Development of Lead-Free Wave Soldering Process

Minna Arra
Flextronics
Tampere, Finland

Dongkai Shangguan and Sammy Yi
Flextronics
San Jose, CA

Robert Thalhammer and Harald Fockenberger
Flextronics
Althofen, Austria

Abstract
Lead-free wave soldering was studied in this work using Sn/Ag/Cu alloy. A process DOE was developed, with three variables (solder bath temperature, conveyor speed, and soldering atmosphere), using a dual wave system. Nine no-clean flux systems, including alcohol- and water-based types, were included in the evaluation. A specially designed "Lead-Free Solder Test Vehicle", which has various types of components, was used in the experiments. Both organic solderability preservative (OSP) and electroless nickel/ immersion gold (Ni/Au, or ENIG) surface finishes were studied. Soldering performance (solder ball, bridging, wetting and hole filling, and flux residues) was used as the responses for the DOE. In addition, dross formation was measured at different solder bath temperatures and atmospheres. Regarding the connector-type component, a pad design giving the best soldering performance was evaluated based on the DOE results. Finally, a confirmation run with the optimum flux and process parameters was carried out using the Sn/Ag/Cu solder, and a comparative run was made with the Sn/Pb solder alloy and the no-clean flux used in production. The soldering results between the two runs indicate that with optimum flux and process parameters, it is possible to achieve acceptable process performance with the Sn/Ag/Cu alloy. Mechanical testing and cross-section study were used to verify the solder joint integrity and compare the mechanical performance between the Sn/Ag/Cu and Sn/Pb solder joints.

Introduction

Due to pending environmental legislation and market requirements, lead-free soldering is fast being adopted by the electronics industry. Lead-free surface mount technology (SMT) has been studied extensively during the past years whereas lead-free wave-soldering has received relatively little attention.

Wave-soldering has been studied, for example, with Sn/Cu, Sn/Bi and Sn/Ag/Cu alloys. The main problems reported with the lead-free solder have been poor soldering yield[1], fillet lifting phenomenon[2] poor wetting of components and PCB by the solder[3] increased dross formation[3], gradual change of alloy composition and contamination of the solder bath during continuous manufacturing[4], dissolution of the pot metal in the solder bath[4] and lack of equipment having a capable pre-heating system ensuring uniform temperature across the board and components. Besides alloy and equipment characteristics, solderability and yield problems have often been associated with immature flux systems.

The objective of this study was to investigate the characteristics of the lead-free wave soldering process and find the right materials and process parameters enabling the process to be adopted for high volume production.

Experiment Set-up

Equipment Settings

As reported in earlier studies, sufficient pre-heating on the board is crucial for satisfactory solder flow into through-holes and wetting of topside pads[3, 4] Normally the superheat available to promote solder flow up and for topside pad wetting is smaller for lead-free alloys as compared with Sn/Pb alloys due to the higher melting temperature of the lead-free solder alloy. Consequently, pre-heat temperatures have been raised for lead-free solders from the level typically used in Sn/Pb process[3].

In the equipment used during this study, the pre-heating tunnel has three heating zones. The first and third zone are equipped with quartz lamps emitting infrared radiation in the wavelength area of 0,5-2,5 µm. In the second zone, forced convection heating is used on the bottom side and quartz lamps on the top side of the PCB. Convection heating helps minimize the temperature differences between the components and the board.

All the experiments were conducted with both chip and lambda wave (main wave) on, as is typical of regular production processes. The geometry or shape of the wave nozzles was not modified from the standard configuration. Standard nozzle materials were used during this study, although it is known that for high volume production, nozzles may need to be replaced with new ones having a plating resistant to the wear-out effect caused by the lead-free solder.

The solder pot has a special surface treatment, which is resistant to the attack from the lead-free solder, so that the dissolution of the pot material to the lead-free solder bath could be avoided. To maintain a good control of the solder level in the pot, the pot is equipped with automatic solder feeding having an accuracy of +/- 0,5 mm of solder level.

The equipment has a nitrogen purge system with three outlets. One of them is placed before the chip wave, second between the chip and lambda wave, and the third on the lambda wave. This system provided nitrogen purge on top of the solder wave surfaces. When nitrogen was used, the purge level was adjusted so that an oxygen concentration of ~100-200 ppm was maintained on the waves.

Alloy Selection

Sn/Ag/Cu alloy (Sn95,5/Ag3,8/Cu0,7, wt-%) was selected for this study, since Sn/Ag/Cu alloy is believed to be the leading choice of the electronics industry and is recommended by numerous international industry and research consortia. Another alloy, Sn/Cu, has also been proposed and studied by some consortia and even adopted by some companies[5]. However, the reliability and wettability concerns of Sn/Cu[6], as well as the desire to use the same alloy in both reflow and wave soldering processes, made Sn/Ag/Cu the most attractive choice. Work is in progress to develop wave-soldering process with the Sn/Cu alloy.

