Effect of Zn-Al Brazing Filler Composition on 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 interface structure between Cu base metal and brazing seam in Cu/Al joints was investigated using SEM, EDS, and XRD, and the correlation among Zn-Al filler metal composition, joint interface structure, and joint shear strength was systematically elucidated. The results revealed that the interface structure between Cu base metal and brazing seam in Cu/Zn-15Al/Al joints consisted of Cu/Al4.2Cu3.2Zn0.7, with a relatively thin Al4.2Cu3.2Zn0.7 interfacial layer measuring 2–3 m in thickness, and the joint exhibited high shear strength of 66.3 MPa. With increasing Al content in the filler metal, the thickness of the Al4.2Cu3.2Zn0.7 interfacial layer at the interface of Cu/Zn-22Al/Al joints gradually increased, and trace amounts of CuAl2 even formed near the Al4.2Cu3.2Zn0.7 interfacial layer in Cu/Zn-28Al/Al joints, leading to a progressive decrease in joint shear strength. When brazing Cu/Al joints with Zn-37Al filler metal containing higher Al content, the interface structure between Cu base metal and brazing seam 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 Zn-45Al filler metal containing the highest Al content, the interface structure between Cu base metal and brazing seam transformed to Cu/CuAl2, yielding the lowest joint shear strength of 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, decrease product weight, and integrate 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 of Cu/Al joints were investigated, and the relationships among Zn-Al filler metal composition, interfacial structure, and shear strength of Cu/Al joints were systematically described. It was found that the interfacial structure of the Cu/Zn-15Al/Al brazed joint was Cu/$Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$. For a thinner $Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$ layer (2–3 m), the shear strength of the joint was higher (66.3 MPa). With increasing Al content in the filler metal, the thickness of the $Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$ layer at the interface increased for the Cu/Zn-22Al/Al joint, and even some $CuAl_2$ phase could be found near the $Al_{4}\cdot_{2}Cu_{3}\cdot_{2}Zn_{0}\cdot_{7}$ layer of the Cu/Zn-28Al/Al joint, resulting in a corresponding decrease in shear strength. When the Cu/Al joint was brazed with the Zn-37Al filler metal, the interfacial structure near the Cu substrate transformed into Cu/$Al_{4 \cdot 2}Cu_{3 \cdot 2}Zn_{0 \cdot 7}$/$CuAl_2$. Due to the higher brittleness of the $CuAl_2$ layer, the shear strength of the joint decreased significantly to 34.5 MPa. Finally, the interfacial structure of the Cu/Zn-45Al/Al joint transformed into Cu/$CuAl_2$, leading to the lowest shear strength of only 31.6 MPa.

KEY WORDS Cu/Al joint, brazing, interfacial structure, intermetallic compound, shear strength

Introduction

Copper and its alloys exhibit excellent electrical conductivity, thermal conductivity, corrosion resistance, and relatively high strength, making them widely used in refrigeration, electrical and electronic industries, aerospace, and other fields. However, copper resources have become increasingly scarce in recent years, with copper prices remaining high. In contrast, aluminum is extremely abundant in the earth' s crust, relatively inexpensive, and possesses good electrical and thermal conductivity, making it an ideal substitute material for copper [?, ?, ?, ?, ?]. Nevertheless, due to the superior comprehensive properties of copper, it cannot be completely replaced by aluminum in some critical components. A feasible approach is to use aluminum in non-critical parts while continuing to manufacture specific parts from copper [?, ?, ?]. When both copper and aluminum are used in the same component, the inevitable problem of joining Cu/Al dissimilar metals arises. Brazing offers advantages such as high efficiency, high precision, low cost, and low residual stress, making it a common method for joining Cu/Al dissimilar metals [?, ?, ?, ?].

