Taking the Pain Out of Pb-free Reflow

Presented at APEX 2003, Anaheim CA

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Abstract

The introduction of Pb-free solder into the electronics industry has required changes to the standard surface mount process. The largest changes are in the reflow process, as Pb-free pastes require higher temperatures and tighter process controls than standard SnPb solders. The goal of this work was to develop a reliable Pb-free process utilizing SnAgCu solder paste as a replacement for SnPb solder paste. In general, SnAgCu solder pastes recommend a peak temperature range of 242°C to 262°C as compared to the range of 208°C to 235°C commonly utilized for SnPb solder. Due to the higher reflow peak temperature; the use of some components may not be feasible for Pb-free assembly. A large number of commonly used components are sensitive to the standard higher peak temperatures of 235-240°C. One of the major goals of the work was to see if new profiling technologies could be used to reduce changeover time from existing SnPb solder profiles to Pb-free profiles. This was done over a variety of test boards ranging from a cell phone emulator to a board with a flexible interposer mounted on an aluminum backing. The second major goal of the study was to determine the lowest possible peak temperature required for a reliable Pb-free process. During the course of the work, yield results were recorded for various peak temperatures and SEM analysis was done to look at the intermetallic growth and grain structure of the solder joints processed at the various peak temperatures.

Introduction

Pb-free soldering is an emerging technology that many companies have begun to explore based on mandates from the European Union and the Japanese government to eliminate Pb from printed circuit board assemblies. The date to have this change implemented has continued to slide from its original 2004 date to a newly legislated proposed phase out date of 2006; many companies, however, are striving to have this technology in place by 2004 and some already offer products without Pb. There are many different alloys of Pb-free solder that are available for use, but the most common alloy in the United States and Europe is a SnAgCu alloy with compositions of 95.6% Sn, 3.7% Ag and 0.7% Cu. Processing of these solders is not much different from processing standard SnPb solders. The printing and placement processes remain the same. The major difference is in the reflow process, as a higher liquidous temperature must be used for most Pb-free solders. SnAgCu alloys generally require the peak temperature to be roughly 30°C (242°C to 262°C) higher than the peak temperature of SnPb solders. Initial research has also shown that the reflow process window is also tighter than that of SnPb solders. Surface energy for Pb-free solder is generally much lower than typical SnPb solders. For this reason, self-alignment of components does not occur as readily in Pb-free assembly as it does in SnPb assembly processes. The reduction of the surface energy can reduce the number of tombstones and solder bridging defects found in 0402 and 0201 packages. Overall, the reliability of Pb-free assemblies has been shown to be comparable to that of SnPb solders, other than in high temperature automotive applications, where the operating temperature can go higher than 150°C.

One of the most serious issues for Pb-free electronics assembly is that peak reflow temperatures are projected to rise to 240°C to 260°C. In general, temperature sensitive electronic components can tolerate a maximum temperature of 235-240°C. While most components will eventually be built to the proposed 260°C tolerance, this transition will take many years. This paper will establish that Pb-free electronic assemblies can be successfully soldered in a wider process window, and at lower process temperatures than have been previously considered, thus offering the potential to limit the impact of profile changes. The experiments will utilize profiling software that is capable of centering the product thermal profile precisely in the process window. Another software package will be used to automatically and continuously monitor the reflow process, thus ensuring that all boards are processed within the specifications. The application of this technology provides an answer to some of the most critical problems raised by Pb-free electronic assembly.

Pb-Free Process Issues

The current SnPb reflow process window is a relatively wide one. The melting point of eutectic Sn63/Pb37 solder is 183°C, and 200-205°C is a common lower temperature limit for reflow. The upper limit is generally 235°C, which is the maximum temperature that most temperature sensitive components can be exposed to. These high and low process limits provide a process window of over 30°C.

SnAgCu, a Pb-free alloy of choice in the United States and Europe, has a eutectic temperature of 217°C. Current practice is that this alloy needs to see a minimum peak reflow temperature of 240°C to ensure good wetting. With a maximum peak temperature based on component tolerances of 260°C, specified in the NEMI Pb-free Roadmap, the process window is only 20^{o}C. However, the NEMI component tolerance specification will present a significant challenge for component and board manufacturers for several years to come.

Although components may perform satisfactorily after being exposed to a 260°C peak reflow temperature, there are many compelling reasons to limit reflow temperatures. Limiting process temperatures minimizes thermal stress on boards and components, reducing the potential for manufacturing defects. Higher temperature processes can cause significant amounts of stress on plated through holes and barrels, which can lead to cracking. High first pass temperatures on double-sided assemblies increases the amount of second side oxidation, which can cause solderability problems on the second pass. Limiting peak temperatures reduces intermetallic growth, especially on bottom-side solder joints, which are exposed to two reflow passes. This also limits the potential for popcorning of components with high moisture content.

The problem of narrow process windows will be further exacerbated by the trend to more complicated assemblies with increased component density. Finding a profile that will reliably reflow a large assembly with large ΔT's across the board has never been easy. The increase in peak temperatures, combined with components of decreasing size and robustness, means that precision tools will be required to find profiles that will safely process products using Pb-free solders.

Profiling Technology

The current method of profiling reflow processes is to attach thermocouples to a product, and, using a wireless device or data-logger, run the device and the product through the oven to record the product thermal profile. There are several problems with the status quo: profiling is time consuming; the software is complicated; and oven setup is a matter of trial and error and experience. For a tight Pb-free process window, it will be very difficult to find an acceptable profile using conventional profiling technology.

The use of a profiling software platform with a radically simplified operator interface offers significant improvements in efficiency and quality. The software includes an updateable database of hundreds of popular solder pastes, which allows the operator to automatically select the specs for the paste being used. A series of screens with clear explanatory graphics steps the operator through the profiling process from beginning to end.

