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Compatibility of Filler and Base Metals in Heat Exchanger Manufacturing Process

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ABSTRACT

Aluminum is one of the most commonly used metals for manufacturing heat exchangers. Mass production of compact aluminum heat exchangers can be achieved by furnace or flame brazing with the assistance of fluxes. It is well known that a brazing process relies on good wetting of liquid filler metal on the base surfaces of various heat exchanger components. Proper selection of heater exchanger materials is essential for the success of a brazing process. The cladded brazing sheet has been widely used in the aluminum heat exchanger manufacturing process. Due to the phase changes of the cladded layer during brazing, the surface properties of the heat exchanger components may be altered during the brazing process. In this study, selected cladded brazing sheets are used for testing under controlled atmosphere brazing (CAB) conditions. During the manufacturing or installation processes of the aluminum heat exchangers, there is often the need to repair small defects on the heat exchangers. The Zn-Al filler metal has been considered a good candidate for brazing of aluminum at relatively low temperatures. Wetting behaviors of selected Zn-Al filler metal on the post-brazing surface of the cladded sheet is investigated. It was found that the phase change of clad material leads to apparent change of the surface morphology. The preliminary wetting tests show that the ZnAl filler metal can wet the post-brazing claded sheet at a relatively low brazing temperature (500 °C) without remelting the Al-Si clad layer. Therefore, ZnAl may be considered as a candidate for the rebraze/repair of aluminum heat exchangers.

1. INTRODUCTION

Aluminum and its alloys are common materials used for the compact heat exchangers in the HVAC&R systems. The development of all aluminum microchannel heat exchangers has significantly improved the system performance and reduced the production cost. Many applications are moving toward the trend to replace the traditional heat exchanger materials such as copper and stainless steel with aluminum alloys.

In general, aluminum microchannel heat exchangers are manufactured by controlled atmosphere brazing (CAB) technology. Heat exchanger core materials are 3xxx series alloys for various components such as the headers, microchannel tubes and fins. Filler metals used for brazing belong to the AWS BAlSi category, such as the AA4045 and AA4343 aluminum alloys that contain Si as the major alloying element. Some of the heat exchanger components are often made of the so-called "brazing sheet", which is a composite aluminum sheet that has a thin layer of filler metal cladded on one side or both sides of the core sheet (AA3xxx alloy). The bond between the filler metal and the core sheet is accomplished by a rolling process. The commonly used brazing sheets have a clad layer thickness that is around 5-15% of the total sheet thickness. The utilization of the brazing sheet makes the prebrazing assembling of the aluminum heat exchanger highly efficient because there is no need to supply and attach the additional filler metal sheet, preform, or paste for joining different components. In the case where the brazing sheet cannot be used as the component material, such as the microchannel tube (which is fabricated by an extrusion process), a pre-coating of the Si powder ,e.g. NOCOLOK® Sil Flux (Solvay Fluro document, 2013) or AA4047 powder on the tube surface is often applied to form the bonding between the fin and the tube. An illustration of a cladded brazing sheet and a Si powder coated sheet are presented in Fig. 1.

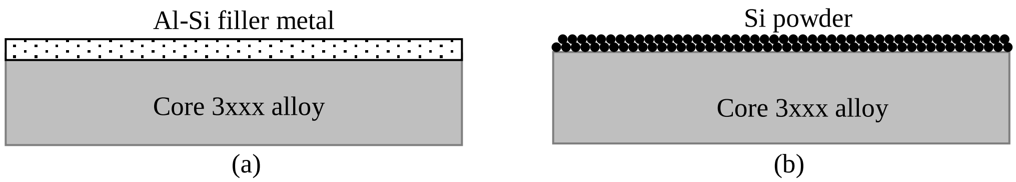


Figure 1: Illustration of the tube material used in aluminum heat exchangers: (a) cladded brazing sheet; (b) Si powder coated tube.

Before brazing, the heat exchanger components usually have relatively smooth surfaces. However, the surface chemical/physical properties may change significantly after brazing due to: 1) the melting/re-solidification process of the clad/filler coating; 2) the NOCOLOK® (a registered trademark of Solvay Fluor GmbH, Hannover, Germany) flux residue, which usually stays on the entire heat exchanger surface. The flux assists the removal/disruption of the aluminum oxide during brazing, and the residue flux is generally considered non-corrosive at normal heat exchanger operating conditions, and does not require a removal process.