Currently, filler metals for Cu/Al brazing mainly include three categories: Al-Si series [?], Sn-Zn series [?], and Zn-Al series [?, ?, ?, ?, ?, ?, ?, ?, ?]. Among these, Zn-Al series filler metals yield Cu/Al joints with relatively superior mechanical properties and are considered ideal filler materials for Cu/Al brazing [?, ?, ?]. However, due to the strong chemical affinity between Al and Cu atoms, brazing Cu/Al joints with Zn-Al filler metals tends to form brittle interfacial layers dominated by Al-Cu-Zn compounds [?] or Al-Cu compounds [?, ?, ?] at the Cu substrate/brazing seam interface. Under external loading, joints typically fracture at these brittle interfacial layers.

Xiao et al. [?] investigated the interfacial structure and mechanical properties of Cu/Zn-3Al/Al brazed joints, finding that the Cu substrate/brazing seam interface was primarily composed of an $Al_{4 \cdot 2}Cu_{3 \cdot 2}Zn_{0 \cdot 7}$ compound layer. Moreover, as the thickness of the $Al_{4 \cdot 2}Cu_{3 \cdot 2}Zn_{0 \cdot 7}$ layer at the interface increased, the joint shear strength gradually decreased. Ji et al. [?, ?] found that when brazing Cu/Al joints with Zn-22Al filler metals, the Cu substrate/brazing seam interface was mainly composed of a brittle $CuAl_2$ layer. When the thickness of the $CuAl_2$ layer at the interface decreased by 27.6% and 45.8%, the shear strength of the Cu/Al joints correspondingly increased by 13.4% and 30.3%.

Evidently, the interfacial structure at the Cu substrate/brazing seam interface (including the type and thickness of interfacial compounds) is a critical factor affecting the mechanical properties of Cu/Zn-Al/Al brazed joints, and different Zn-Al filler metal compositions result in different interfacial structures. However, few reports have addressed the influence of Zn-Al filler metal composition on the interfacial structure of Cu/Al brazed joints, and the pattern and underlying reasons for changes in the Cu substrate/brazing seam interfacial structure with varying Zn-Al filler metal composition remain unclear. Furthermore, systematic research is lacking on the correlation between differences in the Cu substrate/brazing seam interfacial structure and changes in joint mechanical properties.

In this work, Cu/Al joints were brazed using five filler metals: Zn-15Al, Zn-22Al, Zn-28Al, Zn-37Al, and Zn-45Al (mass fraction, %). The effects of Zn-Al filler metal composition on the interfacial structure and properties of Cu/Al brazed joints were systematically investigated, and the relationships among filler metal composition, Cu substrate/brazing seam interfacial structure, and joint mechanical properties were elucidated.

Experimental Methods

The Zn-Al filler metals used in the experiments were prepared by melting 99.995% pure Al and 99.999% pure Zn in a crucible furnace. To prevent oxidation of the filler alloy during melting, a NaCl:KCl = 1:1 molten salt cover was used for protection. The melting temperatures of the prepared Zn-Al filler metals were measured using a CR-G differential thermal analyzer (DTA) under Ar atmosphere protection, with the results shown in . The base materials used were 1060 pure Al plates (60 mm × 20 mm × 3 mm) and TP2 deoxidized pure Cu plates (60 mm × 20 mm × 2 mm). Prior to the experiments, the base materials were chemically treated to remove surface oil and oxide films, then cleaned and air-dried for later use.

Cu/Al joints were assembled in a lap configuration with a lap length of 2 mm and a gap of (0.3 ± 0.05) mm. A schematic diagram of the brazed specimen is shown in [Figure 1: see original paper]. The flux used during brazing was non-corrosive CsF-AlF_3 flux with a melting range of 415–488 °C. The Cu/Al joints were joined in an Ar atmosphere brazing furnace. Since the brazing temperature should generally be 25–60 °C higher than the filler metal melting point in practical applications [?], the brazing temperature in this study was set to the liquidus temperature of each Zn-Al filler metal plus 30 °C (see). During the experiments, the furnace heating rate was 40 °C/min, and the brazing holding time was 40 s. To improve the mechanical properties of the joints, the specimens were rapidly removed from the brazing furnace and quenched at the brazing temperature after the holding period [?].