An oven recipe search engine allows users to find the best profile their process is capable of in under a minute. It can create and evaluate *billions* of potential oven recipes, automatically selecting the recipe that best fits the process window, and center that profile in a process window designated by the user. The oven recipe search engine was utilized and evaluated in the DOE below.

In developing a thermal profile, the critical factors are the size and weight of the assembly, the density of the components on the board, and the mix between large heavy components and lighter ones. Generally, the greater the contrast in component densities, the tougher it is to develop a profile. This is because small components will naturally heat up more rapidly and be heated to higher temperatures than heavier ones. Temperature differentials across the board will be a critical factor in whether a board can be successfully processed with Pb-free solder. With a standard profiling system, it is relatively simple for smaller boards mounting components with consistent thermal mass to make the transition to Pb-free. More complex assemblies with a large mix of components offer a more difficult task, as the temperature differential across the board may push the temperature of lighter components past their thermal stress limit while the densest components may fail to reach an adequate wetting temperature. The profiling of complex boards requires leading edge technology to develop a profile that fits the narrow process window.

Reflow Process Monitoring

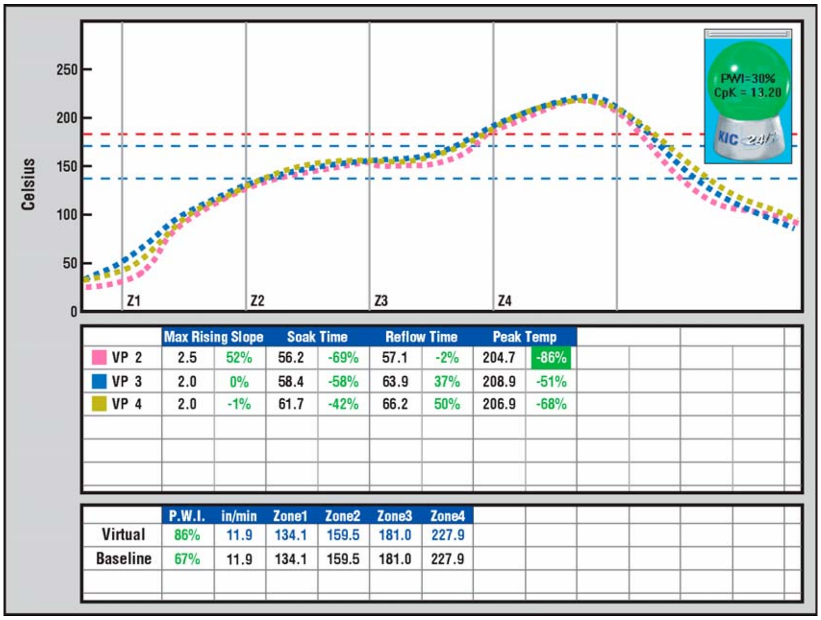
Automated reflow management systems that combine continuous SPC charting, line balancing, documentation, and production traceability into an integrated software package have recently been introduced. These systems are designed to automatically feed real-time process data to engineers and managers, allowing them to make critical decisions affecting production costs and quality. They are capable of providing and recording real-time thermal process data for every product, as opposed to the conventional practice of only periodically checking oven performance. This allows the system to automatically catch potential defects before they happen, rather than discovering actual defects in inspection.

The basic functionality of an automated reflow management system is to accurately and automatically monitor and collect data on product passing through the reflow oven. This functionality allows the system to provide significant benefits:

1. Eliminate the need for process verification profiles.
2. Provide real-time feedback and alarms for zero-defect production.
3. Completely automate reflow process data collection.
4. Provide automated SPC charting of the reflow process, and the capability to alarm based on variances in process Cpk.

One of the most significant differences between an automated reflow management system and previous real-time thermal monitors is that the new systems are a production solution rather than an engineering tool. System software has been designed to be completely intuitive for maximum ease of use, and ease of use means that the process can be monitored with a minimum of human resources.

The means for verifying the profile of every board produced is the virtual profile. A virtual profile is established by running a baseline profile of the product with a real-time profiler while simultaneously collecting real-time data from thermocouple probes in the oven. The mathematical correlation between the temperatures at product level and the temperatures on the product itself allows the software to accurately simulate changes in the product profile. Once a virtual profile has been established, the system goes to monitoring mode with real-time simulation of how the product profile is changing based on probe readings. Process temperature or airflow cannot change without affecting the product temperature, and the software's algorithms accurately extrapolate changes in process temperature to changes in the product profile.



	Max Rising Slope		Soak Time		Reflow Time		Peak Temp	
🟥 VP 2	2.5	52%	56.2	-69%	57.1	-2%	204.7	-86%
🟦 VP 3	2.0	0%	58.4	-58%	63.9	37%	208.9	-51%
🟨 VP 4	2.0	-1%	61.7	-42%	66.2	50%	206.9	-68%

	P.W.I.	in/min	Zone1	Zone2	Zone3	Zone4
Virtual	86%	11.9	134.1	159.5	181.0	227.9
Baseline	67%	11.9	134.1	159.5	181.0	227.9

Figure 1: Example of a virtual profile

Once a profile has been established within a user defined process window, an automated reflow management system monitors production for that particular product. In the real-time monitoring mode, the system produces a real-time profile chart and a table of data that has been selected based on the process window. There are SPC control charts for each statistic, as well as a control chart for the overall Process Window Index of the product itself. Data is updated and saved for each board as it exits the oven.

Another feature of the software platform is the utilization of the Process Window Index (PWI), a statistical method for ranking process performance. The Process Window Index measures how well a process fits within user-defined process limits. This is done by ranking process profiles on the basis of how well a given profile "fits" the critical process statistics. Figure 2 illustrates how the Process Window Index is calculated.

