Lead Free Implementation - A Case Study Correlating the Thermal Profile and Laboratory Analysis

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Abstract
The electronic industry has been migrating to lead-free solder alloys by legislation forces. In Europe the WEEE/RoHS are scheduled to ban Pb alloys in July 2006. China is in process of preparing similar regulation. In Japan legislation governing products containing Pb has already been established. In the US, some states are exploring legislation to require recycling of electronics to reduce Pb in products. The objective of this work is to describe a study of Surface Mounted BGA Components when using a lead-free solder paste and two different reflow profiles. The 387SAC solder paste alloy (95.5Sn/3.8Ag/0.7Cu) was printed on PCBs (Printed Circuit Boards) for one specific phone project under study. The devices were submitted to thermal cycling, shock, humidity, drop and red dye penetration tests according to Motorola's standard tests procedures. The BGAs component interconnects were inspected from cross sectioning for solder joints quality performance. Solder ability tests showed to be correlating with the reflow process parameters and were used as guides to get the process improvement. The laboratory analysis suggested the use of a different thermal reflow profile was required to increase the BGA joints reliability.

Introduction
Tin-lead alloys were generally used to solder electronic components on printed circuit boards. Tin-lead alloys have relatively low melting temperature, good bonding characteristics, good electrical conductivity, and low cost. [1, 2, 3]

Elemental Pb has been a primary constituent of low temperature solder alloys for over 3000 years and, combined with Sn, melts at a low temperature Pb is a heavy metal toxin that can be prejudicial to the human body if ingested. Even in minute quantities Pb exposure can be hazardous to animals and humans. Less than one percent per year of the global Pb consumption is used in solder alloys for electronic products [4,5]. SMC (surface mount components) soldering processes on printed circuit boards generate various residues, such as the solder paste that remains from wrong placing, or the solid solder alloy in printed circuit boards, which could not be recovered. [3,6,7,8]

The American, European and Japanese organizations proposed to limit the lead usage The European Commission created two main directives applicable to electronic industry, the WEEE – Waste Electrical and Electronic Equipment Directive and RoHS – The restriction of Use of Hazardous Substances Directive. According to the WEEE document the components containing lead will have to be removed from any end-of-life electrical and electronic equipment that is destined for a landfill, incineration or recovery. [1,6]

The electronic industry continues making efforts to comply the global guidelines preparing for lead-free solder reflow manufacturing of electronics assemblies. The National Electronics Manufacturing Initiative (NEMI) organization provides the industry with guidelines on lead-free solders and soldering solutions. End product producers are requiring that suppliers provide material declarations that indicate the compliance with the requirements. [9]

Worldwide, much has been discussed to select an ideal lead-free solder composition to be used in the electronics assembly industry. Among the various alloy systems being considered, Sn-Ag-Cu alloy has been recognized as one of the best lead-free standard alloy systems. These systems have relatively low melting temperature and excellent compatibility with current components and PCB finishes. [10]

There is a complex endeavor in changing the factory to lead-free and in addition to usual logistics it is necessary to understanding some basics of lead-free technology, making the "right" selection of process and materials and then installing these selections into the existing infrastructure systematically. The process committed to must be "synchronized" with the materials and components selected such as printed circuit board (PCB), the components ones including the solder alloys. [11]
One of the major changes associated with the new alloys is the decreased wetting force compared to that of tin-lead alloys. Decreased wetting force means that solder exhibits a greater tendency to stay where it is first placed. [12]

The identification of the damage mechanism that could cause failure on a connection by laboratory analysis permits the development of a focused process improvement program. [13]

This paper describes a case study of lead-free plant implementation using SAC387 solder alloy to solder electronic components on PCB surface mounted using two different thermal profiles. It shows the laboratory analyses relevance in the evaluation of the final product performance. The laboratory solderability tests carried on -- thermal cycling, thermal shock, humidity, drop, red liquid dye penetration and SEM cross-sectioning -- showed that the solder joints quality improvement may be due to a process and component-related characteristics. Understanding lead-free technology is important to define the root cause for soldering failures and to achieve better productivity.

