Effects of Reflow Profile and Thermal Shock on Intermetallic Compound Thickness for SnPb and SnAgCu Solder Joints

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Abstract
During the solder reflow processes many reactions occur. There is the reduction of oxides on the metal surfaces, metal dissolution, wetting to different surfaces, and intermetallic compound formation between the bulk solder and the metals being soldering. The intermetallic compound (IMC) is necessary for good solder interconnections. However an excessive IMC may raise solder joint reliability concerns due to its brittle nature. Therefore, a proper IMC thickness is critical for solder joint integrity. The amount of IMC formation is a function of reflow time (Time above Liquidus) and temperature (Peak Temperature). In a Pb-free process, both reflow temperature and time can increase, possibly increasing the thickness of intermetallic formed. During thermal shock, thermal aging or thermal cycling, IMC will grow as well.

The purpose of this study was to investigate the effects of reflow time, reflow peak temperature, and thermal shock on IMC thickness. Four different sizes of chip resistor (1206, 0805, 0603, and 0402) were attached to OSP surface finish boards with Sn-3.0Ag-0.5Cu (SAC305) solder alloy paste. Traditional Sn-37Pb eutectic solder paste was used as the control in this study. Nine reflow profiles for SAC 305 and nine reflow profiles for SnPb were developed with three levels of peak temperature (12°C, 22°C, and 32°C above solder liquidus temperature, or 230°C, 240°C, and 250°C for SAC 305; and 195°C, 205°C, and 215°C for SnPb) and three levels of time above solder liquidus temperature (30 sec., 60 sec., and 90 sec.). Half of the test vehicles were then subjected to air-to-air thermal shock conditioning from -40 to 125°C for 500 cycles.

IMC thickness was measured using Scanning Electron Microscopy (SEM) with Energy Dispersive Spectroscopy (EDS). The results show that the IMC thickness increases with higher reflow peak temperature and longer time above liquidus together with thermal shock testing.

Introduction

Long-term reliability of solder interconnections depend on the intermetallic compound (IMC) formation (Miric and Grusd, 1998). IMC is necessary for a good solder interconnection and its presence shows a bonding layer between the bulk solder and component termination and/or board substrates. The IMC in SnAgCu soldering mostly consists of Cu_6Sn_5 and Ag_3Sn. Solder joint strength can be affected by both lack of IMC as well as excess IMC within the solder joint. If an excessive amount of IMC was formed, its brittle property may raise solder joint fatigue reliability concern.

Reflow profile has a key role in determining the IMC thickness. During the reflow process, the base metal e.g. copper, dissolves into the molten solder and forms the IMC layer at the interface. The effect of reflow profiles on solder joint IMC formation, wetting characteristics, shear strength performance through thermal ageing, and microstructure characterization have been studied widely (Arra, et al., 2002; Bukhari, et al., 2005; Oliver, et al., 2000; Salam, et al., 2004). Salam, et al. (2004) concluded that the peak temperature and the time above liquidus (TAL) during the reflow process are the most critical parameters impacting solder joint reliability. Harris and Chaggar (1998) considered that the most influential factor that affects the quantity of IMC is the nature of the base materials, followed by the reflow peak temperature and the TAL.

It is well known that the liquidus temperatures of a majority of lead-free alloys are higher than that of eutectic SnPb alloy. The liquidus temperature of Sn3.8Ag0.7Cu and Sn3.0Ag0.5Cu is between 217 and 219°C, which is 34 – 36°C higher than eutectic SnPb solder. How significant does the higher reflow temperature contribute to the amount of IMC formation has been indicated by Roubaud and Henshall (2001) who concluded that the higher lead-free solder reflow temperature (250°C) did not lead to a significantly higher thickness of IMC layer between the bulk solder and copper substrate in lead-free assemblies. Arra, et al. (2002) found that the thickness of IMC layer between the solder and the component increased when the peak temperature and the time above liquidus increased. They reported that the IMC thickness between a 1206 component and the SnAgCu solder increased from 2-3μm to 5-8μm when the reflow time above liquidus was increased from 30 to 90 seconds.

