An Overview of a Successful Pb-Free Implementation

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INTRODUCTION

The clock is ticking, on July 1, 2006 the WEEE Initiative will take effect. Thereafter, all electronic assemblers that sell products in Europe must be ready to convert their assembly processes to Pb-free. The nearness of this date raises the question of what can be done to get ready. In response to this need, we will review a pioneering effort in establishing a Pb-free process.

Key Words:
Pb-free, lead free, WEEE, RoHS

ALLOY SELECTION

One issue the assembler does not have to worry about is alloy selection. Work by NEMI[1], JEITA[2], IDEALS[3], NCMS[4] and materials suppliers[5] have concluded that the SnAgCu (SAC) alloy system is the favored alloy for near- to medium-term implementation. The reasons being:

1. SAC contains no Bi, and does not form very low melting point phases with Pb. Formation of a low melting point intermetallic phase is a critical concern with Bi-bearing solder alloys. One cannot assume that Pb will not contaminate assembly processes from component leads or PWB finishes (especially during the early stages of Pb-free transition). Pb contamination of only 3% by weight can cause the formation of a Sn/Bi/Pb eutectic in $SnBi_{10.5}$ or $SnBi_{12}$ that melts at 96°C. See Figure 1.

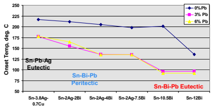


Figure 1. The effect of Pb contamination on first melt in different Pb-free solders.

Not only does this low melting point affect use at high temperatures such as in automobiles, it also has a dramatic affect on mechanical strength in fatigue tests at all temperatures. Since Pb contamination, from component leads, PWB finishes, etc, is a real likelihood for at least several years, solders containing Bi are not viable Pb-free options today. In one respect this situation is a shame because certain Sn/Bi solders melt at temperatures below 150°C, a very gentle assembly temperature. When lead becomes rare in assembly processes, Sn/Bi and Sn/Bi/Ag solders may emerge as the Pb-free solders of choice. Zn-containing lead-free alloys have not received much attention outside of Japan due to processing difficulties and reliability concerns.

2. The melting point of SAC is relatively low, with a liquidus-solidus temperature differential of less than 3°C with SAC alloys of <5.35%Ag and <2.3% Cu, with the most favored SAC alloys melting at about 217°C. See Figure 2.

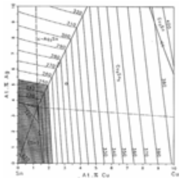


Figure 2. The ternary phase diagram for SAC. (From Carol Handwerker of NIST)

3. SAC contains only three elements. As the number of elements increases in an alloy, issues arise with unwanted impurities, manufacturability becomes more difficult, and the melting point or liquidus/solidus differential becomes more challenging to control from batch to batch of material.
4. In general, SAC is not a patented alloy. There are some regional and compositional exceptions to this. Your choice should be verified for any specific region of use or destination.
5. Preliminary experiments suggest that SAC's reliability in service is equal to or better than SnPb solders.

NEMI selected $SnAg_{3.9}Cu_{0.6}$ as its preferred alloy. However, NEMI also performed valuable work that shows varying silver content from 3.0 to 4.0%, and copper content 0.5 to 0.7%, did not affect assembly performance in a statistically significant way.

Based on the work that NEMI and others have performed, $SnAg_{3.9}Cu_{0.6}$ (+/0.2% for Ag and/or Cu) is the best overall choice for Pb-free assembly at this time.

PWB/COMPONENT FINISHES

In a Pb-free process, the PWB pad surface finish must be completely compatible with the Pb-free solder being used. There are a number of Pb-free surface finishes available today including OSP, Immersion Silver, Immersion Sn, and Electroless Ni/Immersion Gold. Although all of the aforementioned surface finishes are quite robust and can be used in the majority of applications, each has unique pros and cons. The best surface finish for a given process should be determined by evaluating the process requirements and matching them up with the different PWB pad surface finish attributes.

Pb-free finished components are now gradually becoming available. As with board finishes, a Pb-free process must work with all common finishes, such as SnPb, 100% Sn, Pd/Ag, Ni/Pd, Ni/Sn, Ni/Pd/Au, NiAu. In the short term, there are likely to be a number of components that are only available with a Sn/Pb finish so the process must be compatible with Pb-free solder paste, Pb-free PWBs, and Sn/Pb components. Of course, to have a truly Pb-free process, only Pb-free components should be used.

