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Ultrasonic semi-solid coating soldering 6061 aluminum alloys with Sn–Pb–Zn alloys

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ABSTRACT

In this paper, 6061 aluminum alloys were soldered without a flux by the ultrasonic semi-solid coating soldering at a low temperature. According to the analyses, it could be obtained that the following results. The effect of ultrasound on the coating which promoted processes of metallurgical reaction between the components of the solder and 6061 aluminum alloys due to the thermal effect. Al_2Zn_3 was obtained near the interface. When the solder was in semi-solid state, the connection was completed. Ultimately, the interlayer mainly composed of three kinds of microstructure zones: α-Pb solid solution phases, β-Sn phases and Sn–Pb eutectic phases. The strength of the joints was improved significantly with the minimum shear strength approaching 101 MPa.

1. Introductions

Aluminum alloys are widely used in many industrial and structural applications such as aerospace, automotive and electronics due to their good properties such as satisfactory mechanical properties, good thermal conductivity and relatively good corrosion resistance. Soldering may be a very attractive method for aluminum alloys. The process temperature is lower than brazing and fusion welding, so much less heat distortion and defects are obtained. Soldering of aluminum alloys is often required [1]. But the soldering of aluminum alloys is limited to several kinds of aluminum alloys. A lot of high strength level of aluminum alloys are unable to be soldered. On the other hand, the demand that aluminum alloys are soldered has become more and more urgent due to the requirement of product lightweight and esthetics. The current welding level of aluminum alloys has been unable to meet the structural strength, stiffness and esthetic requirement. Thus, some new methods of soldering aluminum alloys are studied. For now, there are some conventional soldering ways to join aluminum alloys such as laser assisted soldering method, brazing method, soldering method and ultrasonic assisted soldering. The laser assisted soldering method is a good way to realize automation, but it cannot be used widely in various fields because of the expensive equipment [2]. The brazing and soldering are used to join aluminum alloys, but it is necessary that the cleaning of surface oxide films with the flux or physical methods. The flux is corrosive that may affect the properties of the parent material even it also is dangerous to people. Thus, using physical methods to clean up oxide films is better. Ultrasonic soldering is a fine approach that solder aluminum alloys without the flux and the equipment is not expensive. The ultrasonic cavitation effect due to ultrasonic waves has been successfully used to destroy oxide films during soldering of aluminum alloys, to enhance the wettability between the liquid metals and particles, and to break up the clustered particles which disperse them more uniformly in liquids during fabrication of aluminum alloys [3–12].

Ultrasonic soldering, which has been well known as a fluxless soldering method, is very attractive as a relatively low temperature joining method. However, the soldering temperature of ultrasonic soldering is higher than the temperature of the thermal annealing. Overheating may result in stress relieving, sagging or warping panels, altering hardness, temper, surface condition, re-alloying of the base metal in the immediate joint area, bot cracking, or even a dreaded meltdown [13]. Above all, a majority of aluminum alloys are heat sensitive and preferably joined at a low temperature to avoid deterioration of mechanical properties [14]. Therefore, the relatively high temperature of ultrasonic soldering is bound to make the sheer strength decrease. But the solder filling process of ultrasonic assisted soldering is very important, so the soldering temperature is not too low to keep the solder melt state. A lot of

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people want to improve the strength by all kinds of means, so as to make up for the lack of strength caused by the relatively high soldering temperature. Yan [15] finds SiC particle reinforced Zn-based filler can increase the bond strength, reaching a value equal to that of the substrate metal. The bond temperature is high and the preparation of SiC particle reinforced Zn-based filler is inconvenience. Meanwhile, the shear strength of the α-Al dendrite-reinforced joints is improved significantly, with the maximum shear strength approaching 60 MPa [16]. Sn-based solders with low melting points are very attractive for the joining of heat-sensitive aluminum alloys. Ultrasonic soldering of pure Al at 300 °C is investigated with Sn-based solders. The tensile strength of the joints can reach more than 80 MPa [14]. However, it will be very meaningful to increase the strength by reducing the temperature too. Semi-solid connection is a very good choice to accomplish the welding at a low temperature, because the interlayer is in semi-solid state. Vibration assisted semi-solid diffusion brazing of Al matrix composites in air is investigated and the high sheer strength of more than 160 MPa comparing to that of the base metal is obtained. But two vibrations at 375 °C and 520 °C are necessary to the high strength in the brazing process [17–18]. The brazing process is very complex.

Therefore, in this report, the ultrasonic semi-solid coating soldering of 6061 aluminum alloys is studied. Sn–Pb–Zn solder alloys with high Sn–Pb alloy content have a low melting point and the connection is completed when it is in semi-solid state. A device for this ultrasonic semi-solid coating soldering method is assembled, which propagates ultrasonic waves in a direction perpendicular to join surface and carries out a certain pressure to perform the joint. The shear strength of the joint is evaluated by tensile tests. The optimal welding conditions are determined, and the crystallization behavior and the mechanism of interfacial reaction are discussed.