Components and PCBs

Both through-hole (TH) and surface mount device (SMD) components were used for the wave soldering process development. Different component plating materials, both Sn/Pb and lead-free, were included as shown in Table 1.

Table 1 - Components Used in the Study

Type	Plating	Component count per board
Pin-header (two rows, 14 pins/row)	Ni/Au	8
DIL14	Ni/Pd	3
DIL14	80Sn/20Pb	3
SOL16	80Sn/20Pb	6
SOT23	100%Sn	36
1206	100%Sn	20
0805	100%Sn	40
0603	100%Sn	150

A special test vehicle was designed for the study. Since the bridging of the pin-header had been one of the major problems in the previous wave soldering trials, several different pad designs were included on the test vehicle for comparison (Table 2). All of the four designs were placed both parallel and perpendicular to the wave soldering direction on the board as shown in Figure 1.

Table 2 - Pinheader Designs

Design	Pad shape	Hole ∅ (mm)	Annular ring ∅ (mm)	Solder thieving bar
1	Oval & round	1,10	1,75	No
2	Round	1,10	1,75	Yes
3	Round	0,95	1,25	No
4	Round	1,10	1,40	No

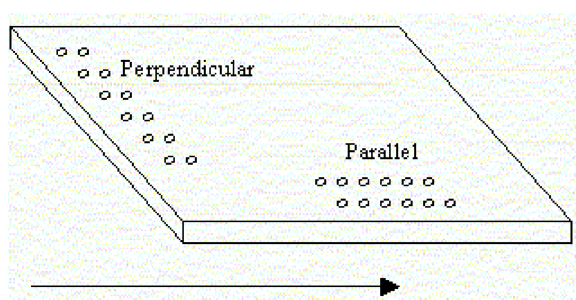

Figure 1 – Orientations of the Pinheaders on the PCB

Two PCB surface finishes were studied: organic solderability preservative (OSP) of type Entek 106 and electroless nickel/ immersion gold (Ni/Au). The laminate base material of the PCBs was FR-4.

Fluxes

Nine different commercial flux systems were evaluated and the best ones were selected for further studies. Both alcohol- and water-based fluxes were included in the study. All the fluxes were of no-clean type and were formulated for lead-free soldering. The properties of the fluxes are presented in Table 3.

Table 3 - Physical and Chemical Properties of the Fluxes Investigated

Flux	Solvent	J-STD-004 classification	Solids content	Acid value
A	Alcohol -based	ORLO	1,8	15
B	Water-based	ORLO	4,45	29
C	Alcohol -based	ORLO	2,2	18
D	Alcohol -based	ORLO	3,9	34
E	Water-based	ORLO	3,25	27
F	(35% water/ 65 % alcohol) - based	RELO	2,7	22
G	Alcohol -based	ROLO	3	18,3
H	Water-based	ORMO	2,1	21
I	Water-based	ORMO	3,4	21

In a preliminary trial run, six boards populated with components were run for each flux with the soldering profile recommended by the flux vendor, and were then inspected for flux residues, solder balling and bridging. The fluxes were ranked according to the results as shown in Table 4. In each test, the best result was given a score 1, second best a score 2, and so on. The smaller the total score, the better the performance of the flux.

Table 4 - Ranking of Fluxes in the Flux Evaluation Study

	Flux residues	Solder balls	Bridging	Total
A	1	3	1	4
B	1	9	5	15
C	3	2	1	6
D	6	4	5	15
E	3	6	4	13
F	6	5	5	16
G	9	8	5	23
H	3	7	9	19
I	6	1	1	8

Based on the results, fluxes A, C, E and I were selected for further studies, where a design of experiment (DOE) was carried out for the wave soldering process.

Design of Experiment (DOE)

The purpose of the DOE was three-fold. First, the performance of each flux through several different process conditions was tested; this is a good indicator of the process window of the flux system. Second, the best process parameters for each flux were established. Third, the dependence of different defects on process conditions was studied.

Three parameters were varied during the study. These parameters were understood to represent the key or basic parameters that need to be established for high volume production; once basic parameters have been established, product-dependent fine-tuning of the process can be carried out. The key parameters selected were solder bath temperature, conveyor speed and soldering atmosphere (air versus nitrogen). Based on this concept, a DOE matrix (Table 5) was designed. The solder pot temperature determines the peak temperature of the wave soldering profile, and the conveyor speed affects the dwell time of the board with the solder wave.