Aging can cause IMC growth as well. Salam, et al. (2004) presented a study of the reflow profile on IMC thickness and reported that the IMC thickness of SnAgCu solder joints increased from 1-2.5μm to 3-4.5μm after ageing at 150°C for 300 hours.

The objective of this study was to investigate the effect of reflow profile and thermal shock on the solder joint shear strength and IMC thickness. The experimental setup and the effect of reflow profile on the solder joint shear strength have been reported (Pan, et al., 2006a; 2006b). The effect of thermal shock on the solder joint shear strength has also been presented (Webster, et al., 2006). The paper will report the effect of reflow profile and thermal shock on the IMC thickness for Sn3.0Ag0.5Cu alloy.

Experimental Design and Procedures

A five-factor factorial design with mixed levels and three replications was selected in the experiment. The input variables were the peak temperature, the duration of time above solder liquidus temperature or TAL, solder alloy, component size, and thermal shock. The peak temperature and the TAL have three levels each and they were: the peak temperature at 12°C, 22°C, and 32°C above solder liquidus temperatures (or 230°C, 240°C, and 250°C for SAC 305 and 195°C, 205°C, and 215°C for SnPb), and the TAL at 30 seconds, 60 seconds, and 90 seconds for both alloys. Therefore, there are nine reflow profiles for eutectic SnPb solder and nine for Sn3.0Ag0.5Cu (SAC305) solder. Test boards were assembled with four different sizes of pure tin plated surface mount chip resistors (0402, 0603, 0805, 1206). The board finish of the test vehicles was Organic Solderability Preservative (OSP). There were fourteen of each resistor size on each board, or 56 components total per board as shown in Figure 1. Three boards were assembled for each experimental run so a total of 54 boards were assembled (3 peak temperatures x 3 TAL x 2 solder alloys x 3 replications). The experimental matrix is listed in Table 1. A 0.1 mm (4 mil) thick laser-cut electro-polished stencil with 1:1 aperture to pad ratio was used. Both SnPb and SAC305 paste were Type 3 with no-clean flux. The reflow process was done in air.

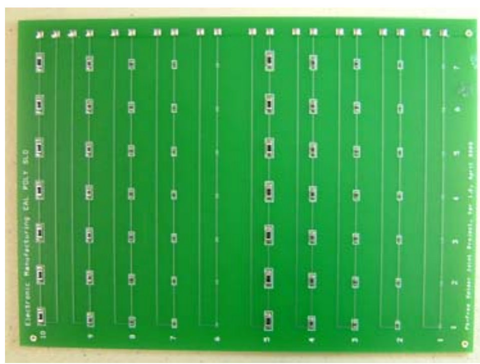

Figure1 - Test Vehicle

Table 1 - Experiment matrix

Factors	**Levels**			
	1	2	3	4
Peak temperature above solder liquidus temperature (°C)	12	22	32	
TAL (sec.)	30	60	90	
Component size	1206	0805	0603	0402
Solder alloy	SnPb	SAC305		
Thermal shock	Before	After		

Each board was cut into two identical pieces. The first half of the board was for the initial time zero evaluation after assembly and the components on the other half of the board were thermally shocked after assembly. The thermally shocked test vehicles were subjected to air-to-air thermal shock conditioning from -40 to 125°C with 30 minute dwell times (or 1 hour per cycle) for 500 cycles.

Samples both from the initial time zero and after thermal shock were cross-sectioned to measure the IMC thickness. The samples were encapsulated in a mixture of epoxy resin and hardener. Care was taken during grinding to not put excessive pressure on the sample to present the different metal layers be smeared. The grit size started from 120, following by the number 320, 600, 800, 1200, 2400, and 4000. For each grit size, the technique was to hold the sample in one direction with a scratch pattern opposite to the previous one. The samples were then polished using 0.3 and 0.05 alumina slurries. For the polishing steps, the samples were rotated against the wheel rotation. The last steps were the etching with 50-50 of NH_4OH and H_2O_2 then sputter coating with approximately 100 Angstroms of platinum.

