Interfacial reaction behavior and mechanical properties of ultrasonically brazed Cu/Zn–Al/Cu joints

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Abstract
Ultrasound-assisted fluxless brazing of Cu/Zn–Al/Cu joint was performed in this study. Evolutions of the microstructure and mechanical properties of Cu alloy joints ultrasonically brazed with Zn–3Al and Zn–14Al filler metals were investigated. Results showed that excellent metallurgical bonding between the Zn–3Al filler metal and the Cu substrate could be obtained by brazing at 450 °C for 4 s, accompanied with the creation of thick CuZn 5 and CuZn n intermetallic compounds (IMCs) layers on the Zn–3Al/Cu interface. Compared with the Zn–3Al/Cu system, much longer ultrasonic vibration time was needed for the completely wetting of the Zn–14Al filler metal on the Cu substrate, but the thick CuZn 5 IMC layer was replaced with a thin Cu based diffusion layer on the Zn–14Al/Cu interface. The wetting of Zn–3Al filler metal on the Cu substrate was attributed to the combined effects of ultrasound-induced cavitation and Cu/Zn metallurgical reaction, while the wetting of Zn–14Al filler metal on the Cu substrate was mainly attributed to the ultrasound-induced cavitation effects. The shear strength of the Cu/Zn–3Al/Cu and Cu/Zn–14Al/Cu joint was 37.9 MPa and 92.1 MPa, respectively; the shearing failure took place within the Cu interfacial layer in all case.

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1. Introduction

Cu alloy joints with a relatively high service temperature are required in some power-device packages with step soldering treatment. For example, a die attachment is initially bonded to a lead frame with high-melting-temperature filler metals, and then the package is connected to a printed wiring board with low-melting-temperature solders. In previous studies, Pb–10Sn [1] and Au–20Sn [2] (mass%) solders with melting temperature of 310 °C and 280 °C, respectively, were used in the fabrication of Cu alloy joints serviced at high temperature. Although showing satisfactory properties such as suitable melting temperature (280–310 °C) and good fluidity and wettability, these solder alloys have some problems associated with high toxicity to the environment (Pb) or high cost (Au), which prevent their wide application.

Recently, Zn–Al based filler metals have been used to develop brazed Cu alloy joints with high service temperature [3–5]. Their advantages include moderate brazing temperature (the eutectic temperature of Zn–Al alloy is approximately 381 °C), low cost, superior corrosion resistance, and high thermal and electrical conductivities [6,7]. However, CuZn 5 IMC layers with thicknesses in the range of tens to hundreds of micrometers were found on the Zn–Al/Cu interface during brazing, owing to the greater reaction activity between Cu and Zn elements [4,8]. The brittle CuZn 5 IMC layer formed on the Cu substrate surface correlates closely to the reliability of Cu alloy joints. High residual stress was easy to accumulate on the thick CuZn 5 IMC layer, which could induce the nucleation of cracks and result in the failure of joint [4,9]. Therefore, decreasing the thickness or preventing the formation of CuZn 5 IMC layer on the Zn–Al/Cu interface is essential in improving the reliability of Cu/Zn–Al/Cu joint.

Significant studies have been done with the intent of adding alloy elements into Zn alloys to inhibit the growth of CuZn 5 IMC layer on the Zn alloy/Cu interface [10–13]. For instance, Mayappan et al. [12,13] found that adding Bi and Co elements in Sn–Zn filler metals could increase the activation energy for the growth of CuZn 5 phase, and thus inhibit the higher-growth of CuZn 5 IMC layer on the Sn–Zn/Cu interface. Ganczarz et al. [4] reported that the addition of 0.5 at.% Ag to Zn–12Al filler metal could effectively decrease the thickness of CuZn 5 IMC layer by lower the diffusion rate of Zn element in the Cu substrate. In our previous studies [14], during brazing Cu and Al dissimilar metals using a Zn–3Al filler metal, the CuZn 5 IMC layer was not found on the Zn–Al/Cu
interface. It seemed that an increased Al content in the Zn–3Al filler metal, which was caused by the dissolution of Al element away from the Al substrate into the filler metal layer, could inhibit the creation of Cu–Al IMC layer. Thus, it is needed to investigate the effect of Al content in Zn–Al filler metal on the interfacial reaction behavior of Cu/Zn–Al/Cu joint.