Typical solder bath temperatures being used by the industry for lead-free alloys range from 250 °C to 255 °C[7,1,4]. However, for this study, bath temperature of 260 °C was chosen based on experiences from earlier experiments. As a higher temperature, 270 °C was chosen.

The dwell time in the wave depends mostly on the conveyor speed and the solder level in the solder pot. Since the solder level in the pot was kept constant the dwell time was varied by changing the conveyor speed. Conveyor speeds of 0,8, 1,2 and 1,6 m/min were chosen for the study, giving different dwell times as shown in Table 6. These conveyor speeds are usually used in high volume production and they cover most applications and throughput requirements.

Table 5 - DOE Matrix For Wave-Soldering Process Screening Study

Run n:o	Solder bath temperature (°C)	Conveyor speed (m/min)	Atmosphere
1	260	0,8	Air
2	260	0,8	Nitrogen
3	260	1,2	Air
4	260	1,2	Nitrogen
5	260	1,6	Air
6	260	1,6	Nitrogen
7	270	0,8	Air
8	270	0,8	Nitrogen
9	270	1,2	Air
10	270	1,2	Nitrogen
11	270	1,6	Air
12	270	1,6	Nitrogen

Table 6 – Average Dwell Time as Function of Conveyor Speed

Conveyor speed (m/min)	Chip wave (s)	Main wave (s)
0,8	0,48	2,80
1,2	0,32	1,89
1,6	0,24	1,39

Six boards, three with OSP and three with Ni/Au surface finishes, were run with each flux for all twelve runs. Wetting, solder balling and bridging were used as response parameters.

Results and Discussion

Performance of The Flux Systems in The DOE

Regarding wetting in general, solder joints of both TH and SMD components fulfilled the IPC-A-610 specification. Since wetting results fulfilled the workmanship standard, a more sensitive categorization system was created. The through-hole fill and topside pad wetting of the six DIL14 components, shown in Figure 2, on every assembled board, were inspected. The results were divided into three different categories. In the first category (Figure 3), the solder had filled the hole and the topside pad was fully wetted by the solder. In the second category (Figure 3), the hole was filled but the topside pad wetting was not complete. In the third and worst case (Figure 5), the solder had not completely filled the hole and the topside pad was not wetted. The average number of category 3 and 2 wetting results per board through all DOE runs for each flux is presented in Table 7.

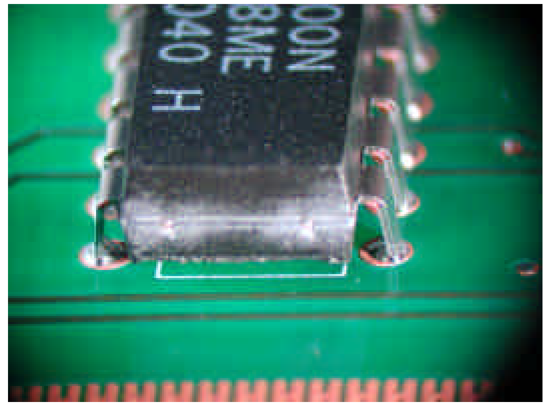

Figure 2 - DIL14 -Component Type Used For Wetting Analysis

Figure 3 – Category 1: Solder Has Filled The Hole Completely and The Topside Pad is Fully Wetted

Figure 4 - Category 2: Solder Has Filled The Hole Completely But The Topside Pad is Not Fully Wetted

Figure 5 – Category 3: Solder Has Not Completely Filled The Hole and Topside Pad is Not Wetted

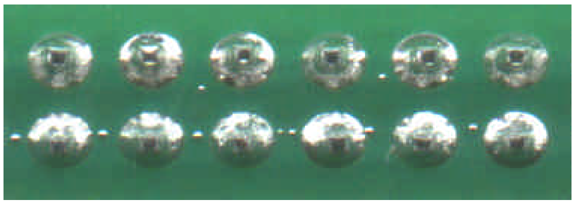

Figure 6 -Example of Solder Balling on the Pin-header

For solder balling, the solder ball count on all of the eight pin-header areas was calculated. The average number of solder balls per board including all DOE runs is presented in Table 7. The solder ball sizes ranged typically from 100 µm to 250 µm. An example of solder balling on pin-header is shown in Figure 6.