The IMC thickness was measured using Scanning Electron Microscopy (SEM) at 5000X magnification with Energy Dispersive Spectroscopy (EDS). There were five measurements on each sample and one sample for each reflow profile. To keep consistency, only the 0603 resistor from each reflow profile was cut out for IMC thickness measurement. Although the IMC formed at both the board pad and component terminal side of the solder joint, only the IMC layer at the board side was measured. This was because the IMC layer on the component side usually was very thin and not easy to distinguish for measurements. Figure 2 shows a sample image of a cross-sectioned sample, and Figure 3 is a magnified image from the rectangular area of Figure 2 showing the solder joint layer structure where the IMC layers can be seen both at the terminal and board pad sides of the joint.

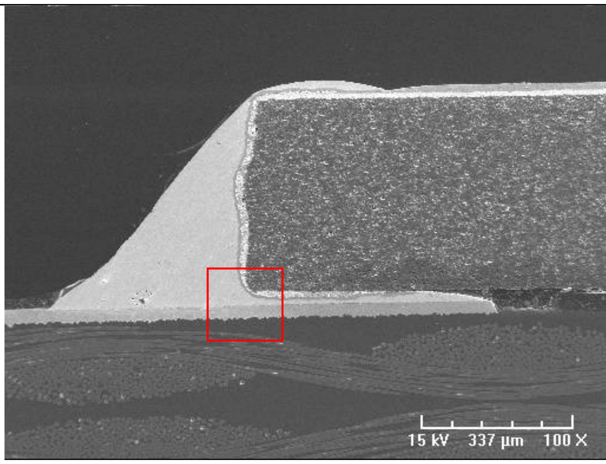

Figure 2 - 0603 Chip Cross-section Sample (100X)

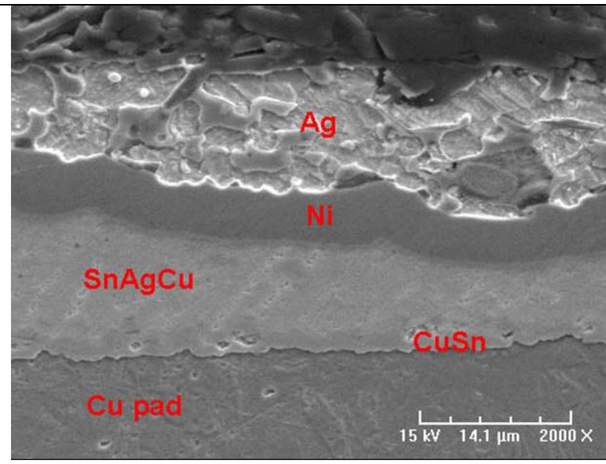

Figure 3 - 0603 Chip Cross-section Sample (2000X)

Results and Discussion

IMC Thickness vs. Reflow Profile

The IMC thicknesses found for this study are summarized in Table 2. Figure 4 shows the SAC305 solder joint IMC thickness before thermal shock increased as the peak temperature and the time above liquidus increased. The IMC thickness increased by 66% when the reflow peak temperature increased from 230°C to 240°C whilst the time above liquidus was kept the same at 90 seconds. But the IMC thickness did not increase when the reflow peak temperature changed from 240°C to 250°C with the same TAL. It was found that there was about a 30% increase in IMC thickness when the TAL increased from 30 sec. to 90 sec. at the peak temperatures of 240°C and 250°C.

Table 2 - IMC Thickness of SAC305 Solder Joints on OSP/Cu Board for Different Reflow Profiles

Reflow Profile		IMC Thickness (µm)			
Peak Temperature (°C)	Time above Liquidus (sec.)	Before Thermal Shock		After Thermal Shock	
		Mean	Standard deviation	Mean	Standard deviation
230	30	1.12	0.04	1.88	0.12
	90	1.14	0.15	1.83	0.18
240	30	1.45	0.03	1.87	0.54
	90	1.90	0.14	2.47	0.42
250	30	1.43	0.08	1.97	0.38
	90	1.91	0.14	2.17	0.51

