Prospect of Lead Free Alternatives for Reflow Soldering

By

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ABSTRACT

The prospects of 10 major lead-free solder alloys for being widely used for reflow soldering are studied in this work. Compatibility of those alloys with a variety of representative flux chemistries is considered essential, and is determined for performance in handling-ability, including shelf life and tack time, and soldering capability, including solder balling, wetting, and solder joint appearance. Results indicate that the control 63Sn37Pb is still the most compatible alloy, rated 27.1 in compatibility out of a full scale 30 when using warm profile. The primary factor which distinguishes 63Sn37Pb from the rest alloys is the soldering performance, particularly the wetting and solder appearance. As to the solder balling, although 63Sn37Pb is also the best, it is fairly close to the best lead-free systems. Among the lead-free options, both SnAgBi alloys studied here, 91.7Sn3.5Ag4.8Bi and 90.5Sn7.5Bi2Ag, turn out to be on the top of lead-free systems, rated 22.9 and 22.8, respectively. This is mainly attributed to the better wetting and solder balling performance. Shelf life and tack time of the SnAgBi systems are also fairly good, while the solder appearance is at best considered average. The six alloys, 99.3Sn0.7Cu, 95.5Sn3.8Ag0.7Cu, 93.6Sn4.7Ag1.7Cu, 96.2Sn2.5Ag0.8Cu0.5Sb, 58Bi42Sn, and 95Sn5Sb, show fairly comparable performance to each other, with compatibility ranging from 19.3 to 20.3. In general, the whole group displays a quite noticeably poorer wetting than SnAgBi systems. 58Bi42Sn exhibits a fairly poor solder balling performance, but an outstanding solder appearance among lead-free systems. 96.2Sn2.5Ag0.8Cu0.5Sb shows a relatively poor performance in both wetting and solder appearance among these six alloys. 96.5Sn3.5Ag, rated 17.1 in compatibility, is ranked below the other alloys described above, mainly due to poor performance in solder balling, and particularly the poor wetting. 89Sn8Zn3Bi, rated only 2.2 in compatibility, falls far short in every category when compared with all other alloy systems. Obviously, this is attributable to the very reactive nature of zinc, which results in excessive oxidation of metal and excessive reaction with fluxes, and consequently a definitely unacceptable performance for solder paste applications. High-tin-content lead-free alloys seem to display a thicker IMC layer than eutectic SnPb when reflowed.

Key words: Lead-free, solder, soldering, reflow, paste, flux, wetting, solder balling, solder appearance, shelf life, tack time

INTRODUCTION

Due to the toxicity of lead, there is a tremendous amount of effort on eliminating lead from the solders used in electronic industry. The move toward lead-free solder alternatives in North America and Europe accelerated significantly [1] since Japanese industry announced their aggressive lead-free roadmap [2]. For instance, Toshiba, Matsushita, and Hitachi have announced plans of elimination of all lead interconnects in one or all products by 2001, 2004, and 2004, respectively. However, the preferred solution for lead-free alternatives varies from region to region, and there is a number of alloys considered promising. The most favorable Pb-free solder systems identified by the industry [3,4] comprise primarily alloys of Sn with Ag, Bi, Cu, Sb, or Zn, such as 99.3Sn0.7Cu, 96.5Sn3.5Ag, 95.5Sn3.8Ag0.7Cu, 93.6Sn4.7Ag1.7Cu, 96.2Sn2.5Ag0.8Cu0.5Sb, 91.7Sn3.5Ag4.8Bi, 90.5Sn7.5Bi2Ag, 89Sn8Zn3Bi, 95Sn5Sb, and 58Bi42Sn. Unfortunately, although some reliability data have been generated in the past [3], most of the promising alloys were evaluated under a single flux system. The compatibility between flux and alloy often dictates the performance of reflow soldering, such as solder balling, wetting, processing window, and stability. Since the flux chemistry varies from supplier to supplier, and since the use of more than one suppliers is considered crucial for assuring a steady process, an alloy being compatible with a wider range of flux systems obviously will have a greater prospect to be accepted by SMT industry. In this study, a group of most promising Pb-free alloys reported are tested against a broad range of commonly used flux chemistries, such as water wash, no-clean, halide-containing, halide-free, nitrogen reflow systems, and air reflow systems, in the form of solder paste. The handling and reflow soldering performance of those paste is evaluated and ranked in order to assess the prospect of those alloys being widely used for reflow soldering applications by the industry.

EXPERIMENTAL DESIGN

1. Materials

Alloys

Among the most promising lead-free alloys, ten representative alloys are chosen, including 99.3Sn0.7Cu, 96.5Sn3.5Ag, 95.5Sn3.8Ag0.7Cu, 93.6Sn4.7Ag1.7Cu, 96.2Sn2.5Ag0.8Cu0.5Sb, 91.7Sn3.5Ag4.8Bi, 90.5Sn7.5Bi2Ag, 89Sn8Zn3Bi, 95Sn5Sb, and 58Bi42Sn. The eutectic tin-lead 63Sn37Pb is used as a control.

Fluxes and Solder Pastes

Ten fluxes vary widely in chemistry, as shown in Table 1, are used to make solder pastes in order to evaluate the compatibility of alloys with reflow soldering applications. The solder paste samples are made by mixing each flux with solder powder (-325/+500 mesh, 25-45 μ) for each alloy. The metal content of solder paste for each alloy system is shown in Table 2, and is set to provide approximately the same solder volume as that of eutectic SnPb solder pastes with 90% metal content when the flux density is 1 g/ml. For the purpose of calculation, the density of F1 to F9 can be approximated as 1.0 g/ml, while that of F10 is 1.25 g/ml. The density of alloys shown in Table 2 is determined with a pycnometer.

Table 1 Fluxes used for lead-free solder pastes

Flux	Description
F1	No-clean, halide-free, air reflow, probe testable
F2	No-clean, halide-free, air reflow, probe testable
F3	No-clean, halide-containing, air reflow
F4	No-clean, halide-containing, air reflow
F5	RMA type, halide-containing, air reflow
F6	No-clean, halide-free, medium residue, nitrogen reflow
F7	No-clean, halide-free, low residue, nitrogen reflow
F8	No-clean, halide-free, ultra-low residue, nitrogen reflow
F9	Water washable, halide-free, medium temperature process, air reflow
F10	Water washable, halide-containing, high temperature process, air reflow

Table 2 Metal content of solder paste samples for each alloy system.

Alloy	Density (g/ml)	Metal content for F1 to F9 system (w/w %)	Metal content for F10 system (w/w %)
63Sn37Pb	8.40	90.0	88.0
96.5Sn3.5Ag	7.36	89.0	86.5
99.3Sn0.7Cu	7.34	89.0	86.7
95.5Sn3.8Ag0.7Cu	7.38	89.0	86.5
93.6Sn4.7Ag1.7Cu	7.43	89.0	86.6
96.2Sn2.5Ag0.8Cu0.5Sb	7.47	89.0	86.5
91.7Sn3.5Ag4.8Bi	7.57	89.0	86.8
90.5Sn7.5Bi2Ag	7.58	89.0	86.8
58Bi42Sn	8.56	90.0	88.2
95Sn5Sb	7.25	89.0	86.3
89Sn8Zn3Bi	7.39	89.0	86.5

2. Tests

As stated earlier, the scope of this work is assessing the compatibility of lead-free alloys with reflow soldering, with emphasis on the handling and soldering performance of solder pastes. In the case of handling, an alloy being incompatible with certain flux chemistry often results in excessive chemical reaction between alloy and flux either at storage temperature or upon exposure to ambient atmosphere. This in turn results in a thickened or crusted paste, and accordingly a poor shelf life and poor tack time.

On the other hand, for certain alloys, the solder oxide may not be readily removable by certain flux chemistries. This would result in poor solder balling, poor wetting, and often a poor solder surface appearance. In certain other cases, some solder alloys may react with base metal very slowly, hence would exhibit a fairly poor wetting when compared with eutectic SnPb systems. For situation like those, conventional flux systems may deem to be inadequate, and a more aggressive flux may be needed in order to achieve a wetting comparable with that of SnPb systems.