An additional concern for both the PWB and components is their capability to withstand the higher reflow temperatures of Pb-free assembly. Since the SAC alloy melts at about 217°C, the components and boards should be rated for reflow temperatures of at least 235-240°C.

The process and solder paste that will be discussed in the remainder of the paper are capable of supporting all of the PWB and component finishes discussed.

ESTABLISHING THE PROCESS

The following will be an overview of the "no-clean" process developed by Motorola Corporation in Plantation, Florida, USA with several solder paste vendors. The solder paste that Motorola implemented for their Pb-free production was developed and manufactured by Indium Corporation of America.[6]

The Success Criteria

In any organized endeavor it is essential to clarify what objectives are to be met. In this process development effort these criteria where established:

1. Printed solder paste printed "brick" volume consistency at time=0, and after a pause of 1 and 4 hours, should be < +/-20%.
2. The solder paste must pass tackiness per IPC-650 and Sanyo TCM 3000.
3. A broad reflow process "window" from peak temperatures varying from 229-245°C and times above liquidus (TALs) from 60-80 seconds must exhibit acceptable wetting and coalescence.
4. A quality assessment consisting of visual inspection, wetting and coalescence must be passed.
5. Surface insulation resistance (SIR) testing using IPC/J-STD-004 and Motorola's own tighter test pattern(IPC-B-25) must be successful.
6. Reliability tests consisting of a drop test, liquid-to-liquid thermal shock and a shear test must be passed.

Motorola tested over 25 solder pastes from 8 suppliers. Their standard Sn/Pb solder paste was also used as a "control." This Pb-free implementation program was completed over a 3-year period at a cost of over US$1 million.

Stencil Printing Evaluation of Solder Paste

A well shaped printed "brick" with good volume consistency, is likely the best predictor of high end of line yields. See Figure 3.

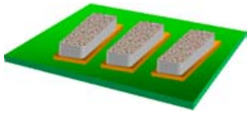


Figure 3. A well shaped printed "brick" with consistent volume is probably the most important predictor of good end of line yields

Too much solder paste in the printed brick could result in shorts, whereas too little may cause opens as shown in Figure 4. Setting solder paste volume specifications and monitoring the printing process for conformance to these specifications can have a positive effect on yields.

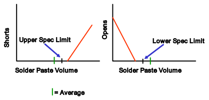


Figure 4. Too much solder paste can cause shorts or too little may result in opens. Setting solder paste volume specifications and monitoring the printing process for conformance can have a positive effect on yields.

The importance of printed volume consistency on end of line yields suggests that its determination is probably the most critical in solder paste evaluation. A gage repeatability and reproducibility (Gage R&R)[7] analysis was used to design an experiment (DOE) to measure stencil printed "brick" volume consistency. Measurements were made at time = 0 (fresh from the jar) and with pause times of 1 and 4 hours. Figure 5a shows Box Plots of printed volume consistency at time = 0 for 5 solder pastes for SMD pads on 0.3mm (12 mil) centers. The control is a SnPb paste. Note that all pastes have approximately +/- 20% 2 sigma printed volume consistency control, which was considered acceptable for this application.

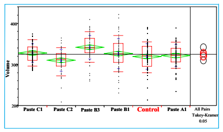


Figure 5a. Box Plots of solder paste volumetric measurements on PWB SMD pads with 0.3mm (12 mil) centers @ t = 0 hours.

After a one-hour pause, one paste (C2) was clearly unacceptable as its mean printed volume decreased by approximately 35% and the range volumes went from just above 0 to 400 cubic mils. Clearly paste C2 was out of the running early on! See Figure 5b.

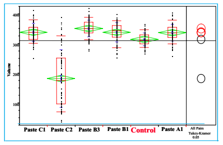


Figure 5b. Box Plots of solder paste volumetric measurements on PWB SMD pads with 0.3mm (12 mil) centers @ t = 1 hours.

Numerous experiments such as these were performed. The results were shared with the solder paste vendors to help them develop new products with improved performance.

