Backward Compatibility Study of Lead Free Area Array Packages with Tin-Lead Soldering Process

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Abstract
In response to RoHS and other international environmental legislation, the semiconductor industry is moving toward the elimination of lead (Pb) from packages. During the transitional period, both leaded and lead-free components coexist with tin-lead and lead-free soldering processes. The compatibility of lead-free area array packages with tin-lead soldering processes is a critical issue if the transition becomes prolonged as several product categories may take advantage of the exemptions and continue to be built with tin-lead solder for some time to come.

The issue of “backward compatibility” arises because for BGA packages, the contribution of solder balls to the solder joint material is very high (typically of 70% to 80%), and the assembly of lead-free BGA packages with tin-lead paste becomes a major concern from the perspective of solder joint metallurgical uniformity and reliability.

In this study, the solder joint metallurgy of mixed alloys was characterized, and the amount of mixing of Pb through the solder joint was analyzed, for different package types and under various process conditions. The results showed that the solder paste amount (ultimately tin (Sn) percentage in the alloy) and the reflow temperature play critical roles in the mixed alloy assembly, both in terms of compositional homogeneity and voiding. Homogeneous solder joints were seen at various reflow temperatures ranging from 210°C to 230°C, depending on the Sn percentage in the mixed solder alloy. This study will shed some light on the process optimization for backward compatible assemblies in order to improve yield and to create more reliable solder joints.

Key Words: Lead-free, SAC, mixed alloy, backward compatibility, backward compatible assembly, tin percentage, reflow temperature.

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Introduction
Although lead-free area array packages assembly with tin-lead solder paste is not recommended, such assemblies exist and will continue to exist for some time. Although many studies have been performed and published in the industry, debates are still on-going regarding whether BGA/CSP packages with lead-free solder spheres should be reflowed using a tin-lead paste and on what process conditions [1-5]. What is the minimum peak temperature in which such assemblies can be reflowed and still achieve a homogeneous microstructure and acceptable reliability? What is the effect of SnPb solder paste volume and reflow temperature on mixed alloy solder joint reliability? This study focuses on process optimization and the metallurgy of mixed alloy assemblies to answer some of these questions, while on-going studies will help address the critical question of reliability in a future publication.

Theory
When SnAgCu balls are assembled with SnPb paste on the substrate, Pb and Sn are the two most dominant elements in the mixed alloy, as the amounts of Ag and Cu are relatively small. If we assume that they have a minimal impact on the melting temperature of the mixed alloy, the SnPb phase diagram (Figure 1) can then be used to explain the behavior of the mixed alloy at different reflow temperatures.

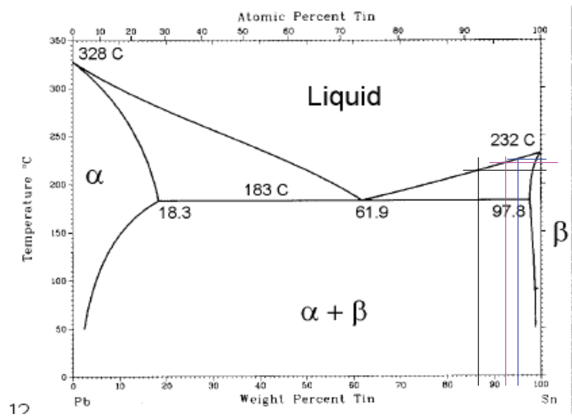

Figure 1 - Sn-Pb Phase Diagram

During reflow, when the temperature reaches 183°C and above, the eutectic SnPb solder paste melts and is in the liquid state. The SnPb liquid diffuses into the SnAgCu ball and dissolves some solder (Sn) from the SnAgCu ball until the equilibrium concentration is reached. The dissolution of Sn into the SnPb solder increases as the temperature increases. More SnPb solder paste dissolves more Sn from the SnAgCu ball at the same temperature. The Sn% and the corresponding theoretical liquidus temperature of the "mixed alloy" are shown in Table 1. This suggests that the mass of the SnPb solder relative to the mass of the SnAgCu ball, as well as the temperature, determine the degree of dissolution and mixing.

