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Shear strength and fracture behavior of reflowed Sn3.0Ag0.5Cu/Cu solder joints under various strain rates

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ABSTRACT

The effects of strain rate on the shear fracture behavior of Sn3.0Ag0.5Cu/Cu solder joints with thin and thick interfacial intermetallic compound layers were investigated. A single lap-shear sample was designed to conduct the study. The Cu/Sn3.0Ag0.5Cu/Cu joints were reflowed at 250 °C and 280 °C for 10 min, respectively, resulting in formations of a thin (6.08 μm) and thick (13.25 μm) intermetallic compound layer between the solder and Cu substrate. The single lap-shear tests were performed at the shear strain rates of 5×10^{-4} s^{-1}, 5×10^{-3} s^{-1}, 2×10^{-2} s^{-1}, 1×10^{-1} s^{-1} and 2×10^{-1} s^{-1} to observe the shear fracture behavior. Experimental results revealed that both the thickness of the interfacial intermetallic compound layer and strain rate had influence on the shear strength and failure mode of the solder joint. The shear strength of the solder joints increased with increasing strain rate, but decreased with thickness of the interfacial intermetallic compound layer. It was observed that the solder joints broke in a ductile manner at low strain rates (5×10^{-4} s^{-1}, 5×10^{-3} s^{-1}), although they exhibited a ductile-brittle mixed manner at intermediate (2×10^{-2} s^{-1}) and a brittle manner at high strain rates (1×10^{-1} s^{-1}, 2×10^{-1} s^{-1}). In the case of low strain rates, the ductile fracture behavior of joints with thin and thick intermetallic compound layers were similar. Nevertheless, more cleavage and broken Cu_6Sn_5 grains were detected on the fracture surface of the solder joint with a thick intermetallic compound layer as the strain rate increased to 2×10^{-2} s^{-1}, 1×10^{-1} s^{-1} and 2×10^{-1} s^{-1}. Furthermore, when the strain rate of 2×10^{-1} s^{-1} was applied, the solder joint with a thin intermetallic compound layer was completely broken inside the Cu_6Sn_5 layer, but partly broken at the Cu_6Sn_5/Cu_3Sn interface for the joints with a thick intermetallic compound layer. Four modes were proposed to explain the detailed ductile-to-brittle transition in failure behavior. In addition, the strain rate sensitivities of the solder joints with thin and thick interfacial intermetallic compound layers were also investigated. It was found that the strain rate of a solder joint with a thick interfacial intermetallic compound layer was lower than that of one with a thin interfacial intermetallic compound layer.

1. Introduction

Due to environmental safety and human health considerations, conventional Sn37Pb eutectic solder has been gradually prohibited. Many studies of lead-free solders and soldering have been performed from this viewpoint [1–6]. Most of them have focused on Sn-based alloys, particularly, the Sn-Ag-Cu system, which is expected to be a substitute for the Sn-Pb eutectic solder alloy because of its better mechanical properties than traditional Sn-Pb solder, such as ductility, creep resistance and thermal resistance [7–11]. As a result, the Sn-Ag-Cu alloy system was introduced as the first lead-free solder in the industry; in particular, the Sn-3.0Ag-0.5Cu lead-free solder has attracted the most attention [12–14].

Since the implementation of Sn-3.0Ag-0.5Cu alloy in many electronic products has been spreading gradually, more investigation are required determine their material characteristics in terms of melting temperature, solderability, mechanical strength, creep resistance, thermal fatigue resistance, corrosion resistance, etc.

Solder joints in electronic products serve not only to connect the electronic components but also to ensure mechanical reliability under the working conditions. The quality of a solder joint is

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directly related to the bond strength of the solder alloy to the substrate. Thus, the mechanical strength of solder joints has been one of the major reliability concerns in electronic assembly technology [15–17].

In the electronic packaging field, strain rate often plays an important role in the mechanical properties of joints as they encounter different strain rates during manufacture, shipping, or service. Moreover, an understanding of the solder joint strength over a range of strain rates is necessary because of the wide range of strain rates encountered. For instance, the thermal stress resulted from thermal expansion coefficient mismatch between the solder and substrate can lead to a low strain rate, a mechanical shock would result in an intermediate strain rate range between quasi-static and dynamic regimes, while a suddenly drop would lead to a high strain rate.

In order to evaluate the reliability of solder joints, the electronics industry widely adopts shear testing, and the majority of studies in this area have focused on the effects of the shear speed on the mechanical response of the solder joints [18–21]. Tests were generally conducted at very high speeds using a Hopkinson bar [18] or miniaturized pendulum impact testing machines [19], and at low speeds using a striker with an attached displacement gauge [20]. A number of studies have been performed on the shear properties of Sn3.0Ag0.5Cu solder joints [11,17,22–24]. For instance, Tian et al. [11] has investigated the effects of bump size on deformation and fracture behavior of Sn3.0Ag0.5Cu/Cu (SAC305/Cu) solder joints during shear testing at a very slow shear speed (60 μm/s). Hu et al. [25] studied the shear strengths and fracture behavior of Cu/Sn3.0Ag0.5Cu/Cu single lap joints with a constant displacement rate of 0.1 mms^{-1}.