Solder Paste Tackiness Experiments

To test for tackiness, candidate pastes were printed and left idle for 0, 1, 2, 4, and 8 hours. The IPC/J-STD-005 tackiness test procedure was then used with a 5mm diameter test probe. Figure 6 shows some of the results. Note that there appears to be no significant difference between the controls or the two Pb-free pastes evaluated in this instance. This situation held true for the majority of other Pb-free solder pastes evaluated as well.

A shake test was also performed after component placement with a vision inspection technique used for verification. Components were purposely placed with an offset to evaluate whether or not the solder pastes would hold the components in the normal positional variations experienced in the component placement process. Results were positive for most pastes considered for further testing. Tackiness and tack over time were two parameters that were not significantly different than the Sn/Pb controls.

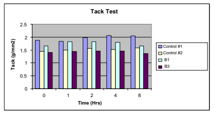
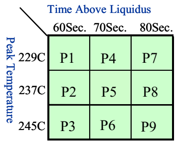


Figure 6. Tack test results using IPC-TM-650. The results indicate no significant difference between pastes.

Reflow Profile Development

The reflow profile development activities proved to be the most important in the entire Pb-free process development effort. The variables were peak temperature (T_p), time above liquidus (TAL) and different solder pastes. The evaluation criteria were coalescence performance and solder joint quality. It was anticipated that this part of the effort would be the most intensive, so screening experiments were performed in this and other aspects of the process development to minimize the number of pastes to be tested. These screening efforts resulted in the need to test only 8 pastes in the reflow DOEs (vendor A, pastes 1-3, vendor B, pastes 1-3 and vendor C, pastes 1 and 2.)

A full factorial 2X3 DOE was performed as shown in Figure 7. This DOE was very demanding in that good reflow performance was desired at a T_p of only 229°C and TAL of 60 seconds. This T_p is nominally only 12°C above the melting point of the solder and is exceeded by many people reflowing eutectic Sn/Pb!



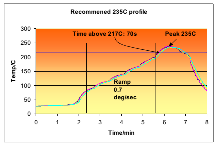
Time Above Liquidus

Peak Temperature	60Sec.	70Sec.	80Sec.
229C	P1	P4	P7
237C	P2	P5	P8
245C	P3	P6	P9

Pb-free reflow DOE

Figure 7. The 2X3 full factorial DOE used to develop the lead free reflow process.

Figure 8 shows the "ramp to peak" profile shape used. Motorola's criteria was that the solder pastes must perform well from P1 through P9 in an air atmosphere.



Peak Temp. = 235 C +/- 5C; Time Above Liquidus = 70Sec +/ 10Sec

Figure 8. The "ramp to peak" reflow profile shape used in the lead free process development.

Only one solder paste, Indium Corporation's NC-SMQ230, was able to provide good coalescence and solder joints with all nine profiles. As a result of meeting all of their Pb-free solder paste requirements, Motorola selected the NC-SMQ230 for their Pb-free solder paste implementation.

Motorola ended up proposing the target profile as shown in Figure 8 for this paste. With a typical reflow process temperature variation of +/-5°C, the reflow process is comfortably within the P1-P9 profile criteria. The good coalescence of this paste versus one of the other paste finalists is shown in Figure 9. It is believed that the poor coalescence of most lead-free solder pastes is due to their flux's inability to protect the lead-free solder powder from oxidation during the air reflow process.

Poor Coalescent Good Coalescent

Figure 9. The excellent coalescence of NC-SMQ® 230 is evident in the above micrograph on the right.

The quality of the solder joints tracked well with coalescence. Only NC-SMQ® 230 produced quality solder joints with good fillets as seen in Figure 10a and 10b. These solder joints were nearly identical to controls that were formed with SnPb solder. The poor solder joints that lack a good fillet would be a reliability concern in the field. A high magnification examination of the interface between the solder and the PWB pad showed consistent intermetallic formation in the NC-SMQ® 230 solder joints as shown in Figure 9.

Poor Solder Joint Good Solder Joint

Figure 10a. Only the NC-SMQ(R)230 provided good solder joints.

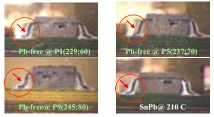


Figure 10b. Cross sections of solder joints with NC-SMQ® 230 at P1, P5, P9 compared to a SnPb solder joint.