In view of the aforementioned situations, it becomes clear that the tests required in order to assess the compatibility of solder alloys with reflow soldering should include (1) shelf life, (2) tack time, (3) solder balling, (4) wetting ability, and (5) solder joint surface appearance. However, before embarking on those performance evaluation, some other information may need to be generated, such as the melting temperature. Melting behavior, particularly the liquidus temperature, is required for setting up a reflow profile.

Melting Temperature Determination

For each alloy system, the melting temperature (see Table 3) is determined on a Seiko DSC (differential scanning calorimetry). The sample is preconditioned at 300°C, followed by cooling down to 0°C at a cooling rate of 5°C per minute, then reheated to 300°C at a heating rate of 5°C per minute.

Table 3 Melting temperature for solder alloys.

Alloy	Solidus (°C)	Liquidus (°C)	Note
63Sn37Pb	182.1	183.0	Eutectic
96.5Sn3.5Ag	219.7	220.8	Eutectic
99.3Sn0.7Cu	225.7	227.0	Eutectic
95.5Sn3.8Ag0.7Cu	216.3	217.5	Multicore
93.6Sn4.7Ag1.7Cu	215.9	217.1	Ames
96.2Sn2.5Ag0.8Cu0.5Sb	216.9	218.2	AIM
91.7Sn3.5Ag4.8Bi	202.1	215.1	Sandia
90.5Sn7.5Bi2Ag	190.6	214.7	Tamura
58Bi42Sn	136.3	138.5	Eutectic
95Sn5Sb	238.3	240.3	Indium
89Sn8Zn3Bi	190.6	195.4	Senju

The onset of the melting endotherm is recorded as solidus temperature, and the peak of the endotherm is recorded as liquidus temperature. The liquidus temperature data in Table 3 have not been corrected for thermal lag effect, which is 0.9°C.

Wetting Ability

The wetting ability of solder pastes is tested by printing solder paste onto copper pads coated with OSP on a PCB, and followed by reflow. The thickness of stencil used is 6 mils (150 µ), and the aperture opening versus pad dimension is one to one. The registration of paste to pad is set 70% off so that only 30% of the paste is printed onto the pads, and 70% of the paste is printed onto the solder mask. Upon reflow, the solder

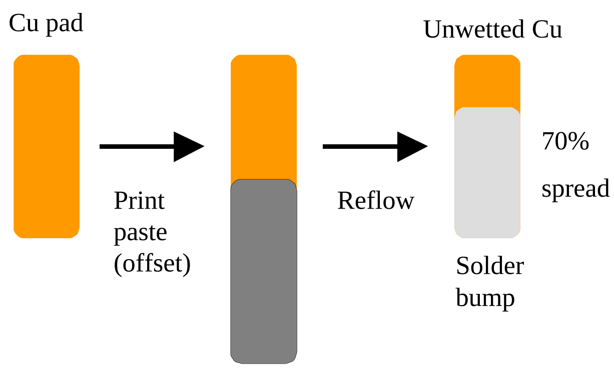

Figure 1 Schematic of wetting test

paste coalesced and pulled away from the solder mask and wetted to the pad side (see Figure 1). The wetting ability of solders is determined by examining the extent of solder spreading on the pads, and the average of 10 pads is expressed as wetting index (WI) which is defined in Table 4. A higher

Table 4 Definition of wetting index (WI).

WI	Spread area (% of pad)
0	0
1	10
2	20
3	30
4	40
5	50
6	60
7	70
8	80
9	90
10	100

value in WI represents a better wetting ability.

Reflow process is conducted with the use of a forced air convection oven, BTU NP70. Two tent-shaped reflow profiles are used for each alloy, with the peak temperature being a function of the liquidus temperature. The first profile (cool profile) exhibits a peak temperature 15°C above the liquidus temperature, while the second profile (warm profile) being 30°C above the liquidus. The ramp-up rate is about 0.7-0.8°C/second. For flux systems F6, F7, and F8, a nitrogen atmosphere is used for reflow, while for the rest flux systems an air reflow atmosphere is used. The use of two profiles would provide insights on (1) minimal temperature required, and (2) potential of improving soldering performance with the use of a higher temperature.

Solder Balling

Solder balling performance is evaluated by examining under a 20X optical microscope the average number of the solder balls

Table 5 Definition of solder balling index (SBI).

SBI	Number of solder balls
0	No reflow
1	> 501, with some reflow
2	401-500
3	301-400
4	201-300
5	151-200
6	101-150
7	51-100
8	21-50
9	11-20
10	0-10

per pad for the results of reflow described above. The average performance of 10 pads is expressed as solder balling index (SBI), as defined in Table 5. A higher value in SBI represents a better solder balling performance.

Tack Time

Tack time of solder paste is determined by the following procedure. (1) Print solder paste onto ceramic coupons, as prescribed by J-STD-006 procedure. (2) Condition the specimen under 76% relative humidity. (3) Measure the tack value, per J-STD-006 procedure, of the conditioned specimen at fresh, 8 hours, 24 hours, 48 hours, and 72 hours. The specimen is discarded after each tack measurement. The tack data is expressed as tack time index (TTI), which is defined in Table 6. A higher value in TTI represents a longer tack time.

Table 6 Definition of tack time index (TTI).

TTI	Description
0	A decreasing tack curve reaching a value at < 10 g at the third day
2	A decreasing curve reaching 10 - 20 g at the third day
4	A decreasing curve reaching 25 - 20 g at the third day
6	The tack initially increases, reaching the maximum, and continuously decreases
8	A continuously increasing curve
10	Constant over three days

Shelf Life

The shelf life of solder pastes is determined by monitoring the viscosity stability of solder pastes at 25°C over a period of one month. A changing viscosity, typically increasing with time, is considered undesirable. For each solder paste sample, the viscosity is determined at 1 day, 7 days, and 30 days after paste manufacturing. The percentage change of viscosity for each sample is calculated for the period from one day to 7 days (change rate A), and for the period from 7 days to 30 days (change rate B). The overall instability is calculated with the equation shown below.

Overall instability = 0.3 x (change rate A) + 0.7 x (change rate B)

The shelf life is expressed as shelf life index (SLI), and is defined in Table 7. A higher value in SLI represents a longer shelf life.

Table 7 Definition of shelf life index (SLI).

SLI	Description
0	Overall instability > 25%
2	Overall instability = 20-25%
4	Overall instability = 15-20%
6	Overall instability = 10-15%
8	Overall instability = 5-10%
10	Overall instability = 0-5%

Solder Surface Appearance

The solder bump surface is examined under optical microscope, and the appearance is expressed as solder appearance index (SAI), as defined in Table 8 and Figure 2. A higher value in SAI suggests a more desirable solder joint quality.

Compatibility

The compatibility of an alloy with reflow soldering is determined by adding up the performance from all five categories. However, much more weight is assigned to solder balling and wetting performance.

