Development of Low-Temperature Drop Shock Resistant Solder Alloys for Handheld Devices

Morgana Ribas, Sujatha Chegudi, Anil Kumar, Ranjit Pandher#, Rahul Raut#, Sutapa Mukherjee, Siuli Sarkar, Bawa Singh#
Alpha
Bangalore, KA, India 560022
#South Plainfield, NJ, USA 07080
mribas@alent.com, rpandher@alent.com

Abstract

As handheld devices become increasingly smaller and complex, there is a shift in reliability requirements of solder pastes. Considering that thermal management and drop resistance of such devices become more challenging, improved thermal fatigue and mechanical shock properties grow into must have requirements. Additionally, multi-step assembly process and a surge in use of temperature sensitive components bring additional challenges that necessitate the use of low temperature alloys. Here we present the findings of our Alloy Development Program on the next generation of low temperature alloys that can be used in reflow soldering temperatures from 170 to 200°C. By using micro-additives we have created low temperature alloys with superior mechanical properties, higher drop shock resistance and improved fatigue life.

Introduction

Recent years have seen accelerated growth of the number of handheld electronic devices. For example, from 2010 to 2015 the number of desktop shipments is expected to remain steady, whereas that of Smart Phones would see a four-fold increase in the same period [1]. Such portable applications have very specific mechanical reliability requirements, which almost invariably include higher drop shock resistance. As the market for handheld electronics increases so does the complexity of their functionality. As a result, suppliers of solder alloys and interconnecting materials face growing challenges on how to maintain or improve existing reliability requirements in these progressively smaller and complex handheld devices.

Sn-Ag-Cu alloys were recommended as lead-free solders by consortiums such as the National Electronics Manufacturing Initiative (NEMI) Lead-Free Assembly Project and the IPC Solder Products Value Council (SPVC) [2]. For example, Sn96.5-Ag3.0-Cu0.5 alloy has excellent thermal cycling properties, which are superior to eutectic Sn-Pb. However, high-Ag alloys do not reproduce Sn-Pb mechanical reliability performance (e.g., mechanical shock). The launch of SACX family of alloys introduced low-Ag Sn-Ag-Cu alloys that have good thermal cycling reliability and enhanced mechanical shock properties, at a lower cost [3-5]. SAC alloys have melting ranges between 217 and 228°C (see Table 1 for examples), enabling reflow temperatures between 245 and 265°C.

Indeed, higher reflow temperature of SAC alloys, especially when compared to eutectic Sn-Pb, is one of its major drawbacks. For assembly of temperature-sensitive applications, such as handheld devices, low-temperature solder alloys are preferred, although SAC alloys will continue to have a considerable presence. In this category are the alloys that can be used in reflow soldering temperatures from 170 to 200°C, which results in lower thermal stresses and defects such as warping during assembly. Most low-temperature alloy systems use Bismuth and Indium for lowering the melting point of the solder, as in Sn48-In52 and Sn42-Bi58 eutectic alloys (Table 1). In general, Sn-Bi alloys have lower cost than Sn-In, which can be an important advantage in a competitive market such as handheld electronic devices. However, how to improve some of Sn-Bi drawbacks, such as brittleness, poor thermal conductivity, poor fatigue life, and expansion on solidification [6-9]?

The use of micro-additives has been successfully used to improve alloy mechanical properties, solderability and mechanical and thermal reliability of SAC alloys, as shown for low-Ag alloys with Bi, Ni, In and Cr small additions [10-12]. Alpha R&D approach to new alloy development includes: 1) Interfacial intermetallics (IMC) control through diffusion modifiers, 2) Interfacial voids control through diffusion compensators and modifiers and 3) Bulk solder property control through bulk IMC and microstructure modification.

In the case of the Sn42-Bi58 eutectic alloy, its thermal-mechanical fatigue properties can be improved by small Ag additions [8,13]. For example, Sn42-Bi57.6Bi-Ag0.4 alloy has been successfully used in ALPHA CVP520 solder paste, resulting in improved mechanical and thermal properties [14]. Although very little has been studied about Sn-Bi drop shock resistance, it is believed that its low ductility results in lower ability of the solder joint to withstand impact, yielding poor drop shock properties.

