Backward and Forward Compatibility

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Introduction

In response to the European Union (EU) Restriction of Hazardous Substances (RoHS) and other countries' impending lead-free directives, the electronics industry is moving toward lead-free soldering. Total lead-free soldering requires not only lead-free solder paste but also lead-free printed circuit board (PCB) finish and lead-free component/packages. Transitioning tin-lead (SnPb) soldering to totally lead-free soldering is a complex issue and involves movement of the whole electronics industry supply chain. In reality, there is a transition period.

In the early transition phase, consumer electronics manufacturers wanted to convert their products to be lead-free quickly to comply with environmental regulations and avoid a marketing disadvantage. But some lead-free components/packages were not available because components manufacturers were slow in responding to the lead-free transition or there was insufficient demand initially. Thus tin-lead components were assembled with lead-free solder paste. This would be termed a forward compatibility situation.

In the late transition phase, many component manufacturers had migrated to lead-free production. Since the demand for tin-lead components was low, component manufacturers did not want to carry both SnPb and lead-free production lines due to the cost concerns. Therefore, some components such as memory modules are no longer being made available in SnPb finish. On the other hand, some products, such as servers, are exempt from the EU RoHS directive until or beyond 2010. Additionally products such as medical equipment, and military and aerospace products are not required to be lead-free. These products want to continue to be built with conventional SnPb solder paste because the reliability of SnAgCu – or lead-free – solder

joints for these high reliability applications is still unknown. This scenario, soldering of lead-free components with SnPb paste, is known as the backward compatibility situation.

Table 7.1 summarizes the transition to total lead-free soldering. Tin-silver-copper (SnAgCu or SAC) solders have been considered to be the best alternative to SnPb solders for most applications. The most common alloys are Sn3.0Ag0.5Cu (SAC305) recommended by Japan Electronics and Information Technology Industries Association (JEITA) and IPC Solder Value Council and Sn3.8-3.9Ag0.6-0.7Cu recommended by iNEMI (InterNational Electronics Manufacturing Initiative) and the European consortium – BRITE-EURAM. Here Sn3.0Ag0.5Cu means 3.0% in weight Ag, 0.5% in weight Cu, with the leading element Sn making up the balance to 100% by weight.

Lead-free PCB finishes are used in both the backward compatibility and the forward compatibility assemblies. The most common lead-free PCB finishes include Organic Solderability Preservatives (OSP), Immersion Silver, Electroless Nickel Immersion Gold (ENIG), and Immersion Tin.

Table 1. Transition to Total Lead-free

	SnPb solder paste	Lead-free solder paste
SnPb components	Traditional SnPb soldering	Forward compatibility
Lead-free components	Backward compatibility	Total lead-free soldering

There are challenges in both forward compatibility and backward compatibility, especially for the BGA (Ball Grid Array)/CSP (Chip Scale Package) component for which this chapter will discuss. The microstructure and reliability data using SnAgCu BGA/CSP spheres with SnPb paste will be reviewed. The estimation of mixed solder composition liquidus temperature will be presented. The chapter then presents leadframe and chip components backward compatibility. Forward compatibility will be also briefly discussed. Finally, status of lead-free press-fit connectors will be presented.

1.1 Challenges to Backward Compatibility

Backward compatibility means lead-free packages/components attached to a printed circuit board (PCB) using SnPb solder paste. Since different package types have different metallizations, backward compatibility issues differ by package types. For BGA/CSP packages, the typical package metallization is a SnAgCu ball. For leadframe components such as Quad Flat Packages (QFPs) and Small Outline Integrated Circuits (SOICs), the typical lead-free component metallization is pure tin (Sn), Sn3.5Ag, Sn1.0Cu,

Fig. 1. Backward Compatibility for Three Package Types (a) SnAgCu BGA sphere with SnPb paste; (b) Leadfree QFP or SOIC with SnPb paste; (c) Pure Sn chip component with SnPb paste

Sn2-4% wt. Bi, NiPdAu or NiAu. For termination or chip components, the most common metallization is pure Sn. Fig. 7.1 shows backward compatibility for these three package types.

A schematic of BGA/CSP backward compatibility is shown in Fig. 7.2. The liquidus temperature of SnAgCu (SAC305 or SAC387) is between 217 to 221°C and the typical reflow peak temperature of SnAgCu solder paste is between 230 to 250°C. The liquidus temperature of eutectic SnPb is 183°C and the typical reflow peak temperature of eutectic SnPb solder paste is between 200 to 220°C. The question is what reflow profile should be used for backward compatibility assembly, a SnPb profile, a SnAgCu profile, or another profile?

If a SnAgCu profile is used, the SnAgCu solder ball will melt and the solder ball will self-align as shown in Fig. 7.3(a). But there are two issues. Firstly, the reflow temperature may be too high for other SnPb components on the same board or the board itself during assembly. Table 7.2 summarizes the component rating per IPC/JEDEC J-STD-020C. Secondly, the flux in SnPb solder paste may not function properly at such a high reflow

Table 2. Component Rating per IPC/JEDEC J-STD-020C

	Eutectic SnPb solder	SnAgCu solder
Liquidus temperature	183°C	217-221°C
Typical reflow peak temp	200 ~ 220°C	230 ~ 250°C
Component rating Per IPC/JEDEC J-STD-020C	225 +0/-5°C for large thick components (240°C for small & thin components)	245°C for large thick components (260°C for small & thin components)

Fig. 2. A Schematic of BGA/CSP Backward Compatibility

Fig. 3. Comparison of different reflow profiles in backward compatibility (a) using a SnAgCu reflow profile; (b) using a SnPb reflow profile

temperature. On the other hand, if the SnPb reflow profile is used, the SnAgCu solder ball will only partially melt and won't be self-aligned as shown in Fig. 7.3 (b). The incomplete mixing of solder and no self-alignment raise reliability concerns. Therefore, the key in BGA/CSP backward compatibility assemblies is to find the minimum reflow peak temperature to be able to achieve complete mixing of SnPb paste with lead-free components with good self-alignment.