The interfacial structure and fracture morphology of the brazed Cu/Al joints were observed and analyzed using a Quanta 250 scanning electron microscope (SEM). The phase composition in the interfacial zone of the Cu/Al joints was analyzed using a STOFD ARMSTADT STOE/2 (Cu Kα) X-ray diffractometer (XRD). Before XRD analysis, the Al substrate side of the Cu/Al joint was removed, and the remaining part was ground to near the Cu/brazing seam interface to prepare the XRD sample. The shear strength of the Cu/Al brazed joints was tested according to GB/T11363-2008 using an MTS810 universal material testing machine. Three specimens were tested for each type of Cu/Al joint brazed with different Zn-Al filler metals, and the average value was taken.

2.1 Effect of Zn-Al Filler Metal Composition on Interfacial Structure Near Cu Substrate

[Figure 2: see original paper] shows the microstructures of the interfacial zones near the Cu substrate in Cu/Al joints brazed with five different Zn-Al filler metals. The microstructure of the Cu substrate/brazing seam interfacial zone in the Cu/Zn-15Al/Al joint is shown in [Figure 2: see original paper]a. The interfacial zone consists of a light gray interfacial layer (A) with fine protrusions, measuring 2–3 m in thickness. EDS analysis results () indicate that this interfacial layer is composed of Al-Cu-Zn compounds.

Based on the XRD analysis results of the Cu substrate/brazing seam interfacial zone ([Figure 3: see original paper]a), only one compound, $Al_{4\cdot 2}Cu_{3\cdot 2}Zn_{0\cdot 7}$, exists in the interfacial zone. Therefore, the interfacial structure of the Cu/Zn-15Al/Al joint is Cu/$Al_{4\cdot 2}Cu_{3\cdot 2}Zn_{0\cdot 7}$. Additionally, according to the XRD results and findings from literature [?, ?, ?], the brazing seam near the $Al_{4\cdot 2}Cu_{3\cdot 2}Zn_{0\cdot 7}$ interfacial layer is primarily composed of α-Al and -Zn solid solutions.

[Figure 2: see original paper]b shows the microstructure of the Cu substrate/brazing seam interfacial zone in the Cu/Zn-22Al/Al brazed joint. Compared with the Cu/Zn-15Al/Al joint, the interfacial layer (B) in the Cu/Zn-22Al/Al joint is significantly thicker at 5–6 m, and a new dark gray phase (C) appears in the brazing seam near the interface. According to EDS analysis results () and XRD results of the interfacial zone ([Figure 3: see original paper]b), the interfacial layer remains $Al_{4\cdot 2}Cu_{3\cdot 2}Zn_{0\cdot 7}$, while the newly appeared dark gray phase (C) is $CuAl_2$.

[Figure 2: see original paper]c shows the microstructure of the Cu substrate/brazing seam interfacial zone in the Cu/Zn-28Al/Al brazed joint. The interface still consists of a light gray interfacial layer (D) with protrusions, and the thickness shows no significant increase. However, a dark gray phase (E) forms around some coarse protrusions of layer (D). Based on EDS analysis results () and reference to the phase analysis at the interfaces of Cu/Zn-15Al/Al and Cu/Zn-22Al/Al joints, the interfacial layer (D) and dark gray phase (E) are $Al_{4\cdot 2}Cu_{3\cdot 2}Zn_{0\cdot 7}$ and $CuAl_2$, respectively. Although a small amount of $CuAl_2$ appears at the interface, the interface is still primarily composed of the $Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$ layer, and the interfacial structure remains $Cu/Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$.