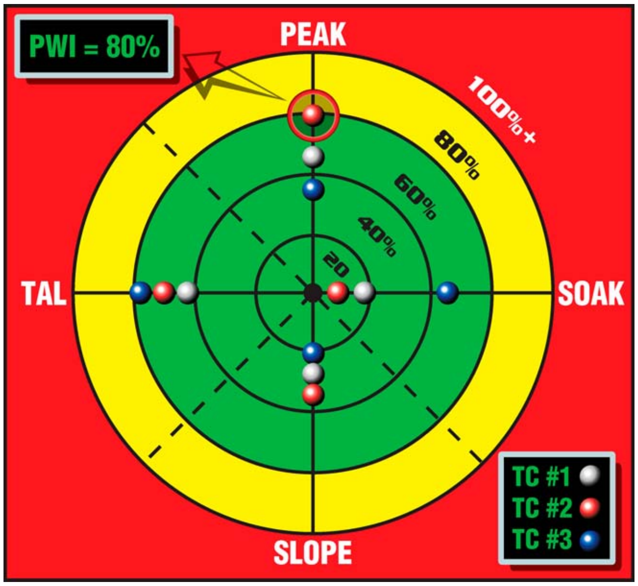


Figure 2: The Process Window Index (PWI)

The Process Window Index reflects the performance of the whole process, which provides a much better indicator of process capability than tracking a single statistic. The PWI thus provides excellent data for SPC and other QC monitoring programs. Automated reflow management systems use the Process Window Index to calculate the overall process Cpk for every board that goes through the oven.

Once the virtual profile has been established, the system will automatically begin to generate SPC data. Every time a board exits the oven, the data set is plotted on frequency histograms. Process data is charted for all critical process specs: peak temperature, soak time, time above liquidous, etc. The data is plotted on real-time control charts and Process Capability (Cpk) is calculated for each spec. The overall Process Window Index is charted, providing a real-time Cpk for the entire process. Any process drift outside of control limits will bring an immediate alarm. Real-time Cpk tracking enables the system to flag an out of control process before the oven has produced a single defect.

Test Vehicles

The test vehicles used for this study represented two typical types of board designs. A high thermal mass board, used in heavy equipment, has a flexible substrate attached to an aluminum plate with a high density connector hence to be referred to as Flexboard. The Flexboard has components ranging from 0603s to a large QFP. The second board was a mock up cell phone board containing six cell phone boards per panel hence to be referred to as Cellphone. The Cellphone board contains components ranging from 0201s to small QFPs and a MicroBGA. These two board types represent a large difference in both thermal mass and in component size and density. Figure 3 shows an image of each board design.

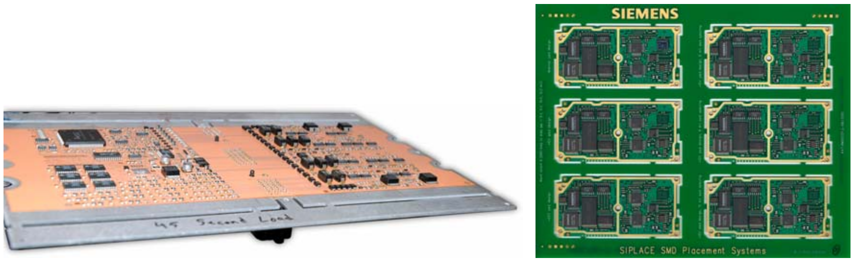


Figure 3: Image of the two test vehicles used in this study.
The Flexboard is on the left and the Cellphone board is on the right.

Experimental Methodology

The work was divided into two main phases. The objective of the work was to verify the ability to successfully reflow Pb-free electronic assemblies in a reduced process window. In Phase One, the primary objective was to verify that a process limit of 242°C for the peak temperature would successfully reflow the selected Pb-free paste. Baseline testing was performed at a temperature of 257°C as the high limit. The second phase of the project included testing to determine the reflow limits of the process and determine whether they can be reduced from 242°C to 232°C or lower. Solder joint quality was evaluated and defects tracked.

Phase One:

Phase One of the experiment used both of the test vehicles to evaluate the ease of the two profiling techniques and determine if the lowest recommended peak temperature, 242°C, of the SnAgCu paste evaluated, achieved quality solder joints. The two profiling techniques that were implemented were the use of automated profiling equipment described in an earlier section and the use of a trial and error operator generated profile. The starting point of both profiling techniques was a standard eutectic SnPb profile with a peak temperature of approximately 220°C. Table 1 shows the experimental matrix for the Phase One test.

Table 1: Experimental Matrix for Phase One

Factor	Variable #1	Variable #2
Profiling Technology	Trial and Error	Automated Prediction
Peak Temperature	242°C	257°C
Board Design	Flexboard	Cellphone

For Phase One, both boards (Flexboard and Cellphone) were used to determine the ease of profile generation using the different profiling methods. A separate profile was generated for each test board based on the defined process window. Monitored items included profile development time, solder joint quality and yield of the assembled boards. Two boards were built per profile for the Flexboard boards and five boards per profile of the Cellphone boards were built. Examples of the high and low profiles can be found in Figures 4 and 5. The process window index of these profiles was based on a ramp rate of less than 1.5°C/sec, time above liquidous (217°C) of 30 to 90 seconds, and a peak temperature variation of +/-5°C from the evaluated temperature. In general, the peak temperature process window index was the highest as this required the tightest control. The profile statistics as well as the process window indexes of the two profiles are shown in Table 2.