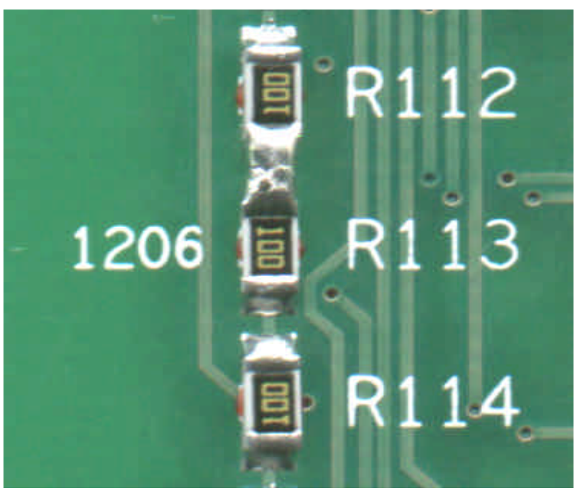

Figure 7 - Example of Bridging Between the 1206 Component Terminations

Bridging was calculated as the number of pins (pin-header and DIL14) or terminations (SMD components) touching, forming a bridge as shown in Figure 7 and Figure 8. If the same pin or termination touched more than one bridge, it was counted only once. The average number of bridged pins or terminations per board for each flux is shown in Table 7.

Figure 8 - Example of Bridging Between the Pin-Header Pins

Flux Selection and Process Parameters

Based on the results presented in Table 7, the flux "I" gave the best overall performance. However, during the trial runs, this flux tended to clog the flux spray nozzle; therefore this flux was not considered for further testing. Flux "E" provided the second best overall results. The best process parameter combination for this flux was bath temperature of 260 °C, conveyor speed of 1,6 m/min., and either nitrogen or air atmosphere. These parameters were later used in the confirmation run.

Influence of Process Parameters

The impact of soldering atmosphere, solder bath temperature and conveyor speed on the defect rates was analyzed. For this study, the average solder balling, bridging and wetting results including all fluxes tested in the DOE phase was considered.

Table 7 - Results From the DOE (Average Through All Runs)

Flux	Solder balls	Bridged pins/ terminations		Hole fill and topside wetting	
		Pin-heades	SMD	Cate-gory 3	Cate-gory 2
I	15	15	0,3	2	20
A	43	23	5	6	32
C	52	21	4	2	25
E	58	16	0,3	0,3	16

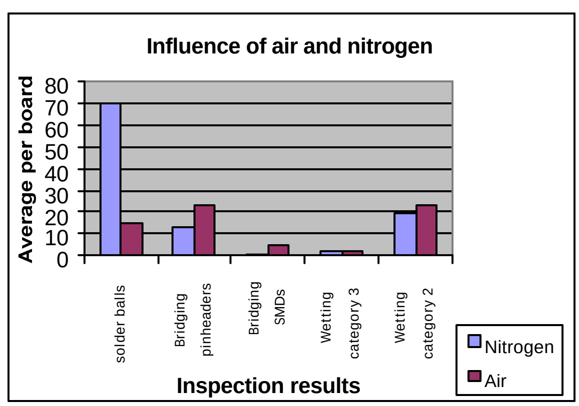

Figure 9 - Influence of Air and Nitrogen on Soldering Results

As can be seen from Figure 9, the most remarkable difference between air and nitrogen was seen in solder balling. More solder balls were formed in the nitrogen atmosphere. Regarding wetting and bridging, nitrogen clearly reduced bridging and improved through-hole wetting. Similar observations have been made in previous studies[13]. This is believed to be due to better conservation of flux activity and improved wettability in a non-oxidizing atmosphere.

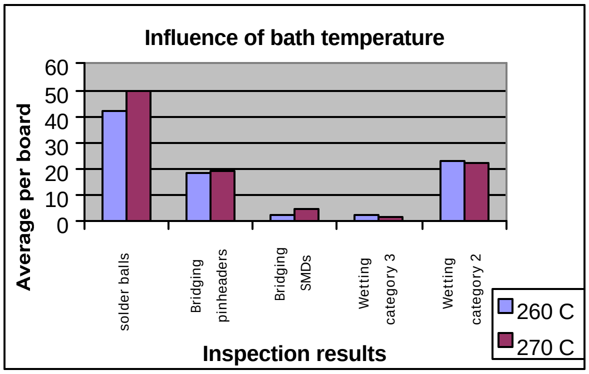

Figure 10 - Influence of Solder Bath Temperature on Soldering Results

Figure 10 illustrates the differences observed when the solder bath temperature was varied between 260 °C and 270 °C. Results for solder balling and bridging were better with 260 °C. This may be again due to the faster degradation of flux activity and performance at higher temperatures. However, through-hole wetting was slightly improved with bath temperature of 270 °C. The improvement of wetting with increased solder bath temperature has also been reported in earlier studies[1]. This can be explained by the fact that the time for the full wetting of surfaces by solder is known to be faster at higher temperatures[8] in addition, the solubility of component and board finish metals into the molten solder increases with temperature[9].