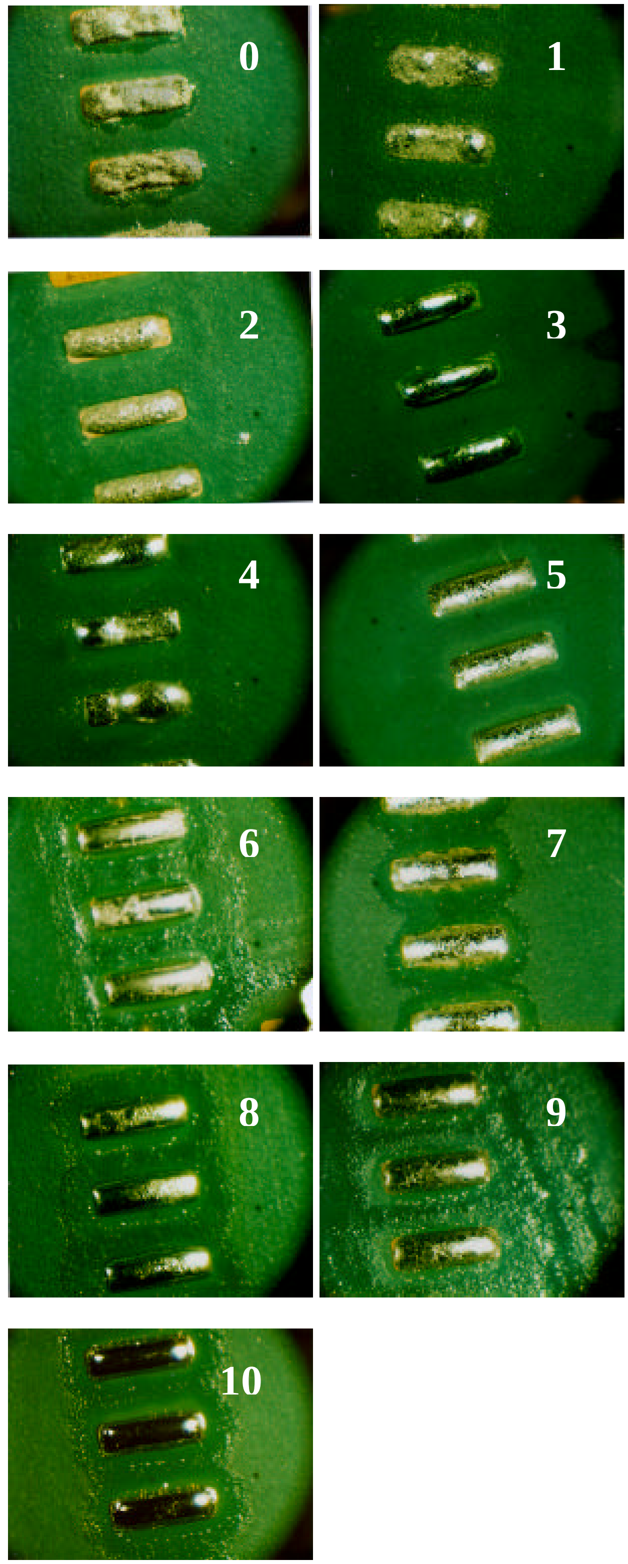

Figure 2 Criteria of solder surface appearance, with SAI value marked in photos.

Table 8 Definition of solder appearance index (SAI)

SAI	Description
0	Not reflowed, with " powder " appearance.
1	Partially reflowed with some melted area.
2	No less than one large cavities.
3	Numerous small pinholes.
4	Solder dewetted to form a few bumps.
5	Rough area 70-100%.
6	Rough area 50-70%.
7	Rough area 30-50%.
8	Rough area 10-30%.
9	Smooth and dull, or shiny with slight roughness (rough area <10%).
10	Shiny and smooth.

The solder appearance received a slightly higher weight than shelf life and tack time. Hence, the compatibility (C) is calculated according to the formula shown below:

$$C = 1 \times SBI + 1 \times WI + 0.3 \times SLI + 0.3 \times TTI + 0.4 \times SAI$$

The higher the value in compatibility, the more compatible the alloy is with reflow soldering. A value of 30 represents 100% compatibility.

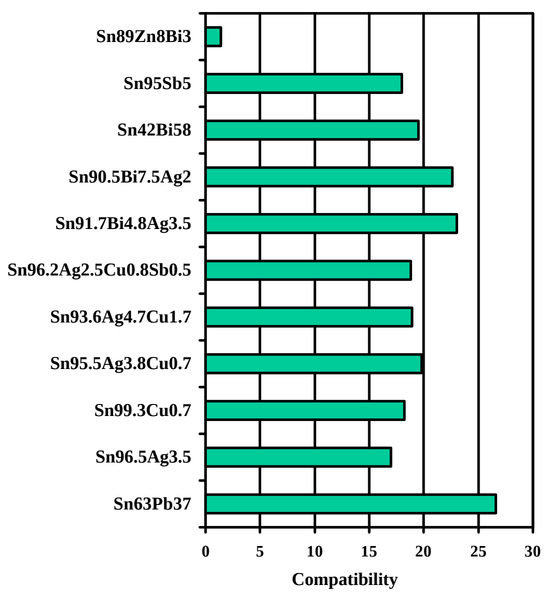

Figure 3 Compatibility of alloys with reflow soldering using warm profile

Cross-section

In order to understand the relationship between surface appearance and solder interior integrity, some solder bumps are cross-sectioned and examined under optical microscope as well as electron microscope.

RESULTS

The results of study on wetting, solder balling, shelf life, tack time, and solder surface appearance for each combination of fluxes and alloys are shown in Table 9. For each alloy, the average performance of paste systems using a variety of fluxes is summarized in Table 10. On the other hand, for each flux, the average performance of paste systems using a variety of alloys is summarized in Table 11. Although the data is presented for all conditions including cool profile, warm profile, and the average value of cool profile and warm profile, the primary comparison of alloys or fluxes is based on the warm profile data. This is due to the consideration that the warm profile simulates the current industrial practice better. Figure 3 shows the schematic ranking of alloys in terms of compatibility for reflow soldering.

1. Compatibility of Alloys

63Sn37Pb

The control 63Sn37Pb exhibits the highest compatibility with reflow soldering, as shown in Table 10. This should not be a surprise, since most of the fluxes are developed for eutectic or near eutectic tin-lead systems. The primary factor which distinguishes 63Sn37Pb from the rest alloys is the soldering performance, particularly the wetting and solder appearance. As to the solder balling, although 63Sn37Pb is also the best, it is fairly close to the best lead-free systems. On the material handling performance, including shelf life and tack time, 63Sn37Pb is merely mediocre and is outperformed by several lead-free systems.

SnAgBi Systems

Both SnAgBi alloys studied here, 91.7Sn3.5Ag4.8Bi and 90.5Sn7.5Bi2Ag, turn out to be on the top of lead-free systems. This is mainly attributed to the better wetting and solder balling performance. Shelf life and tack time of the SnAgBi systems are also fairly good, while the solder appearance is at best considered average.

SnCu, SnAgCu, SnAgCuSb, SnBi, and SnSb Systems

The six alloys, 99.3Sn0.7Cu, 95.5Sn3.8Ag0.7Cu, 93.6Sn4.7Ag1.7Cu, 96.2Sn2.5Ag0.8Cu0.5Sb, 58Bi42Sn, and 95Sn5Sb, show fairly comparable performance, with compatibility ranging from 19.3 to 20.3 (out of a scale with full compatibility being 30) for warm profile. In general, the whole group displays a quite noticeably poorer wetting than SnAgBi systems. 58Bi42Sn exhibits a fairly poor solder balling performance, but an outstanding solder appearance among lead-free systems. 96.2Sn2.5Ag0.8Cu0.5Sb shows a relatively poor performance in both wetting and solder appearance among these six alloys.

SnAg Systems

96.5Sn3.5Ag is ranked below the other alloys described above in compatibility, mainly due to poor performance in solder balling, and particularly the poor wetting.

SnZnBi Systems

89Sn8Zn3Bi falls far short in every category when compared with all other alloy systems. Obviously, this is attributable to the very reactive nature of zinc, which results in excessive oxidation of metal and excessive reaction with fluxes, and consequently a definitely unacceptable performance for solder paste applications.

2. Compatibility of Fluxes

As shown in Table 11, the compatibility of fluxes with alloys is very comparable for almost all of the fluxes studied, with compatibility value ranging from 18.2 to 21.3. The only exception is flux F9, a water-soluble flux, mainly due to poor soldering performance. This may be related to the poor thermal stability of this flux when reflowed under higher temperature condition.

3. Effect of Temperature on Compatibility of Alloys

Generally speaking, a higher reflow temperature results in a better compatibility, as shown in Table 10. Since a higher reflow temperature will favor a higher reaction rate between solder and the base metal, this effect is very much expected. The SnAgBi systems appear to be one exception, with reason unclear.

4. Effect of Temperature on Compatibility of Fluxes

Although a higher reflow temperature often results in a greater compatibility for fluxes, as shown in Table 11, several exceptions are observed, including fluxes F1, F5, and F7. In general, the flux reaction rate increases with increasing temperature [5], therefore a better compatibility will be expected for a higher reflow temperature. However, some fluxes may start to burn off or decompose at a higher temperature. This phenomenon may offset the reaction rate factor and cause a flat or declining compatibility with increasing temperature.