1.2 Challenges to Forward Compatibility

Forward compatibility means tin-lead packages/components attached to a PCB using lead-free solder paste. In BGA/CSP forward compatibility shown in Fig. 7.4, a SnAgCu reflow profile is typically used. However, more voids were found in the forward compatibility solder joints [1, 2]. The greater voiding in the solder joints has become a reliability concern [3]. Another issue is that the high SnAgCu reflow peak temperature may exceed the maximum temperatures that the SnPb components are allowed to reach.

Fig. 4. A Schematic of Forward Compatibility

2 Reliability of BGA/CSP Backward Compatibility

2.1 Microstructure of Backward Compatible Joints

It is important to evaluate the joint microstructure of lead-free BGAs soldered with SnPb solder paste since the microstructure is a good indication of the solder joint reliability. The degree of mixing in backward compatibility assembly is expected to be a function of the reflow peak temperature and time above liquidus.

Grossmann et al. investigated various reflow profiles (peak temperature and time above liquidus) on the microstructure of the solder joint [4]. The package they tested was a PBGA200 with 13 mm × 13 mm component body size, 1 mm thick, 0.8 mm pitch, and 7 mm × 7 mm die size. The solder ball in the PBGA was Sn3.8Ag0.7Cu with a diameter of 0.5 mm and a height of 0.3 mm. The PCBs were made of glass epoxy FR-4 with a thickness of 1.58 mm (62 mil). The PCB finish was electroless Ni immersion Au (ENIG). The stencil used for solder paste printing was laser cut with aperture openings of 0.7 mm (28 mil) (1:1 to the pad size) and a thickness of 0.15 mm (6 mil). The solder paste was Sn36Pb2Ag, Type 3 with rosin-based no-clean flux. Table 7.3 summarizes the results of the work. Their results show that the SnPbAg solder paste interacted with SnAgCu ball even at a peak temperature of 210°C, but the solder ball was only partially mixed with the solder paste. The SnAgCu ball was fully dissolved when the peak temperature reached 217°C. The dendrites got smaller as the peak temperature increases. It should be noted that the melting point of Sn36Pb2Ag is 179°C compared with 183°C for the more common Sn37Pb solder.

Table 3. Summary of Grossmann et al. [4]'s Results

Peak tem- perature (°C)	Time above SnAgCu liq- uidus (sec.)	Time above SAC387 liq- uidus (sec.)	Results
210	62	–	SAC ball partially reacted with SnPbAg solder
217	66	–	SAC ball is fully molten, but the dispersion of Pb is inhomogeneous, IMC is formed
218	82	6	
223	71	28	Completely mixed; the dendrites are smaller than that soldered at 217°C
227	90	46	
233	76	43	Completely mixed; homogeneous distribution of the Pb-rich phase; fine IMC.
246	100	73	

Bath et al. used a FBGA676 I/O, with a pitch of 1.0 mm on their backward compatibility study [5]. The package body was 27 mm × 27 mm in body size containing a die of 17 mm × 17 mm in size. The solder ball diameter was 0.6 mm. The solder ball composition was Sn4.0Ag0.5Cu. The package surface finish was Ni/Au. The printed circuit board was made of FR-4 with a thickness of 2.34 mm (92 mil) and a size of 220 mm × 140 mm. The board finish was OSP. The stencil used was 0.127 mm (5 mil) thick with openings of 0.457 mm (18 mil) diameter. Two reflow profiles were used. One was 205°C peak temperature and 67 seconds over 183°C, and the other was 214°C peak temperature and 77 seconds over 183°C. The microstructures of the solder joints are shown in Fig. 7.5. It is clearly shown that Pb was partially diffused into the SnAgCu ball when the reflow peak temperature was at 205°C. A nearly full mixing was achieved when the reflow peak temperature was at 214°C, but the dispersion of Pb was not uniform.

Zbrzezny et al. investigated various reflow profiles and concluded that complete mixing of the solders was achieved when the reflow peak temperature reached 218 - 222°C [6].

Most of these studies believed that full mixing was achieved only when the reflow peak temperature exceeded 217°C [4, 6, 7], however, a full mixing of the SnPb paste with the SnAgCu ball can be achieved when the peak reflow temperature is below 217°C. For example, Nandagopal et al. observed that a full mixing of the SnPb paste and the SnAgCu ball was accomplished at a peak reflow temperature of 210°C for about 15 to 25 seconds [8, 9]. They used the Differential Scanning Calorimeter (DSC) to characterize the time required to achieve full mixing. Handwerker indicated that full mixing of the tin-lead paste and lead-free Sn3.9Ag0.6Cu solder ball

Fig. 5. SEM pictures of reflowed at a) 205°C peak temperature and 67 seconds over 183°C; b) 214°C peak temperature and 77 seconds over 183°C

occurred at 207°C with a sufficient time, the Sn3.9Ag0.6Cu solder ball constituting 75% of the final solder [10]. Snugovsky et al. described the mixing process using a SnPb phase diagram [11]. From the study, they concluded that a complete mixture may be achieved at a temperature lower than 217°C and that the temperature depends on solder ball composition, ball/solder paste ratio, dwell time, and component size.

