Reliability Studies of Surface Mount Solder Joints—
Effect of Cu–Sn Intermetallic Compounds

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Abstract—Cu–Sn intermetallic compounds (IMC's), formed at the interface between the solder and the copper substrate are found to play a dominant role in determining the thermal fatigue life of surface mount solder joints fabricated from a conventional infrared reflow process. In order to predict the growth of this IMC layer during the operating life of the solder joint and its effect on the thermal fatigue life, the formation characteristics of the IMC's in 0805 and 1206 LCCC solder joints are systematically studied in this investigation. Only the stable Cu₆Sn₅ and η-phase intermetallic compound was observed in all as-solidified solder joints as confirmed by scanning electron microscopy (SEM) and energy dispersive x-ray (EDX). The mean layer thickness was found to increase almost linearly with reflow time up to about 200 s. The thickness of the interfacial IMC layer increased with increasing reflow temperature for 0805-type solder joints up to around 250 °C and reached a saturated thickness of 2.5 μm beyond this temperature. Additional intermetallic formation due to higher reflow temperature or longer reflow time would appear as Cu–Sn whiskers in the bulk solder of the joint. The copper land pad size and quality of component lead metallization were also found to greatly affect the formation of Cu–Sn IMC in surface mount solder joints, and hence its reliability in terms of thermal fatigue life and mechanical properties.

I. INTRODUCTION

One of the crucial factors in the reliability of surface mount solder joints is the formation of an copper–tin intermetallic compound (IMC) between the solder and copper land pad of a solder joint. When molten Sn–Pb solder comes in contact with the copper pad surface, a layer of Cu–Sn IMC, consisting of the Cu₆Sn₅ η-phase adjacent to the solder and the Cu₃Sn ε-phase next to the copper land pad surface, is formed in-between and serve as the bonding material for the solder joint. However, due to its brittle nature and thermal mismatch with the solder and the printed circuit board (PCB), excessive IMC formation at the solder–copper interface of the solder joint will potentially cause weakening in joint strength and eventually fatigue failure. In order to systematically study the formation of intermetallic compound formation in surface mount solder joints, the effect of various infrared-reflow process parameters (such as the reflow time, reflow temperature, and size of copper land pad) were examined in this work.

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II. BACKGROUND

Tin–lead solder alloy is usually the main constituent material in the fabrication of solder joints in surface mount PCB assemblies. When molten Sn–Pb solder comes in contact with the copper pad surface, intermetallic compounds formed are entirely of the Cu–Sn intermetallic species (with an eutectic composition of about 0.7 wt.% Cu). The formation of Cu–Pb intermetallic compounds is negligible due to the low solubility of Cu in Pb (the eutectic composition of the Pb–Cu binary system is 0.06 wt.% Cu).

Various works [1]–[7], [9], [10], [12], [13] have been done on the formation and growth of the Cu–Sn IMC's in different binary metal systems. It is generally observed that a thin layer of η-phase (Cu₆Sn₅) intermetallic compound is formed instantaneously as soon as eutectic Sn–Pb solder is melts on a copper substrate. Tu and Thompson [1] found that Cu₆Sn₅ compound was formed once Cu and Sn thin film came in contact and its thickness grew fairly linearly in a bimetallic Cu–Sn thin film at room temperature but no Cu₆Sn₅ IMC was detected. Dinsfeld and Ramon [2] melted 30Sn–70Pb solder on plug-and-ring copper specimens at 310 °C for a prolonged period of time (up to 64 s). It was observed that the mean thickness of the interfacial intermetallic layer formed increased parabolically with the reaction time of molten solder with copper. Sunwoo et al. [3] studied the intermetallic formation and growth in a double shear specimen structure with eutectic solder between a stack of three copper plates and concluded that only the Cu₆Sn₅ η-phase intermetallic was formed in as-solidified eutectic solder joints. Grivas et al. [4] submerged copper plates in a molten bath of 95Pb–5Sn solder at 400 °C, where it was seen that only ε-phase Cu₃Sn intermetallic compound was present and the interfacial IMC layer thickness increased almost linearly with the time for which the solder was molten.

However, most of the previous works were either performed under nonstandard industrial reflow conditions or are not of direct relevance to practical surface mounted solder joints fabricated from a conventional infrared reflow process. In view of the solder joint miniaturization in advanced surface mount technology, the applicability of these previous data is rather limited for small-geometry solder joints. Therefore, the present studies will focus on 0805 and 1206 LCCC solder joints that are close to those found in practical surface mount PCB assemblies. The effects of various process variables such as reflow time and temperature on the formation kinetics of Cu–Sn IMC's are investigated. It is hoped that such a study
Fig. 1. Basic process flow of experiments.

Fig. 2. A typical IR-reflow temperature profile.

can throw light on some of the critical reliability problems encountered in practical surface mount PCB assemblies.

