Effect of Zn-Al Brazing Filler Composition on the Interfacial Structure and Properties of Cu/Zn-Al/Al Brazed Joints Postprint

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Abstract

Cu/Al joints were fabricated by brazing with Zn-15Al, Zn-22Al, Zn-28Al, Zn-37Al, and Zn-45Al filler metals, respectively. The influence of Zn-Al filler metal composition on the Cu base metal/brazing seam interface structure in Cu/Al joints was investigated using SEM, EDS, and XRD, and the relationship among Zn-Al filler metal composition, joint interface structure, and joint shear strength was systematically elucidated. The results revealed that the Cu base metal/brazing seam interface structure in the Cu/Zn-15Al/Al joint consisted of Cu/Al4.2Cu3.2Zn0.7, with the Al4.2Cu3.2Zn0.7 interfacial layer being relatively thin at 2–3 m, and the joint exhibited a high shear strength of 66.3 MPa. As the Al content in the filler metal increased, the thickness of the Al4.2Cu3.2Zn0.7 interfacial layer at the Cu/Zn-22Al/Al joint interface gradually increased, and even trace amounts of CuAl2 appeared near the Al4.2Cu3.2Zn0.7 interfacial layer in the Cu/Zn-28Al/Al joint, while the joint shear strength progressively decreased. When brazing Cu/Al joints with the higher Al-content Zn-37Al filler metal, the Cu base metal/brazing seam interface structure transformed to Cu/Al4.2Cu3.2Zn0.7/CuAl2; the formation of the brittle CuAl2 layer caused a substantial reduction in joint shear strength to 34.5 MPa. When brazing Cu/Al joints with the highest Al-content Zn-45Al filler metal, the Cu base metal/brazing seam interface structure transformed to Cu/CuAl2, and the joint shear strength was the lowest, at 31.6 MPa.

Full Text

Influence of Zn-Al Filler Metal Composition on Interfacial Structure and Properties of Cu/Zn-Al/Al Brazed Joints

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Abstract

Cu/Al dissimilar metal joints are composite structures that can effectively reduce manufacturing costs and product weight while integrating the advantages of both metals. Due to their excellent comprehensive properties, Cu/Al dissimilar metal joints have broad application prospects in air conditioners, refrigerators, cables, electronic components, solar collectors, and other fields. Brazing is considered a promising method for joining Cu/Al dissimilar metals because of its lower residual stress, lower cost, higher precision, and better adaptability to joint structures. Meanwhile, Zn-Al filler metals are regarded as relatively ideal filler materials due to the superior properties of Cu/Zn-Al/Al joints. However, the influence of Zn-Al filler metal composition on the interfacial structure near the Cu substrate and the properties of Cu/Al joints has not been investigated.

In this work, Cu/Al joints were brazed using Zn-15Al, Zn-22Al, Zn-28Al, Zn-37Al, and Zn-45Al filler metals, respectively. The effects of Zn-Al filler metal composition on the interfacial structure near the Cu substrate in Cu/Al joints were investigated using SEM, EDS, and XRD, and the relationships between Zn-Al filler metal composition, interfacial structure, and joint shear strength were systematically elucidated.

The study revealed that the interfacial structure of the Cu/Zn-15Al/Al brazed joint was Cu/$Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$, with a thin $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ interfacial layer measuring 2–3 m, resulting in a high shear strength of 66.3 MPa. As the Al content in the filler metal increased, the thickness of the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ interfacial layer at the Cu/Zn-22Al/Al joint interface gradually increased, and even a small amount of $CuAl_2$ appeared near the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ interfacial layer in the Cu/Zn-28Al/Al joint, leading to a gradual decrease in shear strength.

When using the higher Al-content Zn-37Al filler metal, the Cu substrate/filler interface structure transformed to Cu/$Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$/$CuAl_2$; the appearance of the brittle $CuAl_2$ layer caused a significant drop in shear strength to 34.5 MPa. With the highest Al-content Zn-45Al filler metal, the interface structure changed to Cu/$CuAl_2$, yielding the lowest shear strength of 31.6 MPa.

Keywords: Cu/Al joint, brazing, interfacial structure, intermetallic compound, shear strength

Experimental Methods

The interfacial structure and fracture morphology of the brazed Cu/Al joints were examined using a Quanta 250 scanning electron microscope (SEM). The phase composition in the interfacial zones of the Cu/Al joints was analyzed using a STOE/STADI P (CuKα) X-ray diffractometer (XRD). Prior to XRD analysis, the Al substrate side of the Cu/Al joint was removed, and the remaining portion was ground down to near the Cu substrate/filler interface to prepare the XRD sample.