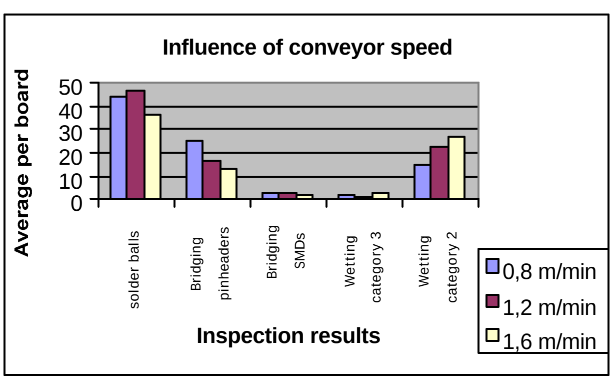

Figure 11 - Influence of Conveyor Speed on Soldering Results

The comparison of different conveyor speeds is shown in Figure 11. Conveyor speed is directly related to the dwell time of the PCB with the wave. A slower conveyor speed means a longer dwell time as shown in Table 6. As can be seen, wetting was enhanced with slower conveyor speeds (or longer dwell time). This can be explained by the fact that the solubility of metals into solder is time-dependent[9]. Solder balling and bridging were reduced when conveyor speeds were increased. Again, according to the assumption presented earlier, the performance of the flux is better conserved throughout the dual-wave soldering operation when the dwell time with the waves is shorter.

Confirmation Run

The flux for the confirmation run was selected based on the overall performance of the fluxes in the DOE phase. In the confirmation run, 24 boards (12 with OSP and 12 with Ni/Au surface finishes) were assembled with the optimum conveyor speed-solder bath temperature combination. Half of the boards were run with nitrogen and half with air atmosphere. The results from the confirmation run are presented in Table 8.

As can be seen from Table 8, the results from the confirmation run are better than those obtained for flux "E" in the DOE run since the optimised conditions were used in the confirmation run.

Table 8 - Results From the Confirmation Run With Flux "E" (Average Per Board)

Solder balls	Bridged pins/ terminations		Hole fill and topside wetting	
	Pin-headers	SMDs	Cate-gory 3	Cate-gory 2
54,2	10,6	2,5	0,07	25,4

Dross Formation

In some earlier investigations, phosphorous has been used as a dopant to prevent dross formation and to give a drier, more powdery and voluminous dross[4]. However, the addition of dopants requires continuous monitoring of the dopant content in the bath and therefore introduces extra process cost. In the scope of this project, no studies with dopants were carried out.

The dross formation rate was measured by keeping the pump on for four hours in two identical solder pots, one of them containing Sn/Pb and the other Sn/Ag/Cu solder. After four hours, the dross was removed from the surface of the pot and weighed. Results are presented in Table 9 and Figure 12.

Table 9 -Dross Formation During Four Hours

Solder	Solder bath temperature (°C)	Air atmosphere	Nitrogen atmosphere
Sn/Ag/Cu	260	2,00 kg	1,27 kg
Sn/Ag/Cu	270	1,90 kg	1,37 kg
Sn/Pb	250	1,92 kg	Not Measured

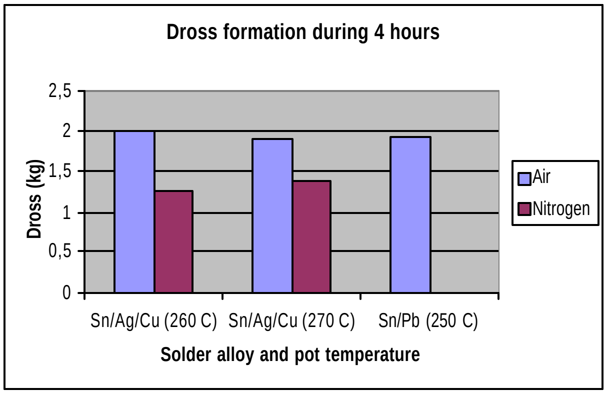

Figure 12 - Dross Formation During Four Hours

As can be seen from Table 9 and Figure 12, the dross formation rate did not differ considerably between Sn/Pb and Sn/Ag/Cu solders. Nitrogen purge helped to reduce the amount of dross for the Sn/Ag/Cu solder by approximately 30 %. When evaluating the cost-effectiveness of the nitrogen purge system, the cost of nitrogen together with the cost and maintenance of the purge system, the price of the solder and the impact of nitrogen on the production yield on the intended product, have to be considered.

Stability of Solder Composition in Solder Bath

Copper has been reported to build up in the solder bath during long-term production causing changes in the fluidity of the solder and bridging of solder joints[4]. Some build-up of Pb can also be expected if Sn/Pb plated components or PCBs with Pb-containing surface finishes are soldered, but Pb levels below 1 wt-% are not considered to influence the solder properties[4].