The complete mixing of SnPb solder with the SnAgCu ball is critical to forming uniform and homogeneous microstructures. A homogeneous joint is believed to have better reliability than an inhomogeneous joint [3]. The question is what SnPb solder paste amount and reflow temperature are needed in order to completely homogenize the SnPb paste and the SnAgCu ball?

In this study, the percentage of Pb and Sn in the mixed alloy is calculated using the following equations:

$$Pb\% = \{m_{(Pb)}/[m_{(Sn,\ ball)}+m_{(Sn,paste)}+m_{(Pb,\ paste)}]\}\ x100\%$$
$$Sn\% =\{m_{(Sn)}/[m_{(Pb,\ paste)}+m_{(Pb,\ paste)}+m_{(Sn,paste)}]\}\ x100\%$$

In which:

$$m_{(Sn,\ ball)} = density_{(SAC305)}\ x\ V_{(ball)}\ x\ Sn\%_{(ball)}$$
$$m_{(Pb,\ paste)} = density_{(SnPb)}\ x\ V_{(actual\ solder)}\ x\ Pb\%_{(ball)}$$
$$m_{(Sn,paste)}=density_{(SnPb)}\ x\ V_{(actual\ solder)}\ x\ Sn\%_{(ball)}$$
$$m_{(Sn)} = m_{(Sn,\ ball)}+ m_{(Sn,paste)}$$

It is noted that the actual solder volume is different from the SnPb solder paste volume applied. The amount of SnPb paste was controlled by the stencil thickness and aperture.

Experimental

BGA components with solder ball composition of Sn3.0Ag0.5Cu (SAC305) were assembled to SnPb solder paste. The solder paste amount was controlled to deposit a pre-calculated Sn%. The solder paste volume was measured and analyzed using an automatic solder paste measurement machine. As mentioned above, different Sn% would require different reflow temperatures for complete mixing to occur (Table 1).

Table 1 - The Sn% and Expected Melting Temperature for Complete Mixing to Occur

Sn%	87	89	92	95
Theo. TL (°C)	213	217	221	225

Samples of different Sn% were reflowed under various reflow peak temperatures of 210°C, 215°C, 220°C, 225°C, and 230°C. Twenty different process conditions were examined, as shown in Table 2.

Table 2 - Experimental Matrix

Process Condition	Sn%	Peak Temp. (deg C)
1	87	210
2	87	215
3	87	220
4	87	225
5	87	230
6	89	210
7	89	215
8	89	220
9	89	225
10	89	230
11	92	210
12	92	215
13	92	220
14	92	225
15	92	230
16	95	210
17	95	215
18	95	220
19	95	225
20	95	230

The oven settings were controlled so that only the peak temperature changed, and the other reflow conditions were the same (or similar). Even though N_2 is typically not required for lead-free reflow, it is used in this study in order to minimize the number of variables. The time above the SnPb melting temperature was around 80-90 seconds. This time was necessary for the concentration equilibrium to be reached and for maximum possible mixing of the SnPb solder paste and SnAgCu ball to occur. The reflow profiles at 210°C and 220°C are shown in Figure 2 and 3, respectively. The temperature difference within a package and between the theoretical and actual values was typically within 1-2°C.