Results and Discussion

2.2 Influence of Zn-Al Filler Metal Composition on Shear Strength of Cu/Al Brazed Joints Variations in Zn-Al filler metal composition significantly affect both the type and thickness of intermetallic compound layers at the Cu/Zn-Al/Al brazed joint interface. This transformation in interfacial structure inevitably exerts a pronounced influence on the mechanical properties of Cu/Al joints. Figure 4 [Figure 4: see original paper] presents the shear strengths of Cu/Al joints brazed with the five different Zn-Al filler metals.

The results demonstrate that, under the experimental conditions of this study, the shear strength of Cu/Zn-Al/Al brazed joints gradually decreases with increasing Al content in the filler metal. The Cu/Zn-15Al/Al joint exhibits a high shear strength of 66.3 MPa. The Cu/Zn-22Al/Al joint follows with a strength of 59.8 MPa, while the Cu/Zn-28Al/Al joint shows a lower strength of 50.9 MPa. Notably, all three joints achieve shear strengths exceeding 50 MPa, which corresponds to more than 72.5% of the Al substrate strength. However, when using higher Al-content Zn-37Al and Zn-45Al filler metals, the shear strengths drop dramatically to 34.5 MPa and 31.6 MPa, respectively—substantially lower than those of the Cu/Zn-15Al/Al, Cu/Zn-22Al/Al, and Cu/Zn-28Al/Al joints.

3. Analysis and Discussion Changes in Zn-Al filler metal composition distinctly alter the interfacial structure at the Cu substrate/filler interface in Cu/Zn-Al/Al joints. As the Al content in the filler metal increases, the interface structure gradually transitions from Cu/$Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$ to Cu/$CuAl_2$.

This transformation arises from the sequential precipitation and interaction of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ and $CuAl_2$ at the interface.

Generally, to reduce nucleation difficulty, intermetallic compounds tend to precipitate at existing interfaces, such as the Cu substrate surface in this study. According to literature [10, 12, 24–26], $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ is more likely to precipitate on the Cu substrate surface than Al-Cu compounds (such as $CuAl_2$, CuAl, and Cu_9Al_4) due to its lower formation energy—a conclusion that this study reaffirms. When brazing Cu/Al joints with the lowest Al-content Zn-15Al filler metal, $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ precipitates first on the Cu substrate surface and grows perpendicular to the interface into the filler, forming a continuous intermetallic layer with fine protrusions (Figure 2a). At this stage, the Cu/Zn-15Al/Al joint interface forms a $Cu/Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ structure.

When using Zn-22Al filler metal, the relative Al content in the liquid filler increases, intensifying $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ precipitation on the Cu substrate surface [12] and thickening the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer. Simultaneously, another compound—$CuAl_2$—begins to precipitate in the filler near the Cu substrate/filler interface (Figure 2b). In the Cu/Zn-28Al/Al joint, $CuAl_2$ precipitation is enhanced, with small amounts even appearing on the surface of the interfacial $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer (Figure 2c). Although the interfaces of Cu/Zn-22Al/Al and Cu/Zn-28Al/Al joints remain primarily composed of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$, the emergence of $CuAl_2$ gradually initiates changes in the interfacial structure.

This transition becomes particularly evident when brazing Cu/Al joints with Zn-37Al and Zn-45Al filler metals. At the Cu substrate/filler interface of the Cu/Zn-37Al/Al joint, abundant $CuAl_2$ precipitates directly on the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer, forming a connected compound layer and transforming the interface structure to $Cu/Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}/CuAl_2$. Moreover, the substantial presence of $CuAl_2$ suppresses $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ precipitation, even causing fracture of large $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ protrusions and hindering their growth into the filler (Figure 2d).

In the Cu/Zn-45Al/Al joint, the further increased relative Al content in the filler promotes additional $CuAl_2$ precipitation near the interface, which further suppresses the nucleation and growth of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ on the Cu substrate surface. The $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer becomes thinner and cannot form a continuous layered distribution. In some interfacial regions, $CuAl_2$ begins to connect directly with the Cu substrate, ultimately transforming the interface structure to $Cu/CuAl_2$ (Figure 2e).

Thus, increasing Al content in Zn-Al filler metals promotes $CuAl_2$ precipitation at the Cu substrate/filler interface, while the precipitated $CuAl_2$ inhibits the nucleation and growth of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ on the Cu substrate surface, thereby inducing the interfacial structure evolution from $Cu/Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7} \rightarrow Cu/Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}/CuAl_2 \rightarrow Cu/CuAl_2$.

The transformation from a fine $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer to a thick, coarse $CuAl_2$ layer at the Cu/Al joint interface inevitably deteriorates the joint shear strength

[27,28]. The influence of interfacial structure on shear strength is directly reflected in the fracture morphology. Figure 5 [Figure 5: see original paper] shows the fracture surfaces on the Cu substrate side of Cu/Al joints brazed with the five Zn-Al filler metals. All joints fractured at the Cu substrate/filler interface.