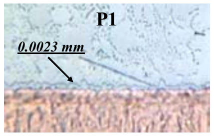


Figure 11. Even at the low T_p = 229°C of profile P1 sufficient intermetallics were formed with NC-SMQ® 230.

Surface Insulation Resistance (SIR) Test

After reflow the pastes must pass SIR tests. Motorola developed a more stringent test than the IPC/J-STD-004 procedure.

Motorola combined the temperature, humidity, and resistance requirements of the J-STD-004 test with an IPC-B-25 comb pattern coupon. The test PWB with the B25 comb pattern is shown in Figure 10.

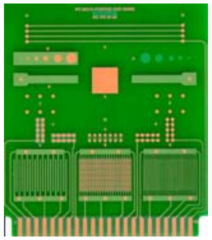


Figure 10. The IPC test PWB for the SIR test.

NC-SMQ® 230 passed both the IPC and Motorola SIR requirements.

Mechanical Reliability Tests

The reliability tests consisted of a drop, shear, liquid-to-liquid thermal shock and accelerated life testing (ALT) on real product (in this case cellular phones). The drop test consisted of:

1. Six mechanical planar, five foot (1.5 meters) drops onto a hard surface
2. Vertical and horizontal vibration for 2 hours
3. Thermal shock for 48 hours (-40 to +80°C)

These steps are repeated 3 times and the units were analyzed for % joint cracks on shields. See Figure 11.

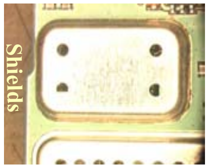


Figure 11. The shield whose joint cracks were evaluated in the drop test.

The results were very encouraging for the NC-SMQ® 230 solder paste as there were significantly less cracking in the shield solder joints for this paste than for the SnPb control as shown in Figure 12.

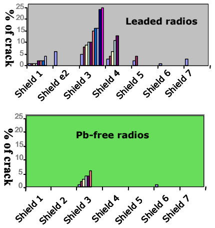


Figure 12. The percent of shield solder joint cracks was significantly less with NC-SMQ® 230 lead-free paste than with the SnPb control.

A shear test was performed on selected components after liquid-to–liquid thermal shock (-55 to +125°C) for 450 cycles. The components selected for testing are shown in Figure 13. The shear testing results are shown in Figure 14.

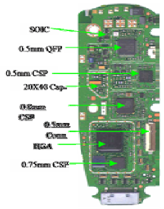


Figure 13. The components selected for liquid to liquid thermal shock and then shear testing

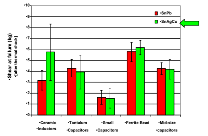


Figure 14. The shear results of selected components after liquid-to-liquid thermal shock.

Note that the results for the SnPb control and the NC-SMQ® 230 appear to be similar and, in fact, are not statistically significantly different.

OTHER CONSIDERATIONS

In addition to process development, there are several other concerns that the process engineer and management should consider prior to implementing Pb-free assembly.

Defects

In most manufacturing processes, defects will be encountered. This section reviews two of the significant defects that presented themselves in this process development and how they were mitigated.

Tombstoning of passive components is often a concern in assembly using Sn/Pb solders. The higher surface tension and higher melting point of lead-free solders makes tombstoning an even greater issue. Figure 15 shows the tombstoning mechanism. The melting of the solder paste on one side of the passive before the other is a common cause of this failure mechanism. Additionally, excessive solder paste on the PWB pads or asymmetrical component placement can also result in tombstoning. In this process development, tombstoning was especially evident when the passive PWB pads were over blind vias. See Figure 16. This phenomenon is likely due to the more rapid heating of the pad over via given the lower thermal mass in the area of the pad.

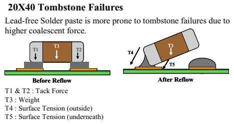


Figure 15. A schematic of the mechanism of tombstoning in passive assembly.