2.2 Reliability of BGA/CSP Backward Compatibility

A significant number of experimental studies have been done recently on investigating the solder joint reliability of BGA/CSP backward compatibility using various reflow profiles [5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16].

Poor Reliability when the BGA/CSP Ball is Partially Mixed

It is evident that the reliability of solder joint interconnections in backward compatibility assemblies degrades significantly if SnAgCu solder spheres are only partly melted in backward compatibility. Hillman et al. evaluated the reliability of a BGA package assembled using a peak reflow temperature of 215°C with the duration time above 200°C at 40 seconds [12]. They observed partial mixing of Pb in the joint microstructure. The reliability of the solder joint was very poor as the solder joint failed at only 137 cycles in temperature cycling from -55°C to +125°C with dwell times of 11 minutes at each extreme and a ramp rate of 10°C/minute maximum per IPC-9701 guidelines. They used BGA/CSP components with Sn4.0Ag0.5Cu

solder alloy. The reflow profile was developed using thermocouples attached to the outside edge of the BGA solder spheres with conductive epoxy. The test vehicle was FR4, 2.08 mm (82 mil) thick, and a glass transition temperature of 170°C minimum. The size of the board was 203 mm × 279 mm (8 inch × 11 inch) and the board finish was ENIG with 18 layers of ½ ounce Cu. The component under test was 256 I/O daisy chained, 17 mm × 17 mm, 1.0 mm pitch, full array, Sn4Ag0.5Cu solder ball alloy. The stencil used was 0.127 mm (5 mil) thick, with 1:1 board pad to stencil aperture match and 0.381 mm (15 mil) diameter round apertures. Though solder paste volume was not measured, 95% paste transfer ratio was assumed.

Gregorich & Holmes reported that the reliability of backward compatibility assemblies when the mixed assembly was reflowed at the peak temperature of 200°C and the duration of time above 183°C at 62 seconds was much poorer than that of the control SnAgCu ball with SnAgCu paste in both the accelerated temperature cycling test from -40°C to +125°C and the mechanical shock test [13]. The poor reliability was believed to be due to the inhomogeneous microstructure resulting from partial mixing of Pb. The reliability of backward compatibility assembly improved as the reflow temperature increased to 225°C. The package investigated was a CSP with 0.5 mm pitch. These components were 14 mm × 14 mm × 1.2 mm in size. The solder spheres in the component were Sn4.0Ag0.5Cu. The PCB was 4-layer, 0.8 mm thick FR-4 board, 100 mm × 40 mm in size, with Ni/Au board surface finish. The stencil used in the study was 0.127 mm (5 mil) thick and 1:1 ratio between package land and board land.

Hua et al. reported similar results showing that incomplete mixing leads to unacceptable solder joints [7, 14]. Therefore, it is critical to achieve complete mixing of SnPb paste with SnAgCu ball in BGA/CSP backward compatibility assembly.

Reliability Comparison between Backward Compatibility versus SnPb Control and SnAgCu Control Assemblies

If complete mixing is achieved in backward compatibility assemblies, is the reliability better, equivalent or worse than that of SnPb control and SnAgCu control assemblies? There are conflicting reports about whether the reliability of backward compatibility assembly is better or poorer than that of SnAgCu balls assembled with SnAgCu solder paste. In general it is equivalent or worse. Bath et al. found that the reliability of backward compatibility assembly in accelerated temperature cycling (ATC) from 0°C to 100°C with 40 minute a cycle, even when the full mixing was achieved, was poorer than that of both SnAgCu ball/SnAgCu paste and SnPb ball/SnPb paste as shown in Fig. 7.6 [5]. It should be pointed out that there is

no statistically significant difference in reliability between the reflow peak temperature of 205°C and 215°C. But Bandagopal et al. found that the reliability of backward compatibility assembly in both ATC from 0°C to 100°C and -40°C to 125°C was better than the SnPb assembly when full mixing was achieved [8]. Bandagopal et al. also found that the reliability of backward compatibility assemblies surpassed the reliability of SnAgCu control assemblies in ATC from -40°C to 125°C, but not in ATC from 0°C to 100°C.

Although a considerable amount of work has been done so far on the backward compatibility assembly and its reliability, the minimum temperature able to achieve full mixing is still unknown. The key in backward compatibility assembly is to develop a reflow profile with the peak temperature high enough to be able to achieve full mixing of the SnPb paste and the SnAgCu ball, but low enough (prefer below 220°C) so that SnPb components and the board won't be damaged. Therefore, it is critical to know the minimum reflow peak temperature that is capable of achieving a complete mixing of SnPb paste with lead-free components.

Work in the iNEMI backward compatibility group is helping to define and understand the peak temperature and time above liquidus to use for certain types of lead-free CSP/BGA components with tin-lead paste which

Fig. 6. Backward reliability data [5]

will be put into ATC reliability testing [17]. Components to be ATC reliability tested in iNEMI project will be the SBGA600 package with a pitch of 1.27 mm and a size of 45 mm × 45 mm, the PBGA324 package with a pitch of 1 mm and a size of 23 mm × 23 mm, the CABGA288 package with a pitch of 0.8 mm and a size of 19 mm × 19 mm, and the CTBGA132 package with a pitch of 0.5 mm and a size of 8 mm × 8 mm.

