exchangers. Capillary flow occurring at high temperature level during brazing is usually much more complicated than the wetting in an inert system with a smooth solid surface. For example, the flow of liquid is not only controlled by surface tension force, but also influenced by interactions between liquid and base metal materials. In addition, the metal surface of heat exchanger components to be brazed is usually not smooth due to the fabrication process such as extrusion or hot/cold rolling. In this paper, the phenomena closely related to liquid filler metal wetting behaviors on base metal with different surface morphologies are presented. Experimental facilities such as heating stage microscopy system and transparent furnace are used to visualize the capillary flow of molten filler metal under typical CAB brazing conditions. The influence of the base metal surface morphology on wetting behavior as well as brazed joint quality are examined, assisted by metallographic analysis of re-solidified brazing joints. The physical and chemical phenomena in the interaction between liquid (molten flux and filler metal) and solid (base metal) are described. The results from this study provide useful insights on how material selection and surface treatment can affect the brazing process and brazed heat exchanger quality.

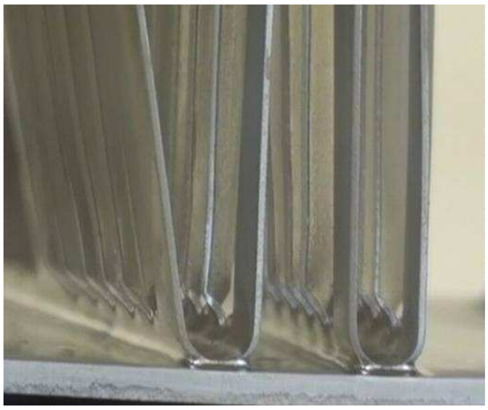
1. INTRODUCTION

Aluminum and its alloys are good material choices for heat exchangers. The cost savings with aluminum is promoting the substitution of copper with aluminum in many industrial applications. One of the trends observed in the Heating, Ventilating, Air-Conditioning and Refrigerating (HVAC&R) industry is to replace the traditional copper heat exchanger products with aluminum heat exchangers. Brazing is a preferred method for manufacturing aluminum heat exchangers owing to the following advantages: (1) various components such as tubes, fins, and headers can be joined simultaneously in a furnace brazing process; (2) the metallurgical bond provides good sealing and mechanical strength; (3) brazing takes place at a moderate temperature which would not significantly degrade base material properties. Since the early 1980s, controlled atmosphere brazing (CAB) has been successfully used in manufacturing automotive aluminum heat exchangers. The process is highly cost effective when a continuous furnace is used for mass production. It is well known that a brazing process is assisted by the capillary flow of liquid filler metal on the base surfaces of various heat exchanger components. Figure 1(a) illustrates a schematic of micro-channel condenser that includes three major components: (1) headers; (2) extruded micro-channel tubes; (3)

louvered fins. Figure 1(b) illustrates the formation of joints between the filler metal claded fins and a base plate during CAB brazing in a transparent lab furnace.



(a) A microchannel condenser



(b) joint formation between fin and base plate

Figure 1 : Manufacturing of aluminum heat exchanger using CAB brazing technology

When an aluminum heat exchanger is manufactured by furnace brazing, all joints between various components are formed simultaneously. A good understanding of the molten flow behavior on aluminum surface is critical in quality assurance of brazed heat exchangers (Zhao, *et al.*, 2012). One of the important issues that are observed in aluminum heat exchanger brazing is the dissolution and erosion of base metal by liquid filler metal. During brazing, flow of molten metal occurring at a high temperature level (around 600 °C) involves interactions between liquid and solid base metal materials. Studies have shown that liquid filler metal from a header/tube joint location can flow over the surface of the tube and arrive in a fin/tube joint location. The liquid metal will dissolve certain amount of the tube wall material upon contact. When the filler metal flows away, a significant reduction of the tube wall thickness is expected and may lead to detrimental failure of the heat exchanger (Solvay Fluro, 2013). In some cases, it is believed that the cause of such undesired filler metal overflow is related to the die lines on extruded tube surfaces (Solvay Fluro, 2013). Such phenomena indicate that base metal surface morphology will influence molten metal flow during heat exchanger brazing process. Studies have shown that certain rough surface conditions will lead to extensive spreading of the filler metals in both aluminum brazing and copper soldering (Yost, *et al.*, 1995; Zhao and Sekulic, 2009).