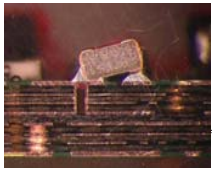


Figure 16. Tombstoning of a passive mounted on a PWB pad above a via

Modification of the stencil aperture design to minimize the amount of solder paste printed on the passive pads alleviated the problem. The stencil aperture design is shown in Figure 17. Subsequent work has also suggested that a slight dwell in the reflow profile 10°C below the liquidus temperature also helps to minimize tombstoning.[8]

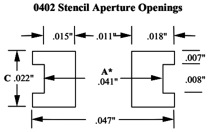


Figure 17. The modified stencil aperture design used to eliminate passive tombstoning.

Voids in BGA and CSP joints are commonly observed in assembly with SnPb solder pastes. Voids are due to the evolution of gases from the solder paste flux that cannot vent through the molten solder. Oxidized solder bumps, pad surfaces, and solder powder also exacerbates void formation.

The Pb-free transition also introduces a new potential mechanism for voiding: some BGAs will only be available with Sn/Pb balls. When using Pb-free paste and a Sn/Pb bumped BGA, the sphere will melt 35°C below the melting point of the paste. During the time period when the sphere is liquid and the paste is not, the flux will outgas directly into the molten sphere creating the potential for massive voids. See Figure 18. A DOE was conducted to determine the effect of reflow profile ramp rate on number of voids formed and their total volume. Ramp rates of 0.5, 0.8 and 1.5°C/s were used. The experiment showed that a higher ramp rate reduced the void volume significantly (Figure 19.)

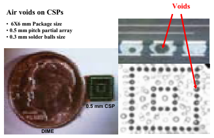


Figure 18. Voids in CSP joints. The CSP was 6 X 6 mm with 0.3 mm solder balls on a 0.5 mm pitch.

The ramp rate did not affect the number of voids produced (i.e. just as many voids were produced, but they were of smaller average size). However, the void volume reduction was significant enough so that specifications were met.

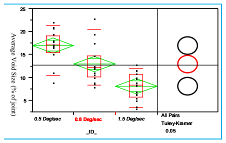


Figure 19. Void size as a function of ramp rate.

Pb-Free Logistics

The implementation of Pb-free technology will require discipline to assure that lead-bearing and lead-free solders, PWBs and components are not mixed. Every assembler should have a "Pb-free logistics team" to set up procedures to establish this discipline.

Statistical Process Control

Statistical process control (SPC) can be very beneficial to ensure high yields in the assembly process and to provide the data for continuous improvement plans. In Sn/Pb processes one could view SPC as helpful, but in Pb-free processes it may be vital to your success. The reason SPC is likely more vital in Pb-free assembly is because of the narrower process windows, especially in reflow to avoid damaging components and PWBs. Excellent workshops are available on SPC and its implementation[9].

Are Your Basic Process Skills World-class?

Can your process engineers design a stencil? Does your reflow profile match the solder past specifications? In general, do you have world-class SMT assembly practices? The more stringent assembly requirements of Pb-free may result in disastrous end product yields without a first rate engineering staff. A software assessment tool, AuditCoach™, is available[10] to help assess the state of a factory's assembly skills and practices.

CONCLUSIONS

Significant work has been performed by others to implement Pb-free processes. Most notable of these efforts is that of Motorola, Plantation, Florida, USA. Their most important process development findings were:

1. Control of the reflow process is most critical
2. In general few lead-free solder pastes have good coalescence or form good solder joints
3. Only one solder paste, Indium's NC-SMQ® 230, of 25 evaluated, produced desirable results in all of the requirements

Motorola's 3 year effort developed a process that has been used to assemble well over 1 million cellular phones world wide using NC-SMQ® 230 solder paste.

ACKNOWLEDGEMENT
Portions of this paper were presented at CEMCEX, September 23, 2003 in Prague and at SMTAI, September 23, 2003 in Chicago

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[1] www.nemi.org/projects/ese/lf_assembly.html
[2] www.jeita.or.jp/index.htm
[3] www.lead-free.org | Research
[4] lead-free.ncms.org
[5] www.indium.com/application_notes/97758.pdf, www.Pb-free.com
[6] NC-SMQ® 230 Pb-Free Solder Paste, for information: www.Pb-Free.com
[7] Gage R&R analyses are important as a precursor to designed experiments (DOE). For information on workshops covering these topics contact Ron Lasky at rlasky@indium.com
[8] Lee's Reflow book
[9] For information on SPC workshops contact Ron Lasky at rlasky@indium.com
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