5. Cross-section of Solder Bumps Formed

Macro-Voiding

Although the solder appearance often is a good indication of the solder joint quality, the results of cross-section show that properties such as macro-voiding may not be reflected by the surface appearance. Figure 4 displays a series of low magnification, such as 50X to 200X, of cross-sections of solder bumps for solder systems with various SAI value. It appears that there is negligible correlation between the macro-voiding and solder appearance. This phenomenon is further illustrated in Table 12, where a system with a low SAI value (such as 5) may exhibit less macro-voiding (13%) than the system with a high SAI value (such as 8, with 56% voiding).

Intermetallic Compound Thickness

Also shown in Table 12 are examples of the intermetallic compound (IMC) thickness. It is interesting to note that most

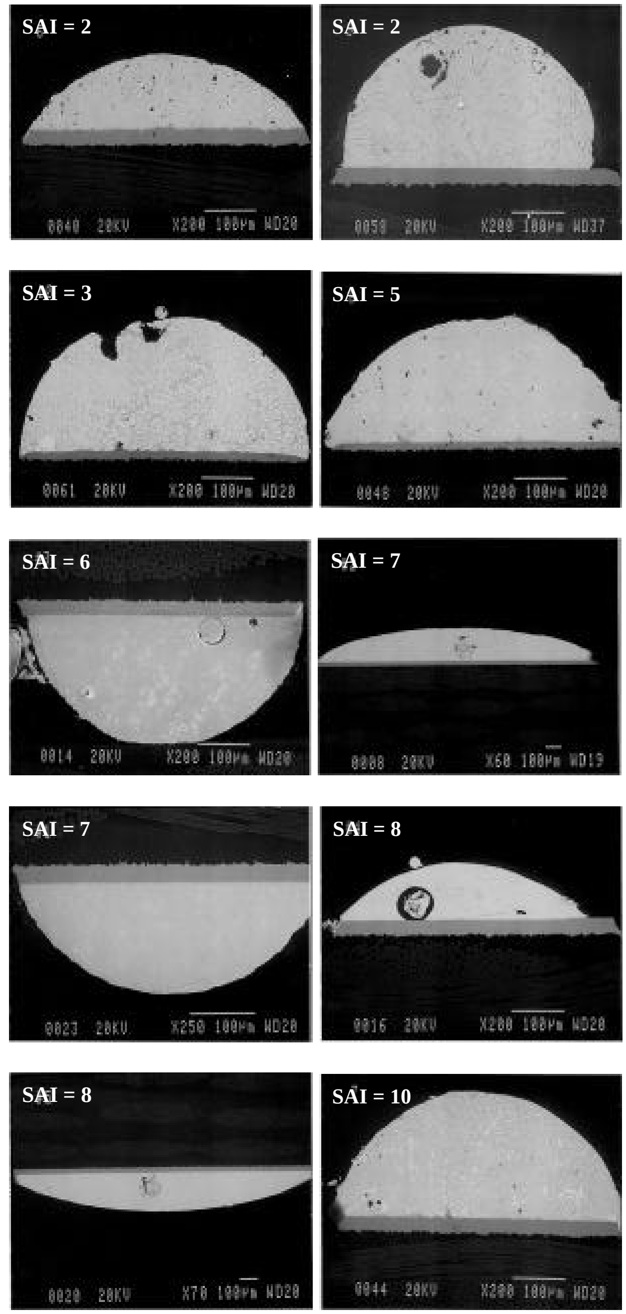

Figure 4 Cross-section of solder bumps for systems with various SAI value. The macro-voiding has negligible correlation with the surface appearance.

of the lead-free alloys, except 58Bi42Sn (0.7 μ in IMC layer thickness), display a thicker intermetallics layer (1.5 – 2.7 μ) than that of 63Sn37Pb (1 μ). The intermetallics thickness appears to increase with either increasing reflow temperature or increasing Sn content.

Table 9 Compatibility between fluxes and solder alloys.