Table 1: Melting range of selected alloys.

Alloy	Melting Range, °C
Sn96.5-Ag3-Cu0.5	217-221
SACX Plus 0807	217-227
SACX Plus 0307	217-228
Sn42-Bi58	138 (E)
Sn48-In52	118 (E)

The main objective of this work is to study alloy characteristics that might lead to better drop shock performance and align them with the electronics industry specific needs, in particular through drop shock tests. Brittleness of Sn-Bi solder is due to presence of Bi rich phase in the bulk. Therefore one of the easiest ways to improve alloy ductility is to reduce the Bi level. However, reducing Bi level will move the alloy away from the eutectic point resulting in higher liquidus temperature, which will then require higher temperature reflow. This increased reflow temperature will still be lower than the Sn-Ag-Cu reflow temperatures so it may be acceptable for certain applications.

978-1-4799-2834-7/13/$31.00

For those applications requiring really low reflow temperatures (well below 200°C) we explore possibility of improving properties of the eutectic Sn-Bi solder with minor additions of alloying elements. Here we present a study of their mechanical and drop shock properties and show a comprehensive summary of the effect of these alloying additions. Finally, a new low temperature alloy with superior mechanical properties, higher drop shock resistance and improved thermal fatigue life is presented.

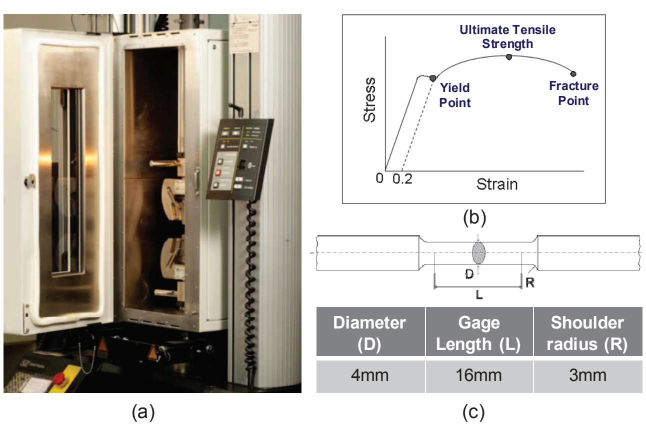
Experimental Methodology

In depth analysis of the new alloy properties, especially its mechanical properties behavior provides strong indication of its performance in real application so it can be used to screen alloys for further investigation of its solder joint interfacial characteristics, and thermal and mechanical reliability. Full product utilization and testing analysis is performed once there is enough information to support the new alloy performance. Here we focus only on alloy properties that can be related to drop shock performance. Please see Ref.16 for additional alloy properties.

Mechanical Properties

Tensile tests were conducted using an Instron model 5566 universal testing machine, Figure 1 (a)-(b). Rounded specimens were prepared as per ASTM E8 tensile test standard, see Figure 1 (c) for details. Stress-strain curves for at least five specimens of each alloy were recorded at room temperature. These tests were performed at a constant strain rate of 10^{-3}mm/s. The average values of ultimate strength, yield strength and elongation are reported here.

The elastic properties provide very important information on the shock and vibration performance of alloys. Since propagation of the sound waves through a material depends on its elastic properties, an ultrasonic pulse-echo technique is used to evaluate these properties without the variability often observed when performing tensile tests. We use the Olympus 38DL PLUS ultrasonic thickness gage, and longitudinal and shear wave transducers to measure the sound velocities through the alloys, which are then used to compute their Young's Modulus, Shear Modulus and Poisson's ratio.



Diameter (D)	Gage Length (L)	Shoulder radius (R)
4mm	16mm	3mm

Figure 1: (a) Instron universal testing machine with environmental chamber, (b) Stress-strain curve schematics and (c) Specimen geometry used for tensile testing.

Shear test of chip resistors was conducted on a DAGE 4000 system, as per the JIS Z3198-7:2003 standard. The shear force was measured on 20-25 #1206 chip resistors at 700 µm/s shear speed and 20 µm shear height.