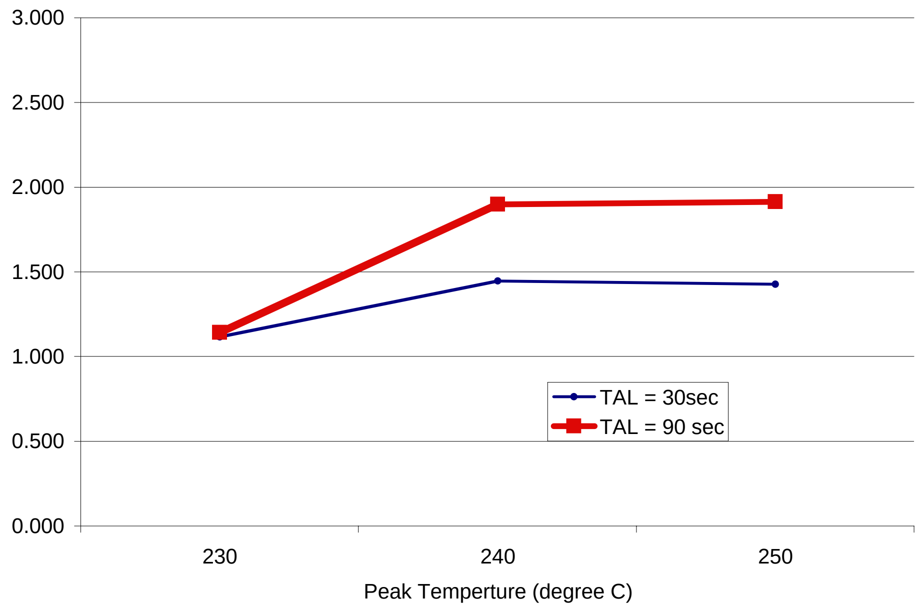

Figure 4 - IMC Thickness of SAC305 Solder Joints before Thermal Shock

IMC Thickness vs. Thermal Shock

IMC thickness comparisons before and after thermal shock from -40 to 125°C for 500 cycles are shown in Figure 5. All the samples appeared a noticeable increase in IMC thickness after thermal shock. There was an over 60% increase in IMC thickness after thermal shock when samples were reflowed at the peak temperature of 230°C. But much smaller increases were found after thermal shock when the initial IMC thickness reached 2 µm. This may be explained by the fact that a thick IMC layer would limit further dissolution of Cu into Sn to form the IMC. Figures 6 and 7 are the cross-sectioned images of 0603 components reflowed at the peak temperature of 240°C and the TAL of 30sec., where the IMC thickness of Cu-Sn was measured by vision gage software. It clearly shows that the IMC thickness after thermal shock was thicker than that before thermal shock.