Flux	Alloy	Cool profile						Warm profile						Ave
		SBI	WI	SLI	TTI	SAI	C	SBI	WI	SLI	TTI	SAI	C	C
F1	63Sn37Pb	9.0	10.0	8.0	10.0	10.0	**28.4**	10.0	8.9	8.0	10.0	10.0	**28.3**	**28.4**
	96.5Sn3.5Ag	6.0	4.0	6.0	10.0	5.0	**16.8**	4.0	3.0	6.0	10.0	6.0	**14.2**	**15.5**
	99.3Sn0.7Cu	8.0	5.8	8.0	4.0	5.0	**19.4**	9.0	5.0	8.0	4.0	8.0	**20.8**	**20.1**
	95.5Sn3.8Ag0.7Cu	8.0	5.2	10.0	8.0	8.0	**21.8**	8.0	4.1	10.0	8.0	8.0	**20.7**	**21.3**
	93.6Sn4.7Ag1.7Cu	7.0	3.5	10.0	6.0	6.0	**17.7**	8.0	5.8	10.0	6.0	7.0	**21.4**	**19.6**
	96.2Sn2.5Ag0.8Cu0.5Sb	8.0	5.7	10.0	10.0	5.0	**21.7**	8.0	3.3	10.0	10.0	6.0	**19.7**	**20.7**
	91.7Sn3.5Ag4.8Bi	10.0	5.5	10.0	8.0	5.0	**22.9**	10.0	6.1	10.0	8.0	5.0	**23.5**	**23.2**
	90.5Sn7.5Bi2Ag	9.0	6.8	10.0	8.0	5.0	**23.2**	10.0	6.5	10.0	8.0	5.0	**23.9**	**23.6**
	58Bi42Sn	6.0	8.0	10.0	10.0	9.0	**23.6**	6.0	6.3	10.0	10.0	9.0	**21.9**	**22.8**
	95Sn5Sb	10.0	4.5	10.0	8.0	5.0	**21.9**	9.0	5.7	10.0	8.0	9.0	**23.7**	**22.8**
	89Sn8Zn3Bi	0.0	0.0	0.0	2.0	0.0	**0.6**	0.0	0.0	0.0	2.0	0.0	**0.6**	**0.6**
	Average	**7.4**	**5.4**	**8.4**	**7.6**	**5.7**	**19.8**	**7.5**	**5.0**	**8.4**	**7.6**	**6.6**	**19.9**	**19.9**
F2	63Sn37Pb	10.0	10.0	10.0	8.0	10.0	**29.4**	10.0	10.0	10.0	8.0	10.0	**29.4**	**29.4**
	96.5Sn3.5Ag	4.0	4.5	8.0	8.0	7.0	**16.1**	4.0	5.5	8.0	8.0	6.0	**16.7**	**16.4**
	99.3Sn0.7Cu	7.0	6.1	10.0	6.0	7.0	**20.7**	8.0	7.0	10.0	6.0	9.0	**23.4**	**22.1**
	95.5Sn3.8Ag0.7Cu	7.0	5.4	10.0	6.0	7.0	**20.0**	9.0	3.1	10.0	6.0	8.0	**20.1**	**20.1**
	93.6Sn4.7Ag1.7Cu	7.0	3.5	8.0	8.0	6.0	**17.7**	8.0	5.8	8.0	8.0	2.0	**19.4**	**18.6**
	96.2Sn2.5Ag0.8Cu0.5Sb	7.0	5.0	10.0	6.0	5.0	**18.8**	8.0	7.0	10.0	6.0	6.0	**22.2**	**20.5**
	91.7Sn3.5Ag4.8Bi	10.0	6.1	6.0	8.0	6.0	**22.7**	10.0	5.3	6.0	8.0	6.0	**21.9**	**22.3**
	90.5Sn7.5Bi2Ag	10.0	6.8	10.0	6.0	6.0	**24.0**	10.0	5.7	10.0	6.0	6.0	**22.9**	**23.5**
	58Bi42Sn	5.0	7.3	8.0	8.0	9.0	**20.7**	6.0	7.5	8.0	8.0	9.0	**21.9**	**21.3**
	95Sn5Sb	9.0	4.3	4.0	8.0	6.0	**19.3**	8.0	5.5	4.0	8.0	9.0	**20.7**	**20.0**
	89Sn8Zn3Bi	0.0	0.0	0.0	0.0	0.0	**0.0**	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
	Average	**6.9**	**5.4**	**7.6**	**6.5**	**6.3**	**19.0**	**7.4**	**5.7**	**7.6**	**6.5**	**6.5**	**19.9**	**19.5**
F3	63Sn37Pb	9.0	10.0	8.0	8.0	10.0	**27.8**	9.0	10.0	8.0	8.0	10.0	**27.8**	**27.8**
	96.5Sn3.5Ag	6.0	3.1	2.0	8.0	7.0	**14.9**	7.0	6.3	2.0	8.0	8.0	**19.5**	**17.2**
	99.3Sn0.7Cu	8.0	6.3	8.0	8.0	8.0	**22.3**	8.0	7.5	8.0	8.0	8.0	**23.5**	**22.9**
	95.5Sn3.8Ag0.7Cu	8.0	6.7	10.0	8.0	8.0	**23.3**	8.0	7.3	10.0	8.0	8.0	**23.9**	**23.6**
	93.6Sn4.7Ag1.7Cu	8.0	6.1	4.0	8.0	7.0	**20.5**	8.0	7.3	4.0	8.0	7.0	**21.7**	**21.1**
	96.2Sn2.5Ag0.8Cu0.5Sb	8.0	5.3	10.0	8.0	6.0	**21.1**	9.0	6.5	10.0	8.0	7.0	**23.7**	**22.4**
	91.7Sn3.5Ag4.8Bi	8.0	7.0	10.0	8.0	8.0	**23.6**	9.0	6.5	10.0	8.0	8.0	**24.1**	**23.9**
	90.5Sn7.5Bi2Ag	7.0	6.1	8.0	8.0	8.0	**21.1**	8.0	6.6	8.0	8.0	8.0	**22.6**	**21.9**
	58Bi42Sn	6.0	5.1	6.0	8.0	9.0	**18.9**	6.0	5.8	6.0	8.0	9.0	**19.6**	**19.3**
	95Sn5Sb	8.0	5.1	10.0	8.0	8.0	**21.7**	8.0	6.8	10.0	8.0	8.0	**23.4**	**22.6**
	89Sn8Zn3Bi	0.0	0.0	0.0	4.0	0.0	**1.2**	0.0	0.0	0.0	4.0	0.0	**1.2**	**12**
	Average	**6.9**	**5.5**	**6.9**	**7.6**	**7.2**	**19.7**	**7.3**	**6.4**	**6.9**	**7.6**	**7.4**	**21.0**	**20.4**
F4	63Sn37Pb	10	10	8	8	10	**28.8**	10	9.5	8	8	10	**28.3**	**28.6**
	96.5Sn3.5Ag	9	5.5	2	8	7	**20.3**	9	6	2	8	7	**20.8**	**20.3**
	99.3Sn0.7Cu	8	5.2	8	8	8	**21.2**	9	6.5	8	8	8	**23.5**	**22.4**
	95.5Sn3.8Ag0.7Cu	8	5.3	10	8	8	**21.9**	8	6.5	10	8	8	**23.1**	**22.5**
	93.6Sn4.7Ag1.7Cu	8	5.3	4	8	6	**19.3**	8	6.7	4	8	7	**21.1**	**20.2**
	96.2Sn2.5Ag0.8Cu0.5Sb	8	5	10	8	5	**20.4**	8	6.7	10	8	7	**22.9**	**21.7**
	91.7Sn3.5Ag4.8Bi	8	6.3	10	8	6	**22.1**	9	6.2	10	8	7	**23.4**	**22.8**
	90.5Sn7.5Bi2Ag	8	4.6	8	8	7	**20.2**	9	6.5	8	8	8	**23.5**	**21.9**
	58Bi42Sn	6	4.6	6	8	9	**18.4**	5	4.8	6	8	9	**17.6**	**18.0**
	95Sn5Sb	8	2.9	10	8	6	**18.7**	8	5.5	10	8	8	**22.1**	**20.4**
	89Sn8Zn3Bi	0	0	0	4	0	**1.2**	0	0	0	4	0	**1.2**	**1.2**
	Average	**7.4**	**5.0**	**6.9**	**7.6**	**6.5**	**19.3**	**7.5**	**5.9**	**6.9**	**7.6**	**7.2**	**20.7**	**20.0**
F5	63Sn37Pb	9.0	10.0	6.0	2.0	10.0	**25.4**	9.0	10.0	6.0	2.0	10.0	**25.4**	**25.4**
	96.5Sn3.5Ag	8.0	8.0	2.0	2.0	2.0	**18.0**	7.0	7.5	2.0	2.0	8.0	**18.9**	**18.5**
	99.3Sn0.7Cu	8.0	5.5	4.0	2.0	6.0	**17.7**	8.0	6.6	4.0	2.0	8.0	**19.6**	**18.7**

Table 9 (continued)