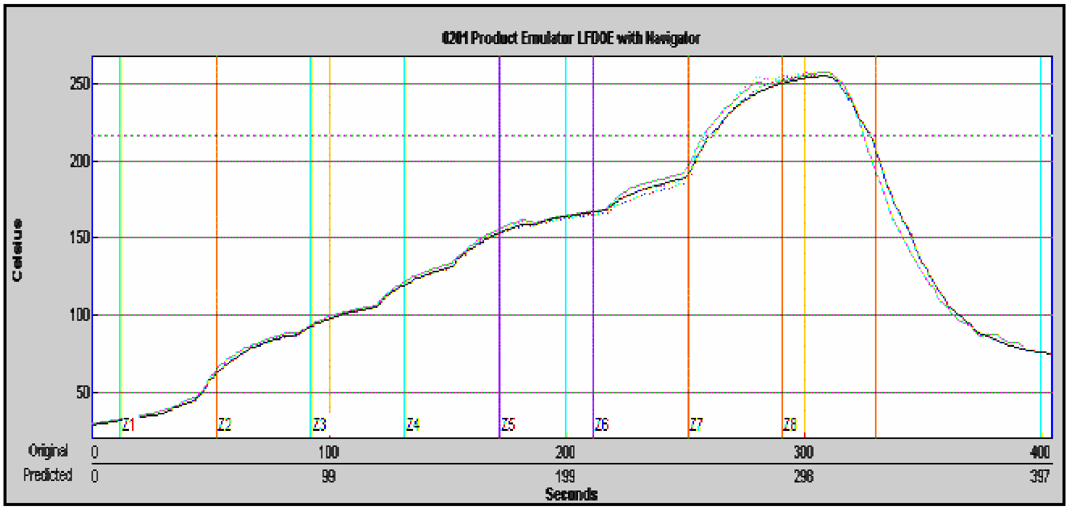


Figure 4: Example of the 257°C profile utilizing the automated profile prediction software

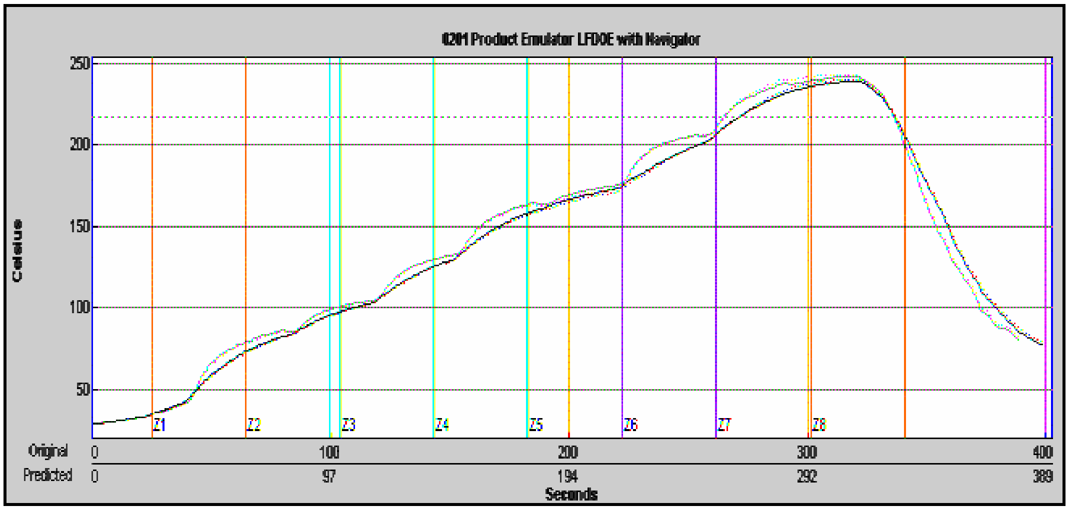


Figure 5: Example of the 242°C profile utilizing the automated profile prediction software

Table 2: Reflow statistics for the profiles used in Phase 1 of the experimentation

Profile	Ramp Rate (°C/sec)	Time >217°C (seconds)	Peak Temp (°C)	Process Window Index (%)
FlexBoard 242 Navigator	0.80	56.2	242.2	43%
FlexBoard 257 Navigator	0.90	63.2	255.6	60%
Cellphone 242 Navigator	0.85	68.6	240.8	31%
Cellphone 257 Navigator	0.90	67.3	256.7	56%
FlexBoard 257 Operator	0.80	72.3	257.3	91%
Cellphone 242 Operator	0.95	46.0	248.7	207%
Cellphone 257 Operator	1.00	51.1	255.5	31%

For the profiles created for Phase One of the experimental work, the automatically defined profiles overall have a lower process window index than the operator generated profiles. The software predicted profiles took fewer iterations and less time to generate than the operator generated profiles. The software prediction took two iterations to go from a standard SnPb reflow profile to the 257°C profile and then one iteration to go from the 257°C profile to the 242°C. The trial and error profiling techniques took five iterations to go from a standard SnPb profile to an acceptable 257°C peak profile and then three iterations to go from the 257°C profile to the 242°C profile. Overall, the time it took for profiling was cut by more than half when the software was used to predict the next profile from the starting point. Profiles for the Cellphone board were generated faster than the profiles generated for the heavier and more diversely populated FlexBoard.

Phase Two:

Given that a reflow profile had been created for the lower peak temperature used in Phase One, 242°C, it was then desirable to determine the lowest possible peak reflow temperature capable of forming quality solder joints for the SnAgCu alloy. The peak temperature was initially lowered from 242°C to 232°C and then in 4°C increments to a lower limit of 220°C. Shear tests and cross sections were performed to determine solder joint quality of the various components on the Cellphone boards assembled with these new profiles.