In practical applications, heat exchanger surfaces can hardly be smooth or have consistent surface texture and roughness. Various surface morphologies may exist due to different manufacturing, machining and cleaning processes. Figure 2 illustrates a sessile drop wetting test of an AA4343 (Al-8wt%Si) filler metal disc (1mm diameter) on a piece of AA3003 plate (~10x10x0.4 mm). Tiny rolling marks on this AA3003 plate can be identified when the plate is examined using a microscope. The sample is placed in a heating stage chamber that is continuously purged with N_2 gas. The melting and spreading process of the filler metal at a high temperature level around 600 °C is captured by a video camera attached to a microscope. Images of liquid metal wetting process are extracted from the video, as illustrated in Figure 2(b)&(c). It is found that upon melting, the bulk liquid spreads with a relatively circular shape. However, some surface grooves are simultaneously attracting liquid by capillary force and lead to more extensive spreading at random locations. It is not difficult to imagine that such irregular surface patterns can cause unexpected distribution of filler metal during a brazing operation.

In this paper, a preliminary study of liquid filler metal wetting behavior on base metals with different surface morphologies during aluminum brazing is presented. Controlled atmosphere brazing (CAB) experiments are performed using a transparent furnace under typical CAB brazing conditions. The influences of base metal surface patterns on wetting and joint formation process are closely examined and compared with theoretical studies related to rough surface wetting (Bico, *et al.*,2001; De Gennes, , *et al.*, 2004). Metallurgical examination of brazed joint using optical microscope is performed to assist in understanding the interfacial reactions during a high temperature wetting process.

(a) filler metal disc on AA3003 plate (b) initial melting of the filler metal (c) extensive spreading of filler metal

Figure 2: Wetting test of Al-Si filler on AA3003 surface

2. MATERIALS AND EXPERIMENTS

2.1 Aluminum base alloys and filler metal

In this study, coupon plates of two types of aluminum alloys are used as substrates for brazing tests: (1) AA3003 alloy that contains Mn (~1.2 wt%) as major alloying element. (2) AA6061 that contain Mg (~1.0wt%) as alloying element. Both alloys are commonly used as heat exchanger materials. The Mg bearing AA6061 alloy is more often used in a vacuum brazing process. It is generally not considered as a good candidate for CAB furnace brazing because the high Mg content in alloy AA6061 leads to flux "poisoning" effect at elevated temperature (Garcia Juan, *et al.*, 2010). The wetting of filler metal on AA6061 alloy is generally poor. The use of AA6061 alloy in this study is to explore how the change of surface morphology may influence wetting behavior in a poor wetting system (i.e., the contact angle on a smooth surface is much larger than zero). Base plate coupons are cut from commercially available sheet with a thickness around 0.8mm. A plate with "as is" surface condition is used as baseline test material. Changes of surface morphology on both alloys are accomplished by sandblasting on one side of the coupon plate. The sandblasting media is alumina bead. Due to the wide application of AA3003 alloy in CAB brazed heat exchangers, an AA3003 coupon plate was also grinded on SiC paper to generate a surface pattern that features small parallel grooves on the alloy surface. Before brazing, all coupon plates are ultrasonically cleaned to prevent any surface contamination that may influence the filler metal wettability.

In this study, AA4047 (Al12wt%Si) alloy that has a melting point of approximately 577 °C is used as filler metal. The filler metal is supplied in the form of a thin foil that has a thickness of 0.1mm. This eutectic filler metal is commonly used in aluminum brazing where good flowability is essential for the brazing operation.

2.2 Experimental facility and sample assembly

Experimental studies of CAB brazing are performed using an in-house built transparent glass furnace. The furnace is equipped with a transparent chamber that provides visual access for real-time observation of a brazing process. Heaters are controlled to provide a uniform heating for the brazing sample. A tightly controlled inert gas atmosphere ensures oxygen depleted environment during brazing. Typical ramp rate and peak brazing temperature around 600 °C for a CAB furnace process are adopted in these lab tests.