Drop Shock

The JESD22-B111 standard is a usual choice for testing board level drop resistance of handheld devices, especially during development of new alloys. Other drop tests used in the electronics industry require full assembly of a device and are generally used only at final development stages.

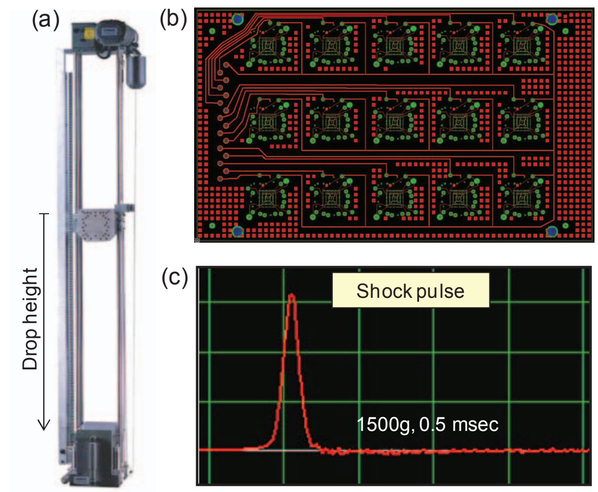


Figure 2: (a) Lansmont drop shock testing machine, (b) Alent drop shock test vehicle and (c) half-sine shock pulse curve corresponding to JEDEC service condition B.

A Lansmont M23 shock machine, shown in Figure 2 (a), is used for performing the drop tests of our customized test vehicle, Figure 2 (b). Test Vehicle follows the JEDEC recommendation and used CTBGA84 components with 84 I/Os with 0.5 mm pitch and 0.3 mm diameter spheres. Pad finish on the component side is NiAu and on the board side is Cu-OSP. By adjusting the drop height and the strike surface it is possible to achieve JEDEC's recommended service condition B (1500Gs, 0.5 msec duration and half-sine pulse), which is monitored as shown in Figure 2 (c).

The electrical continuity of each component is monitored during each drop using an Analysis Tech STD event detector. Each of the BGA84 assembled in the drop shock test vehicle was tested till failure (electrical resistance discontinuity greater than 1000 Ω lasting more than 1 µsec). The BGA failures were recorded once a first discontinuity is followed by three others within five subsequent drops. Weibull curves are built for evaluating the probability distribution of the failures over a period of time.

Test Vehicles

The test vehicles used in this study were reflowed in a seven zone heater reflow machine (Ominiflo7); soaked at 100-120°C for 90sec, with 180°C peak temperature and 60sec TAL.

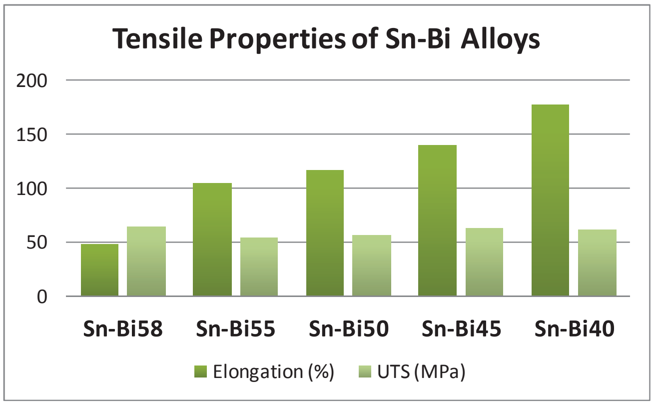


Figure 3: Tensile properties of Sn-Bi Alloys.

Various chip resistors were mounted on a calibrated CERF board; #0402 chips were used for analyzing solder joint microstructure features, whereas #1206 chips were used for the shear test. The test vehicle used for drop shock test is a Cu-OSP finished board with non-solder mask defined 0.225 mm pads, as shown in Figure 2(b). Each board can accommodate up to 15 BGA84, which are individually monitored for electrical discontinuities. For the results shown here all BGA84 components had Sn-Ag3-Cu0.5 spheres.