Furthermore, fluxes were always employed during brazing Cu alloys in previous studies [8,10]. This may increase the metallurgical reaction time of joint and result in the adequate growth of the Cu–Zn IMC layer on the Zn–Al/Cu interface. Moreover, the use of fluxes may induce the creation of reaction cavities, which can deteriorate the mechanical properties of joint [15].

Thus, fluxes may induce the creation of reaction cavities, which can deteriorate the mechanical properties of joint [15]. It has been largely reported that, high intensity ultrasonic waves inducted in liquid medium can generate cavitation effects, which can disrupt the oxide films on the metal substrate surface and enhance the wetting of liquid filler metal on the substrate [16–19]. Thus, with the assistance of ultrasonic waves, fluxes can be obviated during brazing.

In this study, we attempt to fabricate Cu alloy joints with an ultrasound-assisted fluxless brazing method using Zn–Al filler metals. The microstructure and mechanical properties of Cu/Zn–Al/Cu joints were analyzed. The effects of Al content in Zn–Al filler metal on the interfacial wetting behavior and metallurgical reaction behavior of Cu/Zn–Al/Cu joints were investigated. Such a study is expected to be helpful in developing high-reliability Cu alloy joints via manipulating the microstructure of the interfacial reaction layer.

2. Experimental procedures

T2 Cu alloy sheets with a dimension of $10 \times 10 \times 3$ mm$^3$ were used as the base metal. Zn–3Al hypoeutectic alloy and Zn–14Al hypereutectic alloy were used as filler metals. The SEM images of the Zn–3Al alloy and the Zn–14Al alloy are shown in Fig. 1. It can be seen that the Zn–3Al alloy is mainly composed of $\eta$-Zn dendrites with the Zn–Al eutectic phase interspersed between them, the Zn–14Al alloy is mainly composed of $\alpha$-Al phase and Zn–Al eutectic phase. The measured solidus temperature ($T_\text{s}$) and liquidus temperature ($T_\text{l}$) of the Zn–3Al alloy were 380.0 °C and 397.1 °C, and the Zn–14Al alloy were 379.6 °C and 444.6 °C, respectively. The Zn–3Al and Zn–14Al alloys were cold rolled to a thickness of approximately 400 μm and sliced to a dimension of $10 \times 10 \times 2$ mm$^3$. The element compositions of the Cu base metal and Zn–Al filler metals are shown in Table 1.

### Table 1
<table>
<thead>
<tr>
<th>Material</th>
<th>Composition (wt.%)</th>
</tr>
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<tr>
<td></td>
<td>Al</td>
</tr>
<tr>
<td>T2 Cu</td>
<td>–</td>
</tr>
<tr>
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</tr>
<tr>
<td>Zn–14Al</td>
<td>14.43</td>
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</table>

The schematic diagram of the ultrasound-assisted brazing process is shown in Fig. 2. The Cu substrates were fixed in an overlap configuration with a faying area of $10 \times 10$ mm$^2$, the Zn–Al filler metal slice was sandwiched as an interlayer between two Cu substrates. An ohmic heating device was used in this work, and the brazing temperature of joint was monitored by a K type thermocouple inserted in the brazing seam. During brazing, each joint was first heated to 400 °C, and then an ultrasonic vibration horn with a weight of approximately 0.5 kg was put on the upper Cu substrate surface. Subsequently, the joint was heated to 450 °C and held for approximately 10 s, after which the ultrasonic vibration with a frequency of 28.8 kHz and a power of 270 W was applied on the Cu substrate for 4 s, 10 s or 15 s. Ultimately, the joint was cooled in ambient to room temperature. Furthermore, a control sample of Cu/Zn–14Al/Cu joint was fabricated by ultrasonically brazed at 450 °C for 4 s with the same processing parameters above, and then held at 450 °C for 6 s.

### Fig. 1. SEM images of the reflowed (a) Zn–3Al and (b) Zn–14Al filler metals.
3. Results and discussion

3.1. Microstructure of joint

Fig. 4 shows the microstructure of Cu/Zn–3Al/Cu joint ultrasonically brazed at 450 °C for 4 s. A typical microstructure of the cross-section of the Cu/Zn–3Al/Cu joint is shown in Fig. 4a. A brazing seam between the two Cu substrates with a thickness of approximately 310 μm can be distinctly identified in the micrograph. The joint exhibits sound bonding without any cavities or cracks in the brazing seam. The magnified image of the filler metal layer is shown in Fig. 4b. According to the EDS analysis results shown in Table 2, it can be identified that the phase constitutions of the filler metal layer are almost similar to the starting Zn–3Al alloy, as shown in Fig. 1a, except small amounts of dissolved Cu in η-Zn phase (1.6 at.%) and Zn–Al eutectic phase (4.0 at.%). This demonstrates that the metallurgic reaction does not happen in the filler metal layer of Cu/Zn–3Al/Cu joint.