During this study, the solder composition in the solder bath was monitored through 14 days. During the 14 days, the solder bath was kept at the soldering temperature and trial runs were carried out during 8-10 hours per day. No major changes in the solder composition were observed. The silver content increased from 3,68 % to 3,80 %, and the copper content decreased from 0,77 % to 0,72 %. The period of monitoring was considered to be too short to see the long term development of the solder composition for volume production.

Comparison With Sn/Pb Soldering Process

After the lead-free confirmation run, 24 boards, 12 with OSP and 12 with Ni/Au surface finishes, were assembled using Sn/Pb solder and the flux currently used in the factory for high volume production. Only soldering in air atmosphere was tested and the process parameters were selected according to the experience from the production without further optimization, and the results from the Sn/Pb run were compared to those from the lead-free confirmation run.

As can be seen from Table 10, there was no remarkable difference in solder balling between Sn/Ag/Cu and Sn/Pb solders. Through-hole wetting was better with the Sn/Pb solder; this was expected knowing the different wetting properties of the alloys. earlier investigations have reported less through hole fill defects with Sn/Pb solder than with lead-free solder[10,1].

Table 10 - Results From The Comparative Run Between Sn/ Ag/Cu and Sn/Pb

Alloy	Solder balls	Bridged pins/ terminations		Hole fill and topside wetting	
		Pin-headers	SMDs	Cate-gory 3	Cate-gory 2
Sn/ Ag/ Cu	54,2	10,6	2,5	0,07	25,4
Sn/ Pb	52	11	4,1	0,17	11,8

It is important to note that the wetting results with lead-free solders were still acceptable according to the IPC-A-610 workmanship standard. However, even though the through-hole wetting fulfilled the IPC specification with this board, the wetting result could fall closer to the acceptance limit with boards having a more challenging design. Regarding bottom side soldering, smooth, convex fillets and small wetting angles have been reported[10]. In this study, comparison of Sn/Ag/Cu and Sn/Pb solder joints on the same component exhibited little differences in terms of wetting angle and fillet shape as can be seen in Figure 13 and Figure 14. The only major difference was the rougher and duller solder surface exhibited by the Sn/Ag/Cu solder joint, which is only cosmetic.

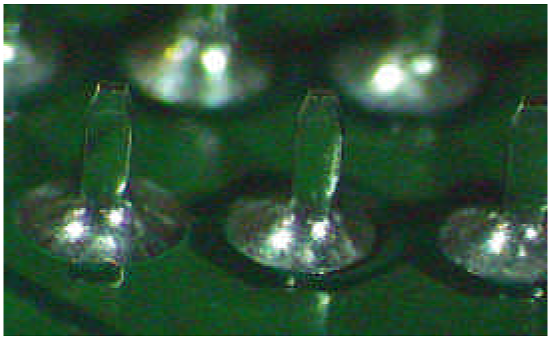

Figure 13 - Sn/PbSsolder Joints

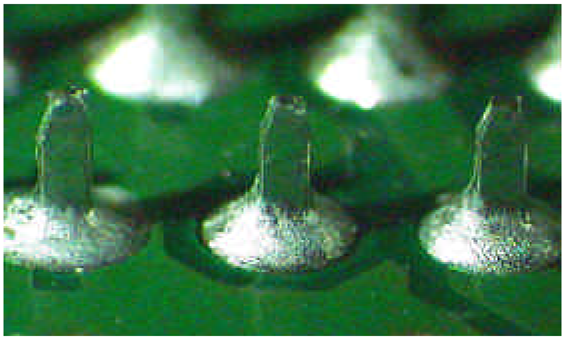

Figure 14 - Sn/Ag/Cu Solder Joints

The number of bridging defects were slightly lower with the Sn/Ag/Cu solder than with the Sn/Pb solder. With some fine-tuning of the Sn/Pb process parameters for this board, the bridging could most probably be reduced to a similar level.

The study shows that with the Sn/Ag/Cu solder and this particular board, it was possible to achieve a yield comparable to that of Sn/Pb solder process. It is known that process yields in general strongly depend on the product design, soldering equipment and solder bath composition; therefore, in real production environment, proper product design and production conditions should be considered for achieving optimized production solution.

Board Design Considerations

The best pin-header design out of the four possibilities shown in Table 2 was investigated by analyzing the result from the DOE phase. Bridging and solder balling were used as response parameters. Results are shown in.

As can be seen from, the parallel orientation was always better than the perpendicular orientation. The orientation of the connector has more influence on the yield than the pad design.