[Figure 2: see original paper]d shows the microstructure of the Cu substrate/brazing seam interfacial zone in the Cu/Zn-37Al/Al brazed joint. EDS () and XRD analysis results ([Figure 3: see original paper]c) indicate that a continuous $Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$ layer (F) still exists at the interface. However, a large amount of dark gray phase (G) appears on the brazing seam side of the $Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$ layer, causing fracture of larger $Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$ protrusions. The $Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$ layer and phase (G) together constitute the Cu substrate/brazing seam interfacial zone. According to EDS analysis results () and XRD analysis results of the interfacial zone ([Figure 3: see original paper]c), phase (G) is $CuAl_2$. Evidently, when brazing Cu/Al joints with the higher Al content Zn-37Al filler metal, the interfacial structure transforms from $Cu/Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$ to $Cu/Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}/CuAl_2$.

[Figure 2: see original paper]e shows the microstructure at the Cu substrate/brazing seam interface in the Cu/Zn-45Al/Al brazed joint. The interfacial zone contains a light gray phase (H) and a dark gray phase (I). According to EDS analysis results, the compound types at the interface remain unchanged, with phases (H) and (I) still being $Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$ and $CuAl_2$, respectively. However, the $Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$ at the interface is significantly reduced and cannot form a continuous layered distribution; the interfacial zone is primarily composed of thick $CuAl_2$.

Thus, as the Al content in the Zn-Al filler metal increases, the interfacial structure near the Cu substrate in Cu/Zn-Al/Al brazed joints undergoes significant changes. When the Al content is 15%-28%, the interfacial structure is $Cu/Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}$. When the Al content reaches 37%, the interfacial structure transforms to $Cu/Al_{4}{\cdot}_{2}Cu_{3}{\cdot}_{2}Zn_{0}{\cdot}_{7}/CuAl_2$. When the Al content further increases to 45%, the interfacial structure transforms to $Cu/CuAl_2$.

2.2 Effect of Zn-Al Filler Metal Composition on Shear Strength of Cu/Al Brazed Joints

Changes in Zn-Al filler metal composition significantly affect both the type and thickness of interfacial compounds in Cu/Zn-Al/Al brazed joints. This transformation in interfacial structure inevitably has a substantial impact on the mechanical properties of Cu/Al joints. [Figure 4: see original paper] shows the shear strength of Cu/Al joints brazed with 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 Zn-Al filler metal. Specifically, the Cu/Zn-15Al/Al joint exhibits relatively high shear strength, reaching 66.3 MPa. The Cu/Zn-22Al/Al joint follows with 59.8 MPa, while the Cu/Zn-28Al/Al joint shows a lower value of 50.9 MPa. Notably, when using these three filler metals to braze Cu/Al joints, the shear strength exceeds 50 MPa, reaching more than 72.5% of the Al base metal strength. However, when using higher Al content Zn-37Al and Zn-45Al filler metals to braze Cu/Al joints, the shear strength decreases dramatically. The shear strengths of Cu/Zn-37Al/Al and Cu/Zn-45Al/Al joints are 34.5 MPa and 31.6 MPa, respectively, substantially lower than those of Cu/Zn-15Al/Al, Cu/Zn-22Al/Al, and Cu/Zn-28Al/Al joints.

Analysis and Discussion

The composition of Zn-Al filler metals significantly alters the interfacial structure at the Cu substrate/brazing seam in Cu/Zn-Al/Al joints. As the Al content in the filler metal increases, the interfacial structure gradually transforms from Cu/$Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$ to Cu/$CuAl_2$. This transformation results from the sequential precipitation and interaction of $Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$ 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 [?, ?, ?, ?, ?], $Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$ has lower formation energy and is more likely to precipitate on the Cu substrate surface than Al-Cu compounds (such as $CuAl_2$, CuAl, and Cu_9Al_4). The present study results further confirm this conclusion. When brazing Cu/Al joints with the lowest Al content Zn-15Al filler metal, $Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$ first precipitates on the Cu substrate surface and grows perpendicular to the interface into the brazing seam, forming a continuous intermetallic compound layer with fine protrusions ([Figure 2: see original paper]a). At this stage, the Cu/Zn-15Al/Al joint interface forms a Cu/$Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$ structure.