Fig. 4c and d shows the magnified images of the upper and lower Cu substrate interfaces in the Cu/Zn–3Al/Cu joint ultrasonically brazed for 4 s. It can be seen that on the either side of the brazing seam, continuous layers of reaction products are created on the Zn–3Al/Cu interfaces. According to the EDS point analysis results shown in Table 2 and previous studies [3], it can be identified that the flat reaction layers marked by “3” and “5” are composed of Cu₅Zn₈ phase with approximately 4.7–4.8 at.% Al dissolved; the scalloped reaction layers marked by “4” and “6” are composed of CuZn₅ phase with approximately 1.7–1.8 at.% Al dissolved. The tested thicknesses of the Cu₅Zn₈ IMC layers and the CuZn₅ IMC layers are in the range of 8.7–12.9 μm and 13.7–16.9 μm, respectively. The formation of such thick reaction products along the Zn–3Al/Cu interfaces indicates that sufficient liquid–solid interaction has occurred during brazing.

It should be noted that, the Cu₅Zn₈ IMC layer on the Cu substrate surface was found to be a Cu element diffusion barrier in previous studies [8]. Thus, the reason why the metallurgic reaction does not happen in the filler metal layer of Cu/Zn–3Al/Cu joint, as shown in Fig. 4b, can be attributed to the diffusion barrier effect of the thick Cu₅Zn₈ IMC layer on the Cu element. The creation of Cu
element in the filler metal layer, as shown in Table 2, may come from the stripped CuZn5 phase on the interfacial layer.

Fig. 5 shows the microstructure of the Cu/Zn–14Al/Cu joint ultrasonically brazed at 450 °C for 4 s. The typical cross-section image of the joint is shown in Fig. 5a. It can be seen that a brazing seam with a thickness of approximately 330 μm is presented in the image. Fig. 5b shows the magnified image of the filler metal layer. Compared with the starting Zn–14Al alloy, as shown in Fig. 1b, the microstructure of the filler metal layer in the Cu/Zn–14Al/Cu joint is of great difference. Serious metallurgic reaction has happened between the Zn–14Al filler metal layer and the Cu substrate. The EDS point analysis results at locations marked in Fig. 5 are shown in Table 3. According to the EDS analysis results and previous studies [14], it can be identified that the filler metal layer is mainly composed of block-like Al4.2Cu3.2Zn0.7 phase and dendritic CuZn5 phase with Al elements interspersed between them. The Zn–Al eutectic phase has disappeared in the filler metal layer. According to the Zn–Al–Cu ternary alloy phase diagram [20], it can be known that both the Al4.2Cu3.2Zn0.7 phase and CuZn5 phase can be formed in the Al–Cu–Zn ternary alloys at a reaction temperature of 450 °C. The formation of Al4.2Cu3.2Zn0.7 phase and CuZn5 phase in the filler metal layer of Cu/Zn–14Al/Cu joint can be attributed to the dissolution of Cu element away from the Cu substrate into the liquid Zn–14Al filler metal during the ultrasound-assisted brazing process.

Table 2
Element and phase constitutions of the regions marked in Fig. 4.

<table>
<thead>
<tr>
<th>Position</th>
<th>Element constitution (at.%)</th>
<th>Phase</th>
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<tbody>
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</tr>
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</tr>
<tr>
<td>2</td>
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<td>38.1</td>
</tr>
<tr>
<td>4</td>
<td>1.7</td>
<td>18.6</td>
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<tr>
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<td>4.8</td>
<td>40.4</td>
</tr>
<tr>
<td>6</td>
<td>1.8</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Fig. 5c shows the magnified image of the upper Cu substrate interface in the Cu/Zn–14Al/Cu joint ultrasonically brazed for 4 s. It can be seen that excellent metallurgic bonding between the Zn–14Al filler metal and the upper Cu substrate has formed, accompanied with the creation of a gray serrated reaction layer and a dark flat layer on the Zn–14Al/Cu interface. According to the EDS analysis results shown in Table 3 and previous literature [14], the serrated reaction layer is estimated to consist of CuZn5 phase with approximately 7.9 at.% Al dissolved, and the dark layer is considered to be a Cu based diffusion layer with approximately 23.9 at.% Al and 25.4 at.% Zn dissolved. The observed concentrations of Al and Zn elements in the Cu based diffusion layer are in agreement with Al and Zn solubility limits in Cu according to the Al–Cu–Zn ternary phase diagram [20]. The measured thickness of the CuZn5 IMC layer and the Cu based diffusion layer is 6.3 μm and 3.1 μm, respectively.