Results and Discussion

Sn-Bi Alloys

Despite being in the initial pool of Pb-free alloys considered for substituting Sn-Pb, use of Sn-Bi as solder alloys has been hindered mostly due to its low ductility. The eutectic Sn-Bi alloy has 58wt.% Bi content and a melting point of 138°C. Compared to other Sn-Bi alloys such as Sn-Bi45 and SnBi40, the Sn-Bi58 has slightly higher mechanical strength and much lower elongation at rupture, as shown in Figure 3. Similar results have been observed in other studies, for example Ref. 6 and 9. Due to its high solubility in Sn, higher Bi content leads to a higher degree of solid solution hardening, which results in the higher mechanical properties of Sn-Bi58. The loss in ductility comes as a consequence of this hardening and is a major drawback for its use in soldering applications. One suggestion is the use of off-eutectic alloys such as Sn-Bi40 and Sn-Bi45 that have higher elongation and reasonable mechanical properties. However, these alloys have a wide melting range (138°C solidus temperature and 170°C liquidus temperature), which is generally undesirable for SMT applications because it can result in various assembly defects.

At this point, a good question to ask is how these mechanical properties relate to an actual drop shock test. Until now, very little has been published about the behavior of Sn-Bi alloys in drop shock testing, which is just assumed to be poor. Figure 4 shows the drop shock results of Sn-Bi alloys with 40, 45 and 58 wt.% Bi. A simple analysis of the average number of drops of these three alloys shows that the drop resistance is higher for lower Bi content, for example, Sn-Bi40 has 150% higher average number of drops than Sn-Bi58. Although higher, such drop shock performance of Sn-Bi40 is not nearly close to what is obtained using Sn-Ag3-Cu0.5 and ALPHA SACX Plus 0307 alloys, as shown in Figure 5.

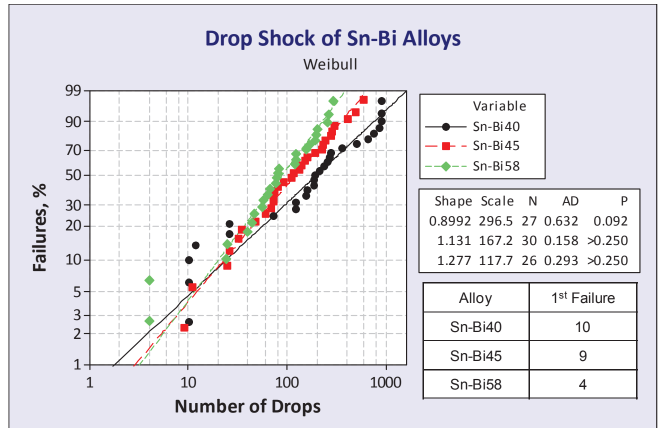


Figure 4: Drop shock results of Sn-Bi alloys.

Besides that, a large number of early failures was observed during drop shock test for all three alloys, which considerably reduces the possibility of using such alloys for handheld devices. Sn-Bi58 first failure was found to be as low as 4 drops, whereas it was 10 drops for Sn-Bi40. Such elevated number of early failures has a higher impact on Sn-Bi40, followed by Sn-Bi45, than on Sn-58Bi. This might be an indication of the increased number of defects of off-eutectic alloys and the lack of support for their use in SMT applications. However, if the components that failed before 40 drops would be removed, the average number of drops of Sn-Bi40 would be about 50% higher and very close to Sn-Ag3-Cu0.5 drop shock performance. Comparatively, removal of the early failures observed for Sn-Bi58 would results in about 20% improvement in the average number of failures.