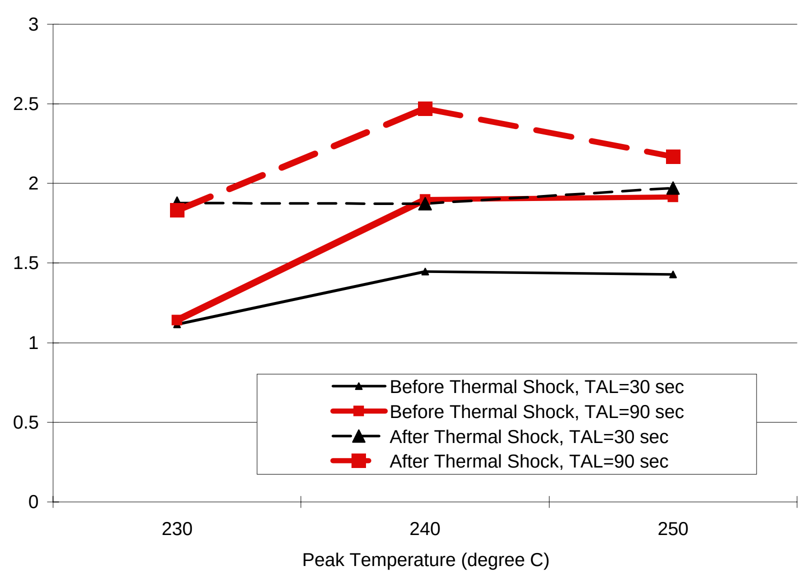

Figure 5 - IMC Thickness Comparison Before and After Thermal Shock

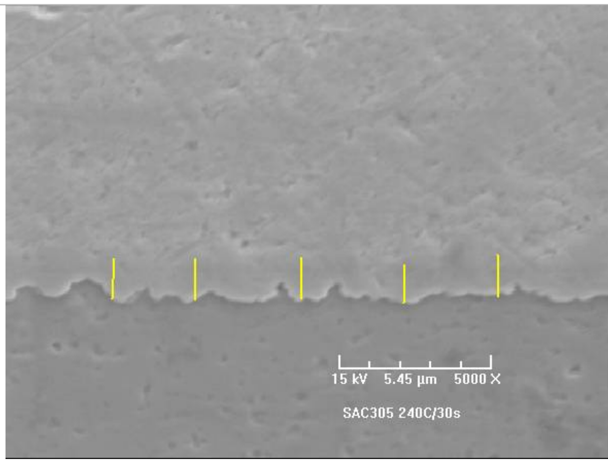

Figure 6 - IMC Thickness Before Thermal Shock

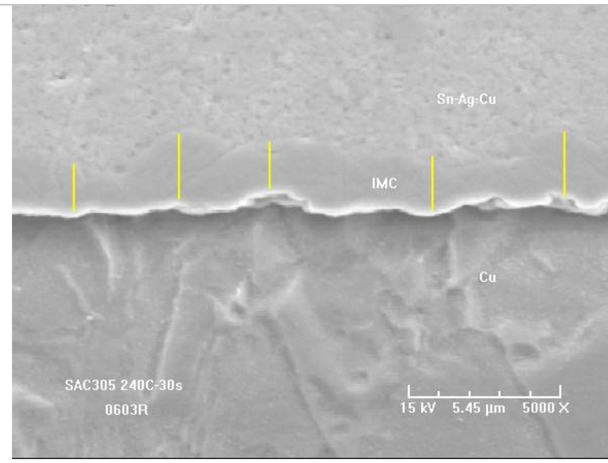

Figure 7 - IMC Thickness After Thermal Shock

IMC Thickness vs. Solder Alloy

The IMC thickness of SnPb and SAC305 solder joints are compared in Table 3. It shows that the IMC of SAC305 solder joints is slightly thicker than that of SnPb solder joints when reflowed at the same peak temperature above liquidus and the same time above liquidus. The results suggest that the high reflow temperature of SnAgCu solder leads to a thicker IMC. It could be explained by the copper dissolving faster at the high reflow temperature and the higher tin content of 96.5Sn3Ag0.5Cu compared with Sn37Pb resulting in more IMC formation.

Table 3 - IMC Thickness Comparison between SAC305 Solder Joints and SnPb Solder Joints

Reflow Profile		IMC Thickness (µm)			
Peak Temperature above liquidus (°C)	Time above Liquidus (sec.)	SnPb Solder Joints		SAC305 Solder Joints	
		Mean	Standard deviation	Mean	Standard deviation
12	30	0.95	0.10	1.12	0.04
	90	1.23	0.10	1.14	0.15
22	60	1.17	0.10	1.29	0.10
32	30	1.05	0.08	1.43	0.08
	90	1.49	0.11	1.91	0.14

Conclusions

The IMC thickness of both SnPb and SAC305 solder joints under different reflow profiles was compared. The IMC thickness of all samples was below 3µm for both SnPb and SAC305 solder joints reflowed at the peak temperature ranging from 12 to 32°C above liquidus temperature and at the time above liquidus ranging from 30 to 90 seconds, before and after thermal shock.

The IMC thickness increased as the peak temperature and the time above liquidus increased. But the increase of IMC thickness was not linear with the peak temperature and the time above liquidus.

Thermal shock from -40 to 125°C for 500 cycles leads to slightly thicker IMC layer. It was also found that there were much smaller increases after thermal shock when the initial IMC thickness had reached 2 µm. The result may imply that a thick IMC layer would limit further dissolution of Cu into Sn to form more IMC.

The IMC of SAC305 solder joints was slightly thicker than that of SnPb solder joints for the same peak temperature above liquidus and for the same time above liquidus. The results suggest that the high reflow temperature of SnAgCu solder and an increased percentage of Sn in SnAgCu compared with Sn37Pb lead to a slightly thicker IMC.

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