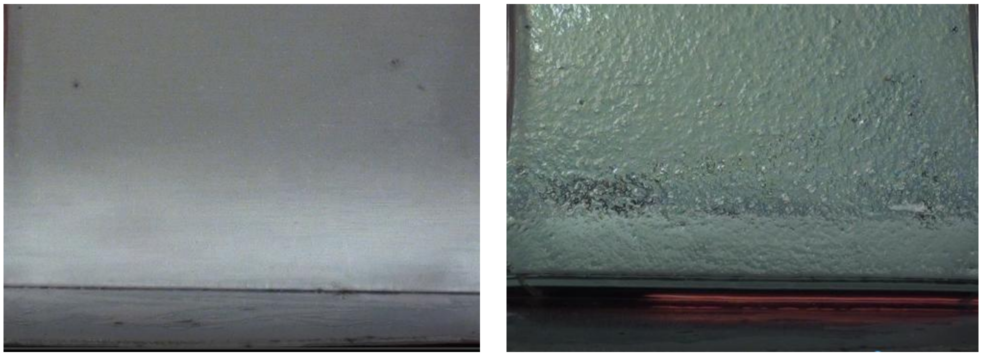
In the practical applications, defects and/or damages on heat exchanger parts and brazed joints are inevitable. It is often desired to repair the small defects on the heat exchanger by furnace or torch re-brazing to save time and cost. However, it is known that re-brazing of aluminum parts with Al-Si filler metal is difficult because the required re-brazing temperature will lead to the re-melting of the original brazed joint and the residue clad layer, causing significant substrate erosion and additional damages at different locations. In recent years, the Zn-Al filler metal became more widely used in aluminum brazing, owing to the development of the cesium bearing fluoride flux that is compatible with the filler metal at the relatively low brazing temperatures (below 500 °C). Studies using Zn-Al filler metals for torch brazing of 3003 aluminum alloy has been reported (Dai et al., 2012), satisfactory brazing results, e.g., good wetting, high mechanical strength of the brazed joint, are achieved when the Al content in the filler metal is less than 8%. Another advantage of the ZnAl filler metal is that it is often suitable for brazing aluminum with dissimilar metals such as copper and stainless steel. Brazing of Cu/Al has been studied (Ji et al.,2012). Among three filler metals, Zn-2Al, Zn-15Al, and Zn-22Al, used for torch brazing of Cu and Al, Zn-15Al alloy produces the joint with the highest shear strength. A modification of the Zn-15Al with the addition of an alloying element Zr may enhance the brazed joint (AA6061/stainless steel) mechanical strength (Yang et al., 2015). A maximum shear strength of the brazed joint was achieved when the Zr addition is around 0.2%, among the studied range of 0-0.3%.

In this study, the feasibility of using the Zn-Al filler metals for brazed joint repair is explored. The focus of the current paper is to provide a preliminary study the wetting behavior of the Zn-Al filler metal on a post-brazing cladded sheet, under the controlled atmosphere furnace brazing conditions.

2. MATERIALS AND EXPERIMENTS

2.1 Cladded Brazing Sheet

The brazing sheets used in this study are double side cladded. The core alloy is AA3003, the cladded filler metal layers (10% of the overall thickness of the sheet) are AA4343 or AA4045 alloys that contain approximately 8wt%Si and 10wt% Si, respectively. In general, the as-received brazing sheet has a smooth surface. To demonstrate the apparent surface morphology change of the cladded sheet during brazing, an example of the AA4343/3003/4343 brazing sheet that went through a brazing cycle is presented in Fig.2. The brazing sample is a T joint setup, the vertical plate is the brazing sheet, and the horizontal plate is an AA3003 plate. The brazing test was performed in a transparent controlled atmosphere aluminum brazing furnace. Figure 2(a) shows the sample before the melting of the clad layer. The brazing sheet surface remains relatively smooth. During the heating process, the clad layer melts, and part of the filler metal flows into the gap to form a joint. However, the surface of the brazing sheet appears to have lost its original smoothness. As illustrated in Fig. 2(b), the residue clad layer is a mixture of liquid and solid phases. A detailed analysis of the influence of the brazing cycle on the surface property change of the brazing sheet is performed in this study.