Materials and Methods

The electronic components were soldered in a BTU oven model VIP 70 using two different temperature profiles. The temperature profile was monitored with Data Pack tracker equipment using K thermocouple attached under the main components.

The mobile group consisted of 52 total units. Half of them were mounted using profiles 1 and 2. Both profiles were meeting solder paste specification for reflow temperatures. The main differences between profile 1 and 2 were the time above liquidus (TAL) and peak temperature oven set ups that were increased for profile 2 in 8°C for peak temperature and in 10 seconds for TAL.

The PCBs used to mount the mobile samples were OSP (Organic Solderability Preservative) finished and BGA components balls were lead-free. [3]

The solder paste alloy used was 95.5Sn/3.8Ag/0.7Cu composition no-clean type approved according Motorola qualification requirements commercially acquired in the market like SAC 387. The solder paste was kept at approximately 25° C, for eight hours before use. The solder paste deposits were measured with Cyberoptics, model Centrum 2000, a three-dimensional laser measuring equipment, to ensure thickness of the solder paste deposit.

The mobile units were submitted to laboratory tests according to Motorola's procedure such as solderability, functional, call, red dye penetration and cross-sectioning to evaluate the quality of the soldered joints.

Solderability tests were carried out with 26 phone units according to recommended Motorola's procedure. This is a procedure applied for lead-free solder pastes inclusive and it must be accomplished for all new products, new manufacturing lines as part of Proto-Certification. The summary of the tests procedures such as thermal shock and temperature cycling are enclosed. [14]

The solderability tests used to evaluate the mobile units consisted of dividing the 26 PCBs samples into five groups of tests. All groups had five units each, except for group 5 with six units. Each group was submitted to several tests under varying conditions. The acceptance criteria define that all five phone units from each individual group must pass in all the tests. If one unit fails the solderability procedure for all five groups is considered as failing with exception of one unit allowed to fail for group five only.

The mobile units assembled by using profile 1 were submitted to laboratory tests as presented in the table 1.

Samples from group 1 were assembled at Motorola assembly lines and submitted to functional and call tests to guarantee phones were working properly before being submitted to solderability procedures. Next step, they were submitted to oven exposure followed by the drop tests allowing random fall using a defined height. Functional, detailed electrical and call processing tests were then performed. All five boards from group 1 were submitted for soldering analysis such as red-dye penetration tests and SEM cross-sectioning inspection to check for solder joints quality.[15] The same procedure was followed for all mobile units to evaluate solder joints obtained with profile 1.

Cross-sectioning analyses were carried out for BGA components U1000; U2100; U2000 interconnects. Component position on the PCB design is designated as U1000; U2100; U2000. Same BGAs were submitted to the red-dye liquid penetration tests. This test is a guide to highlight possible locations of broken solder joints in all types of packages that are soldered to a circuit board. The capillary action of the liquid red-dye allows to find all the small gaps underneath a package. The dye penetration test used was a Motorola's recommendation one. [14]

Similar solderability tests were performed to evaluate the mobile units mounted using profile 2. The 26 PCBs samples were subdivided into five groups. Except for group 5 which had six units, groups 1-4 had five units each. See table 1 for the samples obtained using profile 2. After thermal cycling and thermal shock phone units were submitted to functional tests; detailed electrical and call processing tests.

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The PCBs used to mount the mobile samples were OSP (Organic Solderability Preservative) finished and BGA components balls were lead-free. [3]

Group	Unit	Oven Exposure (time / temperature) (hr/ °C)
1	1.1	Temperature and humidity exposure for 1 (hrs)
	1.2	
	1.3	
	1.4	
	1.5	
2	2.1	Temperature and humidity exposure for t2 (hrs)
	2.2	
	2.3	
	2.4	
	2.5	
3	3.1	Thermal shock cycling for t2 (hrs)
	3.2	
	3.3	
	3.4	
	3.5	
4	4.1	Thermal cycling for t2 (hrs)
	4.2	
	4.3	
	4.4	
	4.5	
5	5.1	No oven exposure different faces drops
	5.2	
	5.3	
	5.4	
	5.5	
	5.6	