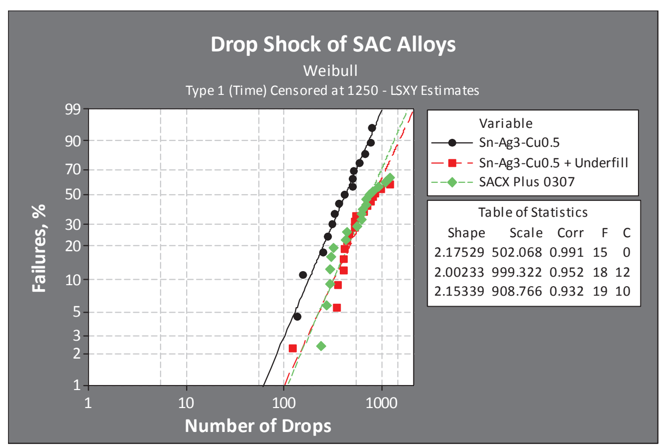


Figure 5: Drop shock results of Sn-Ag-Cu alloys.

Sn-Bi58 Plus Alloys

Considering the results shown above, it becomes clear the complexity involved in improving drop shock performance of low temperature alloys. Multiple steps can be taken towards achieving such improvement, for example, use of additional support such as underfill materials can greatly improve drop shock performance, as shown in Figure 5. Other steps may involve developing specific flux chemistry aiming at minimize soldering defects and early drop shock failures. Eutectic Sn-Bi58 was chosen as the base alloy system to focus on how to improve drop shock resistance of the alloy per se, and leave aside other factors such as soldering defects and assembly problems that could arise from using off-eutectic alloys.

Table 2: Ultimate tensile strength (UTS), elongation and Young's modulus (*E*) of Sn-Bi58 Plus alloys.

Alloys	UTS (MPa)	Elongation (%)	$E^{\#}$ (GPa)
Sn42Bi58	63.6	48.2	39.0
Sn42Bi57.6Ag0.4	67.4	52.6	39.3
Alloy Composition-A	73.0	69.8	38.8
Alloy Composition-B	70.2	66.1	39.1

#Measured by ultrasonic pulse-echo technique.

Small Ag addition to Sn-Bi58 results only in minor improvement of the ultimate tensile strength and % elongation at failure (Table 2). Other alloys without Ag addition, such as alloy composition A and alloy composition B have multiple alloying additions that result in higher strength and elongation. For specimens with identical geometry, Young's modulus measurements provide valuable information on how stiff a material is. So, for higher drop shock properties a material is expected to have a relatively low modulus, i.e., better elasticity. Although we have used an ultrasonic pulse-echo technique for obtaining a very precise value for the Sn-Bi58 Plus alloys, only minor variations were observed in the modulus (~39GPa). However, Young's modulus measurement remains a useful tool for estimating the drop shock performance of a new alloy. For example, Sn-Ag3-Cu0.5 average number of drops is 4x higher than of Sn-Bi58, which is confirmed by its lower Young's modulus (18.2GPa).

In general, when working with small alloying additions, no major differences relatively to the parent alloy system are expected, unless there is a remarkable modification of the alloy microstructure. The 0.4 wt.% Ag addition to Sn-Bi58 refines the alloy microstructure and improves its thermal fatigue resistance. Other alloying additions refine further the microstructure, as occurs in alloy A. However, a noticeable microstructure modification is seen mostly in alloy B, in which Bi appears to form an individual phase instead of the continuous layer that is typical of eutectic Sn-Bi.

Drop shock results confirm these microscopic observations. The average number of drops of Sn-Bi57.6-Ag0.4 is 25% higher than Sn-Bi58, whereas of alloy A is 60% higher and of alloy B is 160% higher (Figure 6). Additionally, Sn-Bi57.6-Ag0.4 and alloy A have a 5x improvement in the number of drops till first component failure, and alloy B first failure was 9x later than Sn-Bi58. Cross sectional analysis of the BGAs after the drop shock test shows that the cracks develop and propagate mostly through the Bi-rich areas, near the intermetallics region (Figure 7). One must note that for all data shown here, only BGAs with Sn-Ag3-Cu0.5 spheres were used. The results of combining low temperature solder paste and spheres will be shown in a separate report.