3 Estimation of Mixed Composition Liquidus Temperature

3.1 Mixed Composition Calculation

There are four alloying elements in the mixed composition when SnAgCu BGA/CSP components are soldered with SnPb paste: Sn, Ag, Cu, and Pb. The percentage of each metal element in the mixed composition can be calculated [18, 19]

$$W_{Pb} = \frac{f_{Pb} \times V_{Paste} \times f_m \times d_{SnPb}}{V_{Paste} \times f_m \times d_{SnPb} + V_{Ball} \times d_{SnAgCu}} \quad (7.1)$$

$$W_{Ag} = \frac{f_{Ag} \times V_{Ball} \times d_{SnAgCu}}{V_{Paste} \times f_m \times d_{SnPb} + V_{Ball} \times d_{SnAgCu}} \quad (7.2)$$

$$W_{Cu} = \frac{f_{Cu} \times V_{Ball} \times d_{SnAgCu}}{V_{Paste} \times f_m \times d_{SnPb} + V_{Ball} \times d_{SnAgCu}} \quad (7.3)$$

$$W_{Sn} = 100 - W_{Pb} - W_{Ag} - W_{Cu} \quad (7.4)$$

where W_{Pb} , W_{Ag} , W_{Cu} , and W_{Sn} are the weight percentages of Pb, Ag, Cu, and Sn in the mixed compositions, respectively; f_{Pb} is the percentage of Pb by weight in SnPb solder paste; f_{Ag} and f_{Cu} are the weight percentage of Ag and Cu in SnAgCu alloy; f_m is the volume percentage of metal content in SnPb solder paste; d_{SnPb} and d_{SnAgCu} are the density of SnPb and SnAgCu alloys. V_{paste} is the SnPb solder paste volume, which can be calculated

$$V_{paste} = \begin{cases} L^2 H(TR) & \text{for square aperture} \\ \pi \left(\frac{D}{2}\right)^2 H(TR) & \text{for round aperture} \end{cases} \quad (7.5)$$

where L is stencil aperture length for square aperture, H is stencil thickness, D is stencil aperture diameter for round aperture, and TR is the paste transfer ratio, which is defined as the ratio of the volume of solder paste deposited to the volume of the aperture.

V_{ball} is the volume of a solder ball in the BGA/CSP component. If the ball diameter, D, is given, the ball volume can be calculated

$$V_{ball} = \frac{4}{3} \pi \left(\frac{D}{2} \right)^3 \quad (7.6)$$

If the sphere is reflowed and the ball height, H, and radius, R, are given, the ball volume can be calculated

$$V_{ball} = \frac{2}{3} \pi R^3 - \pi R^3 \left[\frac{1}{3} \left(\frac{H-R}{R} \right)^3 - \left(\frac{H-R}{R} \right) \right] \quad (7.7)$$

For eutectic SnPb solder paste, f_{Pb} is 37 and typical value of f_m is 0.5 (or 50%). For Sn3.0Ag0.5Cu solder alloy, $f_{Ag}=3.0$ and $f_{Cu}=0.5$. The density of eutectic Sn37Pb, d_{SnPb} , is 8.4 g/cm³ and the density of Sn4.0Ag0.5Cu, d_{SnAgCu} , is 7.394 g/cm³ [20].

Use the Bath et al. study [5] as an example. A 1 mm pitch BGA (FG676) package used with a 0.61 mm (24 mil) Sn3.0Ag0.5Cu ball diameter was assembled with Sn37Pb paste. The solder paste was printed using a 0.127 mm (5 mil) thick stencil with a 0.457 mm (18 mil) diameter round stencil aperture. The SnPb paste had 50% metal content in volume. Assuming a 90% solder paste transfer ratio, using Eq. 7.6, we can calculate that the volume of the Sn3Ag0.5Cu ball is 0.118 mm³ (7235 mil³). Using Eq. 7.5, we can calculate the volume of SnPb paste as 0.0188 mm³ (1125 mil³). Using Eqs. 7.1 to 7.4, we can get the final mixed alloy composition:

$$W_{Pb} = \frac{37 \times 0.0188 \times 0.5 \times 8.4}{0.0188 \times 0.5 \times 8.4 + 0.118 \times 7.394} = 3.07$$

$$W_{Ag} = \frac{3.0 \times 0.118 \times 7.394}{0.0188 \times 0.5 \times 8.4 + 0.118 \times 7.394} = 2.75$$

$$W_{Cu} = \frac{0.5 \times 0.118 \times 7.394}{0.0188 \times 0.5 \times 8.4 + 0.118 \times 7.394} = 0.46$$

$$W_{Sn} = 100 - 3.07 - 2.75 - 0.46 = 93.7$$

Therefore, the mixed alloy joint composition is 93.7% Sn, 3.1% Pb, 2.8% Ag, and 0.5% Cu, all in weight.

3.2 Estimation of Mixed Composition Liquidus Temperature

After we know the mixed compositions, the next question becomes what in this case is the liquidus temperature of the mixed composition Sn3.-1Pb2.8Ag0.5Cu. The phase diagram of common binary and ternary systems that are relevant to solders is available at the Fundamental Properties of Pb-Free Solder Alloys Chapter in this book. But the phase diagram of the complex quaternary SnPbAgCu is currently not available. The phase equilibria can be calculated from thermodynamic databases using the CALPHAD method [21]. Thermodynamic calculation is a very useful tool in obtaining phase diagram information, but it requires reliable thermodynamic databases and specialized knowledge.

