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Influence of high-power-low-frequency ultrasonic vibration time on the microstructure and mechanical properties of lead-free solder joints

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ABSTRACT

Cu/SAC305/Cu solder joints were fabricated at ambient atmosphere using high-power-low-frequency ultrasonic vibration (USV) assisted hot plate reflow soldering. The influences of USV time (within 6 s) on the microstructure, hardness, yield strength and shear strength of the solder joints were investigated. Refinement on the solder matrix microstructure, formation of thinner interfacial Cu_6Sn_5 IMC layer, and enhancement on the hardness, yield strength and shear strength were observed in all the ultrasonic-treated solder joints. Marked morphological change on the β-Sn phase was observed in the joint solder matrix when the USV time was increased from 1 s to 6 s. Thicker interfacial Cu_6Sn_5 IMC layer was observed at the top and bottom substrate/solder interfaces and the difference in thickness between these interfaces was greater at increased USV time. The solder matrix hardness increased with increasing USV time, indicating a reduction in joint ductility. The USV time has no influence on the joint shear strength, but decreased joint yield strength was observed after 1 s of USV time. The influences of the USV time on the solder joint properties were contributed by the combined effects of acoustic cavitation and streaming induced by the USV in the molten solder during reflow soldering.

1. Introduction

In the current electronic packaging industry, Sn-based lead-free solders have been widely used as the joining materials between the electronic components and the printed circuit boards, instead of Sn-based lead solders due to the environmental and health hazards of lead. The Sn-based lead-free solders possess higher melting temperature and Sn content compared to the lead solders, limiting their application in the electronic packaging as they promote the formation of brittle interfacial IMCs at the solder joint interfaces and thermal distortion on the solder joint due to the thermal expansion coefficient (CTE) mismatch between the solder and the packaging components. The reliability of these lead-free solder joints is further aggravated with the demands of miniaturization and multi-functionalization on the electronic packages, in which the joints have to endure extremely high temperature and stress generated by high current density in the complex circuitry. To solve this issue, research has been drawn to improve the solder joint reliability by controlling the microstructure of the solder joint and limiting the formation of interfacial IMCs.

One of the most famous approaches is to replace the Sn-based lead-free solders by composite solders, which are fabricated by adding nanoparticles into the Sn-based lead-free solders. Based on the studies of Chan et al. (2013), Gain et al. (2011), Tang et al. (2013), and Yang et al. (2014), their results showed that the solder joint was strengthen by the dispersion of the added nanoparticles in the solder matrix. The growth of interfacial IMCs was suppressed due to the adsorption of nanoparticles on the solder joint interfaces. However, the performance of these composite solders is highly dependent on the dispersion condition of the nanoparticles in the solders, as the nanoparticles tend to agglomerate and have very little solubility in the solders. The preparation techniques of composite solders are crucial to ensure uniform dispersion of nanoparticles in the solders prior to soldering, according to Shen and Chan (2009) and Ko et al. (2014). The suppression effect of the interfacial IMCs growth may be varied with the amount of nanoparticles added, as observed in the work of Tang et al. (2013). Additionally, Haseeb et al. (2012) and Shen and Chan (2009)

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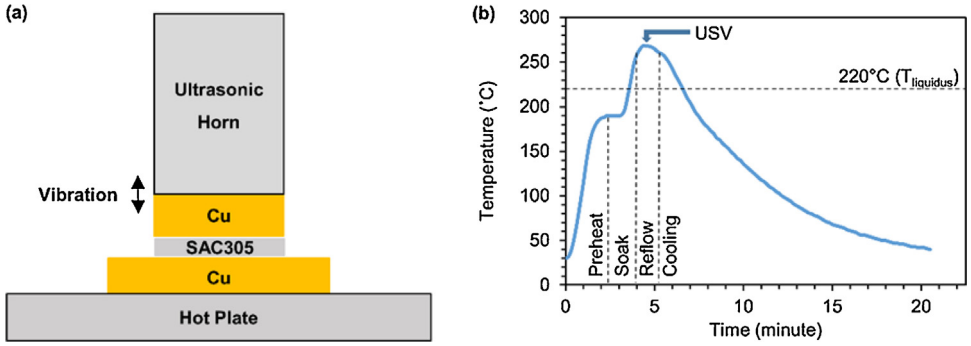

Fig. 1. (a) Schematic diagram of ultrasonic-assisted reflow soldering setup with soldering sample. (b) Reflow soldering profile.

reported that these nanoparticles tend to trap in the solder flux as a waste, instead of being embedded in the solder joint after soldering.