(a) (b)

Figure 2 : The surface change of the brazing sheeting during a brazing cycle: a) before clad layer melting, b) after clad layer melting.

2.2 Brazing Filler Metal and Flux

Recent studies have shown that Zn-Al alloy is a good candidate of low temperature brazing of aluminum and dissimilar metals. The required brazing temperature is usually below 500 °C, which is much lower than the aluminum brazing temperature when the Al-Si filler metals are used.

The filler metal used for the wetting test in this study is the Zn-15wt%Al alloy which has a relatively low melting temperature range (381 - 451 °C). A proper selection of flux is essential to the success of brazing in atmospheric conditions. In this study, a NOCOLOK $CsAlF_4$ flux (manufactured by Solvay Fluor GmbH, Germany) with a low melting temperature range is used.

2.3 Brazing Test Facilities

A batch type lab furnace is used for the brazing cycle tests on the brazing sheet coupons. A typical controlled atmosphere aluminum brazing cycle is applied on the sample coupons. Continuous nitrogen flow is provided as a protective atmosphere. The brazing temperature is around 605 °C.

The wetting tests are performed using a heating stage test facility. The stage is made of stainless steel. Inside the stage chamber, a mini-heating coil is embedded in a ceramic holder. The stage chamber is purged with high purity nitrogen gas to protect the sample surface from oxidation. A quartz glass window provides visual access through a microscope to the wetting and spreading behavior of the molten filler metal. A schematic of the heating stage chamber is presented in Fig.3. A thermocouple Tc measures the substrate bottom surface temperature.

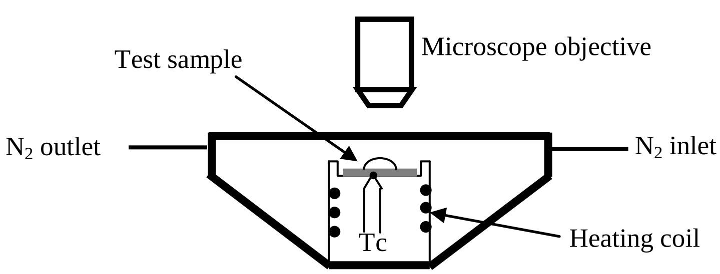


Figure 3 : A schematic of the heating stage test facility for the wetting test

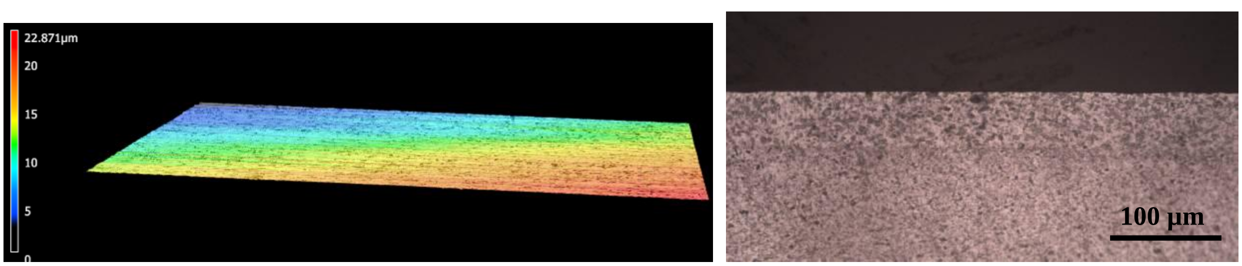
3. RESULTS AND DISSCUSSION

3.1 Influence of Brazing Cycle on the Surface Properties

Brazing sheet coupons (~70mm x 50mm x 0.5mm) were used for the brazing cycle tests. The material involved in this series of experiments is a double side cladded AA4045/AA3003/AA4045 brazing sheet. The first tested coupon sample was not fluxed, therefore, the oxide layer on the aluminum surface cannot be removed/disrupted during brazing. The second tested coupon sample was covered with the NOCOLOK flux (flux load around $10g/m^2$). The flux melts at a temperature slightly lower than the filler metal solidus melting temperature and effectively removes the oxide layer to assist the free flow of the liquid filler metal.