2. Experimental procedures

A 6061-Al shutter 150 mm × 17 mm × 2 mm in diameter was used for the ultrasonic coating tests. The specimens were polished with grinding papers for 45 s and cleaned by the alcohol for 60 s so that it can reveal the metallic luster for easier wetting. The accurate chemical composition of parent metals was listed in Table 1. The specimens were fixed easily. It was necessary to use simple clamping jigs. The Sn–Pb–Zn alloys were composed of 90–92% Sn–Pb, 1.5–2% Ag–Cu, 6–10% Zn and little Bi. The solder was heated to 280 °C in air and was located in the bath with heating pipe to keep the temperature.

The process of the soldering was divided in two steps. The first step was to perform the coating of the parent metals with the Sn–Pb–Zn alloys. A k-type thermocouple was installed 20 mm away from the coating interface. The induction coil heated pieces to the proper coating temperature is 280 °C. The average heating rate was 15°Cs^{-1}. The molten solder was placed on the specimens to start the ultrasonic coating that ultrasonic vibration of 600 W at a frequency of 20 kHz for 30–60 s. The ultrasonic vibration was propagated in a direction perpendicular to faying surfaces through a 6061 aluminum substrate. The ultrasonic coating time was 30–60 s. The second step was to complete the connection of two coated specimens. The coated aluminum alloys cooled to 190 °C that became semi-solid state. Then the two samples immediately were bonded at 0.3 MPa for 10 s and the interlayer was kept between the parent metals. After the bonding process, the soldering joint was air cooled to room temperature. The detailed test parameters is listed in Table 2.

Table 1
Major alloying elements of 6061 aluminum alloy (wt.%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.4–0.8	0.7	0.15–0.4	0.15	0.8–0.12	0.04–0.35	0.25	0.15	Bal.

Table 2
The detail parameters of the ultrasonic coating process and the joining process.

	Ultrasonic vibration (W)	Frequency (kHz)	Coating time (s)	Pressure (MPa)	Pressure time (s)
1	600	20	30	0.3	10
2	600	20	40	0.3	10
3	600	20	60	0.3	10

Microstructure of the joint was observed by scanning electron microscope (SEM). The composition of the interfacial reactants was quantitatively analyzed by energy dispersive X-ray spectrum (EDS) equipped in the SEM. The crystal state of the solder and the phase composition of the interfacial reactants were examined by X-ray diffraction (XRD). The step size and speed of the XRD analysis were 0.02° and 4°/min, respectively. The shear strength of specimens was measured according to zivick020 testing machine with a displacement rate of 0.5 mm/min. The hardness of the joints was tested by a Vickers hardness tester under a load of 100 g and a loading time of 10 s.

3. Results and discussions

3.1. Microstructure

The typical SEM cross-sectional image of the whole joint is shown in Fig. 1. The middle zone is the solder, and the other zones are the 6061 aluminum alloy. A convex interface is found, which is not caused by the solder itself, but by the ultrasonic energy. When the ultrasonic vibration propagates along the surface of the 6061 aluminum alloy, the oxide films are broken with the cavitation effect during the coating stage, making the solder touch the parent metal directly. Therefore, the cavitation effect is the key to break

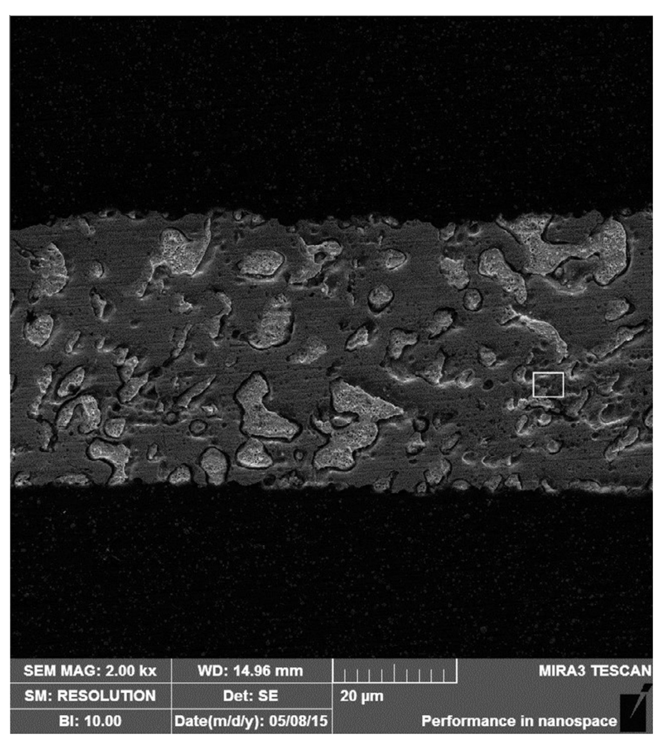

Fig. 1. The cross-sectional image of the whole joint.