Fig. 5d shows the magnified image of the lower Cu substrate interface in the Cu/Zn–14Al/Cu joint ultrasonically brazed for 4 s. Interestingly, some corrosion pits are created on the Cu substrate surface. According to the EDS analysis results shown in Table 3, it can be found that the corrosion pit is filled with a continuous Cu based diffusion layer and a block-like CuZn5 IMC layer, which has the same phase constitutions with the upper Cu substrate interfacial layer. Furthermore, the EDS analysis result at the place marked by “9” demonstrates that, the Cu substrate surface located away from the corrosion pit is not wetted by the filler metal. This demonstrates that the metallurgic bonding between the filler metal layer and the lower Cu substrate is not continuous but is point-connected.

Fig. 6 shows the microstructure of the Cu/Zn–14Al/Cu joint obtained by ultrasonically brazed at 450 °C for 15 s. The cross-section microstructure of the joint is shown in Fig. 6a. It can be seen that the brazing seam is continuous and no defects, such as pores or cracks, are found in the filler metal layer. The Cu substrate surface is uneven due to the dissolution of Cu element into the filler metal layer during brazing, and the thickness of the brazing seam is increased to approximately 360 μm. The magnified image of the filler metal layer is shown in Fig. 6b. It can be seen that the...
filler metal layer is mainly composed of block-like CuZn$_5$ and Al$_{4.2}$Cu$_{3.2}$Zn$_{0.7}$ particles and tiny CuZn$_5$ dendrites, which has the same phase constitutions with the filler metal layer of Cu/Zn–14Al/Cu joint ultrasonically brazed for 4 s. The magnified images of the lower and upper Cu substrate interfaces are shown in Fig. 6c and d, respectively. It can be seen that with the increase of the ultrasonic vibration time, both the lower and upper Cu substrates are wetted completely by the Zn–14Al filler metal. Excellent metallurgic bonding has been formed between the Zn–14Al filler metal and the two Cu substrates, accompanied with the creation of CuZn$_5$ IMC layer and Cu based diffusion layer on the Zn–14Al/Cu interface. Some white blocks are interspersed in the diffusion layer, which can be surmised to be Cu$_{5}$Zn$_8$ phase according to previous studies [4]. The tested thicknesses of CuZn$_5$ IMC layers and Cu based diffusion layers are in the range of 5.1–8.6 $\mu$m and 3.5–5.4 $\mu$m, respectively. Obviously, the thickness of the Cu interfacial layer in the Cu/Zn–14Al/Cu joint is much smaller than that in the Cu/Zn–3Al/Cu.

### 3.2. Interfacial wetting mechanism of joint

The results above demonstrate that fluxless brazed Cu/Zn–Al/Cu joints can be fabricated successfully with an ultrasound-assisted brazing method. Previous studies [21,22] have demonstrated that, high intensity ultrasonic waves inducted into liquid medium can create cavitation effects, which is the formation, growth, and rapid collapse of micro-bubbles. The ultrasound-induced bubbles tend to create on the liquid/solid interface, owing to the defects or gaps located on the liquid/solid interface can act as active sites of bubble nucleation [22,23]. The rapid implosion of bubbles near the solid/liquid surface may lead to the emission of microjets and shockwaves, resulting in localized extreme conditions on the solid surface in terms of high temperature and high pressure estimated to be approximately 5000 K and 0.1 GPa [17,24]. Thus, the combined effects of microjets and shockwaves on the solid surface can enhance the interfacial wetting and cause the erosion of base metal during the ultrasound-assisted brazing process [14,25]. Obviously, the interfacial wetting of Zn–Al filler metals on the Cu substrate surfaces in the fluxless brazed Cu/Zn–3Al/Cu and Cu/Zn–14Al/Cu joints is associated with the ultrasound-induced cavitation effects. Furthermore, according to previous studies [18], it can be surmised that corrosion pits formed on the Cu substrate surface shown in Fig. 5d are caused by cavitation-induced erosion effects.