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Group	Unit	Oven Exposure (time / temperature) (hr/ °C)
1	1.1	Temperature and humidity exposure for t1 (hrs)
	1.2	
	1.3	
	1.4	
	1.5	
2	2.1	Temperature and humidity exposure for t2 (hrs)
	2.2	
	2.3	
	2.4	
	2.5	
3	3.1	Thermal shock cycling for t2 (hrs)
	3.2	
	3.3	
	3.4	
	3.5	
4	4.1	Thermal cycling for t2 (hrs)
	4.2	
	4.3	
	4.4	
	4.5	
5	5.1	No oven exposure different faces drops
	5.2	
	5.3	
	5.4	
	5.5	
	5.6	

Table 1 – Mobile Groups Under Test and Oven Exposure Conditions

RESULTS and DISCUSSIONS

Laboratory results for thermal profile 1 are shown in Table 2.

Table 2 - Solderability results summary for profile 1.

Group	Units	Solderability Flow Results For Profile 1				
		Funct.	Call	Drop	Call	Red Dye
1	1.1	Pass	Pass	Pass	Pass	Pass
	1.2	Pass	Pass	Pass	Pass	**Fail**
	1.3	**Fail**	**Fail**	**Fail**	**Fail**	**CS**
	1.4	Pass	Pass	Pass	Pass	**Fail**
	1.5	Pass	Pass	Pass	Pass	Pass
2	2.1	Pass	Pass	Pass	Pass	Pass
	2.2	Pass	Pass	Pass	Pass	Pass
	2.3	Pass	Pass	Pass	Pass	Pass
	2.4	Pass	Pass	Pass	Pass	Pass
	2.5	Pass	Pass	Pass	Pass	Pass
3	3.1	Pass	Pass	Pass	Pass	Pass
	3.2	Pass	Pass	Pass	Pass	**Fail**
	3.3	Pass	Pass	Pass	Pass	**Fail**
	3.4	Pass	Pass	Pass	Pass	**Fail**
	3.5	Pass	Pass	Pass	Pass	**Fail**
4	4.1	Pass	Pass	Pass	Pass	**Fail**
	4.2	Pass	Pass	Pass	Pass	**Fail**
	4.3	Pass	Pass	Pass	Pass	**CS**
	4.4	Pass	Pass	Pass	Pass	**Fail**
	4.5	Pass	Pass	Pass	Pass	**Fail**
5	5.1	Pass	Pass	**Fail**	Fail	**Fail**
	5.2	Pass	Pass	**Fail**	Fail	**Fail**
	5.3	Pass	Pass	Pass	Pass	Pass
	5.4	Pass	Pass	**Fail**	**Fail**	**Fail**
	5.5	Pass	Pass	**Fail**	**Fail**	**CS**
	5.6	Pass	Pass	**Fail**	**Fail**	**CS**

Table 2 – Test Results

Group 1 presented 1 phone unit failing from 5 units total tested and failure was detected during the functional test. Opened joints were confirmed when this unit was submitted to the dye penetration test. BGA U1000 presented 8 opened pins total since those were found as highlighted per the red liquid. Four out of those 8 pins are presented on Figure 1. The primary failure mode was component side solder fracture possibly in the intermetallic layer since the fractured surface was found as very smooth pointing us the brittle fracture is occurring.

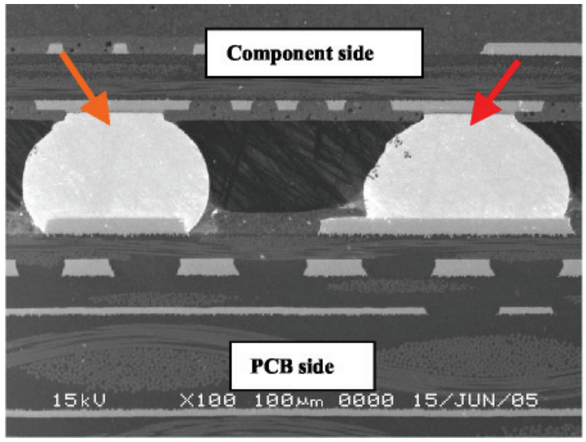

Figure 1 – Microscopic Picture for BGA U1000 at 64X Magnification and Red Dye Test Results

Other two units were found as failing for group one during the red dye test results. In this case the interconnect fracture possibly occurred after the last step during the drop tests. Summary for group 1 was 3 failures out of 5 total after completed the solderability tests. BGAs U1000 and U2000 presented more than one opened interconnect. BGA U2100 interconnects were found as good for all solder joints.