III. EXPERIMENTAL PROCEDURE

The basic process flow of the experiments carried out is shown in Fig. 1. Four 0805 LCCC and eight 1206 LCCC resistors were soldered on FR-4 PCB's using a standard infrared reflow process: MULTICORE SN63 RM92 solder paste of 63Sn-37Pb were applied onto the PCB using stencil printing. The amount of solder paste applied on each copper land pad was carefully controlled in order to minimize the effect of different amounts of tin available for Cu–Sn intermetallic formation in the soldered joint. The solder paste height was measured to be within 160–180 μm. Components were then placed onto the copper pads of the PCB using a semi-automatic pick-and-place machine. The surface mount assembly was subsequently passed through a PRECISOLD PS-3000 IR reflow soldering system.

To study the effect of reflow time and temperature on the formation of Cu–Sn intermetallic compounds, different IR-reflow temperature profiles were selected (as typical IR-reflow temperature profile is shown in Fig. 2). Seven specimens were
reflowed at 230 °C for various times, whereas the other seven were reflowed at different temperatures for 100 s. The preheat temperature and time were kept constant at 100 °C and 100 s. From our previous work [14], such a preheat condition could minimize the formation of porosity in surface mount solder joints.

For metallographic observations, specimens of single component were first mounted in Klarmount and cross-sectioned perpendicular to the solder-copper interface of the solder joint. They were then successively grounded down to 1000 grit on a silicon carbide paper under water cooling. Polishing was performed using 5 μm Al₂O₃ suspension followed by 0.25 μm diamond compound in Aerosol. The specimens were etched in a freshly prepared mixture of 4 ml concentrated H₂O₂, 6 ml concentrated NH₄OH, and 6 ml H₂O for 30–60 s to reveal the Cu₃Sn phase. This was followed by deep etching...
in a dilute solution of 2% concentrated HCl, 6% concentrated HNO₃ and 92% H₂O, as this process would blacken the Sn–Pb solder for 30 s to contrast the boundary between Cu₆Sn₅ and the solder. Both optical and scanning electron microscopy (SEM) were used to study the microstructural morphology of Cu–Sn intermetallic compounds in the as-soldered solder joint. A powerful image processing system incorporating a NIKON optical microscope and OPTIMAS software was used to observe the microsection of the sample and measure the mean IMC thickness.

IV. RESULTS AND DISCUSSION

A. Microstructural Morphology in As-Solidified IR-Reflowed Solder Joint

Fig. 3(a) is a high magnification SEM micrograph of the solder–copper substrate interface in an as-solidified 0805 surface mount solder joint reflowed at 230 °C for 25 s. A continuous layer of ε-phase Cu₆Sn₅ intermetallic compound located at the solder–copper substrate interface was identified by means of EDX and ZAF-4 analyzes. Such an IMC layer has a fine globular structure. No evidence of the ε-phase Cu₃Sn IMC was found in the as-solidified solder joint. This can simply be explained by the equilibrium phase diagram of Cu–Sn binary system [9] shown in Fig. 4. From this, ε-phase can only be formed when the eutectic solder joint is reflowed at a temperature greater than 415 °C, the peritectic temperature of the ε-phase. Other researchers [5]–[8] found that ε-phase IMC was formed at the copper/ε-phase interface only after prolonged ageing of that solid solder/solid copper substrate interface. Boundaries of the ε-phase Cu₆Sn₅ interfacial intermetallic layer were more easily observable in the back-scattered electron image shown in Fig. 3(b). Such a closely matched boundary of the IMC layer in the as-solidified solder joint indicates that tin is the dominant diffusion species through the ε-phase intermetallic compound for the formation of Cu–Sn intermetallic compound during infrared reflow, in good agreement with the results of Mei et al. [9].

Besides, it was generally observed in all solder joints that the Cu–Sn interfacial intermetallic layer formed underneath the component terminal metallization was thinner than that formed below the bulk solder (Fig. 5). In the present study,
Fig. 7. (a) EDX and (b) ZAF-4 results showing the presence of only Cu$_6$Sn$_5$ in the interfacial IMC layer in SMT solder joint even after prolonged period of reflow.

Fig. 8. Mean interfacial Cu-Sn intermetallic layer thickness in both 0805 and 1206 surface mount solder joints as a function of reflow time.

The metallization of both 0805 and 1206 leadless components was solder plated nickel layer. Although the dissolution rate of Ni in liquid solder is much slower than that of Cu [10], [11], Ni-Sn intermetallic compound could indeed be formed as well. The competition for tin due to the Ni-Sn and Cu-Sn intermetallic formation in the solder joint would eventually tend to lower the formation rate of the latter. This undesirable effect is expected to be more serious and can cause reliability problems in fine pitched surface mount solder joints where the solder thickness between component lead and copper substrate is very small.

**B. Effect of Reflow Time**

0805-type and 1206-type solder joints infrared-reflowed at 230 °C for various times were studied. As shown in Fig. 6, the interfacial Cu$_6$Sn$_5$ intermetallic was thicker for longer
reflow time and again no Cu₃Sn η-phase was revealed by EDX and ZAF-4 analyzes (Fig. 7) even after prolonged period of infrared reflow. The mean thickness of the interfacial Cu–Sn intermetallic in both 0805 and 1206 solder joints as a function of reflow time is shown in Fig. 8.