Interestingly, the wetting behaviors between the Zn–3Al/Cu and Zn–14Al/Cu interfaces during brazing are of great difference. In the Cu/Zn–3Al/Cu joint ultrasonically brazed for 4 s, as shown in Fig. 4, excellent metallurgic bonding is formed between the Zn–3Al filler metal and the two Cu substrates. However, in the Cu/Zn–14Al/Cu joint ultrasonically brazed for 4 s, as shown in Fig. 5, only the upper Cu substrate is wetted by the Zn–14Al filler metal completely. These indicate that the Al content in Zn–Al filler metal can affect the wetting behavior of Zn–Al/Cu interface during the ultrasound-assisted brazing process.

Previous studies [4,12] demonstrated that Zn and Cu elements had strong reaction activity. Zn element could react with Cu substrate severely and form CuZn$_5$ and Cu$_{5}$Zn$_8$ IMC layers on the Zn alloy/Cu substrate interface during the liquid-state brazing process or the solid-state aging treatment. The growth of the CuZn$_5$ IMC layer is mainly controlled by ripening during the liquid-state reaction process, while the growth of the Cu$_{5}$Zn$_8$ IMC layer is mainly controlled by the volume diffusion of Zn element [3,9]. For the present reaction system, during brazing Cu/Zn–3Al/Cu joint with

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Table 3

<table>
<thead>
<tr>
<th>Position</th>
<th>Element constitution (at.%)</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51.7 38.3 10.0</td>
<td>Al$<em>{4.2}$Cu$</em>{3.2}$Zn$_{0.7}$</td>
</tr>
<tr>
<td>2</td>
<td>2.4 15.7 81.9</td>
<td>CuZn$_5$</td>
</tr>
<tr>
<td>3</td>
<td>23.9 50.7 25.4</td>
<td>Diffusion layer</td>
</tr>
<tr>
<td>4</td>
<td>7.9 24.1 68.1</td>
<td>CuZn$_5$</td>
</tr>
<tr>
<td>5</td>
<td>53.9 37.3 8.8</td>
<td>Al$<em>{4.2}$Cu$</em>{3.2}$Zn$_{0.7}$</td>
</tr>
<tr>
<td>6</td>
<td>23.8 49.1 27.1</td>
<td>Diffusion layer</td>
</tr>
<tr>
<td>7</td>
<td>8.2 25.6 66.2</td>
<td>CuZn$_5$</td>
</tr>
<tr>
<td>8</td>
<td>52.0 38.6 9.4</td>
<td>Al$<em>{4.2}$Cu$</em>{3.2}$Zn$_{0.7}$</td>
</tr>
<tr>
<td>9</td>
<td>0.3 99.0 0.7</td>
<td>Cu</td>
</tr>
</tbody>
</table>

Fig. 6. SEM images of (a) the cross-section, (b) the filler metal layer, (c) the upper Cu substrate interface, and (d) the lower Cu substrate interface of Cu/Zn–14Al/Cu joint ultrasonically brazed at 450 °C for 15 s.
the assistance of ultrasound, the cavitation-induced microjets and shockwaves can break the oxide film located on the Cu substrate surface and form some gaps on it. With the help of pulse hot point caused by cavitation effects [17], Cu atoms in these gaps will dissolve quickly from the Cu substrate into the Zn–3Al filler metal and react with Zn atoms, leading to the formation of CuZn$_5$ IMC layer on the Cu substrate surface. As the activation energy for the growth of CuZn$_5$ phase is lower than that of CuZn$_3$ phase [3], Zn atoms in the liquid Zn–3Al filler metal will diffuse into the Cu substrate through the CuZn$_5$ grain boundary and result in the formation of CuZn$_5$ IMC layer. Subsequently, the CuZn$_5$ IMC layer can grow rapidly in the cavitation-induced gaps, owing to the high diffusion rate of Zn element in the CuZn$_5$ phase and the low formation energy of CuZn$_5$ phase [4]. Undoubtedly, the full growth of the CuZn$_5$ IMC layer in the Cu substrate can further break the oxide films on the Cu substrate surface located around the cavitation-induced gaps, and thus enhance the wetting of Zn–3Al filler metal on these places. Ultimately, the Cu substrate can be wetted quickly by the Zn–3Al filler metal during the ultrasound-assisted brazing process. Therefore, it can be concluded that the wetting of Zn–3Al filler metal on the Cu substrate surface in the ultrasonically brazed Cu/Zn–3Al/Cu joint is attributed to the combined effects of ultrasound-induced cavitation and CuZn$_5$ metallurgic reaction.