Group 2 presented all five units passing on all solderability tests. The only difference in between group 1 and group 2 was the temperature and humidity oven conditions. Group 1 has more aggressive conditions.

Group 3 presented 4 failing units out of 5 total. Those failures were identified during the red dye penetration test or on the last step of the solderability procedure and U1000 ; U2000 interconnects only were affected. In this case thermal shock possibly caused a stress level as high as to conduce to solder joints cracking. Besides it is not possible to confirm what was the step failures occurred without the cross-section analysis we believe based on our personal experience the complete fracture did not occur since phones were passing when the call processing tests were executed. Interconnect failure mode was found component side solder fracture. This result was expected since the component side joint is brittle when compared to the PCB side joint. For all BGAs under analysis the bumper SAC solder alloy was Sn-Ag-Cu and the BGAs Cu pad plating were gold over nickel. BGA substrate side will form SnNi structure or Ni_3Sn_4. For PCB side interfacial structure is more robust since it will be Cu_3Sn and Cu_6Sn_5 layered interface [16,17, 18].

Group 4 presented 4 units failing out of 5 total. This was after temperature cycling step. Major failure mode was identified as PCB side fractures and again U1000 and U2000 interconnects were affected.

Group 5 presented 5 units failing out of 6 total. In this case all BGAs U 1000; U2000 and U21 00 were affected and the major failure mode was considered as component side fracture. This result was detected during the call processing post drop tests. Beside group 5 tests are very aggressive since many drops are carried on different phone faces this result was not expected since the solderability test procedure used was designed for the lead free solder alloys and Motorola worked with preferred paste suppliers to meet the company's quality and product reliability standards [14]. The results summary for group 1 to group 5 are presented on table 2 as follows. The cross- sectioning analyses were represented per the letters CS in the table bellow.

Test results for thermal profile 3 are summarized in table 3.

Group	Profile 1	Profile 2	Failing BGAs for Profile 1	Failing BGAs for Profile 2
1	3 failures/5 total	0 failures/5 total	U1000; U2000	All good
2	0 failures/5 total	1 failures/5 total	All good	U2000
3	4 failures/5 total	2 failures/5 total	U1000; U2000	U2000
4	4 failures/5 total	2 failures/5 total	U1000; U2000	U2000
5	5 failures/6 total	2 failures/6 total	U1000; U2000	U2000

Table 3 – Results for Profile 2

Group 5 presented 2 failing units out of 6 total. In this case BGA U2000 only was affected. Failures were detected during the red dye tests and for cross-section analysis. Major failure mode was component side fractures as reported for groups 3 and 4. Figure 2 shows an example of the cross-section analyses.

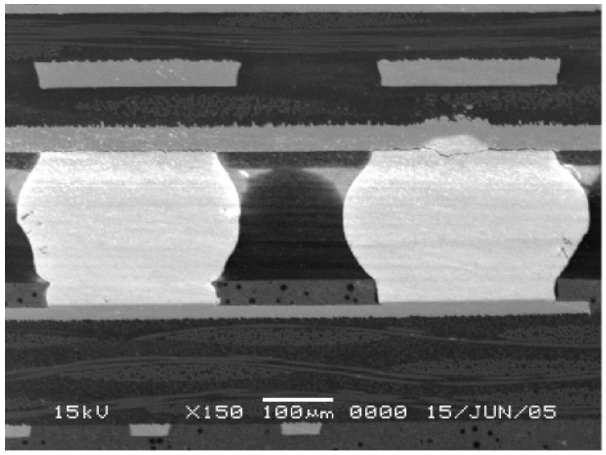

Figure 2 – Cross Section Example

All failures detected for U2000 are possibly component related since the fracture occurred at the BGA-Cu pad –SAC interfacial structure and may be associated to the Cu pad plating embrittlement at the pad periphery. Motorola specification requires the component bumper to be lead-free. However the BGA cup-pad plating microstructure composition may be affected for the elevated temperatures that lead free requires.