It can be seen that the formation rate of the interfacial intermetallic layers in both 0805 and 1206 solder joints is fairly linear. According to classical kinetic analysis, a linear growth rate indicates that the formation of the interfacial Cu–Sn intermetallic layers is an interfacial-reaction-controlled process. The formation of the interfacial IMC layer in a liquid solder/solid η-phase/solid Cu substrate matrix involves two rate-determining steps: 1) diffusion of tin through the formed η-phase to the η-phase/copper substrate and 2) reaction between tin and copper at the interface to form the IMC layer. Since at such a high reflow temperature, tin in liquid solder may move around freely and the diffusion of tin through the already formed η-phase Cu₃Sn₅ intermetallic layer is fast, makes the whole process of the interfacial intermetallic formation to be reaction-controlled. Moreover, only trace amounts of Cu–Sn IMC whiskers were observed even after 150 s of IR-reflow (Fig. 9).

In addition, it was found that the formation rate of the interfacial IMC layer in 0805 solder joints was slightly higher than that in the 1206 solder joint. This can be explained by the fact that the heat supply rate from the panel heater of the IR-reflow machine is constant during soldering. The larger 1206 land pad size means more reactions between copper and tin are required to form one crystal layer of the interfacial Cu–Sn intermetallic compound. Thus, the thickening of intermetallic layer between the copper substrate and solder may be suppressed by a larger copper land pad.

C. Effect of Reflow Temperature

The mean thickness of the interfacial Cu–Sn intermetallic layer in 0805 solder joints reflowed at various temperatures for 100 s versus the reflow temperature is shown in Fig. 10. The intermetallic layer increases fairly linearly with reflow temperature from 190 °C to 250 °C and attains a peak thickness of about 2.5 μm. It then drops slightly for higher reflow temperature. This small drop in layer thickness is attributed to the development of Cu–Sn whiskers in the bulk solder of solder joints reflowed at higher temperature, as illustrated in series of optical micrographs in Fig. 10.

At lower reflow temperature, the formation rate of Cu–Sn intermetallic is so slow that its formation is confined to the solder–copper interface during the reflow time (100 s) in this study. Hence no Cu–Sn whisker was observed in the bulk solder [Fig. 11(a)]. At higher reflow temperature, the formation rate is faster and the IMC intermetallic layer thickness increases with reflow temperature for a given reflow time. The thickness of the interfacial IMC layer reaches a saturated value of about 2.5 μm at a reflow temperature of 250 °C within the designated reflow time. Further formation of Cu–Sn intermetallic appears as faceted rod-like crystal growing out, most likely by a screw dislocation mechanism, from the interfacial intermetallic layer into the bulk solder. The rods then break off by turbulence in the molten solder [12] and reappear as whiskers in bulk solder of the solder joint [Fig. 11(c)]. The random breaking point of the faceted Cu₃Sn₅ rods leaves behind different amounts of Cu–Sn intermetallic compounds in the interfacial layer. As a result, the mean thickness of the interfacial intermetallic layer tends to fluctuate around the saturated thickness.

V. CONCLUSION

From a systematic study of the Cu–Sn intermetallic formation in both 0805 and 1206 LCCC solder joints fabricated through a conventional infrared reflow process, it is clearly shown that a continuous layer of η-phase Cu₃Sn₅ intermetallic compound, as confirmed by SEM and EDX analyzes, is present at the solder-copper interface in all the solder joints.
No evidence of $\varepsilon$-phase Cu$_3$Sn intermetallic is found. The formation rate of the interfacial Cu–Sn intermetallic compound beneath the component terminal metallization is also found to be suppressed by Sn-metal (Sn–Ni in the present case) intermetallic compound formed at the solder/component terminal metallization interface. However, the precise quantitative effect on the mechanical properties or reliability of solder joint requires further investigation for a better understanding. The mean thickness of the $\eta$-phase interfacial intermetallic layers in both 0805 and 1206 solder joints increases almost linearly with reflow time up to 200 s and the formation rate in a 0805 solder joint is faster than that in a 1206 solder joint under similar reflow conditions. This is most likely due to the larger land pad size of the 1206 LCCC solder joint. Moreover, the thickness of the interfacial Cu–Sn IMC layer in 0805 LCCC solder joints that have been infrared-reflowed for 100 s increases with increasing reflow temperature up to around 250 °C and reaches a saturated thickness of 2.5 $\mu$m. Above this temperature, additional growth of the IMC is found to be minimal. Instead, the additional formation of Cu–Sn IMC's simply appears as Cu–Sn whiskers in the solder bulk of the joint. Generally, it is observed that the copper land pad size and quality of component lead metallization greatly affect the formation of Cu–Sn IMC in surface mount solder joints, and hence its reliability in terms of thermal fatigue life and mechanical properties.

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References


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