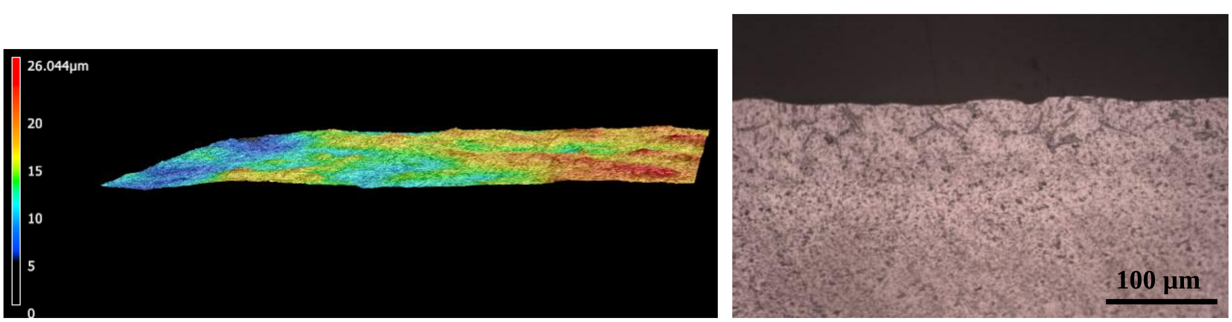
After the brazing cycle test, a series of analyses were performed on the coupon samples: 1) A randomly selected area (~0.5mm x 0.7mm) on the sample surface was scanned by a 3D laser scanning confocal microscope (Keyence Corp. of America) instrument for the surface profile analysis, and 2) Cross section samples were prepared by a standard metallurgical sample preparation process, i.e., cutting, mounting, grinding, and polishing. The cross section images were taken by an optical microscope. An “as-is” brazing sheet (no brazing cycle applied) is included in the analysis as the baseline.

Figures 4-6 illustrate the examples of both analyses results. In Fig. 4(a), it is clear that the “as is” brazing coupon has a relatively smooth surface. The cross section image in Fig. 4(b) shows the clad layer attached to the core alloy. Si alloying elements are uniformly distributed in the aluminum matrix. In Fig. 5(a), the coupon surface shows a slightly increased roughness. Such a surface change indicates that during the brazing cycle, even though the filler metal is restricted by the surface oxide layer (no flux applied on this sample), the surface morphology is still altered due to the phase change involved in the melting/solidification processes of the filler metal. The cross section image in Fig. 5(b) illustrates the apparent phase change of the clad layer after the brazing cycle. Finally, the sample that went through the brazing cycle with flux coverage shows a significant change on the surface morphology, as illustrated in Fig. 6(a). The surface of the brazing sheet becomes quite rough with peaks and valleys all around the surface. The cross section images at two different locations are presented in Fig. 6(b), which indicates that the roughness varies from location to location.



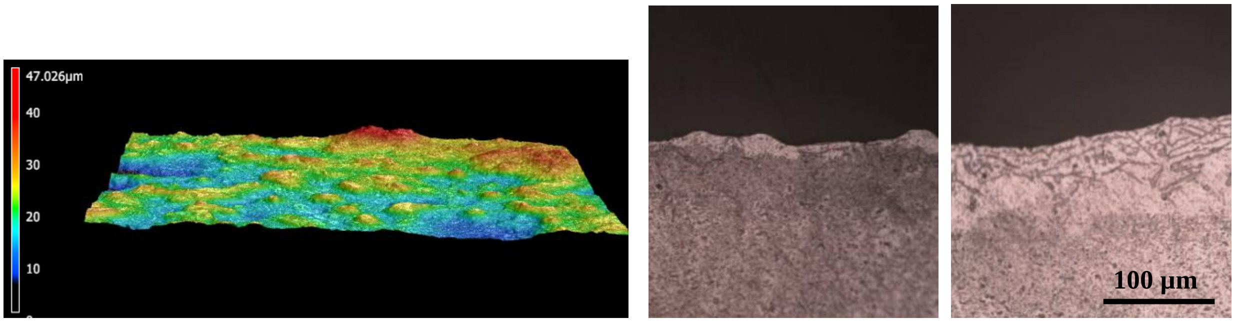
(a) (b)

Figure 4: Surface of the “as is” brazing sheet: (a) surface profile; (b) cross section image



(a) (b)