For Phase 2, the Cellphone board was the only test board implemented based upon the availability of the boards. Five Cellphone boards were assembled at each peak temperature tested. Yield and solder joint quality was measured for each of the changes that were made to the profile. Examples of the profiles that were created for the 232°C and 224°C peak temperature reflow profiles are shown in Figures 6 and 7. The process window indexes of the profiles for this phase of the experiment are based upon a ramp rate of less than 1.5°C/sec, a time above liquidous (217°C) of between 30 and 90 seconds, and a peak temperature range of +/-2°C. As with the previous phase of work, the highest process window index generally came from the peak temperature, as the process window for the peak temperature was only 4°C. The reflow statistics of each of the profiles used in Phase Two of the experimentation are shown in Table 3.

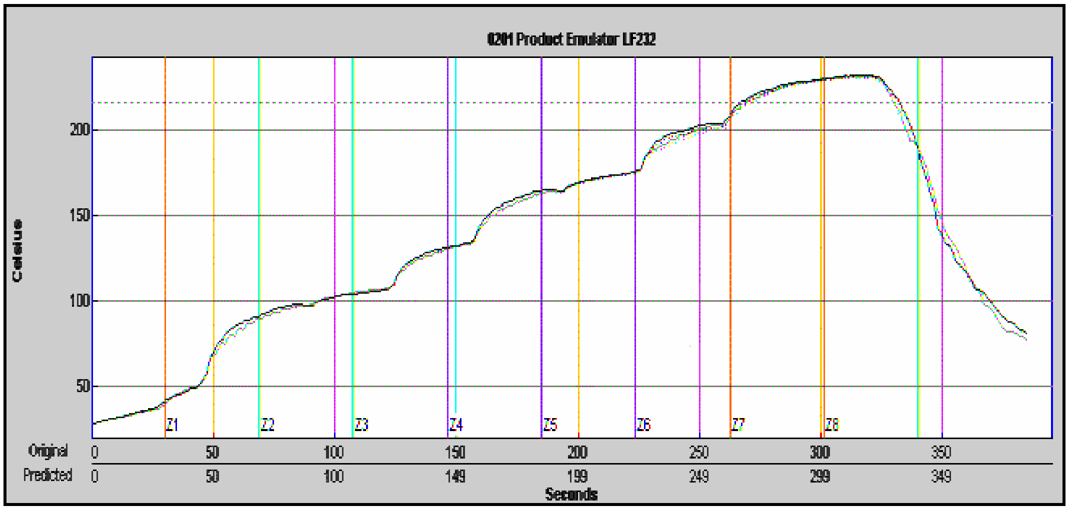


Figure 6: Reflow profile for the 232℃ peak temperature

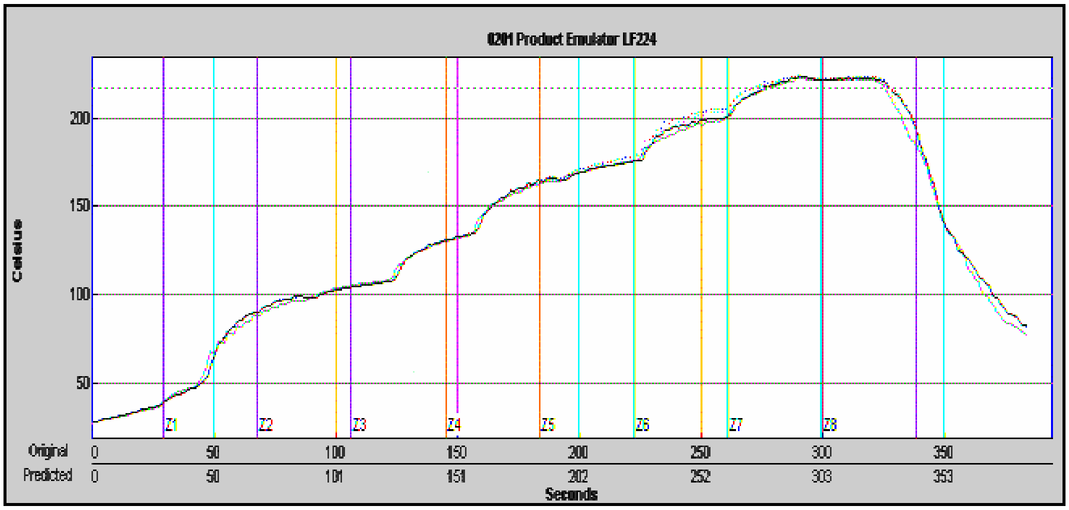


Figure 7: Reflow profile for the 224℃ peak temperature

Table 3: Reflow statistics for the reflow profiles used in Phase 2 of the experimentation

Profile	**Ramp Rate (°C/sec)**	**Time >217°C (seconds)**	**Peak Temp (°C)**	**Process Window Index (%)**
LF232	0.8	63.3	232.8	58%
LF228	0.8	56.1	227.7	50%
LF224	0.8	50.3	223.2	58%
LF220	0.8	59.3	220.2	19%

Experimental Results

Overall, it was found that solder wetting did occur at all six peak temperatures to varying degrees. A noticeable aspect of the wetting of Pb-free paste is that the paste will not flow out to the edges of the bond pad. Due to this, when a reduced aperture is used it is unlikely that the solder will fully wet out the entire pad, compared to standard SnPb paste that wets out the entire length of the pad. An example of this is shown in Figure 8.

Figure 8: SnPb and SnAgCu QFP joints

In Figure 8, the Pb-free solder has wet out to near the edge of the pad, but has not completely covered the pad. The area where the solder is not shiny is beyond the printed area of the solder paste and therefore does not wet, but there is diffusion of the Sn across the remainder of the immersion Au covered bond pad that causes the gray tint of the pad. This phenomenon is independent of the peak reflow temperature. The image on the left of Figure 8 shows wetting of the same component pads when standard SnPb paste is utilized.

Shear testing was done on a sampling of 0201 components to determine the solder joint strength of the Pb-free solder pastes. Comparison data was taken from a sample of SnPb components as a benchmark for the Pb-free samples. The results of the shear data are shown in Table 4 and Figure 9. Figure 9 shows the average shear strength of the different experiments run as well as the addition of the standard deviation of the data.

