Study on the Microstructure and Properties of Al/Cu Laser Filled Solder Joint

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Abstract. Using IPG-YLS-4000 fiber laser to weld T2 copper plate and LY16 aluminum alloy plate, using Zn-10%Al flux cored wire as filler material, the microstructure of the joint was observed and analyzed by SEM and EDS, and the effects of laser power, welding speed and welding line energy on the mechanical properties of the joint were studied. The results show that the joints are mainly divided into copper side brazing area, weld center area and aluminum side fusion welding area. Among them, there are two interface reaction layers composed of intermetallic compound (IMC) in the copper side brazing area, the first layer is CuZn compound in the form of strip, and the second layer is Al₂Cu phase in the form of shoot. The central area of the weld is mainly composed of massive α-Al phase and branched β-Zn phase. The tensile strength of the joint increases first and then decreases with the increase of laser power, welding speed and welding line energy. The thickness of IMC layer grows linearly with the increase of line energy. The best process parameters: when the laser power is 2200 W, the welding speed is 0.9 m/min, the welding line energy is 1446.67 J/cm, the IMC layer thickness is 10.11 μm, and the tensile strength reaches the maximum value, 252.6 MPa.

1. Introduction

In actual production, copper resources are scarce and expensive, while aluminum resources are rich in content, cheap in price and light in quality, and aluminum and copper have excellent corrosion resistance, conductivity and thermal conductivity, so some aluminum or aluminum alloys can be used to replace copper in refrigeration, chemical industry, electric power, aerospace and other fields[1]. This method of "replacing copper with aluminum" or aluminum copper composite connection not only gives full play to the advantages of the two materials in cost and performance, but also achieves the purpose of saving cost and reducing structural weight[2-7]. Therefore, the connection of Al/Cu composite materials has important research significance and application value in the actual production and even in the industrial development of our country.

At present, the common welding methods of Al/Cu dissimilar materials are pressure welding, laser welding[8-9], and fusion welding[10-15]. Among them, T.Solchenbach[8] carried out the Al/Cu laser welding lap test, using the combination of high-intensity beam and circular beam oscillation to control the heat input, so that the temperature distribution of the Al/Cu interface was uniform, and the maximum shear strength of the joint was 121 MPa. Mai[9] reduced the formation of brittle intermetallic...
compounds and improved the mechanical properties of the joint by changing the laser input and action position. When Zhang\cite{10} used zn-15% flux cored Al wire to study the Al/Cu TIG welding lap process, the tensile strength of the joint was up to 129 MPa, and the fracture occurred in the weld. Zhou\cite{11} et al. used Zn-2% Al flux cored wire to carry out TIG welding and lapping test on aluminum/brass. It was found that the welding wire has good wettability on the surface of brass base metal and can obtain high-quality joints.

In conclusion, the growth of intermetallic compound can be controlled by laser welding or adding appropriate welding wire to improve the mechanical properties of Al-Cu joint. However, the current research on laser brazing of Al/Cu is rare, and generally no welding wire is added, mostly lap test. Therefore, in this paper, we add Zn-10%Al flux cored wire to carry out laser welding test for aluminum copper dissimilar metals, and control the heat input by adjusting the laser power and welding speed during the butt test, so as to adjust the thickness of IMC layer, so as to improve the mechanical properties of the Al-Cu joint. At the same time, we study the structure distribution under the optimum process parameters of the joint, and weld the joint with aluminum copper laser filler wire. The study of microstructure and properties and the selection of process parameters have important practical significance and data reference.

2. Experimental materials and methods

In the experiment, IPG-YLS-4000 fiber laser (laser wavelength 1070 nm, maximum output power 4 kW) was used. LY16 aluminum alloy plate with size of 120×60×2 mm and T2 copper plate with size of 120×60×2.5 mm were selected. Meanwhile, Zn-10% Al flux cored wire with diameter of 2 mm was used as filler material. Before the butt welding test, the oxide film on the surface of the specimen is removed, and then the oxide film residue and oil stain are cleaned with acetone. The laser power is 1800~2600 W, the welding speed is 0.5~1.3 m/min, and the gas flow rate is 15 L/min under the protection of pure argon. In the welding process, using the melting point difference between aluminum and copper, the laser beam directly acts on the aluminum side, making part of the aluminum base metal melt into liquid metal, spread to the copper side which is still in the solid state, and form the weld through the interaction between the elements at the interface. According to the preliminary test, the better welding parameters are: laser power 2000~2400 W, welding speed 0.7~1.1 m/min. After the test, cut the sample perpendicular to the weld with the cutting machine under the best process parameters, polish it, observe each area of the joint with the microscope, and analyze the microstructure of the joint by SEM and EDS. Make a tensile specimen, with the weld in the middle of the specimen, and the size shown in Figure 1. At room temperature, WDW~100 electronic tensile testing machine was used to test the samples under different process parameters, and the tensile speed was set to 1 mm/min. After analyzing the influence of laser power and welding speed on the tensile strength of the joint, the mechanical properties of the joint are analyzed by using the welding line energy and IMC layer thickness.