Kattner and Handwerker stated that the liquidus temperature of ternary and quaternary systems could be calculated using the simple linearization of the binary liquidus lines [22]

$$T_l = 232^\circ\text{C} - 3.1W_{Ag} - 1.6W_{Bi} - 7.9W_{Cu} - 3.5W_{Ga} - 1.9W_{In} - 1.3W_{Pb} + 2.7W_{Sb} - 5.5W_{Zn} \quad (7.8)$$

limits: $W_{Ag} < 3.5$; $W_{Bi} < 43$; $W_{Cu} < 0.7$; $W_{Ga} < 20$; $W_{In} < 25$; $W_{Pb} < 38$; $W_{Sb} < 6$; $W_{Zn} < 6$

where T_l is the liquidus temperature of Sn-rich solder alloys, 232°C is the liquidus temperature of Sn, W_{Ag} , W_{Bi} , W_{Cu} , W_{Ga} , W_{In} , W_{Pb} , W_{Sb} , W_{Zn} is the percentage in weight of Ag, Bi, Cu, Ga, In, Pb, Sb, and Zn, respectively. The coefficient before these alloying elements is the slope of the binary liquidus lines. For example, 7.9 is the slope of SnCu binary liquidus lines when Cu is less than 0.7% in weight; 1.3 is the slope of SnPb binary liquidus lines when Pb is less than 38% in weight; and so on. It should be emphasized that the limitation of the simple linearization is $W_{Ag} < 3.5$; $W_{Bi} < 43$; $W_{Cu} < 0.7$; $W_{Ga} < 20$; $W_{In} < 25$; $W_{Pb} < 38$; $W_{Sb} < 6$; $W_{Zn} < 6$. It should also be noted that Eq. 7.8 is an approximation.

Based on Eq. 7.8, the liquidus temperature of the quaternary SnPbAgCu system, a typical alloy system in both forward compatibility assembly and backward compatibility assembly, can be calculated

$$T_l = 232^\circ\text{C} - 3.1W_{Ag} - 7.9W_{Cu} - 1.3W_{Pb} \quad (7.9)$$

with limits: $W_{Ag} < 3.5$; $W_{Cu} < 0.7$; $W_{Pb} < 38$;

Based on Eq. 7.9, the liquidus temperature of Sn3.0Ag0.5Cu is,

$$T_l = 232^\circ\text{C} - 3.1 \times 3.0 - 7.9 \times 0.5 - 1.3 \times 0 = 219^\circ\text{C}$$

If Ag content is over 3.5% and less than 4% wt, Ag₃Sn is primary phase. In this case, Eq. 7.9 is not valid. A simple fix is to add 5°C to Eq. 7.8. Thus, the liquidus temperature of Sn_{3.8}Ag_{0.7}Cu is

$$T_l = 232^{\circ}\text{C} - 3.1 \times 3.8 - 7.9 \times 0.7 - 1.3 \times 0 + 5 = 220^{\circ}\text{C}$$

Currently the reflow profiles in backward compatibility assembly are developed through costly trial-and-error methods. It is expected that the estimation of the mixed composition liquidus temperatures will be able to guide process engineers to develop the right reflow profile in backward compatibility assembly.

Table 7.4 summarizes the final joint compositions and liquidus temperature with SnAgCu ball and Sn37Pb paste for typical BGA/CSP component pitch levels. The aperture size, shape, stencil thickness and ball diameter are based on typical guidelines for no-clean paste. The transfer ratio is assumed based on experience. It shows that the final liquidus temperature is lower than 217°C, the liquidus temperature of SnAgCu. The liquidus temperature can be as low as 201°C. As the component pitch decreases (except for the case of 0.5 mm pitch), the weight percentage of Pb increases and the liquidus temperature decreases. Eqs. 7.1 to 7.4 imply that the liquidus temperature depends on the ratio of BGA ball volume and solder paste volume.

Table 4. Final Joint Compositions and Liquidus Temperature with SnAgCu Ball and Sn37Pb Paste

Pitch (mm)	1.27	1.0	0.8	0.65	0.5
Aperture size in mm	0.533	0.457	0.406	0.356	0.279
(mil)	(21)	(18)	(16)	(14)	(11)
Aperture shape	Round	Square	Square	Square	Square
Stencil thickness in mm	0.152	0.127	0.127	0.127	0.102
(mil)	(6)	(5)	(5)	(5)	(4)
Solder paste transfer ratio (%)	100	90	85	80	90
Ball diameter in mm	0.711	0.559	0.356	0.254	0.254
(mil)	(28)	(22)	(14)	(10)	(10)
Weight % of Pb	3.4	4.8	11.1	17.0	11.9
Weight % of Ag	2.7	2.6	2.1	1.6	2.1
SAC305 Weight % of Cu	0.5	0.4	0.3	0.3	0.3
Ball Estimated liquidus temperature (°C)	216	214	208	203	208
Weight % of Ag	3.6	3.5	2.8	2.2	2.7
SAC405 Weight % of Cu	0.5	0.4	0.3	0.3	0.3
Ball Estimated liquidus temperature (°C)	218	217	206	201	205

3.3 Effect of Pb Content on Backward Compatibility Reliability

Eq. 7.9 shows that a higher Pb percentage in the mixed composition can reduce the mixed composition liquidus temperature. The higher Pb percentage can be achieved by printing more SnPb solder paste or reducing the SnAgCu solder ball volume. But increasing the lead content in the solder joint can also lead to more issues as lead tends to segregate at the tin grain boundaries which can be a source of crack initiation or propagation. Zhu et al. studied the effect of Pb contamination on the lead-free solder joint microstructure and observed a Pb-rich phase formed in the bulk solder when the lead-free solder contains Pb impurity [23]. Zeng discussed the influence of the Pb-rich phase on solder joint reliability [24]. The Pb-rich phase may be the weakest region in the bulk solder, and the crack may propagate along the Pb-rich phase interface during reliability testing.