Table 4: Shear test results for 0201 components based upon the solder material and peak temperature

Profile	**Eutectic 215**	**LF224**	**LF228**	**LF242**	**LF257**
Shear Force Average (grams)	649	702	669	781	758
Standard Deviation (grams)	101	159	138	96	96
Maximum Shear Force (grams)	920	1040	1080	1040	1050
Minimum Shear Force (grams)	370	350	350	460	500

Based on the results shown in Table 4 and Figure 9, it is shown that the Pb-free assemblies had higher average shear strengths than the SnPb assemblies. Statistically, the only two conditions producing different results are the SnPb sample and the Pb-free peak 257°C sample set. The average shear strengths of the other different temperatures fall within the standard deviations of each other. Even the Pb-free 0201s assembled with a peak temperature of 224°C had a higher average shear strength than the 0201s assembled with the Eutectic SnPb solder paste.

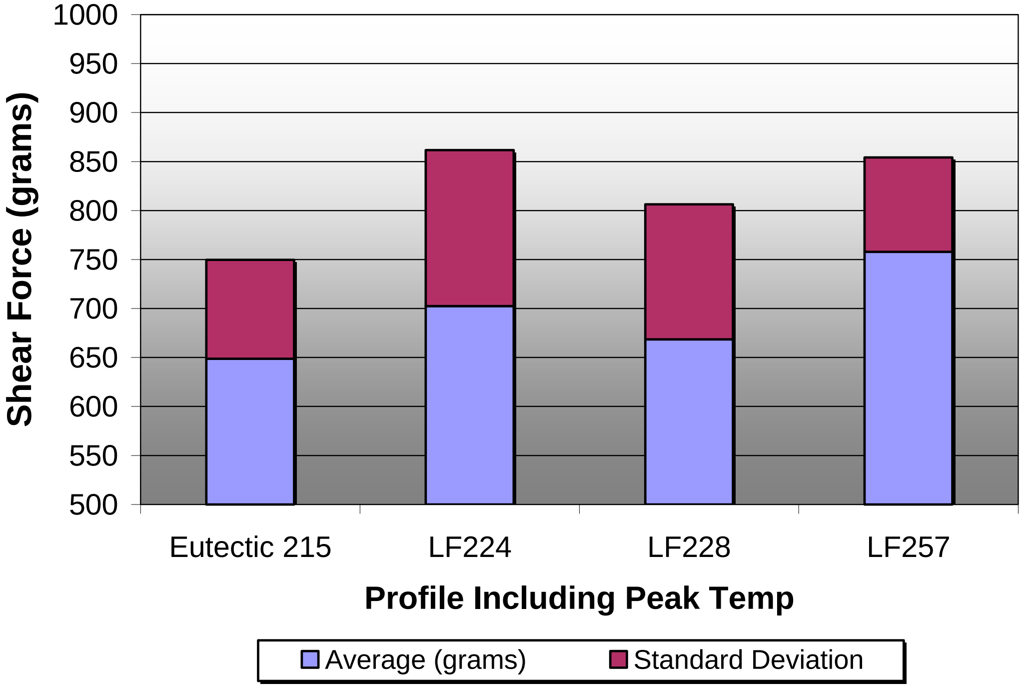


Figure 9: Average shear force and standard deviationfor 0201 components reflowed at different temperatures

For Phase One of the experimental matrix, boards were assembled at peak temperatures of 242°C and 257°C. Two Flexboards and five Cellphone boards were built for each profile. Optical inspection was performed on every board to IPC 610 rev C class 3 specifications. No wetting defects were found on any of these boards. There were some defects found in the trial and error produced profile assemblies. These defects were mainly tombstoned 0201 components and were caused by the higher ramp rates near the peak zone. Cross sections of some of the components were performed so that scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) could be used to evaluate the wetting of a number of different components. Figure 10 shows SEM images of 0201s assembled at 242°C and 257°C.

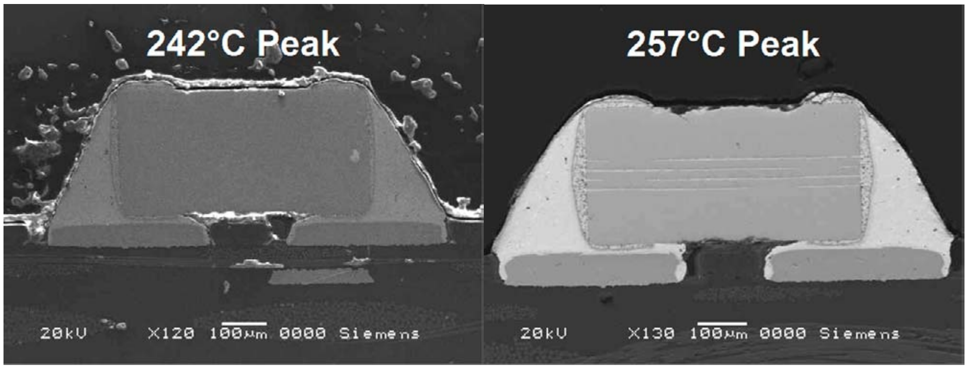


Figure 10: 0201s assembled at 242°C and 257°C peak temperatures

Both 0201 components shown in Figure 10 are representative of solder joints on passive components reflowed at this temperature. All of the passive components that were evaluated at these two peak temperatures showed even and full wetting to both the bond pad and the component termination. There was no noticeable difference in solder joint quality between these two peak temperatures.