However, the lack of investigations on the shear properties of a single lap Sn-3.0Ag-0.5Cu/Cu solder joint at a wide strain rate range (from low to high) is the motivation for the present study. Therefore, in the current study, we employ the Sn-3.0Ag-0.5Cu/Cu solder joints, which were reflowed at 250 °C and 280 °C as examples to reveal the effect of strain rate ranging from 5×10^{-4} to 2×10^{-1} s^{-1} on the shear fracture behavior for a comprehensive understanding of the interfacial strength and failure mode of the lead-free solder joint. Comparisons of fracture behavior between different solder joints with thin and thick interfacial IMC layers are performed as well.

2. Experimental procedure

Copper (99.99%) plates with dimensions 30 mm × 5 mm × 2.5 mm were used as the substrate. Before soldering, the Cu plates were ground and polished with 1 μm diamond paste. A Sn-3.0Ag-0.5Cu (5 mm × 5 mm × 0.05 mm) solder paste (KOKL, Korea) square was placed on the Cu plate. Fig. 1 shows the structure of the Cu/Sn3.0Ag0.5Cu/Cu single lap solder joint. The solder joints were established through the reflowing process in a reflow oven, where the specimens were clamped and reflowed at 250 °C and 280 °C for 10 min to form single-lap joints, respectively. Additionally, two aluminum spacers with the same thickness of 0.05 mm were placed on either side of the solder to keep the gap distance between two copper plates to be 0.05 mm, as schematically shown in Fig. 1. They were removed after reflowing. It can make sure that the thickness of the solder between two copper plates is 0.05 mm for all single-lap samples.

In order to obtain the shear forces of the soldered joints, a uniaxial micro-force test system was used to perform the shear tests on different joint specimens. The specimens were tested at room temperature with the strain rate ranging from 5×10^{-4} to 2×10^{-1} s^{-1}. For each condition, 5 samples were sheared and the average shear force was calculated using a 30% trimmed mean.

The interfacial microstructure and the fracture micromorphologies were analyzed by using a scanning electron microscope (SEM, FEI Quanta200F). An Energy Dispersive Spectrometer (EDS) analysis was performed to confirm the compositions of the interfacial intermetallic compound (IMC) layers of the joints.

3. Results and discussion

3.1. Interfacial microstructure of the solder joints

Fig. 2a and b show the morphologies of the interfacial IMC layer of Sn3.0Ag0.5Cu/Cu joints reflowed at 250 °C and 280 °C, respectively for 10 min. For all the as-reflowed solder joints, an IMC bilayer consisting of the Cu_6Sn_5 η-phase and Cu_3Sn ε-phase were observed. The solder/Cu_6Sn_5 interface showed a scallop shape and was extremely rough, while both the Cu_6Sn_5/Cu_3Sn and Cu_3Sn/Cu interfaces exhibited a more planar shape. This phenomenon has been also observed in the previous literature [3]. Both interfacial Cu_6Sn_5 layer and Cu_3Sn layer thickened with increasing reflow temperature from 250 °C to 280 °C for the same reflow time. The thicknesses of interfacial Cu_6Sn_5 and Cu_3Sn were 5.82 μm and 0.26 μm for reflow temperature of 250 °C, while the reflow thicknesses were 11.64 μm and 1.61 μm for the reflow temperature of 280 °C. These IMC layer are much thicker than the IMC layer of SAC305/Cu solder joint reflowed at 250 °C for 1 min (1.16 μm) proposed in our previous work [25]. That can be explained by the prolonged reflow time (10 min) or higher temperature (280 °C) adopted in the present study. In addition, some chunk-like Cu_6Sn_5 IMC and particle-like Ag_3Sn IMC were observed in the bulk solder, as indicated in Fig. 2a. A chemical composition determination using energy dispersive X-ray spectroscopy (EDX) was adopted to determine the IMCs, which were observed in Fig. 2. The detailed EDX results are shown in Fig. 3. It is believed that the emergence of Cu_6Sn_5 phase can be attributed to the supersaturation of Cu atoms in the bulk solder, while the Ag_3Sn particles were precipitated during the solidification of molten solder.

Generally speaking, the formation of interfacial IMCs (including Cu_6Sn_5 and Cu_3Sn) between the Sn-based solder alloys and Cu substrate are controlled by chemical reaction between the Cu substrate and the molten solder alloys [5]. The growth of those IMCs during the reflow process is believed to have resulted from

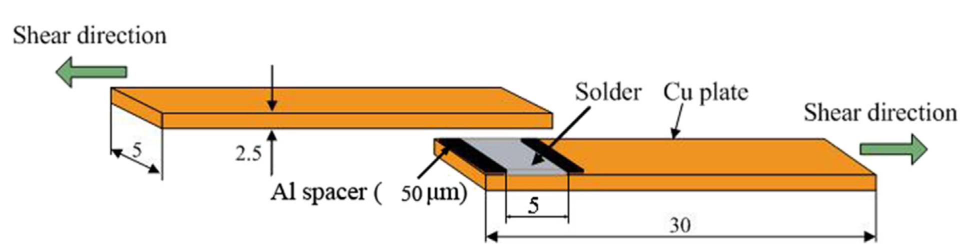

Fig. 1. Sketch of the Sn37Pb/Cu joint shear sample. (unit: mm).