The fracture morphology of the Cu/Zn-15Al/Al joint (Figure 5a) consists of fine dimples (J) and cleavage planes (K) resulting from brittle fracture. EDS analysis indicates that the dimple region J contains 53.9Al-36.92Cu-9.18Zn (at%), which, combined with the intermetallic compound analysis in Section 2.1, identifies these dimples as intergranular fracture of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$. The cleavage plane K contains 46.27Al-44.64Cu-9.1Zn, corresponding to transgranular fracture at the root of the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer. The thin (2–3 m) $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ interfacial layer with fine protrusions requires greater energy for crack propagation, which is the primary reason for the observed ductile intergranular fracture and the high shear strength of the Cu/Zn-15Al/Al joint.

For the Cu/Zn-22Al/Al joint (Figure 5b), the increased thickness of the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer (5–6 m) results in significantly fewer dimples and larger brittle cleavage planes compared to the Cu/Zn-15Al/Al joint, leading to reduced shear strength. The Cu/Zn-28Al/Al joint fracture morphology (Figure 5c) shows a further increase in cleavage area due to the thicker $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer and the presence of small amounts of brittle $CuAl_2$ at the interface, which decreases the energy required for crack propagation and makes the joint more susceptible to brittle fracture, further reducing its strength.

The fracture morphology of the Cu/Zn-37Al/Al joint (Figure 5d) exhibits, in addition to cleavage planes (L) from brittle fracture of the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer, a new cleavage plane (M). EDS analysis shows that region M contains 63.91Al-32.78Cu-3.31Zn, identifying it as fractured $CuAl_2$. Since the interfacial structure of the Cu/Zn-37Al/Al joint has transformed to $Cu/Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}/CuAl_2$, the extremely brittle $CuAl_2$ facilitates crack initiation and propagation [13,14], causing a substantial decrease in shear strength compared to joints brazed with Zn-15Al, Zn-22Al, and Zn-28Al filler metals.

The Cu/Zn-45Al/Al joint fracture morphology (Figure 5e) shows a completely brittle cleavage fracture. EDS analysis of cleavage plane (N) reveals a composition of 65.70Al-31.17Cu-3.13Zn, confirming it as $CuAl_2$. The thick, coarse $CuAl_2$ layer at the Cu substrate/filler interface serves as a crack source, further degrading the joint' s mechanical properties.

Based on the results regarding interfacial structure, mechanical properties, and fracture morphology of Cu/Zn-Al/Al joints, Zn-Al filler metal composition significantly influences both the Cu substrate/filler interfacial structure and the joint shear performance. When the Al content in the filler metal is 15%–28%, the Cu/Zn-Al/Al joint interface structure is $Cu/Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$, and the relatively thin $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer is beneficial for shear strength. At 37% Al content, the interfacial structure becomes $Cu/Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}/CuAl_2$, and the appearance of the thick, brittle $CuAl_2$ layer causes a sharp decline in shear strength. When Al content further increases to 45%, the interface structure transforms to Cu/$CuAl_2$, resulting in the poorest shear performance. Therefore, when selecting Zn-Al filler metals for brazing Cu/Al joints, the Al content should not exceed 28%.

Conclusions

1. When the Al content in Zn-Al filler metal is 15%-28%, the Cu/Zn-Al/Al joint interface structure is Cu/$Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$. At 37% Al content, the interface structure transforms to Cu/$Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$/$CuAl_2$. When Al content further increases to 45%, the interface structure becomes Cu/$CuAl_2$. This evolution is caused by the sequential precipitation and interaction of $Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$ and $CuAl_2$ at the interface.
2. The Cu/Zn-15Al/Al joint, with its thin (2-3 m) $Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$ interfacial layer, exhibits high shear strength of 66.3 MPa. When brazing Cu/Al joints with Zn-37Al filler metal, the interface structure changes to Cu/$Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$/$CuAl_2$, and the appearance of the thick, brittle $CuAl_2$ layer causes a significant drop in shear strength to 34.5 MPa. The Cu/Zn-45Al/Al joint, with its Cu/$CuAl_2$ interface structure, shows the lowest shear strength of only 31.6 MPa.
3. The Cu substrate/filler interfacial structure is the primary factor affecting the mechanical properties of Cu/Al brazed joints. Once a continuous $CuAl_2$ layer forms at the Cu substrate/filler interface, the joint strength drops sharply. Therefore, when selecting Zn-Al filler metals for brazing Cu/Al joints, the Al content should not exceed 28%.

Note: Figure translations are in progress. See original paper for figures.

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