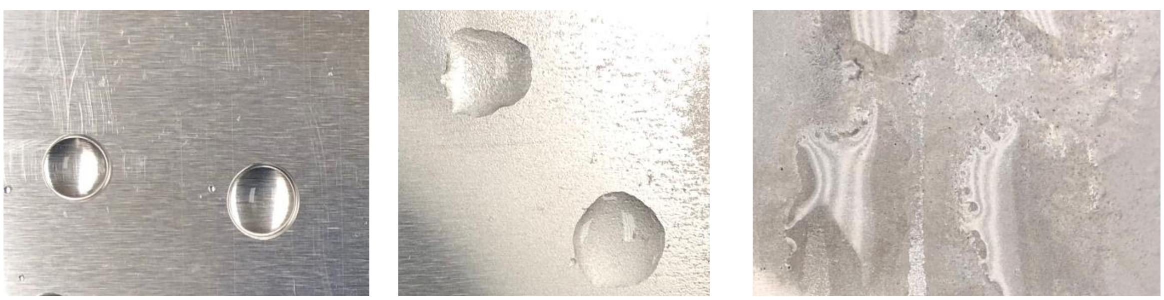
Figure 5: Surface of the brazing sheet (without flux) after heated to the brazing temperature: (a) surface profile; (b) cross section image



(a) (b)

Figure 6: Surface of the brazing sheet (with flux applied) after heated to the brazing temperature: (a) surface profile; (b) cross section images

The scanning and cross section microscopy images illustrate the changes of the surface morphology, as well the metallurgical phases, of the clad layer due to the brazing process. How would such changes affect the surface properties, such as the surface tension, remains unknown. A very simple and quick water droplet wetting test was performed on each of the coupon samples for a visual assessment. Small droplets of water were manually applied on the brazing sheet coupon samples using a pipette, assuming the volume of each droplet is similar by carefully applying minimal force on the pipette. Figure 7 shows the pictures of the droplets on the three surfaces. It appears that the water droplet has the largest wetting contact angle on the "as is" surface without any brazing cycle treatment (see Fig. 7(a)). On the second coupon sample, it appears that the heating to brazing temperature (without flux) does change the surface property. More extensive spreading but less circular triple line shape are observed, see Fig. 7(b), which indicate a smaller contact angle and a less homogenous surface structure. In the last example that uses the heated coupon with the flux coverage, as illustrated in Fig.7(c), the spreading of the water drop becomes much more extensive, and the triple line shape is irregular, indicating a highly wettable and non-homogenous surface.



(a) (b) (c)

Figure 7: Wetting behavior of the water droplet on the brazing sheet that is: (a) "as is" condition; (b) post-brazing condition, without flux; (c) post-brazing condition, with flux.

According to the Young equation, the contact angle of the liquid on a solid surface, θ, is determined:

$$\cos\theta = (\sigma_{SG} - \sigma_{LS})/\sigma_{LG} \qquad (1)$$

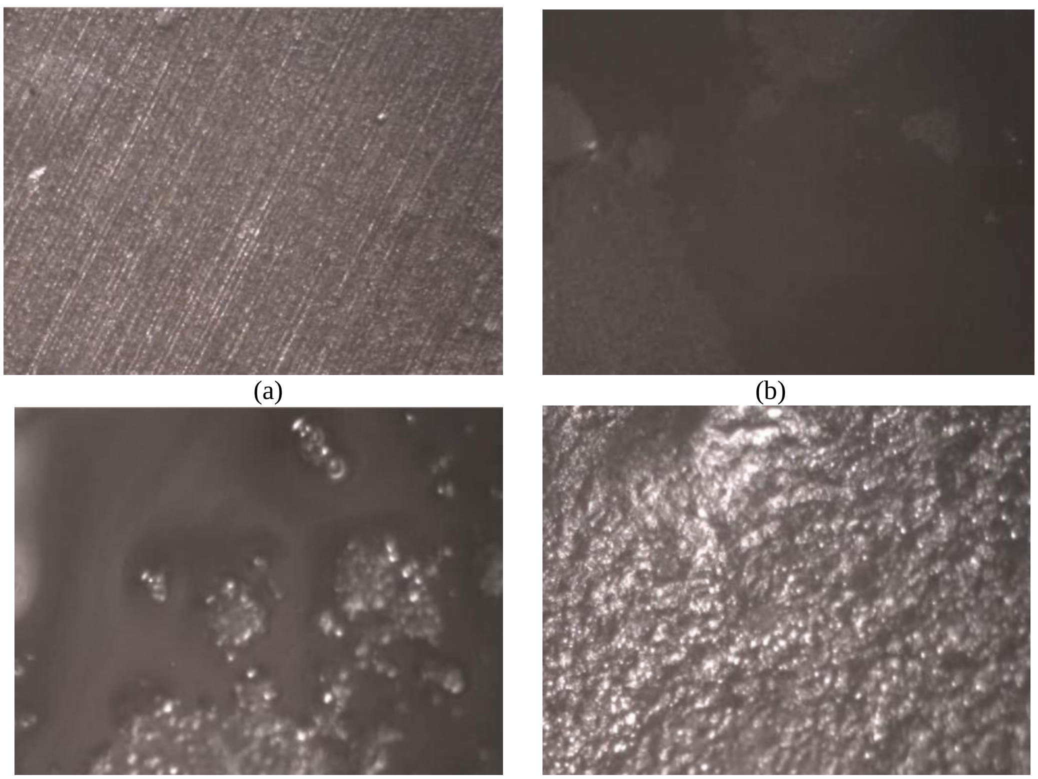
Where σ_{SG}, σ_{LS} and σ_{LG} are the surface tensions between solid/gas, liquid/solid and liquid/gas, respectively. As the surface tension between the water and the air σ_{LG} is unchanged, the difference between σ_{SG} and σ_{LS} has increased when the sample coupon was heated, and when heated with the flux coverage. The increase of the wettability of water may seem to be a direct consequence of the increased surface roughness. However, the other factors such as the clad material phase change as well as the influence of the flux coverage must be taken into consideration in future studies.