Actually, the diffusion rate of Al element in Cu substrate is a little higher than that of Zn element in Cu substrate. According to the Arrhenius-type equation, the calculated diffusion rates of Al and Zn elements in the Cu substrate at 450 °C are $5.3 \times 10^{-14}$ cm$^2$/s and $3.9 \times 10^{-14}$ cm$^2$/s, respectively. Furthermore, the reaction activity between Al and Cu elements is strong [9]. For example, the activation energy of Al$_2$Cu$_7$ phase is lower than that of Cu$_5$Zn$_8$ phase at 450 °C [9]. However, Al–Cu reaction products cannot be found in the Cu/Zn–3Al/Cu joint. This may be interpreted by the way that, when the Al content in the Zn–Al filler metal is low, the Al element is mainly dissolved in the thick Cu$_5$Zn$_8$ IMC layer (the Al content in the Cu$_5$Zn$_8$ phase is approximately 4.8 at.% according to the EDS analysis results shown in Table 2).

As to the Cu alloy joint ultrasonically brazed with Zn–14Al filler metal, an increased Al content in Zn–Al filler metal results in the creation of the thin Cu based diffusion layer on the Cu substrate surface, accompanied with the disappearance of the thick Cu$_5$Zn$_8$ IMC layer. This can be ascribed to two facts. On the one hand, as the diffusion rate of Al element is higher than that of Zn element in the Cu substrate, the Al element will diffuse into the Cu substrate firstly and occupy some Cu lattice vacancies. This may decrease the diffusion rate and the solubility of Zn element in the Cu substrate, and thus inhibit the creation of Cu$_5$Zn$_8$ IMC layer in the Cu substrate. On the other hand, the dissolved Zn element in the Cu substrate can restrain the diffusion of Al element and the formation of Al–Cu IMCs in the Cu substrate. As a result, a thin Cu based diffusion layer with a thickness range of 3.5–5.4 μm, as shown in Fig. 6c and d, is formed on the Zn–14Al/Cu interface due to the mutual restraints of Al and Zn elements in the Cu substrate. Obviously, compared with the Cu$_5$Zn$_8$ IMC layer formed on the Zn–3Al/Cu interface, the growth-limited Cu based diffusion layer formed on the Zn–14Al/Cu interface is less beneficial to the interfacial wetting behavior of joint. In order to make clear the main driven force for the wetting of Zn–14Al filler metal on the Cu substrate surface during the ultrasound-assisted brazing process, a control experiment was performed.

Fig. 7 shows the microstructure of Cu/Zn–14Al/Cu joint ultrasonically brazed at 450 °C for 4 s then held for 6 s and Cu/Zn–14Al/Cu joint ultrasonically brazed at 450 °C for 10 s. The magnified image of the lower Cu substrate interface in Cu/Zn–14Al/Cu joint ultrasonically brazed for 4 s then held for 6 s is shown in Fig. 7a. It can be seen that, compared with lower Cu substrate interface in the Cu/Zn–14Al/Cu joint ultrasonically brazed for 4 s (as shown in Fig. 5d), an isothermal reaction at 450 °C for 6 s without the assistance of ultrasonic vibration has little effects to the wetting area of the Zn–14Al/Cu interface. This result is consistent with the conclusion above that, the wetting of Zn–14Al filler metal on the Cu substrate surface may be inhibited by the Cu based diffusion layer. Fig. 7b shows the magnified image of the lower Cu substrate interface in Cu/Zn–14Al/Cu joint ultrasonically brazed for 10 s. It can be seen that increasing the ultrasonic vibration time from 4 s to 10 s increases the number of corrosion pits formed on the lower Cu substrate surface, and thus increases the wetting area of Zn–14Al/Cu interface. This demonstrates that the wetting of Zn–14Al filler metal on the Cu substrate surface correlates closely to the ultrasonic vibration. It has been noted above that, the corrosion pits formed on the Cu substrate surface are caused by the cavitation-induced erosion effects. Therefore, it can be concluded that the wetting of Zn–14Al filler metal on the Cu substrate is mainly attributed to the ultrasound-induced cavitation effects during the ultrasound-assisted brazing process.