The wedge T joint assembly is used throughout this study. A side view of the basic sample set-up is illustrated in Figure 3. An AA3003 plate (~30mm x 25mm , as is surface condition) is used as horizontal plate for all tests. One surface of the vertical plate (AA3003 or AA6061) was treated by sandblasting or abrasive grinding. The AA4047 filler metal foil is located between the horizontal and vertical plates. Non-corrosive fluxes were applied on both filler metal and substrate surfaces to ensure adequate removal of oxide film on metal surfaces during brazing. All sample parts were cleaned and fluxed before exposed to the heating process. A video camera was used to capture filler metal melting and joint formation process.

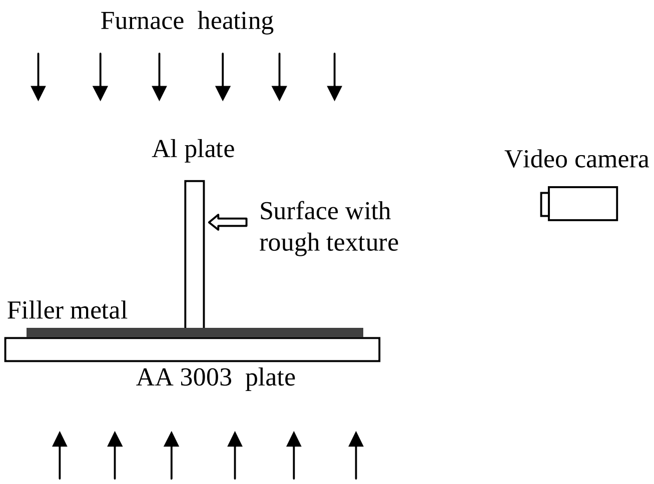
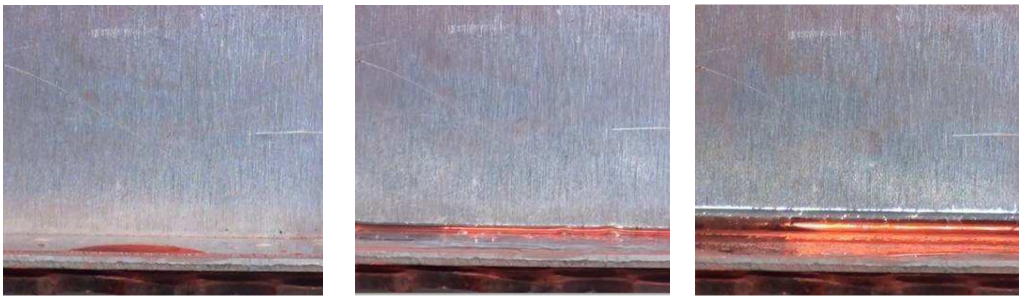


Figure 3 : Experimental set-up using a transparent glass furnace

3. RESULTS AND DISCUSSION

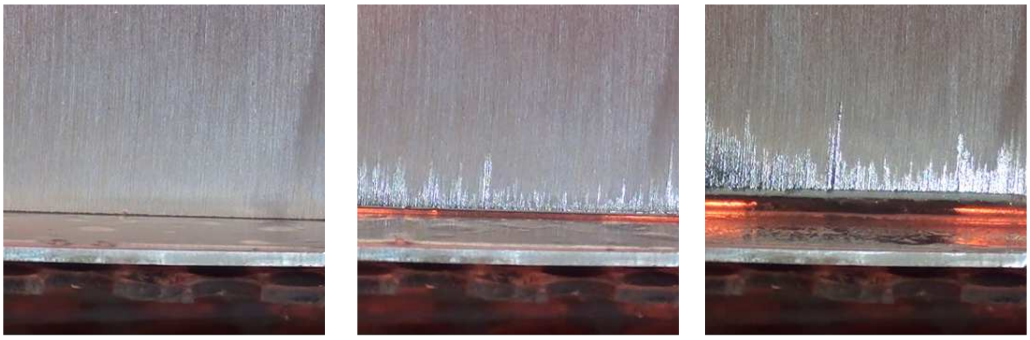
3.1 Filler metal flow behavior on AA3003 plate