3.2 Filler Metal Wetting Test

The surface analysis in the previous section shows that surface properties change significantly after the brazing process. To utilize the low melting temperature Zn-Al filler metal for the heat exchanger repair, the brazing wetting test should be performed on a post-brazing cladded sheet. To generate a post-brazing substrate, a small piece of brazing sheet coupon (~5mm x 5mm x 1mm) was placed in the heating stage and went through a brazing cycle. A small amount of NOCLOK flux was applied to the coupon surface. The post-brazing coupon is then used for the next wetting test. As illustrated in Fig.3, the temperature readings recorded from the experiments are measured by the thermocouple (Tc) attached to the bottom of the substrate, which is directly exposed to the radiative heating from the heating element. Since the top surface of the substrate and the filler metal are mainly heated through conduction, the local temperature will be slightly lower than the bottom surface temperature.

3.2.1 Post-brazing Substrate

The coupon plate for the wetting test is the double side claded brazing sheet with AA4045 filler metal (~10% Si content) as the clad layer. During the brazing cycle, the surface change is monitored through a video camera attached to the microscope. Figure 8 illustrates a few images extracted from the video that shows the clad layer melting and re-solidification process. When the sample is heated to the temperature slightly above the flux melting point, the surface layer is still in the solid state, the directional rolling patterns on the “as-is” surface can be identified (see Fig. 8(a)). When the filler metal melts, the coupon surface is covered by the film of liquid filler metal, as illustrated in Fig. 8(b). During cooling, the liquid solidifies as presented in Fig. 8(c), and the post-brazing surface appears to have a very rough morphology (Fig. 8(d)).



(a) (b) (c) (d)

Figure 8: The change of surface appearance of a cladded sheet during a brazing cycle: (a) before clad melting; (b) molten filler metal surface; (c) onset of filler metal solidification; (d) rough surface after filler metal solidification.

3.2.2 Wetting Test of Zn-Al Filler Metal

The “post-brazing” cladded brazing sheet is then used as the substrate for the wetting test. A small disc of Zn15Al filler metal, approximately 1mm in diameter, 0.36mm in thickness, was placed on the substrate plate. A small amount of NOCOLOK $CsAlF_4$ flux is applied on the filler metal and the substrate. Two repeated tests were performed in the heating stage chamber under a nitrogen gas protected atmosphere. The peak Tc temperature is around 500 °C. Since the brazing cycle is performed at a relatively low temperature, no additional re-melting of the substrate surface layer will take place. The images from one of the tests representing the filler metal melting and wetting process are presented in Fig. 9. The dashed circle in Fig.8(a) illustrates the approximate diameter of the filler metal disc, which is covered by the flux powder before brazing. It was found that, upon melting, the molten filler metal forms a round ball (at the Tc temperature around 460 °C) which is an indication of non-wetting between the liquid filler metal and the substrate. However, as the heating temperature increases, the liquid filler metal starts to spread on the substrate surface, and eventually reaches a relatively large coverage area on the substrate upon cooling, see Figs 8(c) & (d). The temperature at which the liquid ball starts to wet the substrate varies from test to test, in a range of 480 °C to 495 °C. It has been illustrated in the previous section that the clad layer on the post brazing sheet has a non-uniformly distributed rough surface feature. Therefore, the wetting behavior of the filler metal may be affected by the local surface feature. A more comprehensive study on the correlation between post-brazing surface feature and the ZnAl filler metal wetting behavior will be included in the future work. .