When using the Zn-22Al filler metal, the relative Al content in the liquid brazing seam increases, intensifying the precipitation of $Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$ on the Cu substrate surface [?] and thickening the $Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$ layer. Simultaneously, another compound—$CuAl_2$—begins to precipitate in the brazing seam near the Cu substrate/brazing seam interface ([Figure 2: see original paper]b). In the Cu/Zn-28Al/Al joint, the precipitation of $CuAl_2$ is enhanced, even showing a phenomenon where small amounts of $CuAl_2$ precipitate on the surface of the $Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$ layer at the interface ([Figure 2: see original paper]b). Although the interfaces of Cu/Zn-22Al/Al and Cu/Zn-28Al/Al joints are still primarily composed of $Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$, the appearance of $CuAl_2$ gradually initiates changes in the interfacial structure. This transformation becomes particularly evident when brazing Cu/Al joints with Zn-37Al and Zn-45Al filler metals.

At the Cu substrate/brazing seam interface of the Cu/Zn-37Al/Al joint, large amounts of $CuAl_2$ precipitate directly on the $Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$ layer, forming a connected compound layer and transforming the interfacial structure to Cu/$Al_{4}\cdot{}_{2}Cu_{3}\cdot{}_{2}Zn_{0}\cdot{}_{7}$/$CuAl_2$. Meanwhile, the abundant $CuAl_2$ also inhibits the precipitation of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ at the interface, even causing fracture of larger $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ protrusions and hindering the growth of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ into the brazing seam.

In the Cu/Zn-45Al/Al joint, the relative Al content in the brazing seam further increases. The precipitated $CuAl_2$ near the interface further suppresses the precipitation and growth of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ on the Cu substrate surface, making the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer thinner and preventing the formation of a continuous layered distribution. In some regions at the interface, $CuAl_2$ begins to connect directly with the Cu substrate, and the interfacial structure ultimately transforms to $Cu/CuAl_2$.

Therefore, increasing Al content in Zn-Al filler metals promotes the precipitation of $CuAl_2$ at the Cu substrate/brazing seam interface, and the precipitated $CuAl_2$ inhibits the precipitation and growth of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ on the Cu substrate surface, thereby causing the interfacial transformation in Cu/Al joints 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 of the interfacial compound layer from a thin $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer to a thick $CuAl_2$ layer inevitably deteriorates the shear strength of the joints [**?**, **?**]. The effect of interfacial structure on joint shear strength is directly reflected in the fracture morphology. [Figure 5: see original paper] shows the fracture morphologies on the Cu substrate side of Cu/Al joints brazed with five different Zn-Al filler metals. All five joints fractured at the Cu substrate/brazing seam interface.

The fracture morphology of the Cu/Zn-15Al/Al joint is shown in [Figure 5: see original paper]a. The fracture consists of fine dimples (J) and cleavage planes (K) produced by brittle fracture. EDS analysis reveals that the composition at dimple J is 53.9Al-36.92Cu-9.18Zn. Combined with the analysis of interfacial compounds in Section 2.1, dimple J can be identified as formed by ductile intergranular fracture of $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$. The composition at cleavage plane K is 46.27Al-44.64Cu-9.1Zn, indicating that this region formed by brittle transgranular fracture at the root of the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer. The thin $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer (2–3 m) with fine protrusions at the Cu substrate/brazing seam interface requires greater energy for crack propagation, which is the main reason for the observed ductile intergranular fracture. Consequently, the Cu/Zn-15Al/Al joint exhibits relatively high shear strength.