For comparison purpose, a wedge T brazing test using AA3003 plate with "as is" surface was first performed. Figure 4 illustrates the evolution of the meniscus formed by molten metal between the horizontal and vertical plates. A clear movement of the triple line (boundary between liquid, solid and gas phases), as illustrated in Figure 4(b)&(c), can be observed. In a following experiment as presented in Figure 5, one side of the vertical plate surface morphology is altered by a light grinding (in vertical direction) which leaves a consistent groove pattern. During brazing, the bulk liquid metal formed a meniscus between the horizontal and vertical plates. At the same time, many small liquid branches were climbing along the surface grooves; see Figure 5(b). The capillary rise at some locations can be higher than 5 mm at peak brazing temperature, see Figure 5(c). Apparently, a simple grinding on the aluminum surface changes the wetting behavior of filler metal and leads to the extensive flow of a small portion of the liquid beyond the bulk joint area. These grinding lines may be considered as randomly distributed (but along the same direction) micro-grooves. Liquid metal is drawn into these grooves by capillary action. In some circumstances, such an extensive spreading of liquid metal may be undesirable because the grooves provide passes for filler metal flowing away from designated joint location. The uncontrolled flow can lead to serious consequences such as base metal erosion and microchannel blockage. Therefore, the surface pattern generated in heat exchanger component fabrication process (e.g., extrusion, rolling and machining) should be carefully examined before the brazing process.



(a) onset of filler melting (b) onset of mensics formation (c) joint formation

Figure 4: Wetting of eutectic filler on as is AA3003 surface



(a) onset of filler melting (b) onset of mensics formation (c) joint formation

Figure 5: Wetting of eutectic filler on grinded AA3003 surface

Sandblasting on aluminum surface provides a quick and easy method to generate a relatively uniform rough surface pattern. It is important to understand liquid filler metal wetting behavior on such surfaces because sandblasting is commonly used in cleaning and surface treatment for metal components. However, the impact of such surface treatment on the manufacturing process is often ignored. In this study, a vertical AA3003 plate that has the surface sandblasted is used in a wedge T joint formation experiment. The experimental result is illustrated in Figure 6. As usual, the bulk liquid gradually forms a meniscus between the horizontal and vertical plates during brazing. However, it is interesting to observe how a wicking phenomena of the liquid metal by the rough surface takes place (Figure 6(c)). In this case, the capillary rise of filler metal on the rough surface is much more uniform than the random distribtion on the grinded surface. A capillary rise around 4mm is observed at the peak brazing temperature. Similar phenomina of capillary rise on rough surfaces in a non-reactive wetting system have been reported in literatures (Bico *et al*., 2001; De Gennes *et al*., 2004). Theroetical study (Bico *et al*., 2001) has predicted a square root relation between the wicking height and time by a balance between surface tension and viscous forces. A final height *h* of the capillary rise was also predicted by balancing the surface tension and gravity forces (Bico *et al*., 2001):

$$h = \gamma / \rho g \delta (\cos\theta - \cos\theta_c) / \cos\theta_c \qquad (1)$$

Where γ is surface tension of the liquid, ρ is density, δ is a height related to the rough feature of the surface, θ is the equalibrium contact angle of the liquid on a smooth solid surface, θc is a critical parameter that equals to the maximum contact angle for the imbibition on a rough surface surface taking place, i.e.:

$$\theta < \theta_c \quad \text{with} \quad \cos\theta_c = \frac{1 - \Phi_S}{r - \Phi_S} \qquad (2)$$

Whre *r* and ϕs are parameters related to the surface morphology: *r* is the surface roughness, ϕs is the solid fraction remaing dry during imbibition. Although no measurement data of these parameters are available for current study, simple calcuations can be performed by estimating some moderate values, e.g., assuming $r=1.2$ and $\phi s=10\%$, δ =0.1mm (radius of the alumina bead), and $\theta=0$ (due to good wetting of eutecic Al-Si filler metal on AA3003 surface). According to Equation (1), these assumed surface parameters can result in a final capilary rise *h* of the order of magnitude of 1 m, if the rough surface is imersed in a large reservoir! However, these predictions are based on an inert wetting system in which chmical compositions of both liquid and solid are unchanged. The wetting behavior of liquid filler metal on base metal surface may follow the theories for non-reactive wetting at the initial stage, but the inevitable interaction between liquid metnal and base metal will lead to changes of material compositions and properties. More sophiscated theoritical analysis is needed to build models that are suitable for flow behavior during a brazing process. Figure 7 shows a microscope image of a crossection of the resolidified joint (obtained through a series of metallurgical procedures including sample cutting, mounting in expoxy resin, polishing and chemical etching). The dotted lines illustrate how the interaction between liquid and solid has led to significant substrate dissolution during brazing.