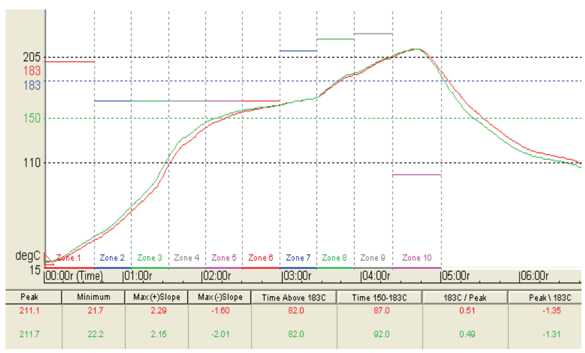

Figure 2 - Reflow Profile at 210°C Peak Temperature

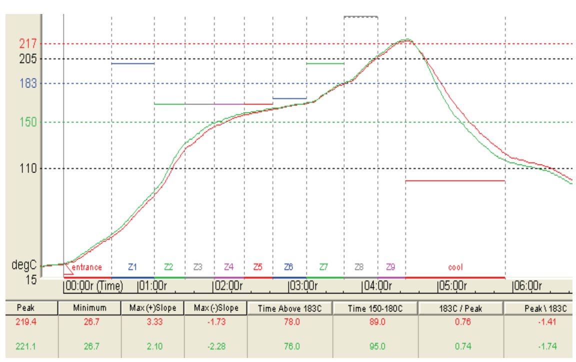

Figure 3 - Reflow Profile at 220°C Peak Temperature.

2D transmission x-ray equipment was used to inspect and characterize voids in the solder joints. Cross sectioning and SEM analysis were performed to characterize the metallurgical integrity of the solder joints and the mixing of Pb in the lead-free solder.

Results and Discussion

Void Characterization and Analysis

The main effect plot for void percentage and for area of largest voids are shown in Figure 4 and Figure 5.

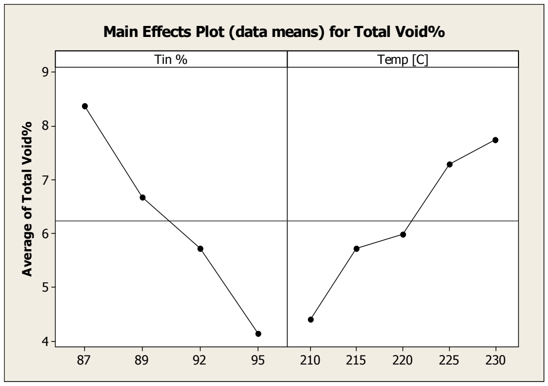

Figure 4 - Main Effects Plot for Total Void%

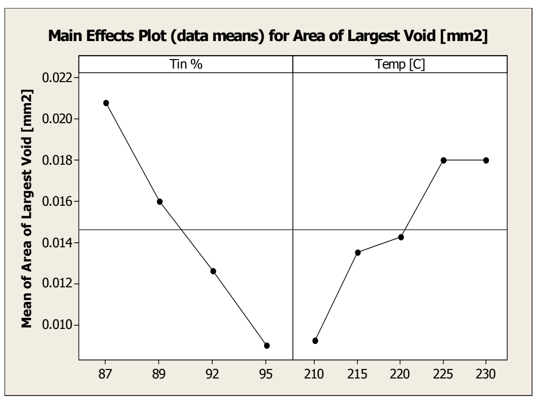

Figure 5 - Main Effect Plots for Area of Largest Void.

The results showed that more and larger voids were seen when the Sn% increased and/or when the reflow temperature increased. This means that if we increase the amount of SnPb solder paste used, we would see fewer voids and smaller voids. When the assembly is reflowed at higher temperatures, more voids can be expected, probably due to the interaction of fluxes with temperature.

Examples in Figures 6-7 show that high Sn% and low reflow temperatures resulted in the least amount of voids and smaller voids in the solder joints (Figure 6), whereas low Sn% and high reflow temperatures resulted in more voids and larger voids (Figure 7). In the case of 95% Sn reflowed at 210°C, only 1.9 % total voiding was seen in the solder joint, and the average area of largest voids in the joints was $0.004mm^2$ (Figure 6). In the case of 87% Sn reflowed at 230°C, on the other hand, 9.2% total voiding was observed, and the average area of largest voids was $0.022mm^2$ (Figure 7).