[Figure 5: see original paper]b shows the fracture morphology of the Cu/Zn-22Al/Al joint. Due to the increased thickness of the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer (5–6 m) at the Cu substrate/brazing seam interface, the fracture shows significantly fewer dimples and larger cleavage planes produced by brittle fracture compared with the Cu/Zn-15Al/Al joint, resulting in decreased shear strength. [Figure 5: see original paper]c shows the fracture morphology of the Cu/Zn-28Al/Al joint. The area of cleavage planes produced by brittle fracture further increases because the thicker $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer and small amount of brittle $CuAl_2$ at the Cu/brazing seam interface reduce the energy required for crack propagation, making the joint more susceptible to brittle fracture and further decreasing its strength.

[Figure 5: see original paper]d shows the fracture morphology of the Cu/Zn-37Al/Al joint. In addition to cleavage planes (L) produced by brittle fracture of the $Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$ layer, a new type of cleavage plane (M) appears. According to EDS results, the phase composition at cleavage plane M is 63.91Al-32.78Cu-3.31Zn. Based on the phase analysis at the interface of the Cu/Zn-37Al/Al joint in Section 2.1, cleavage plane M can be identified as resulting from fracture of $CuAl_2$. This occurs because the interfacial structure of the Cu/Zn-37Al/Al joint has transformed to Cu/$Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$/$CuAl_2$. Due to the extreme brittleness of $CuAl_2$, cracks easily initiate and propagate in this compound, accelerating brittle fracture of the joint [**?**, **?**]. Consequently, the shear strength of the Cu/Zn-37Al/Al joint decreases significantly compared with Cu/Zn-15Al/Al, Cu/Zn-22Al/Al, and Cu/Zn-28Al/Al joints.

[Figure 5: see original paper]e shows the fracture morphology of the Cu/Zn-45Al/Al joint, where the fracture has completely transformed to a brittle cleavage fracture mode. EDS analysis of cleavage plane N reveals a composition of 65.70Al-31.17Cu-3.13Zn, corresponding to the $CuAl_2$ compound. The thick $CuAl_2$ layer at the Cu substrate/brazing seam interface becomes the crack source for brittle fracture, further reducing the mechanical properties of the joint.

Based on the investigation of interfacial structure, mechanical properties, and fracture morphology of Cu/Zn-Al/Al joints, Zn-Al filler metal composition significantly influences the interfacial structure near the Cu substrate and the shear strength of Cu/Zn-Al/Al joints. When the Al content in the filler metal is 15%-28%, the interfacial structure of Cu/Zn-Al/Al joints 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. When the Al content reaches 37%, 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 decrease in shear strength. When the Al content further increases to 45%, the interfacial structure transforms to Cu/$CuAl_2$, resulting in the poorest shear strength. 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 metals is 15%-28%, the interfacial structure of Cu/Zn-Al/Al joints is Cu/$Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$. When the Al content reaches 37%, the interfacial structure transforms to Cu/$Al_{4\cdot2}Cu_{3\cdot2}Zn_{0\cdot7}$/$CuAl_2$. When the Al content further increases to 45%, the interfacial structure transforms to Cu/$CuAl_2$. The transformation of interfacial structure in Cu/Al joints results from 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. Due to the $Al_{4 \cdot 2}Cu_{3 \cdot 2}Zn_{0 \cdot 7}$ layer with a thickness of 2–3 m at the interface, the Cu/Zn-15Al/Al joint exhibits relatively high shear strength of 66.3 MPa. When brazing Cu/Al joints with Zn-37Al filler metal, the interfacial structure transforms 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 decrease in shear strength to 34.5 MPa. The Cu/Zn-45Al/Al joint has an interfacial structure of Cu/$CuAl_2$ and the lowest shear strength of only 31.6 MPa.
3. The interfacial structure at the Cu substrate/brazing seam interface is the primary factor affecting the mechanical properties of Cu/Al brazed joints. Once a continuous $CuAl_2$ layer appears at the Cu substrate/brazing seam interface, the joint strength decreases sharply. Therefore, when selecting Zn-Al filler metals for brazing Cu/Al joints, the Al element content should not exceed 28%.

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