(a) onset of filler melting (b) onset of mensics formation (c) joint formation

Figure 6: Wetting of eutectic filler on sandblasted AA3003 surface

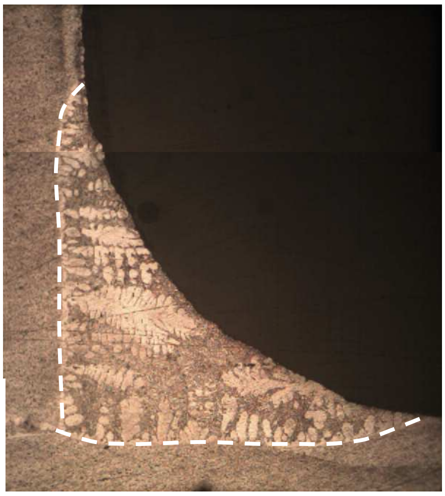


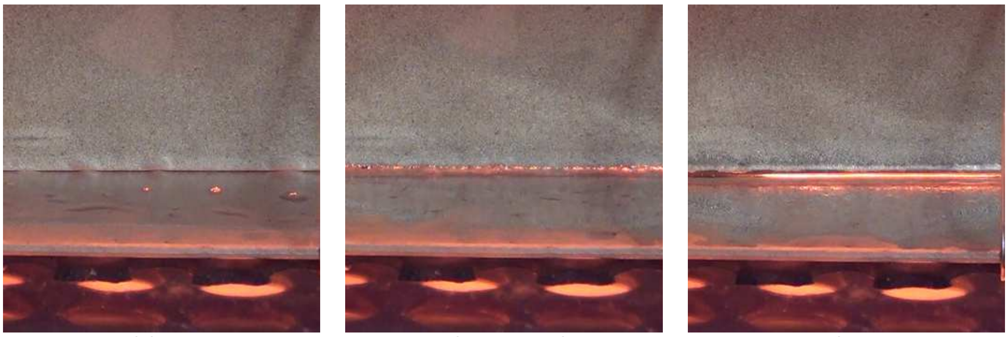
Figure 7: Cross section image of resolidified joint after brazing

3.2 Filler metal flow behavior on AA6061 plate

AA6061 alloy has good mechanical strength and machinability. However, the high Mg content makes it very difficult to be brazed in a CAB furnace process. A non-wetting (i.e., $\theta>\pi/2$) result of molten filler on the AA6061 alloy is generally expected. Recent development of the Cs bearing flux has effectively improved the wettability of filler metals on Mg-bearing aluminum alloys (Garcia Juan *et al.*, 2010). Partial wetting of filler metal (i.e., $0<\theta<\pi/2$) on the AA6061 alloy may be achieved, but the contact angle is still quite large when compared to the good wetting system uses AA3003 alloy as substrate. A wedge T joint formation on an as is AA6061 vertical plate surface is illustrated in Figure 7. It is important to study whether a change of surface morphology has any impact on the wettability of filler metal on AA6061 alloy. A wedge T joint formation experiment is arranged so the vertical plate is an AA6061 alloy and the surface is treated with sandblasting to generate a homogenous roughness. A Cs bearing flux was applied on the sample to assist brazing. It is found that the meniscus formed on the AA6061 plate (see Figure 8(c)), is much smaller than the meniscus formed on an AA3003 plate. No imbibition of the liquid metal to rough surface texture can be directly observed. According to Equation (2), the wicking of liquid by a rough surface will occur when the equilibrium contact angle θ (on a smooth surface) is smaller than the critical value θc. In 3.1, it has been estimated that a surface with a moderate roughness has the critical contact angle value around $\theta c= \pi/5$. Such a critical angle is probably too small for imbibition to take place on the sandblasted AA6061 alloy surface. The observation from current experiment seems to agree with the theory presented by Equation (2). However, a more detailed observation of the wetting behavior at a microscopic level will be useful to confirm that there is no wicking of liquid metal by rough surface structure on the AA6061 alloy. The future study will be performed using a heating stage microscopy system.