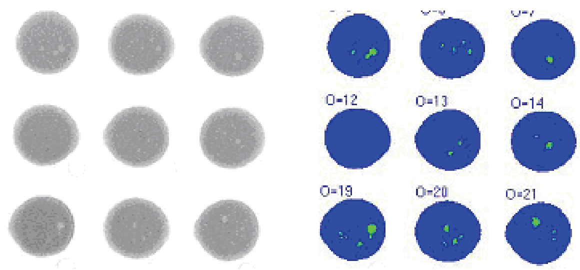

Figure 6 - X-Ray Radiograph of BGA Package on High Sn % and Low Reflow Peak Temperature (best case scenario of void)

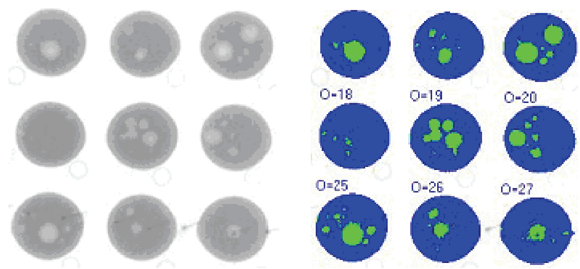

Figure 7 - X-Ray Radiograph of BGA Package on Low Tin % and High Reflow Temperature (worst case scenario of voids)

Solder Joint Characterization and Analysis

Cross sectioning was performed to analyze the mixed alloy solder joint characteristics. Surprisingly, good mixing of Pb into the SnAgCu ball was seen in most cases, and Pb was fairly uniformly distributed from the top to the bottom of the solder joints, with the only exception of 95 Sn% reflowed at 210°C (Figure 8). In this case, the Pb-rich phase looks like veins in the cross section image, and very little Pb was seen near the component side of the solder joint. The microstructure of the solder joint looked much rougher than typical SnPb solder joint (Figure 9) and SnAgCu solder joint (Figure 10).

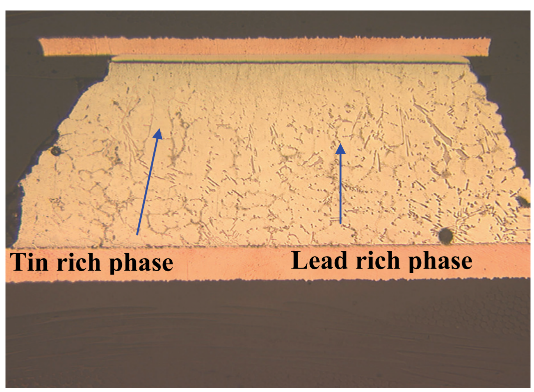

Figure 8 - Cross-Section Image of BGA Package, with About 95% of Sn in The Mixed Alloy, Reflowed at 210°C

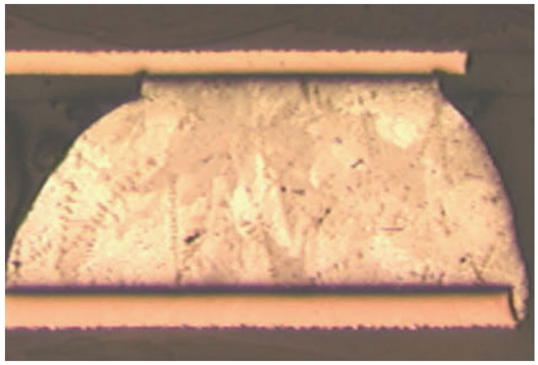

Figure 9 - Tin-Lead Solder Joint of The Same Component Type

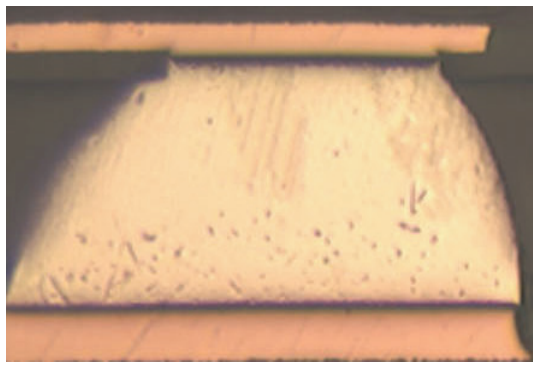

Figure 10 - SnAgCu Solder Joint of The Same Component Type

There were noticeable differences in the microstructure of mixed alloy joints assembled at different process conditions. Samples with higher Sn content and reflow temperatures (Figure 11) appeared to exhibit smaller and more finely dispersed Pb-rich phases than samples with lower Sn content and reflow temperatures (Figure 12).