Table 11 - Soldering Result With Different Pin-header Pad Designs and Orientations Using Sn/Ag/Cu Solder

Design	Orientation of the component to the soldering direction	Bridging (average on board)	Solder balls (average on board)
1	Parallel	0	11,1
	Perpendicular	3,2	7,3
2	Parallel	1,1	8,6
	Perpendicular	3,1	11,1
3	Parallel	0	2,2
	Perpendicular	1,1	1
4	Parallel	0	0,9
	Perpendicular	2,1	1,2

The results demonstrate that design 3, which has the smallest pad (annular ring) and hole size, provided the best result. However, design 3 has its limitations regarding automatic component insertion.

Mechanical Testing of Solder Joints

The reliability of the lead-free solder joints has been investigated in many studies. For wave-soldered solder joints, thermal cycling tests have not shown significant failures[10], and lead-free solder joints have even been reported to show considerable increase in the reliability[3]. During this study, the mechanical performance of the solder joints was investigated with pull test. The pin-headers (designs 3 and 4) were included in the study. Individual pins were pulled straight upwards from the topside of the board with a pull speed of 10 mm/min. The maximum force before failure was recorded.

The results presented in Table 12 show that the pull force needed to break a lead-free solder joint is higher than that needed for the Sn/Pb solder joint.

Table 12 – Average Pin Pull Force (N) For Sn/Pb and Sn/Ag/Cu Solder Joints

	OSP	Ni/Au
Sn/Pb	187,3 N	184,0 N
Sn/Ag/Cu	232,7 N	220,4 N

Cross-Section Study

Fillet lifting has been reported both with Bi containing solder alloys and also with other lead-free alloys when components with Sn/Pb plating were used[2]. However, in some studies fillet lifting has not been observed at all[1]. If fillet lifting has occurred, it has normally been seen on the top-side of the solder joint[2]. Fillet lifting has been explained as the formation of a low-melting point composition at the solder/land interface[3]. The tendency for fillet lifting has been found to increase with board thickness, land size, CTE mismatch between the PCB and the solder, and the Pb, Bi and Cu concentrations in the solder alloy[10]

During this study, no fillet lifting has been observed for any component, with any component plating or any of the tested PCB surface finishes. Some examples from Sn/Pb plated components with Sn/Ag/Cu solder are presented in Figure 15 through Figure e18.

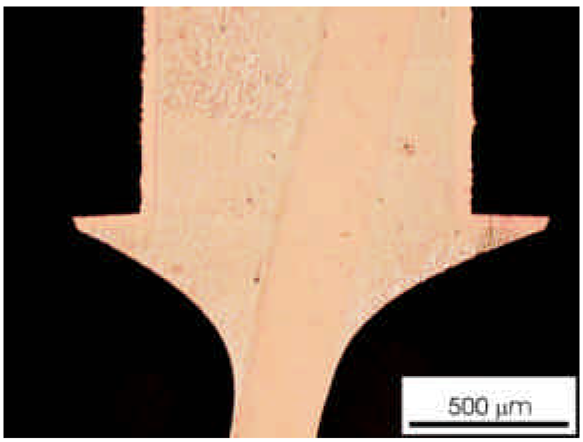

Figure 15 - Cross-Section From a DIL14 Wth Sn/Pb Pated Leads Soldered on a Board With OSP Finish

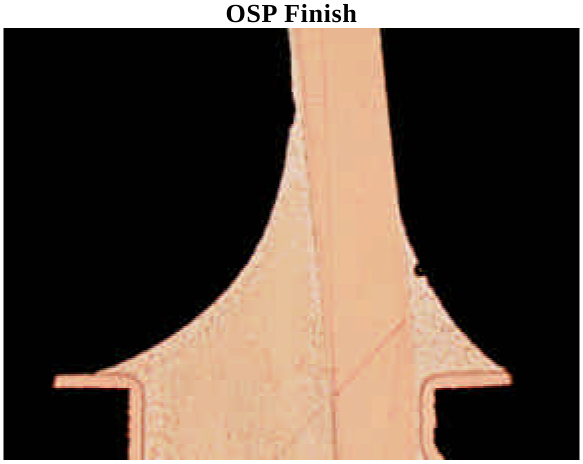

Figure 16 -Cross-Section From a DIL14 With Sn/PbPlated Leads Soldered on a Board With Ni/Au Finish