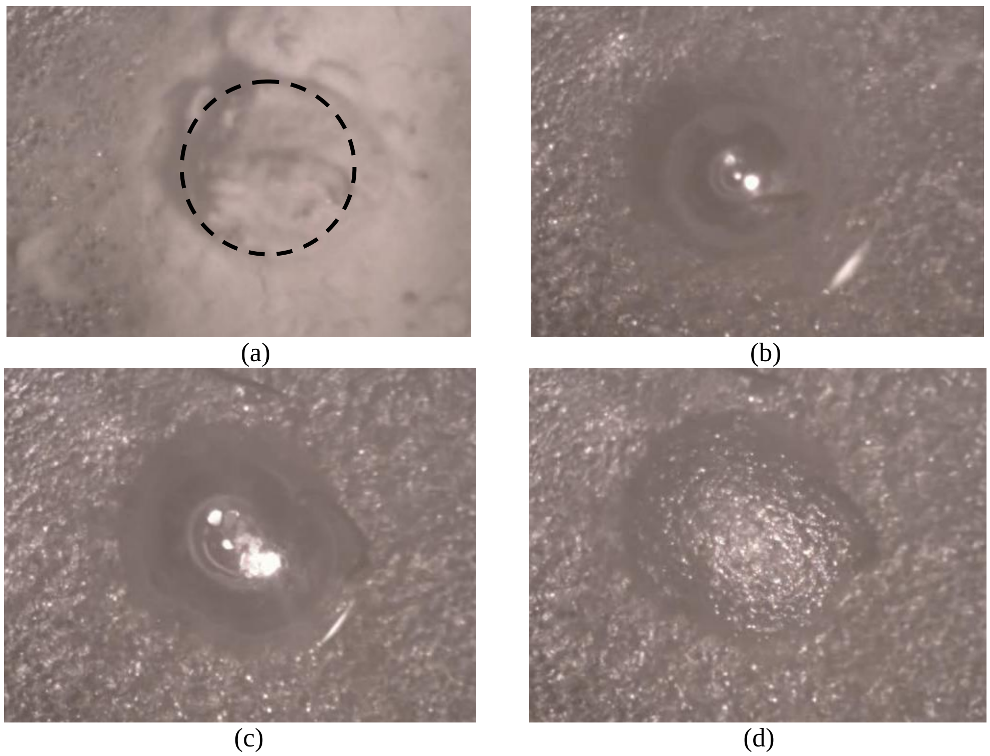
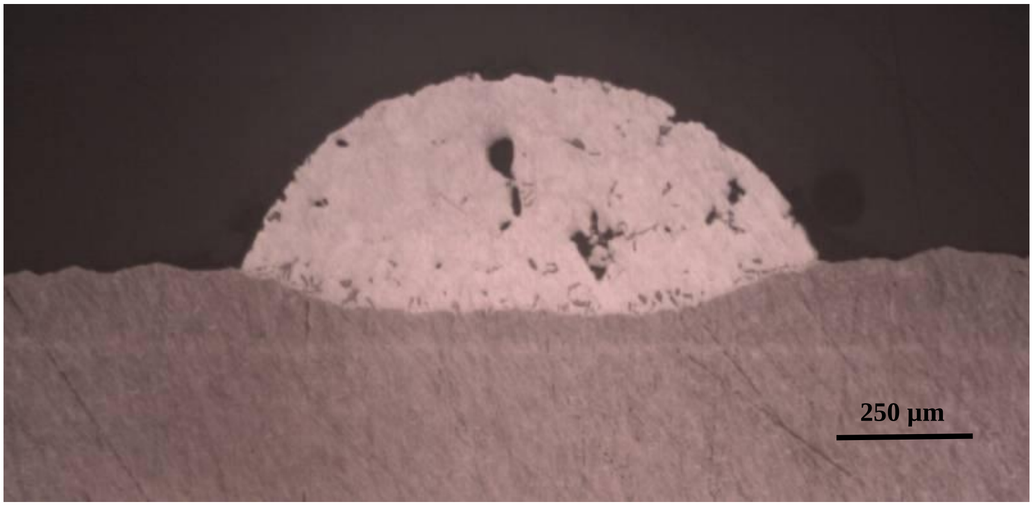
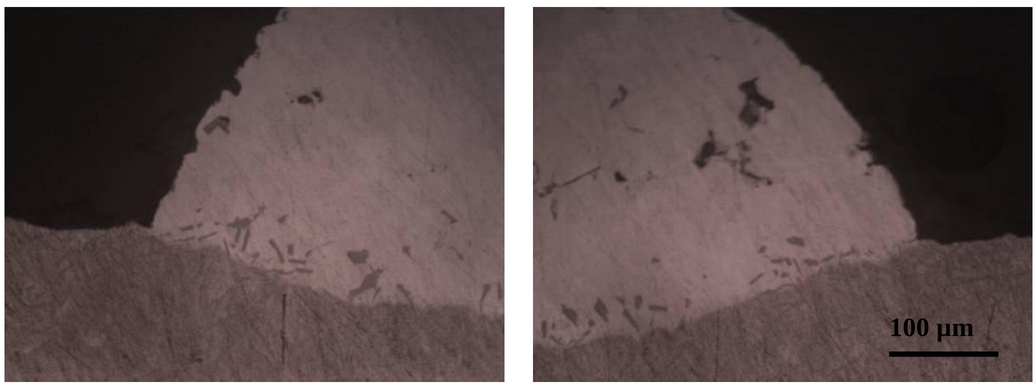