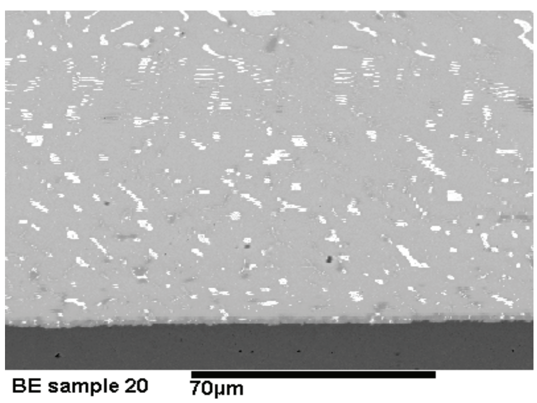

Figure 11 - SEM Micrograph of Cross Section of Sample with High tin Content Reflowed at High Temperature

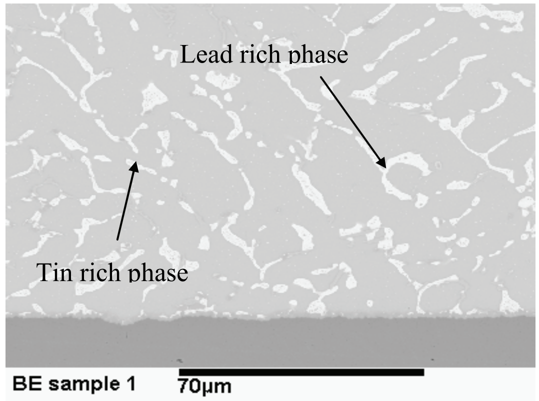

Figure 12 - SEM Micrograph of Cross Section of Sample with Low Tin Content Reflowed at Low Temperature

The microstructure of mixed alloy solder joints assembled at low Sn content and high reflow temperatures is shown in Figure 13, and the solder joint microstructure of a sample assembled at a high Sn content and low reflow temperature is shown in Figure 14. In general, the solder joints of low reflow temperatures result in a larger grain size and Pb-rich phase (Figure 12 and Figure 14). The solder joints of high reflow temperatures look more homogeneous and uniform (Figure 11 and 13).

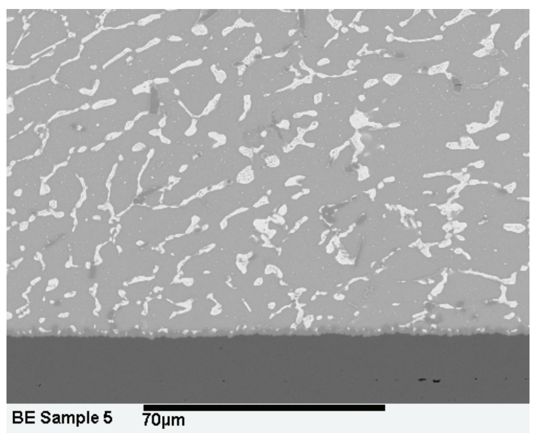

Figure 13 - SEM Micrograph of Cross Section of a Sample with Low Tin Content Reflowed at High Temperature

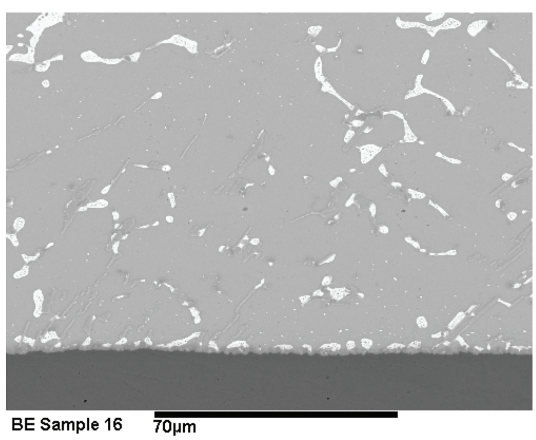

Figure 14 - SEM Micrograph of Cross Section of a Sample with High Tin Content Reflowed at Low Temperature

The SEM EDX spectra of various process conditions were analyzed. The samples have a similar EDX spectrum of the Sn-rich phase area, as shown in Figure 15.