However, some experimental results did not follow the explanation. Bandagopal et al. found that the reliability of backward compatibility assembly in both ATC from 0°C to 100°C and -40°C to 125°C was better than the SnPb assembly when full mixing was achieved [9]. Furthermore, the reliability data of SnPb BGA ball soldered with SnAgCu paste (or forward compatibility), where higher Pb content existed in the mixed compositions, was better or equal to that of SnPb ball/SnPb paste control assemblies [25]. Hunt and Wickham concluded that there should be few solder joint reliability problems when mixing SnPb and lead-free components and solder alloys (with lead contamination in the range of 1 to 10%) [26]. Therefore, it is difficult to draw a conclusion regarding the effect of Pb content on backward compatibility reliability although there is evidence to show that it could be detrimental [12]. For the case where the lead-free SnAgCu paste is assembled with SnPb BGA/CSP components, if the voiding is excessive, this may lead to reliability issues from excess voiding which reduce the effective solder cross-sectional area or if the ball size and pitch is small, bridging may occur between adjacent spheres.

3.4 Comparison of Estimated Liquidus Temperature and the Experimental Results

To assess the method to calculate estimated liquidus temperatures, calculated liquidus temperatures were compared with published experimental results. The estimated temperatures and the published experimental results are summarized in Table 7.5. If the reflow peak temperature used was higher than the estimated liquidus temperature, full mixing was expected.

Table 5. Comparison of the Estimated Liquidus Temperature and the Reported Experimental Results

Reference	Estimated liquidus temperature	Peak reflow temperature used	Experimental results
Gregorich & Holmes [13]	209°C	200°C	Partial mixing
		225°C	Full mixing
Hillman et al. [12]	219°C	215°C	Partial mixing
Grossmann et al. [4]	216°C	210°C	Partial mixing
		217°C	Full mixing
Nandagopal et al. [9]	212°C	210°C	Full mixing
		227°C	Full mixing
Bath et al. [5]	218°C	205°C	Partial mixing
		214°C	Full mixing

Otherwise, partial mixing was expected. Overall, Table 7.5 shows that the estimated liquidus temperatures are generally consistent with reported experimental results. There are small variances between the estimated temperature and the reported results of studies in Nandagopal et al. [9] and Bath et al. [5]. This could be due to the inaccuracy of paste transfer ratio assumptions and the fact that a sufficient time over liquidus (183°C) for the tin-lead solder paste could also affect the result. Since only a few studies have reflow peak temperatures close to the estimated liquidus temperature, further experimental study is needed to validate the accuracy of the estimation method.

4 Chip Component and Lead-Frame Component Backward Compatibility

4.1 Calculation of Mixture Composition Liquidus Temperature for Chip Terminations

The typical surface finish for SnPb chip terminations is 90Sn10Pb with a liquidus temperature of 219°C. The typical surface finish for lead-free chip terminations is 100% Sn with a liquidus temperature of 232°C. Using the 0603 chip as an example, given chip component dimensions [27, 28] and a final plating of 100% Sn (lead-free) or 90% Sn10% Pb (SnPb) of 7.5 to 15 micron thickness, the solder volume in the chip component can be calculated. Knowing the component size and typical stencil apertures, the SnPb solder paste volume deposited can be calculated.

Table 7.6 summarizes the calculated minimum and maximum liquidus temperature of mixed compositions with Sn37Pb paste based on the minimum

Table 6. Calculated Final Liquidus Temperature of Chip Component Solder Joint

Chip Component Size	2512	1206	0805	0603	0402	0201
Lead-free (100% Sn)	187 – 190°C	189 – 192°C	188 – 191°C	191 – 196°C	198 – 206°C	195 – 202°C
SnPb (90Sn10Pb)	186 – 189°C	187 – 190°C	187 – 189°C	189 – 193°C	195 – 200°C	192 – 197°C

(7.5 micron) and maximum (15 micron) coating thickness mentioned. It shows that there is no significant increase in mixed composition liquidus temperature from 90Sn10Pb to a lead-free pure tin termination. Another point to make is that the final alloy composition for both SnPb and lead-free components are similar, which is close to Sn37Pb. The reason is that the coating thickness on a chip component is considerably thinner than that for a BGA/CSP component so it does not significantly affect the mixed solder joint alloy composition.

4.2 Calculation of the Solder Joint Mixed Composition Liquidus Temperature for Lead-Frame Components

The typical surface finish for SnPb lead-frame components is 90Sn10Pb with a liquidus temperature of 219°C. There are several common surface finishes for lead-free leadframe components, for example, 100% Sn, Sn3.5Ag, Sn1.0Cu, Sn2-4% wt. Bi, NiPdAu and NiAu. Different surface finishes have their own advantages and disadvantages. In this chapter, the liquidus temperature calculation is limited to the most common lead-frame surface finish, 100% Sn.

The typical plating thickness for leadframe components of 100% Sn (lead-free) or 90% Sn10% Pb (SnPb) is 7.5 to 15 micron. Given a leadframe component dimensions [27, 28], the solder volume in the leadframe component can be calculated. Knowing the component pitch and its appropriate stencil aperture openings and paste transfer ratios, the solder paste volume can be calculated.

Table 7.7 summarizes the calculated minimum and maximum liquidus temperature of mixed component joint compositions with Sn37Pb paste based on the minimum (7.5 micron) and maximum (15 micron) coating thickness mentioned for leadframe components. It shows that there is no significant increase in the mixed joint composition liquidus temperature from 90Sn10Pb termination to the lead-free pure tin termination similar to the case of the chip component. Again the final alloy composition for both SnPb and lead-free pure tin components with SnPb paste are similar, which is close to the composition of Sn37Pb solder.