Results for the 52 mobile units are shown in Table 4 for profiles 1 and 2.

Group	Units	Solderability Flow Results For Profile 2				
		Funct.	Call	Drop	Call	Red Dye
1	1.1	Pass	Pass	Pass	Pass	**CS**
	1.2	Pass	Pass	Pass	Pass	Pass
	1.3	Pass	Pass	Pass	**Fail**	Pass
	1.4	Pass	Pass	Pass	Pass	Pass
	1.5	Pass	Pass	Pass	Pass	Pass
2	2.1	Pass	Pass	Pass	Pass	**CS**
	2.2	Pass	Pass	Pass	Pass	Pass
	2.3	Pass	Pass	Pass	Pass	**Fail**
	2.4	Pass	Pass	Pass	Pass	Pass
	2.5	Pass	Pass	Pass	Pass	Pass
3	3.1	Pass	Pass	Pass	Pass	**CS**
	3.2	Pass	Pass	Pass	Pass	Pass
	3.3	Pass	Pass	Pass	Pass	**Fail**
	3.4	Pass	Pass	Pass	Pass	Pass
	3.5	Pass	Pass	Pass	Pass	**Fail**
4	4.1	Pass	Pass	Pass	Pass	**CS**
	4.2	Pass	Pass	Pass	Pass	Pass
	4.3	Pass	Pass	Pass	Pass	**Fail**
	4.4	Pass	Pass	Pass	Pass	**Fail**
	4.5	Pass	Pass	Pass	Pass	Pass
5	5.1	Pass	Pass	Pass	Pass	**CS**
	5.2	Pass	Pass	Pass	Pass	**CS**
	5.3	Pass	Pass	Pass	Pass	**Fail**
	5.4	Pass	Pass	Pass	Pass	Pass
	5.5	Pass	Pass	Pass	Pass	**CS**
	5.6	Pass	Pass	Pass	Pass	**Fail**

Table 4: Results

Based on the results presented on table 4 the profile 2 showed an improvement of the solderability quality performance when compared to the profile 1. Process optimization was confirmed when the reflow temperature was increased for profile 2 since the number of failures have decreased from 16 failures / 26 units to 7 failures / 26 units total. The table 4 shows that for profile 1 the solder joint issues occurred on U1000 and U2000 BGAs positions on the PCB design. Failures in profile 2 were mainly detected on component U2000 BGAs positions.

The Motorola's acceptance criteria as described previously define that 1 failure only is acceptable for group 5 after the drop tests completed the other groups are required to pass in all 5 units tested. Based on this criteria process still needs to be improved.

The red penetration tests were done in all of the components and the main issues were found in the U1000 and U2000 component positions. [19,20]

Cross Section Analysis

A deeper interpretation of the results was possible by the SEM and cross-sectioning analysis. Poor solder joints were found for BGA U1000 and for BGA pins close to a large PCB ground pad. This result was expected since copper from ground pad is consuming the heat required to melt the solder paste. This was an issue associated to the phone project. In this case large ground pad area needs to be very well monitored for temperature reflow profile. The larger BGA U1000 / 341 pin was the major concern due to fractured solder joints as shown in Figure 3.