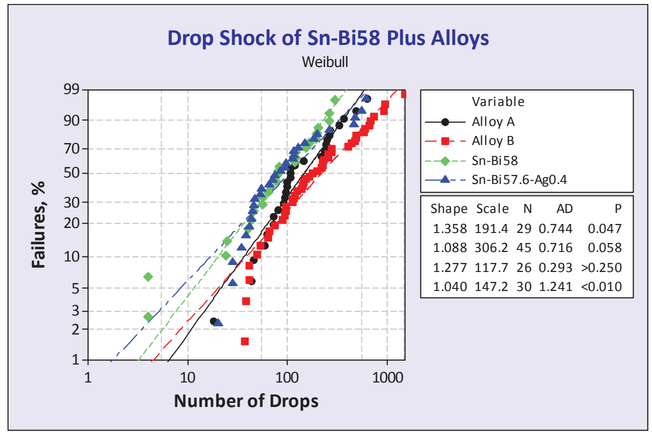


Figure 6: Drop shock results of Sn-Bi58 Plus alloys.

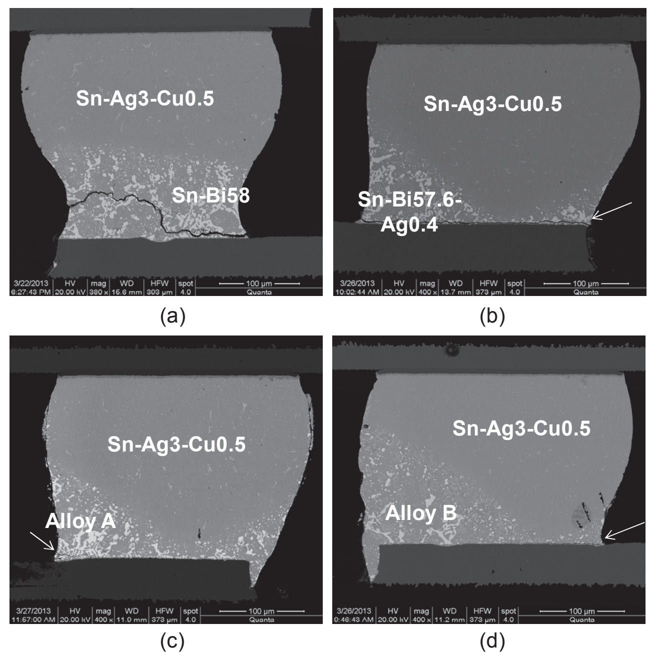


Figure 7: Failure mode of BGAs after drop shock test: (a) Sn-58Bi, (b) Sn-Bi57.6-Ag0.4, (c) Alloy A and (b) Alloy B solder paste; the BGA is Sn-Ag3-Cu0.5.

Despite such remarkable improvements in drop shock performance, it is important to keep in mind that results obtained from the JEDEC test are not expected to correspond exactly to the actual drop of handheld devices. However, the trend shown in both tests should be quite similar, especially if analyzed in light of available supporting information, as presented here.

Effect of alloying additions

The work presented here is part of a much larger effort of developing new alloys to suit specific needs of our customers, especially for growing markets such as handheld devices. Various alloying additions and a much larger pool of alloys have been investigated (for additional examples, see Ref. 16). Not always the expected effect of such additions on the alloy properties corresponded to the observed effect. A glimpse of our major findings is summarized in Table 3.

Table 3: Effect of alloying additions.

Alloy Additive	Expected Effect	Observed Effect on Alloy Properties
Ni	Improved mechanical properties and reliability	Some microstructure refinement Better mechanical prop. Aging stability
Co	Improved mechanical properties	Higher toughness Superior tensile prop. Best microstructure refinement
Ti	Improved mechanical properties	Higher thermal conductivity Good thermal fatigue life
Mn	Improved drop shock prop.	High toughness
Cu	Increased ductility and thermal fatigue properties	Best overall mechanical, drop shock and creep properties Excellent fatigue life

Conclusions

Use of low temperature alloys results in a series of benefits for handheld applications, such as lower incidence of defects caused by higher reflow temperature (e.g., warping and popcorning) and possibility of step soldering in combination with higher melting point alloys. However, these progressively smaller and elaborated devices require good thermal-mechanical properties. We have focused here only on the properties that are found to be related to the drop shock behavior, for which our main findings are:

1. Alloys with higher Bi addition have lower ductility, which directly impacts their drop shock performance. The average number of drops of Sn-Bi40 is 150% higher than of Sn-Bi58.