3. Results and analysis

3.1. Microstructure analysis

Figure 2 shows the macro structure of the butt joint when the laser power is 2200 W, the welding speed is 0.9 m/min and the welding line energy is 1466.67 J/cm. According to Fig.2, the joint is composed of copper base metal area A, weld area B and aluminum base metal area C. Among them, the boundary line of copper side is clear and straight, indicating that the melting amount of copper side
is little or not, showing typical characteristics of brazed joint. The aluminum side shows a single side "X" shape, and the grains in the fusion zone grow along the opposite direction of heat conduction, making the fusion width of the weld area narrow in the middle and wide on both sides, showing typical characteristics of fusion welding joints. Therefore, the whole butt joint forms the copper side brazing area D in the copper side weld and the aluminum side fusion welding area E in the aluminum side weld, which makes the whole joint show the characteristics of fusion brazing.

![Figure 2. Macroscopic morphology of joints](image)

Figure 2. Macroscopic morphology of joints

Figure 3 is the SEM image of each area of the joint, in which Fig.3(a) is the copper side brazing area, Fig.3(b) is the weld center area, and Fig.3(c) is the aluminum side fusion welding area. It is known from the D region that there is a dense IMC layer growing from the shoot like to the center of the weld in the copper side brazing area. Because in the process of laser welding, the formation of Al-Cu joint is essentially a process of mutual diffusion and reaction between Al and Cu atoms in the brazing area of copper side: At the beginning of welding test, with the continuous filling of Zn-10%Al welding wire, aluminum alloy and welding wire gradually melt and mix under the action of laser beam, with the increase of temperature, the liquid solder gradually spreads on the copper base metal, Al and Zn raw materials. The interaction between solid and liquid is increasing. Because of the wetting and spreading of the liquid-phase molten pool at the interface, the dissolution of some copper base metals is accelerated, and the unsteady diffusion of Cu atoms from the copper side to the liquid-phase molten pool occurs under the action of the molten pool flow. According to the phase diagram of Al-Cu binary alloy, the solubility of Al in Cu is relatively high, and the Al and Zn atoms diffused from the molten pool to the copper base metal produce large temperature gradient and concentration gradient in the copper base metal, which makes the Al, Cu and Zn atoms aggregate, disperse and react with each other under the action of surface tension. With the rapid drop of bath temperature, Cu-Zn and Al-Cu compounds gradually saturated, and finally formed a complete and stable IMC layer in the brazing area of copper side.

In the weld zone, it is mainly solidified Al phase solid solution and Zn phase solid solution. It can be seen from area B that the central area of the weld is mainly composed of black massive phase and white branched phase. It is speculated that it is Al phase solid solution and Zn phase solid solution. At the same time, the porosity in area B in Fig.3(a) is due to the fact that the Zn in the welding wire changes into vapor due to the temperature rise, and it is generated by melting into the molten pool during the evaporation process. Properly increasing the heat input of the joint can avoid excessive Zn melting into the weld.

![Figure 3. SEM images of each joint area: (a) brazing zone on copper side; (b) central zone of weld; (c) area of aluminum side fusion welding](image)
Figure. 4 is an EDS analysis of the microstructure near the brazing area on the copper side. It can be seen from Fig.4 that the interface layer D area is actually composed of two parts (I and II): the first layer is in black strip shape, and the second layer is in shoot shape growing towards the center of the weld. Table 1 shows the EDS analysis results of each point in Fig.4. Among them, 1 point is the location of Cu base metal near the seam area, and the content of Cu atom is 100%, indicating that the diffusion distance of Al and Zn atoms in the molten pool is limited, and they do not contact the inner part of the copper base metal area. 2 and 3 points are located in the first and second layers of the IMC respectively. It is obvious that there are Cu-Zn and Al-Cu compounds in the IMC. The atomic content of Cu and Zn is 40.07%, 39.29% and 1:1 respectively. The atomic contents of Al and Cu are 61.79%, 33.14% and 2:1 respectively. According to the research of Jiang\cite{3}, the diffusion reaction of Al and Cu under the action of high temperature. According to the thermodynamic analysis and calculation, Al$_2$Cu compounds are the first to be formed in the interface layer. It is also known from the study of Zhou\cite{11} that there are indeed CuZn compounds in the interface layer. Therefore, it can be determined that CuZn and Al$_2$Cu are the main compounds in the interface layer by the ratio of 2 and 3 atoms and the phase diagram of binary alloy. 4 and 5 points are located in the central area of the weld, mainly Al and Zn atoms. Among them, the atomic content of Al in 4 points is 69.61%, which is black block; the atomic content of Zn in 5 points is 71.99%, which is white branch. Therefore, according to the atomic contents of Al and Zn at 4 and 5 points, the black block phase is $\alpha$-Al phase, and the white branch phase is $\beta$-Zn phase. This is due to the high thermal conductivity of copper and aluminum. In the test, the liquid metal in the molten pool cools and solidifies, resulting in a large number of dendritic structures in the weld, while the Zn atoms in the weld precipitate with the growth and decomposition of the dendrites\cite{7}, forming a white dendritic $\beta$-Zn phase. Therefore, the central area of the weld is mainly composed of black massive $\alpha$-Al phase and white branched $\beta$-Zn phase.