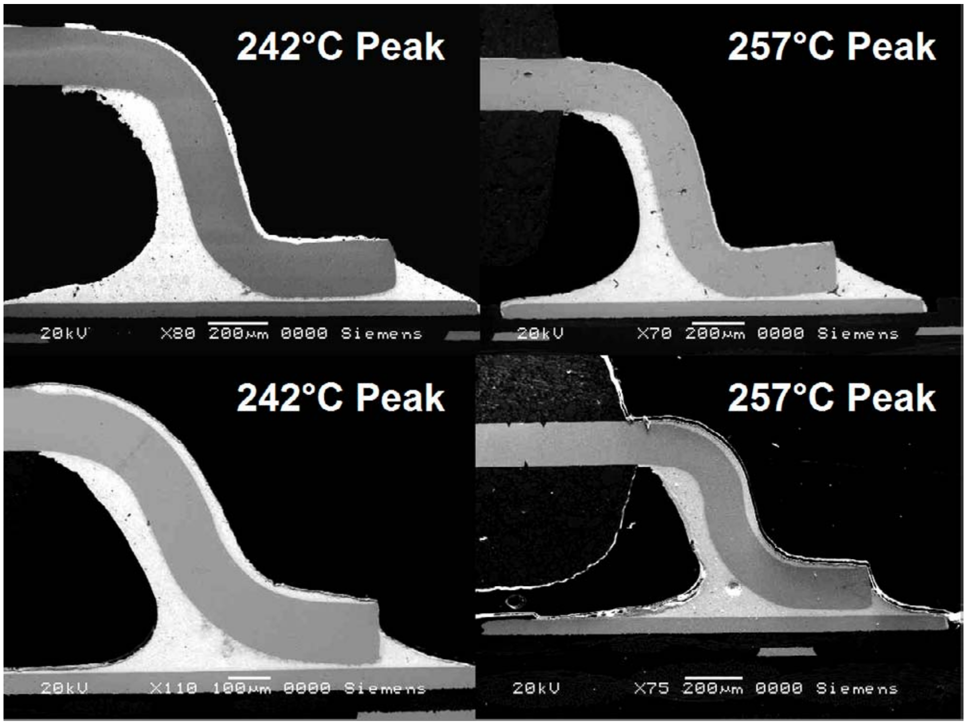


Figure 11: SEM images of SOIC (top) and TSOP (bottom) leads assembled at a peak temperature of either 242°C or 257°C

Figure 11 shows representative SEM images of SOIC leads and TSOP leads from Phase One of the project. As with the passive components, good wetting was achieved on all of the leads. Full wetting can be seen on both the substrate bond pad and the component lead. The lead is completely wet from the toe of the joint all the way to the component body. SEM analysis was also done to analyze the intermetallic region at both the component terminal and on the board. There was found to be no real difference in the intermetallic regions based upon the reflow temperature that the component was subjected to.

Upon the completion of the Phase One, Phase Two of the project was started. In Phase Two, the goal was to determine the minimum peak reflow temperature that formed quality interconnects. Based on the results of Phase One and results other work, it was determined that the first temperature to be tried was 232°C and then the peak reflow temperature would be reduced by 4°C until insufficient wetting was found. The four peak reflow temperatures were 232°C, 228°C, 224°C, and 220°C. For each temperature, five Cellphone boards were assembled. Optical inspection was performed to check the solder joint quality and number of defects. Sample parts from each peak temperature were then cross-sectioned and SEM analysis of the solder joint quality was then performed upon these components.

No noticeable defects were found on the boards built with either the 232°C or 228°C peak temperature. Some minor wetting defects were found when the 224°C peak reflow temperature was used. A greater number of defects were found at a peak reflow temperature of 220°C. This was not unexpected as the peak temperature was only 3°C above the liquidous temperature (217°C) of the SnAgCu solder alloy that was used. Small solder balls were found attached to wetted solder joints, indicating all the printed paste did not melt. Cross section analysis of the components showed that incomplete wetting could be seen on components assembled at temperatures of 228°C and below. Figure 12 shows some representative images of 0201 components assembled with the Pb-free solder at varying peak temperatures.