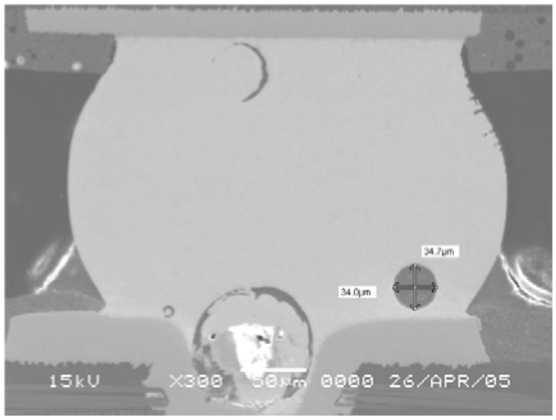

Figure 3 – Cracked Solder Joints on U1000

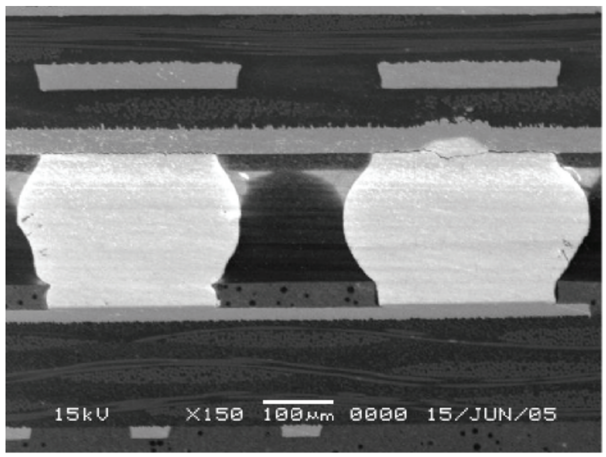

Figure 4 – Voids in BGA Solder Joints When Vias are Present in Pads

Other failure modes were seen for group 4. In this case PCB side fractures were seen. Based on those findings or on both sides PCB and BGA fractures the failures were considered as process related. The low reflow profile such as peak temperature and time above liquidus won't allow the intermetallic to growth and conduced to solder joint embrittlement. Solder joints were found not robust to support drops as required per Motorola specifications.

Another study conducted was BGA voiding when vias in pads are present. The via-in-pads usually cause the large voids to form. Via-in-pads when dimensioned per cross-sectioning analysis were found near the double size of the regular voids size. Regular voids means the voids usually dispersed inside the BGA bumpers bulk solder and far from the via –in-pad interface. This study purpose was not to be a complete voiding study that is recommended to be conduced by X-Ray techniques. Via-in-pads were found opened near to the via-in and this was considered related to the printing step. Copper filled via-in-pads are recommended. This is because when printed the via-in-pads may not be completely filled by the solder paste. In this case when OSP starts evaporating gases will create the large voids. Figure 4 is showing us the via-in-pad as the larger void. Smaller void on picture is what we have called the regular void. In this example the diameter dimension for the regular void was found 34.7 micros meter.

There was no major concern when regarding to the regular voids. Voids were considered as small sized and in a low quantity as expected. Regular voids are related to solder paste flux material and the humidity from the PCB and components. The gases CO_2 and H_2O produced per deoxidization reaction taking place during the reflow are considered the main root cause for voids.

Conclusions

The majority of the soldering related defects found for some of the 52 mobile units inspected were associated to the fracture at the BGA side interface connections and the feel number of voids detected did not represent an issue since no cracks were seem as starting from those voids even considering the via-in-pads large voids.

This study has confirmed it is important to get the temperature reflow profile optimized by increasing peak temperature and time above liquidus. This is to allow the intermetallic to growth properly and to obtain a robust interconnect. The solder joint is required to be able to absorb the impact energy when phones are dropped to avoid cracks to initiate.

The larger BGAs have showed to be the main concern regarding its solder joints. The delta of temperature in between components has to be very well monitored and a special care is required for PCB projects when large ground pads are present.

Red dye penetration tests when associated to the cross-sectioning have showed to be helpful and the laboratory results allowed the process engineering team to correlate the quality performance of the solder joints obtained to the process reflow variables.

The process optimization when using the profile 2 showed to be the correct approach since the failures was reduced. However fractures were not eliminated and part of this result was attributed to component U2000 itself. Beside of the component issue we believe as well the delta between components monitoring is recommended to be improved in order to have it reduced as much as possible.

Acknowledgements
This work was developed at Motorola MFAL Laboratory under an IPE and Motorola Brazil Project supported by Brazilian Science and Technology Ministry.

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