Table 7. Calculated Final Liquidus Temperature of Leadframe Component Solder Joint

Component Lead-frame Pitch (mm)	1.0	0.8	0.65	0.5	0.4
Lead-free (100% Sn)	191 – 197°C	188 – 192°C	187 – 190°C	187 – 189°C	188 – 196°C
SnPb (90Sn10Pb)	190 – 194°C	187 – 190°C	186 – 189°C	186 – 188°C	187 – 189°C

**4.3 Backward Compatible Solder Joint Reliability
of Chip and Lead-frame Components**

The reliability of chip and lead-frame component solder joints in backward compatibility assemblies is not expected to be significantly different from the SnPb control assemblies. Since the volume of SnPb solder paste is significantly greater than that of the solder in surface finish of the chip or lead-frame components, the final alloy composition in backward compatibility is similar to Sn37Pb solder. Thus the liquidus temperature and the reflow profile needed for the final mixed compositions are similar to the eutectic SnPb solder. There are many years of historical data showing that lead-free chip and lead-frame components in backward compatibility assemblies are reliable. Table 7.8 lists the reliability data of the 2.36 mm (93 mil) Solelectron lead-free surface mount test board after ATC from 0 to 100°C for 6,013 cycles. It shows that the reliability of backward compatibility assemblies is comparable to that of SnPb control assemblies.

Table 8. Reliability Data of Lead-free Pure Sn Leadframe Coatings with SnPb Paste

	Reflow peak temperature	Number of samples failed over number of samples tested		First failure occurred (cycles)	
		Sn10Pb	Leadfree pure Sn	Sn10Pb	Leadfree pure Sn
28mm QFP256 0.4mm pitch	205 - 215°C	2/32	2/16	1,022	2,213
SOIC20 1.27mm pitch	205 - 215°C	0/32	0/16	–	–
PLCC20 1.27mm pitch	205 - 215°C	1/32	2/16	3,595	1,305
7mm MLF 0.5mm pitch	205 - 215°C	10/48	6/24	603	4,070

In Japan, OEMs have successfully used lead-free SnBi component coatings for lead-free product. The question that has created concern is the use of lead-free SnBi component coatings with SnPb soldering materials due to the potential for the formation of low melting point phases. Work has been done by NIST (National Institute of Science and Technology) to understand the SnBiPb phase diagram [29]. The ternary eutectic composition is approximately 51.5Bi15.5Sn33Pb with a melting temperature of 96°C. Considering a thickness of 0.076 mm (3 mil) reflowed 63Sn37Pb solder joint and a 97Sn3Bi component coating with a coating thickness of 10 micron, the final composition of the joint is around 62.7Sn37Pb0.3Bi (< 1wt% Bismuth). Based on calculations by NIST the solidus temperature of 62.7Sn37Pb0.3Bi is 174°C so the 96°C ternary eutectic would not form. Calculations have also been done for different SnPbBi compositions namely Sn37Pb1Bi with a solidus temperature of 159°C and Sn37Pb3Bi with a solidus temperature 119°C.

The JEDEC/IPC JP002 document [30] indicates that the ternary eutectic phase will not form using Sn1-4wt%Bi coatings with Sn37Pb solder. For most components SnBi plating is acceptable for use with SnPb solder. But there may be a risk of excessive intermetallic growth if the storage product temperature exceeds 135°C. Excessive IMC was observed in ageing experiments with SnAgCu soldered SnBi coated surface mount components [31]. Additional reliability testing is needed to validate its use at elevated storage temperatures.

For tin-lead wave soldering, there are still potential restrictions on the use of SnBi components because the bismuth can leach into a tin-lead wave solder pot and bismuth could accumulate over time in the solder pot, which can lead to a lowering of the melting temperature of the pot and potential reliability issues such as fillet lifting.

5 Forward Compatibility

Only a few studies have been published on the reliability of forward compatibility assemblies, or lead-free solder paste (SnAgCu) assembled with tin-lead BGA/CSP and lead-frame and chip components. Though more voids were observed in forward compatibility assemblies for BGAs/CSPs [1], the reliability of forward compatibility assemblies is equivalent or better than the reliability of the SnPb balled BGAs with SnPb solder paste [2, 25, 32].

Nurmi and Ristolainen reported that forward compatibility assemblies did not show any serious reliability risks and can withstand temperature

cycling stress better than SnAgCu control assemblies [25]. Experimental studies from the iNEMI lead-free assembly project found no ATC reliability problems in forward compatibility assemblies as well as shown in Table 7.9 [2]. This included lead-free SnAgCu paste with tin-lead CSP169, CSP208, PBGA256, CBGA256 and 2512 chip resistors. Lau et al. concluded that the quality of the SnPb balled FLEXBGA solder joints with lead-free solder paste on Ni-Au PCB is better than that with SnPb solder paste on an OSP PCB with 99 percent confidence level [32]. Note that all studies in forward compatibility assembly used SnAgCu reflow profiles.

However, Seelig et al. found that a lead-free SnAgCu soldered joint with a tin-lead coated leadframe component caused a concentration of lead at the joint/board surface interface which was the last area of the solder joint to solidify [33]. The SnPbAg with a melting temperature of 179°C could be present in this area. The resulting solder joint was found to have a weak interface at this point.

For tin-lead coated through-hole components or tin-lead HASL coated boards waved with lead-free solder, the risk of lead contamination of a lead-free wave solder pot (>0.1wt% lead which is the European Union ROHS limit) would mean that this specific mixing should not be attempted. Fillet lifting may also occur in the wave soldered joint.

There are issues as to whether the tin-lead component or other components on the board or the board itself are rated to the higher lead-free soldering temperatures. Based on our knowledge, this has not been discussed in published literature. In addition, the resulting solder joint would not be compliant to legislative direction.