| Table 1 | EDS analysis results of corresponding points in Fig.4 |
|---------|-----------------------------------------------|
|         | A          | D          | B          |
| At%     | 1 | 2       | 3       | 4  | 5  |
| Al      | 0 | 20.64   | 61.79   | 69.61 | 13.83 |
| Cu      | 100 | 40.07  | 33.14  | 2.00  | 14.18 |
| Zn      | 0 | 39.29   | 5.07    | 28.39 | 71.99 |

3.2. Mechanical property analysis

From the above analysis, it can be seen that the thickness of IMC layer has an important influence on the mechanical properties of the joint. IMC layer is the connecting layer of the brazing interface, which plays a connecting role in the joint; and it is composed of the intermetallic compound Al$_2$Cu phase and CuZn phase, which is brittle in itself, and is the weak point of the joint. When IMC layer is thin, the connection is not tight enough and the joint strength is low; when IMC layer is too thick, the fracture form of joint changes from toughness to brittleness, which will also reduce the strength. Therefore, the IMC layer thickness should be controlled to make it in a suitable range to improve the tensile strength. The thickness of IMC layer is closely related to the linear energy of the joint. Therefore, through the change of the thickness of IMC layer by the linear energy, the forming effect of
the joint can be further analyzed. The linear energy is the heat input to the unit length weld by the welding energy, which can be expressed as follows (ideal state):

\[ Q = \frac{P}{v}, \quad (1) \]

Where: \( Q \) is the welding line energy (J/cm); \( v \) is the welding speed (cm/s); \( P \) is the laser power (W).

The process parameters of three groups of better weld forming are selected: the laser power is 2000, 2200, 2400 W, the welding speed is 0.7, 0.9, 1.1 m/min, and nine line energy values can be obtained from the calculation of formula (1). By using the orthogonal experiment method, the values of line energy which are close to and too large error are excluded, seven line energy values are obtained, corresponding to seven IMC layer thickness values. As shown in Fig.5, when the welding line energy increases from 1000 to 2000 J/cm, the tensile strength increases first and then decreases, and the thickness of IMC layer increases linearly. When the welding line energy is 1090.91 J/cm, the joint heat input is low, and the reaction among Al, Cu and Zn atoms is not strong enough, so the thickness of IMC layer is thin, only 6.9 μm, and the corresponding tensile strength is only 82.16 MPa. With the increase of heat input, the welding line energy increases to 1333.33 J/cm, the joint temperature is higher and higher, the Zn Al welding wire is fully wetted and spread to the copper base, the reaction among the Al, Cu, Zn atoms becomes strong, and the thickness of IMC layer increases to 9.83 μm. When the linear energy increases to 1466.67 J/cm, the molten pool completely soaks the whole copper side interface in the long-term high temperature environment, which makes the reaction between atoms become more and more intense, and more Al$_2$Cu and CuZn compounds are generated. Finally, the thickness of the reaction layer increases to 10.11 μm, and the tensile strength reaches the maximum value, 252.6 MPa. At this time, the IMC layer is relatively dense, and the mechanical properties of the joint reach the best. It can not only maintain the effective connection of the Al Cu joint, but also make it have a high tensile strength. With the increase of the linear energy, too many compounds are formed in the interface reaction, the IMC layer is more than the appropriate thickness, the joint becomes more brittle, unable to bear too high load, and the tensile strength decreases.

![Figure 5. Effect of welding heat input on IMC layer thickness and tensile strength](image)

4. Conclusion

(1) In the laser welding butt test of Al/Cu dissimilar materials, the joint is divided into copper side welding area, weld center area and aluminum side welding area. The wettability of Zn-10%Al flux cored wire at the interface is good, and the welding joint with good forming effect can be obtained.

(2) The copper side brazing area consists of two IMC layers composed of interface compounds. The first layer is CuZn compound in the shape of black strip, and the second layer is Al$_2$Cu compound in the shape of shoot to the center of the weld. The central region of the weld consists of a eutectic structure composed of black massive α-Al phase and white branched β-Zn phase.

(3) The tensile strength of the joint increases first and then decreases with the increase of welding line energy, while the thickness of IMC layer grows linearly with the increase of line energy. The best process parameters are as follows: the laser power is 2200 W, the welding speed is 0.9 m/min, the welding line energy is 1466.67 J/cm, the IMC layer thickness is 10.11 μm, the tensile strength reaches the maximum value, 252.6 MPa, and the mechanical properties of the joint are the best.
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