Flux	Alloy	Cool profile						Warm profile						Ave
		SBI	WI	SLI	TTI	SAI	C	SBI	WI	SLI	TTI	SAI	C	C
F5	95.5Sn3.8Ag0.7Cu	7.0	7.0	10.0	0.0	8.0	**20.2**	7.0	7.3	10.0	0.0	8.0	**20.5**	**20.4**
	93.6Sn4.7Ag1.7Cu	9.0	6.1	4.0	2.0	2.0	**17.7**	9.0	6.3	4.0	2.0	7.0	**19.9**	**18.8**
	96.2Sn2.5Ag0.8Cu0.5Sb	8.0	7.3	8.0	0.0	6.0	**20.1**	8.0	6.0	8.0	0.0	7.0	**19.2**	**19.7**
	91.7Sn3.5Ag4.8Bi	10.0	7.8	8.0	0.0	5.0	**22.2**	10.0	6.7	8.0	0.0	2.0	**19.9**	**21.1**
	90.5Sn7.5Bi2Ag	10.0	8.0	6.0	0.0	7.0	**22.6**	8.0	8.8	6.0	0.0	7.0	**21.4**	**22.0**
	58Bi42Sn	6.0	5.0	4.0	2.0	9.0	**16.4**	7.0	5.2	4.0	2.0	9.0	**17.6**	**17.0**
	95Sn5Sb	9.0	6.0	6.0	2.0	7.0	**20.2**	8.0	6.0	6.0	2.0	2.0	**17.2**	**18.7**
	89Sn8Zn3Bi	1.0	0.0	0.0	0.0	0.0	**1.0**	1.0	0.0	0.0	0.0	0.0	**1.0**	**1.0**
	Average	**7.7**	**6.4**	**5.3**	**1.1**	**5.6**	**18.3**	**7.5**	**6.4**	**5.3**	**1.1**	**6.2**	**18.2**	**18.3**
F6	63Sn37Pb	6.0	10.0	0.0	0.0	10.0	**20.0**	10.0	10.0	0.0	0.0	10.0	**24.0**	**22.0**
	96.5Sn3.5Ag	10.0	6.3	10.0	2.0	7.0	**22.7**	10.0	5.3	10.0	2.0	7.0	**21.7**	**22.2**
	99.3Sn0.7Cu	10.0	6.0	0.0	6.0	8.0	**21.0**	9.0	7.5	0.0	6.0	8.0	**21.5**	**21.3**
	95.5Sn3.8Ag0.7Cu	9.0	6.7	10.0	6.0	7.0	**23.3**	10.0	6.3	10.0	6.0	7.0	**23.9**	**23.6**
	93.6Sn4.7Ag1.7Cu	10.0	6.7	8.0	6.0	6.0	**23.3**	10.0	6.0	8.0	6.0	6.0	**22.6**	**23.0**
	96.2Sn2.5Ag0.8Cu0.5Sb	9.0	6.1	10.0	6.0	5.0	**21.9**	10.0	5.1	10.0	6.0	5.0	**21.9**	**21.9**
	91.7Sn3.5Ag4.8Bi	10.0	7.1	10.0	6.0	5.0	**23.9**	10.0	6.8	10.0	6.0	5.0	**23.6**	**23.8**
	90.5Sn7.5Bi2Ag	9.0	8.3	2.0	6.0	5.0	**21.7**	10.0	6.5	2.0	6.0	5.0	**20.9**	**21.3**
	58Bi42Sn	8.0	7.1	0.0	6.0	2.0	**17.7**	10.0	5.7	0.0	6.0	9.0	**21.1**	**19.4**
	95Sn5Sb	8.0	5.0	0.0	4.0	5.0	**16.2**	10.0	5.7	0.0	4.0	5.0	**18.9**	**17.6**
	89Sn8Zn3Bi	0.0	0.0	0.0	0.0	0.0	**0.0**	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
	Average	**8.1**	**6.3**	**4.5**	**4.4**	**5.5**	**19.2**	**9.0**	**5.9**	**4.5**	**4.4**	**6.1**	**20.0**	**19.6**
F7	63Sn37Pb	9.0	10.0	8.0	0.0	10.0	**25.4**	10.0	10.0	8.0	0.0	10.0	**26.4**	**25.9**
	96.5Sn3.5Ag	10.0	1.0	8.0	0.0	4.0	**15.0**	10.0	1.0	8.0	0.0	4.0	**15.0**	**15.0**
	99.3Sn0.7Cu	10.0	4.5	10.0	0.0	6.0	**19.9**	10.0	5.3	10.0	0.0	8.0	**21.5**	**20.7**
	95.5Sn3.8Ag0.7Cu	10.0	5.1	10.0	0.0	6.0	**20.5**	10.0	5.3	10.0	0.0	6.0	**20.7**	**20.6**
	93.6Sn4.7Ag1.7Cu	10.0	5.5	4.0	0.0	6.0	**19.1**	10.0	5.0	4.0	0.0	6.0	**18.6**	**18.9**
	96.2Sn2.5Ag0.8Cu0.5Sb	10.0	4.8	10.0	0.0	5.0	**19.8**	10.0	5.3	10.0	0.0	5.0	**20.3**	**20.1**
	91.7Sn3.5Ag4.8Bi	10.0	8.7	10.0	0.0	5.0	**23.7**	10.0	6.8	10.0	0.0	5.0	**21.8**	**22.8**
	90.5Sn7.5Bi2Ag	10.0	8.1	10.0	0.0	5.0	**23.1**	10.0	7.1	10.0	0.0	5.0	**22.1**	**22.6**
	58Bi42Sn	9.0	6.3	10.0	0.0	9.0	**21.9**	9.0	5.0	10.0	0.0	9.0	**20.6**	**21.3**
	95Sn5Sb	10.0	3.0	6.0	0.0	5.0	**16.8**	10.0	4.5	6.0	0.0	5.0	**18.3**	**17.6**
	89Sn8Zn3Bi	0.0	0.0	8.0	0.0	0.0	**2.4**	0.0	0.0	8.0	0.0	0.0	**2.4**	**2.4**
	Average	**8.9**	**5.2**	**8.5**	**0.0**	**5.5**	**18.9**	**9.0**	**5.0**	**8.5**	**0.0**	**5.7**	**18.9**	**18.9**
F8	63Sn37Pb	10.0	10.0	8.0	6.0	10.0	**28.2**	10.0	10.0	8.0	6.0	10.0	**28.2**	**28.2**
	96.5Sn3.5Ag	10.0	7.3	10.0	6.0	2.0	**22.9**	10.0	6.3	10.0	6.0	5.0	**23.1**	**23.0**
	99.3Sn0.7Cu	9.0	1.0	10.0	6.0	8.0	**18.0**	10.0	7.0	10.0	6.0	3.0	**23.0**	**20.0**
	95.5Sn3.8Ag0.7Cu	10.0	5.0	10.0	8.0	4.0	**22.0**	9.0	7.0	10.0	8.0	2.0	**22.2**	**22.1**
	93.6Sn4.7Ag1.7Cu	10.0	7.0	10.0	6.0	6.0	**24.2**	10.0	5.8	10.0	6.0	5.0	**22.6**	**23.4**
	96.2Sn2.5Ag0.8Cu0.5Sb	8.0	6.1	10.0	6.0	6.0	**21.3**	10.0	5.0	10.0	6.0	5.0	**21.8**	**21.6**
	91.7Sn3.5Ag4.8Bi	10.0	7.0	10.0	8.0	5.0	**24.4**	10.0	7.5	10.0	8.0	5.0	**24.9**	**24.7**
	90.5Sn7.5Bi2Ag	10.0	7.3	10.0	6.0	5.0	**24.1**	10.0	7.6	10.0	6.0	5.0	**24.4**	**24.3**
	58Bi42Sn	10.0	7.6	6.0	8.0	3.0	**23.0**	10.0	4.5	6.0	8.0	3.0	**19.9**	**21.5**
	95Sn5Sb	10.0	5.2	10.0	8.0	5.0	**22.6**	10.0	6.5	10.0	8.0	5.0	**23.9**	**23.3**
	89Sn8Zn3Bi	0.0	0.0	0.0	0.0	0.0	**0.0**	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
	Average	**8.8**	**5.8**	**8.5**	**6.2**	**4.9**	**21.0**	**9.0**	**6.1**	**8.5**	**6.2**	**4.4**	**21.3**	**21.2**
F9	63Sn37Pb	10.0	8.8	10.0	0.0	9.0	**25.4**	10.0	8.6	10.0	0.0	9.0	**25.2**	**25.3**
	96.5Sn3.5Ag	1.0	0.0	10.0	0.0	4.0	**5.6**	1.0	0.0	10.0	0.0	4.0	**5.6**	**5.6**
	99.3Sn0.7Cu	0.0	0.0	10.0	0.0	0.0	**3.0**	1.0	0.0	10.0	0.0	1.0	**4.4**	**3.7**
	95.5Sn3.8Ag0.7Cu	1.0	0.0	10.0	0.0	1.0	**4.4**	1.0	0.0	10.0	0.0	1.0	**4.4**	**4.4**
	93.6Sn4.7Ag1.7Cu	1.0	0.0	10.0	6.0	1.0	**6.2**	1.0	0.0	10.0	6.0	1.0	**6.2**	**6.2**
	96.2Sn2.5Ag0.8Cu0.5Sb	0.0	0.0	10.0	2.0	0.0	**3.6**	0.0	0.0	10.0	2.0	0.0	**3.6**	**3.6**

Table 9 (continued)