Table 7.9. Relative ATC Performance [2]

Component (ImAg board finish unless indicated)	–40°C to 125°C			0°C to 100°C		
	Pb	Mixed	LF	Pb	Mixed	LF
48 TSOP	0	–	0			
48 TSOP, NiAu boards	0	+	+			
R2512 resistor	0	0	0			
R2512, NiAu boards	0					
169CSP	0	+	+	0	0	+
208CSP	0	0	+	0	+	+
208CSP, JEITA alloy (Sn3Ag0.5Cu)			0			
256PBGA	0	0	0	0	0	0
256CBGA				0	–	+

Note: 0 = equivalent, + = superior, – = inferior

6 Press Fit Connector Interconnections

6.1 Introduction for Press-Fit Connectors

The European Union RoHS Directive covers various aspects of electronics manufacturing including press-fit interconnections. In spite of the current exemption for lead used on compliant pin connector systems, the transition to lead-free press-fit interconnect components is inevitable and in progress. OEMs, EMSs, and connector suppliers are working together to make the connectors used in electronics products RoHS compliant. In the transition period, lead-free press-fit connectors are required to have backward and forward compatibility meaning they can be used in both lead-free and tin-lead assembly processes on any surface finish selected.

6.2 Current Status of Lead-Free Press-Fit Connectors

In the area of press-fit interconnections, lead-free impacts are seen in the changes of press-fit connector compliant pin plating, PCB laminate material, and board surface finish. For press-fit connector compliant pins, the main plating includes matte Sn and electroplated Au (over nickel). For the PCB, the major board surface finishes include Immersion Sn, ENIG (NiAu), Immersion Ag, and OSP. The combination of the compliant pin plating with the board surface finish will generate various press-fit insertion force results as opposed to tin-lead connector compliant pin plating with the board surface finish. To date, no comprehensive studies and industry-accepted conclusions are available that satisfy all design and assembly conditions. Nevertheless, there are a few mixed observations obtained from production experience or derived from OEM/EMS/connector supplier studies:

- Lead-free compliant pins experienced increased insertion forces due to interactions among various pin design attributes (eye-of-needle and other custom-made compliant sections), compliant pin plating type, and board surface finish type, as compared to its tin-lead coated counterpart compliant pins given the same PCB Plated Through Hole (PTH) size. Failures such as bent pins and PTH damage have been seen when pressing in lead-free coated compliant pins into the board [34].
- Depending on the compliant pin design, PCB surface finish type, the pin-to-hole area ratio, the lead-free coated compliant pin can have as high as a 15% average increase in insertion force over tin-lead coated compliant pin [35].
- According to a study [36], the NiAu board surface finish caused higher insertion/retention force as opposed to other board surface

finishes tested. This study recommended immersion Ag as a suitable choice among RoHS compliant PCB finishes in terms of relatively lower insertion/retention force with lead-free press-fit connectors.

- Another study showed that immersion Sn caused highest insertion forces with the lead-free press-fit connector, among six board surface finishes tested [37].
- The actual PCB laminate material used (such as Phenolic non-dicy laminate) that is rated for lead-free reflow conditions might contribute partially to the increase of insertion forces with lead-free press-fit connectors as it may be harder and less forgiving than the standard laminate material (dicy laminate) used for typical tin-lead soldering. This phenomenon is yet to be fully understood and studied.

With the increase of compliant pin insertion forces, changes in design and assembly processes have to take place accordingly to ensure that the yield and performance of lead-free press-fit interconnection are not compromised. Long-term solutions for the lead-free press-fit connector supplier could be 1) to change the compliant pin geometry design to be more suitable for lead-free insertion assembly, or 2) to study the lead-free compliant connectors' press-fit behavior on various lead-free PCB surface finishes and update their connector specifications accordingly. Before this can materialize, short-term solutions include 1) reducing the connector pressing speed into the board, 2) using lubricant to reduce insertion force, or 3) changing PCB PTH drill and/or finished hole size.

6.3 Lead-Free Press-Fit Connector Summary

Due to the press-fit compliant pin plating changing from SnPb to a lead-free finish, the press/insertion process needs to be re-characterized. Currently there are only limited studies done by OEM/EMS/connector suppliers in this regard. No conclusion can be drawn yet in terms of the selection of the best PCB surface finish, PCB laminate material, and compliant pin plating. It is recommended that EMS providers and their OEM customers, as well as connector suppliers work together to make the lead-free press-fit interconnection transition smooth without compromising quality and reliability.

Summary

In this chapter, backward compatibility and forward compatibility have been reviewed with emphasis on the reliability of BGA/CSP backward compatibility assemblies. It is evident that the reliability of solder joint

interconnections in backward compatibility assemblies degrades significantly if SnAgCu solder spheres are only partly melted in backward compatibility. If complete mixing is achieved in backward compatibility assemblies, there are conflicting experimental results on the reliability of BGA/CSP backward compatibility. Data show that the backward compatibility assemblies of chip components and leadframe components are reliable in terms of solder joint integrity.

The estimation of the liquidus temperature of mixed composition in backward compatibility has been presented for BGA/CSP, lead-frame and chip components. The estimation for BGA/CSP components could be used to guide the development of a reflow profile, but it should be noted that the estimation is an approximation and further experimental study is needed to validate the accuracy of the method.

The majority of forward compatibility studies show little or no issues but excessive voiding of tin-lead BGA/CSP components is a concern. The effect of Pb content in mixed assemblies (forward compatibility and backward compatibility) is still questionable.

Both the backward and forward compatibility situations should be considered as transitional processes only with a full movement to lead-free paste with lead-free components being the general goal to avoid any reliability issues associated with the two transition assembly situations.

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