Apart from the above mentioned approach, a few studies revealed that solder joint strengthening and interfacial IMC growth suppression effects can also be achieved by integrating ultrasonic vibration (USV) in the range of 20–60 kHz into reflow soldering process. Kago et al. (2004) first reported that the Cu/Sn-Bi solder joints obtained better peel strength, refined solder matrix microstructure and thinner interfacial IMC layer after treated with several seconds of 58 kHz USV during the solidification stage in a hot-air reflow soldering process. In the work of Chinnam et al. (2011), Cu/Sn-4.0Ag-0.5Cu/Cu solder joints with refined solder matrix microstructure, thinner interfacial IMC layer and improved hardness were obtained when treated with 240 s of 40 kHz USV within 40 W of ultrasonic power in an ultrasonic-assisted oven reflow soldering. Ji et al. (2014b) and Ji et al. (2016) further examined the effect of ultrasonic power (up to 267 W) on the Cu/Sn-3.0Ag-0.5Cu/Cu solder joint properties by applying 28 kHz USV in a hot-plate reflow soldering. Their studies showed that the ultrasonic-treated solder joints have better shear strength even though the solder matrix microstructure was coarser when treated with USV of 200 W and above. Although promising results have been reported, the research on ultrasonic-assisted reflow soldering is still in its infancy as only very limited works can be found in the literatures, and hence more extensive studies would be valuable.

Therefore, our present study is focused on the effect of USV time on the microstructural and mechanical properties in terms of the shear strength and hardness of the lead-free solder joints. Cu substrate was chosen in this study due to its common application as a metallization element in the electronic packages, whereas Sn-3.0Ag-0.5Cu (SAC305) solder was chosen for its conventional application in the electronic packaging industry. It was intended to lay a foundation for ultrasonic-assisted reflow soldering of the conventional lead-free soldering materials.

2. Materials and methods

2.1. Sample preparation

Copper (Cu) plates (99% purity) with the dimension of 20 mm × 20 mm × 3 mm (bottom plate) and 15 mm × 15 mm × 3 mm (top plate) were used as substrates in the experiment. They were first grinded using silicon carbide sandpaper with grit size of 30 μm, 15 μm, 10 μm and 5 μm, followed by polishing using 1 μm diamond suspension and fine polishing using 0.05 μm colloidal silica suspension. Next, they were ultrasonically cleaned with acetone for 6 min and dried in hot air. The Sn-3.0Ag-0.5Cu (SAC305) solder paste (LFM-48W TM-HP, ALMIT SRC) was then deposited on the bottom Cu plate through a mask having an opening of 10 mm × 10 mm and a thickness of 0.42 mm (equivalent to deposited solder mass of 0.27 g) prior to soldering.

2.2. Soldering procedures

An ultrasonic-assisted reflow soldering system was assembled with a digital ceramic hot plate (CHP-170DN, AS-ONE) and a customized USV output unit. The USV output unit consisted of an ultrasonic generator and a transducer with horn. The vertical USV generated at the tip of the horn was 20 kHz in frequency and 169 W in power (equivalent to 30 μm in amplitude). The schematic diagram of the soldering arrangement is shown in Fig. 1a. The assembled sample was heated on the hot plate at ambient atmosphere according to the heating profile as shown in Fig. 1b. Ultrasonic horn was loaded on the top Cu plate when the temperature reached 260 °C, at a pressure of 125 kPa, and vibrated for 1, 2, 3, 4, and 6 s. The sample was then air-cooled to room temperature. Non-ultrasonic-treated samples were fabricated to serve as control samples.

2.3. Cross-sectional observation

The soldered samples were cross-sectioned at the center and then mounted in epoxy. The surface of the cross-sectioned samples was grinded and polished using the same procedures as mentioned in Section 2.1. All the samples were etched in the solution of 10 vol.% of HCl + 90 vol.% of methanol for 15 s to reveal their microstructure. The microstructure and elemental composition of the samples were characterized by scanning electron microscope (SEM, Phenom ProX) equipped with energy-dispersive X-ray spectroscopy (EDS). The total area of interfacial IMC layer and its length of coverage were measured using an image analysis software (Image J, NIH software). As illustrated in Fig. 2, the IMC layer thickness was then calculated using Eq. (1). The average IMC layer thickness was obtained from the SEM images taken at ten different spots.

$$\text{IMC layer thickness, } h = A/L \quad (1)$$

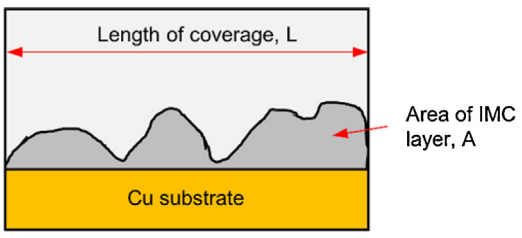

Fig. 2. Calculation method of interfacial IMC layer thickness.