2. Lowering Bi content does not improve the excessive number of early failures or solderability issues that may be caused by their wide melting range. Instead, small alloying additions to the eutectic Sn-Bi58 were used.

3. Alloying additions such as in Sn-Bi57.6-Ag0.4 and alloy A refine the eutectic microstructure. A more noticeable microstructure modification is seen in alloy B, in which the Bi continuous layer that is typical of eutectic Sn-Bi breaks down as if forming an individual phase.

4. The average number of drops of Sn-Bi57.6-Ag0.4 is modestly 25% higher than Sn-Bi58, whereas of alloy A is 60% higher and of alloy B is 160% higher. Of especial importance for handheld application is the increase of number of drops till first component failure that occurs 5x later for Sn-Bi57.6-Ag0.4 and alloy A, and 9x later for alloy B.

Thus, we finally conclude by presenting alloy B as our next generation low temperature alloy for applications that require superior drop shock performance. We expect that similar trends shown in the JEDEC drop shock test will be matched by other tests such as actual drop of handheld devices. Results of further reliability testing of this and other alloys will be shown in other reports of this series.

References

1. SMT online, July 2012. http://www.smtonline.com/pages/zone.cgi?topic=0&artcatid=0&a=85437&artpg=1&artid=85437&pg=1&_pf_=1.
2. “Round Robin testing and Analysis of Lead Free Solder Pastes with Alloys of Tin, Silver, Copper” – Final Report, IPC Solder Products Value Council.
3. Tucker, K. L. and Ma, U., patent “Low Toxicity Alloy Compositions for Joining and Sealing”. United States Patent No. 4,929,423 (1990).
4. Ingham, A. *et al.*, patent “Solder Alloy”. International publication No. WO 2006/ 059115 A1 (2006).
5. ALPHA SACX® Plus 0807 Product Guide.
6. Glazer, J., “Metallurgy of low temperature Pb-free solders for electronic assembly”. *Int. Mater. Rev.*, Vol. 40, No. 2 (1995), pp. 65-93.
7. Mei, Z. *et al.*, “Low-Temperature Solders”. *Hewlett-Packard Journal*, Article 10, August (1996), pp. 1-10.
8. Hua, F. *et al.*, “Eutectic Sn-Bi as an Alternative Pb-Free Solder”. *Proc 48th Electronic Components and Technology Conf.*, Seattle, WA, May. 1998, pp. 277-283.
9. Takao, H. *et al.*, “Mechanical Properties and Solder Joint Reliability of Low-Melting Sn-Bi-Cu Lead Free Solder Alloy”. *R&D Review of Toyota CRDL*, Vol. 39, No. 2 (2004), pp. 49-56.
10. Pandher, R. *et al.*, “Drop Shock Reliability of Lead-Free Alloys - Effect of Micro-Additives”. *Proc. 57th Electronic Components and Technology Conf.*, Reno, NV, May. 2007, pp. 669-676 .
11. Pandher, R. and Healey, R., “Reliability of Pb-free Solder Alloys in Demanding BGA and CSP Applications”. *Proc. 58th Electronic Components and Technology Conf.*, Orlando, FL, May. 2008, pp. 2018-2023.
12. Lall, P. *et al.*, “Interogation of System State for Damage Assessment in Lead-free Electronics Subjected to Thermo-Mechanical Loads”. *Proc. 58th Electronic Components and Technology Conf.*, Orlando, FL, May. 2008, pp. 918-929.
13. McCormack, M. *et al.*, “Significantly Improved Mechanical Properties of Bi-Sn Solder Alloys by Ag-Doping”, *J. Electron. Mater.*, Vol. 26 (1997), pp. 954-958.
14. ALPHA® CVP-520 Solder Paste Product Guide.
15. Ribas, M. et al., “Low Temperature Alloy Development for Electronics Assembly – Part II”, Proc. SMTA International, Fort Worth, TX, Oct. 2013.