Flux	Alloy	Cool profile						Warm profile						Ave
		SBI	WI	SLI	TTI	SAI	C	SBI	WI	SLI	TTI	SAI	C	C
F9	91.7Sn3.5Ag4.8Bi	10.0	6.5	10.0	0.0	5.0	**21.5**	10.0	7.5	10.0	0.0	5.0	**22.5**	**22.0**
	90.5Sn7.5Bi2Ag	10.0	6.5	10.0	2.0	5.0	**22.1**	10.0	5.7	10.0	2.0	5.0	**21.3**	**21.7**
	58Bi42Sn	9.0	6.5	10.0	2.0	8.0	**22.3**	10.0	8.1	10.0	2.0	9.0	**25.3**	**23.8**
	95Sn5Sb	0.0	0.0	10.0	0.0	0.0	**3.0**	1.0	0.0	10.0	0.0	1.0	**4.4**	**3.7**
	89Sn8Zn3Bi	0.0	0.0	0.0	0.0	0.0	**0.0**	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
	Average	**3.8**	**2.6**	**9.1**	**1.1**	**3.0**	**10.6**	**4.1**	**2.7**	**9.1**	**1.1**	**3.3**	**11.2**	**10.9**
F10	63Sn37Pb	10.0	10.0	6.0	6.0	9.0	**27.2**	10.0	10.0	6.0	6.0	10.0	**27.6**	**27.4**
	96.5Sn3.5Ag	6.0	6.1	8.0	6.0	5.0	**18.3**	7.0	7.5	8.0	6.0	8.0	**21.9**	**20.1**
	99.3Sn0.7Cu	10.0	5.0	0.0	6.0	7.0	**19.6**	9.0	7.5	0.0	6.0	8.0	**21.5**	**20.6**
	95.5Sn3.8Ag0.7Cu	8.0	6.5	4.0	6.0	7.0	**20.3**	8.0	8.0	4.0	6.0	8.0	**22.2**	**21.3**
	93.6Sn4.7Ag1.7Cu	10.0	6.3	6.0	6.0	8.0	**23.1**	9.0	7.0	6.0	6.0	8.0	**22.8**	**23.0**
	96.2Sn2.5Ag0.8Cu0.5Sb	8.0	6.1	4.0	6.0	5.0	**19.1**	9.0	7.0	4.0	6.0	5.0	**21.0**	**20.1**
	91.7Sn3.5Ag4.8Bi	9.0	7.6	6.0	6.0	6.0	**22.6**	9.0	7.5	6.0	6.0	8.0	**23.3**	**23.0**
	90.5Sn7.5Bi2Ag	9.0	8.5	10.0	6.0	5.0	**24.3**	9.0	7.8	10.0	6.0	8.0	**24.8**	**24.6**
	58Bi42Sn	1.0	4.5	4.0	6.0	8.0	**11.7**	1.0	4.5	4.0	6.0	8.0	**11.7**	**11.7**
	95Sn5Sb	10.0	6.0	0.0	6.0	5.0	**19.8**	9.0	6.6	0.0	6.0	7.0	**20.2**	**20.0**
	89Sn8Zn3Bi	1.0	5.0	0.0	2.0	2.0	**7.4**	10.0	4.6	0.0	2.0	2.0	**16.0**	**11.7**
	Average	**7.5**	**6.5**	**4.4**	**5.6**	**6.1**	**19.4**	**8.2**	**7.1**	**4.4**	**5.6**	**7.3**	**21.2**	**20.3**

Table 10. Summary of compatibility of solder alloy systems with variety of fluxes.

Alloy	Cool profile						Warm profile						Average					
	SBI	WI	SLI	TTI	SAI	C	SBI	WI	SLI	TTI	SAI	C	SBI	WI	SLI	TTI	SAI	C
63Sn37Pb	9.2	9.9	7.2	4.8	9.8	**26.6**	9.8	9.7	7.2	4.8	9.9	**27.1**	9.5	9.8	7.2	4.8	9.9	**26.8**
96.5Sn3.5Ag	7.0	4.6	6.6	5.0	5.0	**17.1**	6.9	4.8	6.6	5.0	6.3	**17.7**	7.0	4.6	6.6	5.0	5.7	**17.4**
99.3Sn0.7Cu	7.8	4.4	6.8	4.6	6.3	**18.2**	8.1	6.0	6.8	4.6	6.9	**20.3**	8.0	5.2	6.8	4.6	6.6	**19.3**
95.5Sn3.8Ag0.7Cu	7.6	5.3	9.4	5.0	6.4	**19.8**	7.8	5.5	9.4	5.0	6.4	**20.2**	7.7	5.4	9.4	5.0	6.4	**20.0**
93.6Sn4.7Ag1.7Cu	8.0	5.0	6.8	5.6	5.4	**18.9**	8.1	5.6	6.8	5.6	5.6	**19.6**	8.1	5.3	6.8	5.6	5.5	**19.3**
96.2Sn2.5Ag0.8Cu0.5Sb	7.4	5.1	9.2	5.2	4.8	**18.8**	8.0	5.2	9.2	5.2	5.3	**19.6**	7.7	5.2	9.2	5.2	5.1	**19.2**
91.7Sn3.5Ag4.8Bi	9.5	7.0	9.0	5.2	5.6	**23.0**	9.7	6.7	9.0	5.2	5.6	**22.9**	9.6	6.8	9.0	5.2	5.6	**22.9**
90.5Sn7.5Bi2Ag	9.2	7.1	8.4	5.0	5.8	**22.6**	9.4	6.9	8.4	5.0	6.2	**22.8**	9.3	7.0	8.4	5.0	6.0	**22.7**
58Bi42Sn	6.6	6.2	6.4	5.8	7.5	**19.5**	7.0	5.7	6.4	5.8	8.3	**19.7**	6.8	6.0	6.4	5.8	7.9	**19.6**
95Sn5Sb	8.2	4.2	6.6	5.2	5.2	**18.0**	8.1	5.3	6.6	5.2	5.9	**19.3**	8.2	4.7	6.6	5.2	5.6	**18.7**
89Sn8Zn3Bi	0.2	0.5	0.8	1.2	0.2	**1.4**	1.1	0.5	0.8	1.2	0.2	**2.2**	0.7	0.5	0.8	1.2	0.2	**1.8**
Average	7.3	5.4	7.0	4.8	5.6	**18.5**	7.6	5.6	7.0	4.8	6.1	**19.2**	7.5	5.5	7.0	4.8	5.8	**18.9**

Table 11. Summary of compatibility of flux systems with variety of alloys.

Flux	Cool profile						Warm profile						Average					
	SBI	WI	SLI	TTI	SAI	C	SBI	WI	SLI	TTI	SAI	C	SBI	WI	SLI	TTI	SAI	C
F1 (NC, air, no-X, probe)	7.4	5.4	8.4	7.6	5.7	**19.8**	7.5	5.0	8.4	7.6	6.6	**19.9**	7.4	5.2	8.4	7.6	6.2	**19.9**
F2 (NC, air, no-X, probe)	6.9	5.4	7.6	6.5	6.3	**19.0**	7.4	5.7	7.6	6.5	6.5	**19.9**	7.1	5.5	7.6	6.5	6.4	**19.5**
F3 (NC, air, X)	6.9	5.5	6.9	7.6	7.2	**19.7**	7.3	6.4	6.9	7.6	7.4	**21.0**	7.1	6.0	6.9	7.6	7.3	**20.3**
F4 (NC, air, X)	7.4	5.0	6.9	7.6	6.5	**19.3**	7.5	5.9	6.9	7.6	7.2	**20.7**	7.5	5.4	6.9	7.6	6.9	**20.0**
F5 (RMA, air, X)	7.7	6.4	5.3	1.1	5.6	**18.3**	7.5	6.4	5.3	1.1	6.2	**18.2**	7.6	6.4	5.3	1.1	5.9	**18.3**
F6 (NC, air, no-X)	8.1	6.3	4.5	4.4	5.5	**19.2**	9.0	5.9	4.5	4.4	6.1	**20.0**	8.5	6.1	4.5	4.4	5.8	**19.6**
F7 (NC, N2, no-X, low R)	8.9	5.1	8.5	0.0	5.5	**18.9**	9.0	4.9	8.5	0.0	5.7	**18.9**	9.0	5.0	8.5	0.0	5.6	**18.9**
F8 (NC, N2, no-X, ultra-low R)	8.8	5.7	8.5	6.2	4.9	**21.0**	9.0	6.1	8.5	6.2	4.4	**21.3**	8.9	5.9	8.5	6.2	4.6	**21.2**
F9 (WS, air, no-X, med. Temp)	3.8	2.6	9.1	1.1	3.0	**10.6**	4.1	2.7	9.1	1.1	3.3	**11.2**	4.0	2.6	9.1	1.1	3.1	**10.9**
F10 (WS, air, X, high temp)	7.5	6.5	4.4	5.6	6.1	**19.4**	8.2	7.1	4.4	5.6	7.3	**21.2**	7.8	6.8	4.4	5.6	6.7	**20.3**
Average	7.3	5.4	7.0	4.8	5.6	**18.5**	7.6	5.6	7.0	4.8	6.1	**19.2**	7.5	5.5	7.0	4.8	5.8	**18.9**

Table 12 Relation between macro-voiding, solder appearance SAI, and intermetallic compound (IMC) thickness.