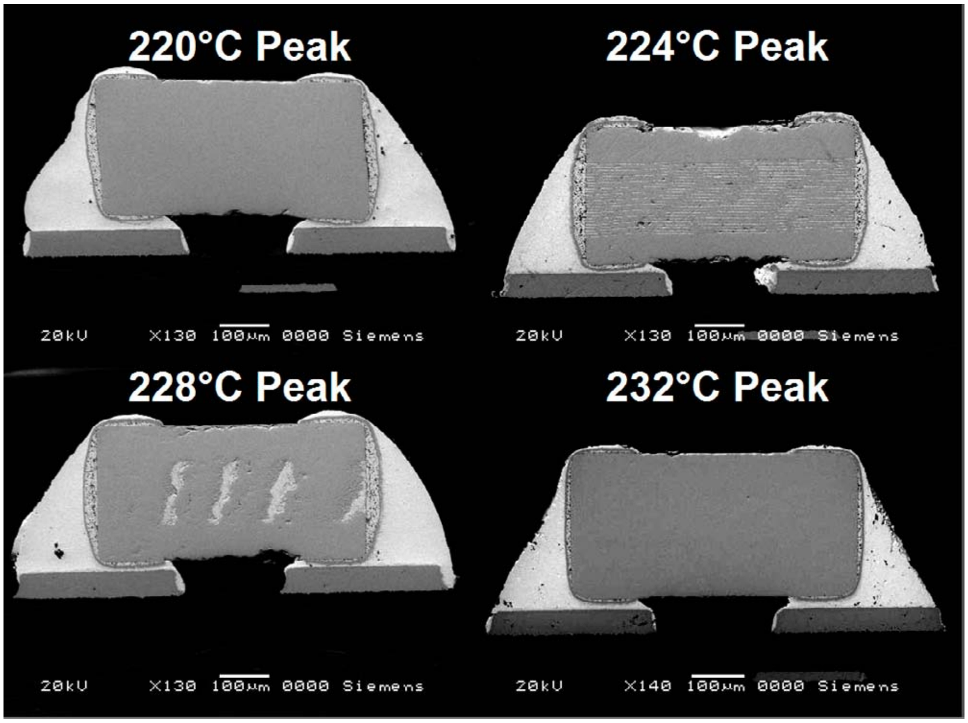


Figure 12: SEM Images of 0201s reflowed below the recommended peak temperature

The wetting of the 232°C component was just as good as components assembled in Phase One of the study. As the temperature decreased from 232°C, the wetting was not as good and decreased as the peak temperature decreased. At 228°C, the solder did not completely wet down the pad although there was full wetting to the component termination. The worst wetting was seen at the 220°C peak temperature as the solder joints in Figure 12 shows. The solder joint for the 220°C peak temperature on the left hand side of the component exhibits a sharp angle at the bottom of the joint. This angle may affect the reliability of this joint as it could act as a crack propagation site during thermal cycling. Figure 13 shows SEM images of TSOP leads reflowed at varying peak temperatures.

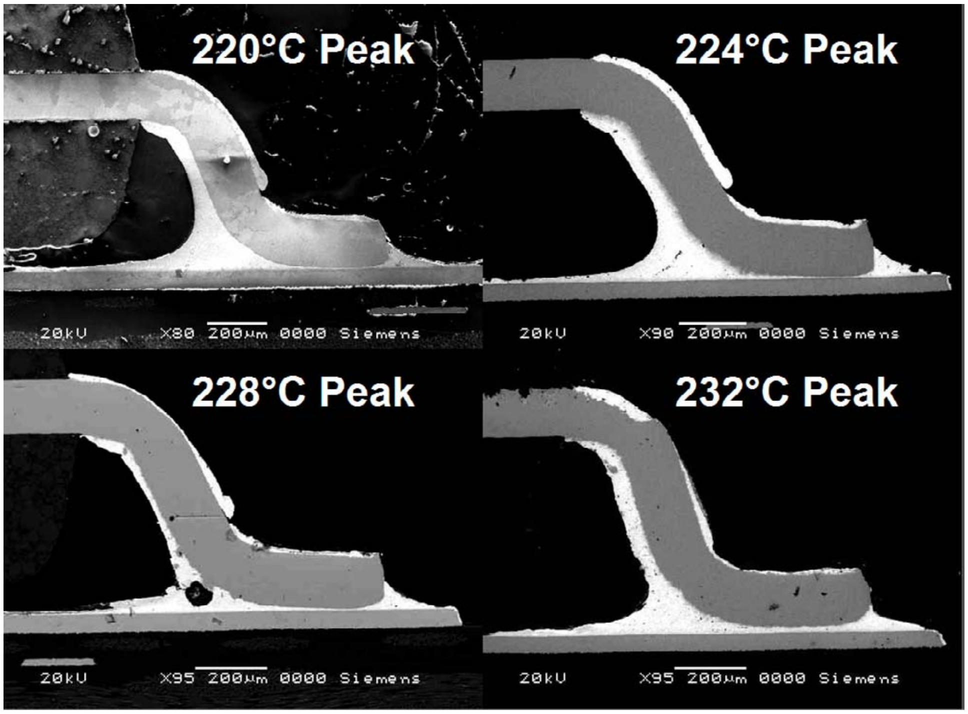


Figure 13 SEM images of TSOP leads assembled below the recommended peak temperature of 242°C

Although almost complete wetting can be seen at the various peak temperatures tested in Phase Two of the study, differences can be seen. The representative images from these temperatures show that not all of the lead has been fully wetted by the solder paste. The noticeable difference is seen at the 228°C peak temperature and below images. In these images, it looks like a drop of solder moving down the lead can be seen leaving what looks like a ball halfway down the outside of the joint. From the analysis of the boards built in Phase Two of the project, it has been found that good SnAgCu joints can be formed outside of the manufacturers' recommended peak temperature range, but a large reduction of peak temperature can lead to excessive solder balling and incomplete wetting of the solder to both the bond pads and components. From the SEM analysis of the boards, it would be recommended that the peak temperature of the solder be 232°C or above in order to achieve more reliable wetting of the bond pads. Although joints can be formed at lower peak reflow temperatures, even down to 220°C, this may lead to problems as large parts may not reach a temperature above 217°C, the liquidous point for this SnAgCu paste, and therefore may be subject to insufficient wetting and reduced reliability.

Conclusions

From this study, it was found that the peak temperature necessary to achieve sufficient wetting should be 232°C or above. In Phase One of the research, it was shown that new profiling techniques can significantly reduce the time and number of iterations necessary to create new profiles. These new profiling techniques can be implemented to significantly reduce the time required to change over from a standard SnPb profile to a Pb-free profile. Profiling techniques such as the one implemented in this study can also be used to create Pb-free profiles that are between the minimum recommended peak temperature found in this study, 232°C, and the maximum allowable peak temperature associated with most temperature sensitive components, 240°C, a process window of only 8°C. For Phase One of the testing, it was found that there was no real difference between utilizing a peak temperature of 242°C and a peak temperature of 257°C. For Phase Two of the study, it was important to find the lowest peak temperature that would lead to sufficient wetting of all of the solder joints. At peak temperatures below 232°C, full solder wetting of all parts of the component and bond pad did not occur for all of the interconnects tested. Therefore, temperatures below 240°C can be used for SnAgCu reflow allow temperatures below 232°C would not be recommended. This means that components that are currently temperature sensitive to temperatures above 240°C can be used in Pb-free processing. It was also shown that the shear strength of the Pb-free solder joints were as good if not better than the solder joint strength of the standard SnPb solder.