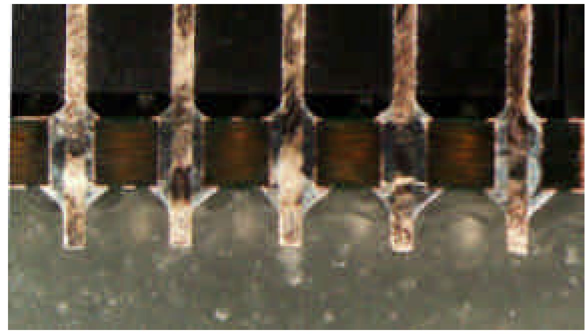

Figure 17 - Cross-Section From a Connector With Sn/Pb -Plated Leads

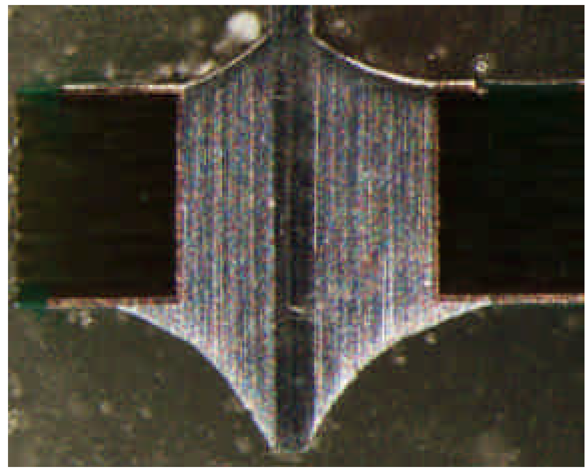

Figure 18 - Cross-Section From a Radial Type Component With Sn/Pb-Plated Leads

Conclusion

In this study, several important aspects of lead-free wave soldering have been studied. The selection of a flux with a wide process window is important for a successful lead-free wave-soldering process. A DOE study revealed the performance of the flux systems under different process conditions, and a water-based flux system was found to provide the best results in this study. Increase in dwell time or solder bath temperature and the use of air atmosphere generally decrease the performance of the flux systems.

Confirmation run with the best flux selected and optimized process parameters have shown acceptable results when compared with the Sn/Pb solder process. The through-hole wetting with Sn/Ag/Cu was poorer than with Sn/Pb solder but still fulfilled the IPC-A-610 specification; it is noted, however, that when more challenging boards are soldered, the wetting results with Sn/Ag/Cu solder could fall closer to the acceptance limit set by the IPC standard.

The dross formation rate of the Sn/Ag/Cu solder was found to be very similar to that of the Sn/Pb solder. Solder composition in the solder pot did not change significantly during the monitored period of 14 days.

With regard to connector-type components, the best design to increase yield was given by reducing the pad size and hole size on the board. Addition of soldering thieves and modification of pad shapes were found to be less effective. However, the most important factor is the orientation of the connectors on the board; orientation parallel to the soldering direction gave far better soldering yield than the perpendicular orientation.

Pull tests performed in this study show that the strength of the Sn/Ag/Cu solder joints is slightly better than that of the Sn/Pb solder. Furthermore, fillet lifting was not observed at all, with different component types and component plating materials.

Acknowledgements
The authors would like to thank the Flextronics Lead-Free Solder Team, especially Frank Grebenstein and Hannu Heinämäki, for providing support, valuable knowledge and experience for the project.

References

1. Miyaki, M., Kanai and M., Ogata, S. (1999) "Soldering Properties for Lead-free Solders of Sn-Ag-Cu System Solders", Proceedings of The 3rd 1999 IEMT/IMC Symposium, Tokyo, Japan, pp.125-130
2. Suganuma K. (2000) "Mechanism and Prevention of Lift-Off in Lead-Free Soldering", Proceedings of the iMAPS 33rd International Symposium on Microelectronics, Boston, USA, pp. 303-307
3. Vincent, J.H and Humpston, G. (1994) "Lead-Free Solders for Electronic Assembly", GEC Journal of Research, Vol 11 No 2, pp.76-89
4. Forsten, A. et al. (2000) "Development and validation of lead-free wave soldering process", Soldering & Surface Mount Technology, Vol 12 No 3, pp. 29-34
5. Trumble, B. (1998) "Get the Lead Out!", IEEE Spectrum, May 1998, pp. 55-60
6. UK Department of Trade and Industry (1999), Lead-Free soldering- An Analysis of the Current Status of Lead-Free Soldering, available from www.lead-free.org.
7. Nomura, S. et al. (2001) "Improvement of Wave Soldering Equipment for Lead-free Solder", Proceedings of the iMAPS 34th International Symposium on Microelectronics, Baltimore, USA, pp.541-546.
8. Danielsson, H. (1995), Surface Mount Technology with Fine Pitch Components, Chapman & Hall, London.
9. Harris, P.G. and Shaggar, K.S. (1998) "The role of intermetallic compounds in lead-free soldering", Soldering & Surface Mount Technology, Vol 10 No 3, pp. 38-52
10. National Center for Manufacturing Sciences (1997), Lead-Free Solder Project, Final Report, No 0401RE96