Location/ Interested Area	Pb Area [mm2]	Sn Area [mm2]	Pb/Sn ratio	Pb % (of total joint)	Sn % (of total joint)
Top (component side, 1/3 area of joint)	2564	51549	0.05	1.46	29.41
Middle section (1/3 area of joint)	5699	53138	0.11	3.25	30.31
Bottom (PCB side, 1/3 area of joint)	7539	54798	0.14	4.30	31.26
Total	15802	159485	0.10	9.01	90.99

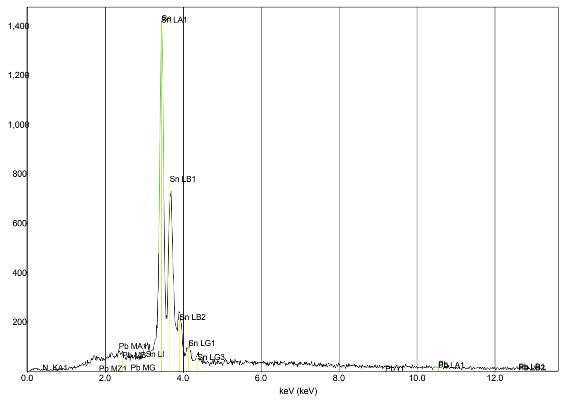

Figure 15 - Typical EDX Spectrum of The Tin Rich Phase in The Mixed Alloyed Solder Joint

Sn% and Pb% Verification

The Sn% and Pb% of the actual mixed alloy solder joint were estimated by measuring the areas of Sn and Pb in a solder joint cross section. As an example, Figure 16 illustrates how Pb areas were selected. Table 3 summarizes the estimated Pb/Sn ratio in the case of process condition #16. The estimated Sn % in the mixed alloy joint was 94.4%, close to the theoretical value (95%).

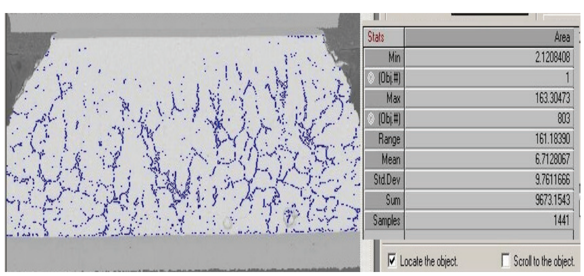

Figure 16 - Pb Area (Blue) in The Solder Joint

Table 3 - Sn% and Pb % Measurement

Location	Pb Area [mm2]	Sn Area [mm2]	Pb/Sn ratio	Pb % (of total joint)	Sn % (of total joint)
A whole joint	9673	163695	0.06	0.06	94.42

To characterize how the Pb was dispersed in a non-homogeneous solder joint, we measured the amount of Pb at different locations of the solder joint. Table 4 shows their measurements in the case of high Sn and low reflow temperature. At the bottom of the solder joint, there was about 4.3% Pb. In the middle of the solder joint, we measured about 3.2% Pb. Only 1.5% Pb was seen at 1/3 top section of the solder joint. The data showed that more Pb was present at the bottom side of the solder joint, and the Pb amount was decreasing toward the component side of the joint, indicating that Pb was vertically and gradually dispersed into the lead-free solder sphere, as the lead-free ball began to melt from the bottom side.

Table 4. Sn% and Pb % at different joint location.

Summary

The complete mixing of SnPb solder with SnAgCu depends on the volume of the SnPb solder relative to that of the SnAgCu ball and the soldering temperature. It can happen at reflow temperatures below 217°C if the right amount of SnPb solder paste is used. The reliability study of mixed alloy solder joints is on going.

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