(a) onset of filler melting (b) onset of mensics formation (c) joint formation

Figure 7: Wetting of eutectic filler on as is AA6061 surface

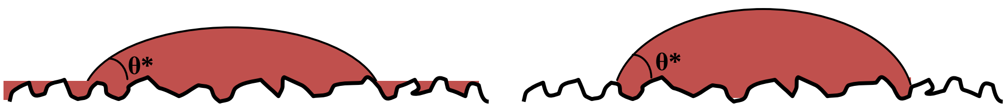


(a) onset of filler melting (b) onset of mensics formation (c) joint formation

Figure 8: Wetting of eutectic filler on sandblasted AA6061 surface

3.3 Discussion of rough wetting in aluminum brazing

Wenzel's theory (Wenzel, 1936) on rough surface wetting has predicted that the increase of surface roughness can only improve wetting when the liquid is wettable on the smooth surface. That is, if θ^* is the apparent contact angle of the liquid on a rough surface, and θ is the contact angle of the liquid on a smooth surface, $\theta^*<\theta$ only when $\theta<\pi/2$. In addition, a recent study (Bico et al., 2001) predicts that when θ is sufficiently small ($\theta<\theta c$), the rough surface area ahead of the bulk liquid triple line is "wetted" by a thin film of liquid, as illustrated in Figure 9(a). In this case, $cos\theta^* = 1- \phi s\ (1-cos\theta)$. Wetting is improved by the existence of such a wet film ($\theta^*<\theta$, except when $\theta=0$). For aluminum brazing, experiments presented in 3.1 confirms that imbibition on rough surface occurs in a good wetting system where equilibrium contact angle θ is close to 0. Bico's theory (Bico *et al*., 2001) also predicts that when the contact angle θ on a smooth surface is relatively large so that $\theta>\theta c$, the rough surface will be dry beyond the contact line of the bulk liquid, see Figure 9(b), which seems to interpret the observation from the experiment presented in 3.2. The apparent contact angle Figure 9(b) is predicted as: $cos\theta^*=rcos\theta$. It is expected that the relation between θ^* and θ in the reactive wetting system (such as in aluminum brazing) will not be the same as in a non-reactive wetting system. However, the quantitative values for contact angles are difficult to measure in current experimental set-up. A precise sessile drop technique will be used to evaluate the contact angle in future study.



(a) liquid imbibition by rough surface (b) dry surface before the trip line

Figure 9: Illustration of apparent contact angle θ* on a rough surface (Bico et al., 2001)

4. CONCLUSIONS

In this paper, wetting behavior of liquid filler metal on aluminum alloy surface is experimentally studied. The main objective is to understand how the change of metal surface morphology will influence a CAB brazing process. It was found that in a good wetting system where AA3003 alloy is used as base material, wetting behavior of liquid filler meal is very sensitive to the change of surface morphology. A surface with moderate roughness generated by abrasive grinding or sandblasting can lead to the spreading of a liquid film ahead of the bulk liquid triple line. Such extensive film spreading can be related to filler metal flow control issues in heat exchanger manufacturing process. In the case where the Mg bearing AA6061 alloy is used as base metal, the surface roughness generated by sandblasting does not show a significant impact the filler metal flow. Such properties may be utilized in brazing when extensive flow of filler metal need to be avoided. In future studies, the correlation of filler metal wetting behavior with precisely controlled rough surface pattern will be explored. Quantitative measurements on surface roughness parameters (r, ϕs) and liquid contact angle (θ, θ^*) need to be collected to build a proper model for rough wetting in a reactive wetting system in aluminum brazing.

NOMENCLATURE

h	capillary rise	(m)
g	gravitational acceleration	(m/s^2)
r	surface roughness	
ϕs	solid fraction	
ρ	density	(kg/m^3)
γ	surface tension	(N/m)
μ	viscosity	(Pa s)
θ	contact angle	(radians)

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