Flux	Alloy	Profile	SAI	IMC (μ)	*Voiding %
F5	91.7Sn3.5Ag4.8Bi	Warm	2	2.7	13
F10	89Sn8Zn3Bi	Warm	2	2.0	100
F8	58Bi42Sn	Cool	3	0.7	79
F5	91.7Sn3.5Ag4.8Bi	Cool	5	1.7	13
F2	90.5Sn7.5Bi2Ag	Cool	6	1.5	75
F5	90.5Sn7.5Bi2Ag	Cool	7	2.0	15
F5	90.5Sn7.5Bi2Ag	Warm	7	2.0	50
F5	95.5Sn3.8Ag0.7Cu	Warm	8	2.0	27
F5	95.5Sn3.8Ag0.7Cu	Cool	8	2.0	56
F5	63Sn37Pb	Cool	10	1.0	0

* Percentage of bumps cross-sectioned exhibiting macro-voiding

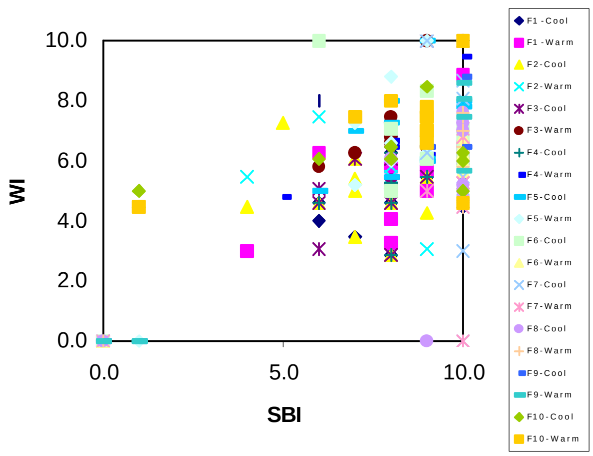

Figure 5 Relation between SBI and WI.

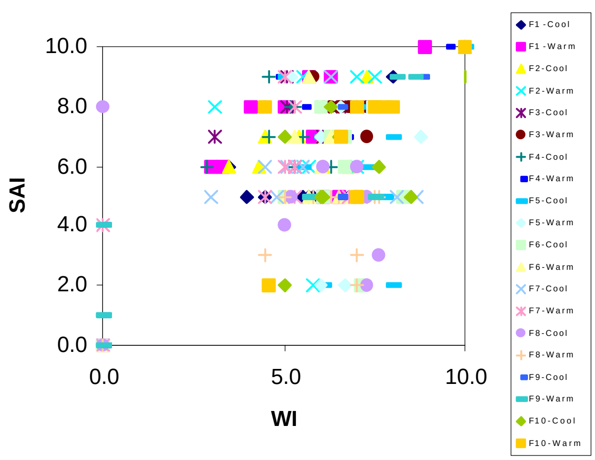

Figure 6 Relation between WI and SAI

However, for the solders studied here, the reflow temperature happens to increases roughly with increasing Sn content. Thus the reflow temperature is the lowest for 58Bi42Sn (with the lowest Sn content), is medium for 63Sn37Pb (with medium Sn content), and is the highest for the rest lead-free alloys (with Sn content no less than 89%). In theory, both high Sn content and high reflow temperature could promote formation of a thicker IMC layer. Data here is insufficient to clarify the relative effect of reflow temperature versus Sn content on the thickness of IMC. However, it does suggest that for those high-tin-content lead-free alloys, which exhibit a melting temperature higher than eutectic SnPb solder, the IMC thickness may tend to be thicker than eutectic SnPb system therefore may pose some concern on the reliability for reflow applications.

DISCUSSION

1. Significance of SBI, WI, and SAI

To assess the compatibility of alloys with reflow applications, it is essential to recognize all of the crucial independent performance parameters. For soldering performance, it may appear that the wetting ability, solder balling, and solder appearance are all related to each other, and may be reflected by a single parameter. The relation among those three parameters is examined by plotting WI vs SBI (see Figure 5) and SAI vs WI (see Figure 6) for all of the measurements conducted in this work. Results indicate that the relation among wetting ability, solder balling, and solder appearance is very weak, if any exists, and all three properties have to be monitored in order to assess the compatibility of alloys.

However, it should also be pointed out that while the smoothness of solder appearance may serve as a very good indicator for solder joint quality for the same alloy system, the same criteria may not be applicable when comparing solders with different solder compositions. Therefore, an alloy with some crystalline surface texture may be more reliable than another alloy with a smooth surface texture. For this reason, the solder appearance factor is weighed less than other properties such as solder balling and wetting in this study.

2. Wetting Index

For systems not fully reflowed, the wetting index value assigned is always zero, even if a partial wetting may be observed on the copper pad.

3. Potential of Alloys

The reflow profiles used in this study allows the maximum temperature to be 30°C above the liquidus temperature. In some of the industrial practice, a profile with a higher peak temperature, such as 40°C above the liquidus temperature, may be possible. Under those conditions, most of the lead-free alloy systems investigated here may have better compatibility than what has been demonstrated in this study.

4. Solder Paste Deposition

In this work, the printability and dispensability of solder paste are not evaluated. The impact on compatibility study is considered minimal, since those deposition performance is mainly a function of the flux rheology, not a function of alloy type.

5. Testing without Components

Since no components are used in the experiment, certain specific process defects such as tombstoning, wicking, solder beading, and skewing can not be predicted by the work here. As to the voiding, which is often a function of coverage area by the components [6], the performance will be difficult to predict as well.

6. Surface Finishes

The surface finish is confined to OSP coating in this work. Varying the surface finish may not affect the results reported on solder balling and solder appearance, but may alter the conclusion on wetting ability. Surface finishes containing lead poses special concern on reliability for Bi-containing alloys [3,4]. This concern may outweigh the compatibility advantage in terms of soldering capability and handling-ability displayed by SnAgBi solder systems for reflow applications.

7. Beyond Reflow Soldering

The compatibility results are applicable to solder paste applications only. Alloys being ruled out due to solder paste stability problem, such as 89Sn8Zn3Bi, may still be promising for other applications such as wave soldering. On the other hand, alloys being compatible with reflow soldering may suffer defects such as fillet lifting at wave soldering [3].

CONCLUSION

The prospects of 10 major lead-free solder alloys for being widely used for reflow soldering are studied in this work. Compatibility of those alloys with a variety of representative flux chemistries is considered essential, and is determined for performance in handling-ability, including shelf life and tack time, and soldering capability, including solder balling, wetting, and solder joint appearance. Results indicate that the control 63Sn37Pb is still the most compatible alloy, rated 27.1 in compatibility out of a full scale 30 when using warm profile. The primary factor which distinguishes 63Sn37Pb from the rest alloys is the soldering performance, particularly the wetting and solder appearance. As to the solder balling, although 63Sn37Pb is also the best, it is fairly close to the best lead-free systems. Among the lead-free options, both SnAgBi alloys studied here, 91.7Sn3.5Ag4.8Bi and 90.5Sn7.5Bi2Ag, turn out to be on the top of lead-free systems, rated 22.9 and 22.8, respectively. This is mainly attributed to the better wetting and solder balling performance. Shelf life and tack time of the SnAgBi systems are also fairly good, while the solder appearance is at best considered average. The six alloys, 99.3Sn0.7Cu, 95.5Sn3.8Ag0.7Cu, 93.6Sn4.7Ag1.7Cu, 96.2Sn2.5Ag0.8Cu0.5Sb, 58Bi42Sn, and 95Sn5Sb, show fairly comparable performance to each other, with compatibility ranging from 19.3 to 20.3. In general, the whole group displays a quite noticeably poorer wetting than SnAgBi systems. 58Bi42Sn exhibits a fairly poor solder balling performance, but an outstanding solder appearance among lead-free systems. 96.2Sn2.5Ag0.8Cu0.5Sb shows a relatively poor performance in both wetting and solder appearance among these six alloys. 96.5Sn3.5Ag, rated 17.1 in compatibility, is ranked below the other alloys described above, mainly due to poor performance in solder balling, and particularly the poor wetting. 89Sn8Zn3Bi, rated only 2.2 in compatibility, falls far short in every category when compared with all other alloy systems. Obviously, this is attributable to the very reactive nature of zinc, which results in excessive oxidation of metal and excessive reaction with fluxes, and consequently a definitely unacceptable performance for solder paste applications. High-tin-content lead-free alloys seem to display a thicker IMC layer than eutectic SnPb when reflowed.

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