3.3. Shear strength of joint

It is known that the reaction layers on the filler metal/Cu interface are always the sources for stress concentration and cracks [4,26]. Thus, the changes in the Cu interfacial layer microstructure will surely have an influence on the mechanical properties of Cu/Zn–Al/Cu joints. The shear test results showed that, the strength of the Cu/Zn–3Al/Cu joint ultrasonically brazed for 4 s is 37.9 MPa, while the Cu/Zn–14Al/Cu joint ultrasonically brazed for 15 s is 92.1 MPa. Fig. 8a shows the SEM image of the Cu fracture surface for Cu/Zn–3Al/Cu joint ultrasonically brazed for 4 s. It can be seen that the joint exhibits a typical intergranular fracture type. The XRD pattern of this fracture surface is shown in Fig. 8a. No additional peaks of other phases are found except the Cu$_5$Zn$_8$ phase.
peaks from the measurement. This convincingly suggests that the Cu/Zn–3Al/Cu joint is shear failed in the Cu interfacial layer. It can be inferred that the thick Cu$_5$Zn$_8$ and CuZn$_5$ IMC layers induce the embrittlement in coalescence of faying surfaces when the joint is under shearing load, which results in a low shear strength of the Cu/Zn–3Al/Cu joint. Fig. 8b shows the SEM image of the Cu fracture surface for Cu/Zn–14Al/Cu joint ultrasonically brazed for 15 s. It seems that the joint exhibits a ductile fracture mode, and some nicks are presented on the Cu fracture surface. The XRD pattern of this fracture surface is shown in Fig. 9b. Weak peaks of Cu$_5$Zn$_8$ phase, along with the peaks of Cu from the substrate, are indexed in the profile. These demonstrate that the residual composition on the Cu fracture surface is the Cu based diffusion layer. Thus, it can be inferred that the decreased thickness of the interfacial reaction layer on the Cu substrate surface is probably behind the increase in shear strength of Cu/Zn–14Al/Cu joint. Furthermore, the uneven Cu substrate surface in the Cu/Zn–14Al/Cu joint, which was caused by the ultrasound-induced corrosion effects, can inhibit the plastic deformation and crack propagation during shear testing, and thus further improve the shear strength of the joint.

4. Conclusions

Cu/Zn–3Al/Cu and Cu/Zn–14Al/Cu joints were fabricated with an ultrasound-assisted fluxless brazing method. Comparative studies on the interfacial reaction behaviors and mechanical properties of the joints were performed. Major conclusions were summarized as follows:

(1) In the joint brazed with Zn–3Al filler metal, the filler metal layer was composed of Zn–Al eutectic phase and η-Zn phase, the Cu interfacial layer was composed of a scalloped CuZn$_5$ IMC layer and a flat Cu$_5$Zn$_8$ IMC layer with a thickness range of 8.7–12.9 μm and 13.7–16.9 μm, respectively.

(2) In the joint brazed with Zn–14Al filler metal, the filler metal layer was composed of α-Al phase, CuZn$_5$ phase and Al$_{4.2}$Cu$_{3.2}$Zn$_{0.7}$ phase, the Cu interfacial layer was composed of a serrated CuZn$_5$ IMC layer and a Cu based diffusion layer with a thickness range of 5.1–8.6 μm and 3.5–5.4 μm, respectively.

(3) Much longer ultrasonic vibration time was needed for the Zn–14Al filler metal than the Zn–3Al filler metal to completely wet the Cu substrate surface during brazing. The wetting of Zn–14Al filler metal on the Cu substrate was mainly attributed to the ultrasound-induced cavitation effects, while the wetting of Zn–3Al filler metal on the Cu substrate was attributed to the combined effects of ultrasound-induced cavitation and Cu/Zn metallurgic reaction.

(4) Shear strength test results showed that, all the joints were failed in the Cu interfacial layer, the strength of the well-bonded Cu/Zn–3Al/Cu joint and Cu/Zn–14Al/Cu joint was 37.7 MPa and 92.1 MPa, respectively.

Acknowledgments

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