Figure 9: Wetting test of the Zn15Al on the post-brazing cladded sheet: (a) Filler metal before melting; (b) Filler metal melts and forms a ball; (c) liquid filler metal spreads on the substrate surface; (d) Re-solidified filler metal

After the wetting test, a metallurgical cross section sample is prepared to further analyze the wetting angle and the liquid/solid interface interaction. The optical microscope images are presented in Fig. 10. It is found that the contact angle between the filler metal and the substrate surface is smaller than 90 degrees; therefore, the Zn-15Al filler metal is wettable on the studied post-brazing sheet. However, certain level of substrate dissolution is identified in this example, see Fig. 10(a). It is apparent that the original clad layer has been partially dissolved by the filler metal. From Fig. 10 (b) (images are taken at a larger magnification), it seems that some Si flakes from the clad layer are concentrated at the filler metal and substrate interface. Therefore, the composition of the filler metal must have been changed with the inclusion of Al and Si alloying elements. The addition of these elements may change the filler material properties, such as the melting temperature and wetting behavior, as well as the brazed joint mechanical properties. Significant substrate dissolution and erosion should be avoided in brazing and re-brazing processes. However, the fact that the Zn-15Al filler metal is wettable on the post-brazing sheets indicates that it is possible to use this series of low temperature brazing filler metal in the application of repairing damaged aluminum heat exchangers.



(a)



(b)

Figure 10: Cross section of the sample after wetting test: (a) Small magnification image (b) larger magnification images show the filler metal/substrate interaction.

4. CONCLUSIONS

In this study, the material compatibility related to the changes of surface properties of the heat exchangers brazed with cladded brazing sheet is explored. A series of brazing tests were performed with the commonly used brazing sheets for manufacturing heat exchangers. It was demonstrated that the surface roughness of the cladded sheet increases after the brazing cycle, especially under the typical brazing conditions when the flux is applied to assist the oxide removal. The phase change of clad material may also lead to significant changes on the heat exchanger material surface properties. The wetting test of the Zn-15Alloy on a post-brazing cladded sheet shows an initial non-wetting behavior upon melting of the filler metal. It was found that the increased brazing temperature approaching 500 °C will effectively promote the wetting, as well as the interaction between the filler metal and the substrate. Apparent clad layer dissolution into the filler metal has been observed. The Zn-Al series filler metal may be a candidate for heat exchanger re-braze/repair applications owing to the relative low brazing temperature required. However, the control of the interaction between the liquid filler metal and the substrate at interface must be carefully considered.

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