LEAD-FREE REWORK PROCESS FOR CHIP SCALE PACKAGES

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ABSTRACT

Legislation against the use of lead in electronics has been the driving force behind the use of lead-free solders, surface finishes, and component lead finishes. The major concern in using lead-free solders in the assembly and rework Chip Scale Packages (CSPs) is the relatively high temperatures that the components and the boards experience. Fine-pitch CSPs have very low standoff heights following assembly making inspection and rework of these components more difficult. One other concern pertinent to rework is the temperature of the neighboring components during rework. These issues, coupled with the limitations of rework equipment to handle lead-free reflow temperatures, make the task of reworking lead-free assemblies more challenging.

In this research endeavor, lead-free CSPs with tin-silver and tin-silver-copper solder balls were assembled and reworked. In addition, tin-lead CSPs were assembled and reworked as a baseline for comparison. Different rework sequences, redressing and fluxing techniques were evaluated. Post-assembly and post-rework analysis was done following assembly and rework using x-ray inspection, standoff measurements and cross-section microscopy. The reworked assemblies have completed 920 cycles of 0°C to 100°C Air-to-Air Thermal Cycling (AATC). No instances of time-zero electrical failures were found in post-rework tests. Useful guidelines for lead-free rework of fine-pitch components and CSPs in particular were developed and are presented in this paper.

Key words: lead-free, CSP, BGA, assembly, and rework.

INTRODUCTION

The rework of lead-free CSPs is similar to that of eutectic tin-lead CSPs. Both lead-free and tin-lead CSP rework includes the following steps [1]:

- Thermal profiling;
- Removal of defective component;
- Site re-dressing;
- Solder replenishment or flux application;
- New component placement;
- Reflow soldering.

One main issue associated with lead-free assembly and rework using lead-free solder alloys such as tin-silver and tin-silver-copper is the comparatively high melting temperatures (~220°C) of these alloys compared to the eutectic tin-lead alloy (183°C). The peak reflow temperatures for many lead-free solders are approximately 240°C-250°C as compared to tin-lead soldering temperatures of 210°C-220°C. This increase in reflow temperatures makes it necessary to re-evaluate the component and PCB materials for multiple reflows at lead-free temperatures. The assembly and rework processes need to be optimized to ensure that the integrity of the component and Printed Circuit Board (PCB) materials is not compromised.

In CSP rework, the PCB is subjected to multiple reflow cycles during component removal, site redressing, and soldering the new component. With the use of lead-free solders, the board is subjected to multiple thermal excursions at temperatures in the range of 240°C-250°C. These high processing temperatures potentially degrade the PCB materials and may lead to excessive warpage, delamination, solder mask discoloration, and damage. In addition, multiple reflow cycles during rework may result in the degradation of the PCB surface finish and result in the oxidation of the copper pads. This is typically observed in PCB pads with Organic Solderability Protection (OSP).

CSP ASSEMBLY

Three different packages were considered in this study. Two CSP packages utilized lead-free solder alloy balls and one had eutectic tin-lead solder balls. Table 1 gives the details of the components. Package A has non-solder mask defined component pads while Package B and C have solder mask defined pads on the component side. All the three packages are mechanically equivalent samples with daisy-chained structures obtained for evaluation purposes.

The test vehicle used for this study was a 62.0 mils thick multilayered FR-4 board with electroless Ni / immersion Au finish. The board contained assembly sites for three CSPs adjacent to each other. Three pad sizes of 11.0 mils, 13.0 mils, and 15.0 mils were located on the PCB. The electrical continuity and resistance of the three sites and each of the sites can be determined through a series of probe pads on the test vehicle.

Package	I/Os	Pitch (mm)	Solder Alloy	External Dimensions (mils)			Solder Ball Dia (mils)	Solder Ball Height (mils)
				Length	Width	Thickness		
A	46	0.75	63Sn/37Pb	306.0	220.0	34.5	13.0	10.0
B	46	0.75	96.3Sn/3.2Ag/0.5Cu	310.0	228.0	32.8	12.5	7.0
C	46	0.75	96.5Sn/3.5Ag	310.0	228.0	32.5	12.5	7.0

Table 1. Package Details

Twelve samples each of Package A, B and C were assembled. Package A was assembled using a Type 4 63%Sn/37%Pb paste with 90% metal content. Package B was assembled using a Type 4 95.8%Sn/3.5%Ag/0.7%Cu paste with 89% metal content. Package C was assembled using a Type 4 96.5%Sn/3.5%Ag paste with 89% metal content.

A 5.0 mil thick laser cut stainless steel stencil was used in printing the solder pastes. The print parameters were optimized to obtain consistent paste deposits, which measured approximately 4.0 mils in height for all the solder pastes. The paste deposits were measured using a laser profilometer. Figure 1 shows tin-silver (96.5Sn/3.5Ag) paste deposits on the test site.

The components were then placed on the test vehicle and reflowed. A single reflow profile with a peak of 245°C was used for the reflow soldering of both Package B and C. The difference in melting temperature of tin-silver and tin-silver copper is in the order of a few degrees Celsius and a single reflow profile was found to be sufficient for both solder alloys. This was validated by initial x-ray inspection and cross-sectional analysis of the assembled packages. Figure 2 shows the reflow profile used for the assembly of the lead-free packages. Table 2 gives the reflow parameters for both the eutectic tin-lead profile and the lead-free profile. It is evident from the reflow profiles that in lead-free soldering, the components and boards are subjected to longer and higher temperature excursions as compared to eutectic tin-lead soldering.

The assemblies were inspected using x-ray and cross-sectional analysis. There was no instance of bridging or opens observed. However, there were some small voids observed in a few of the assemblies. The presence of such small voids does not significantly affect the reliability of the solder joints [2]. No large voids or large numbers of small voids were observed during the x-ray inspection of the assemblies. Figure 3 shows an x-ray image of an assembled Package B. All the assemblies were electrically good and the resistance values were noted for comparison after rework. The standoff heights of the assemblies were measured using a laser profilometer.

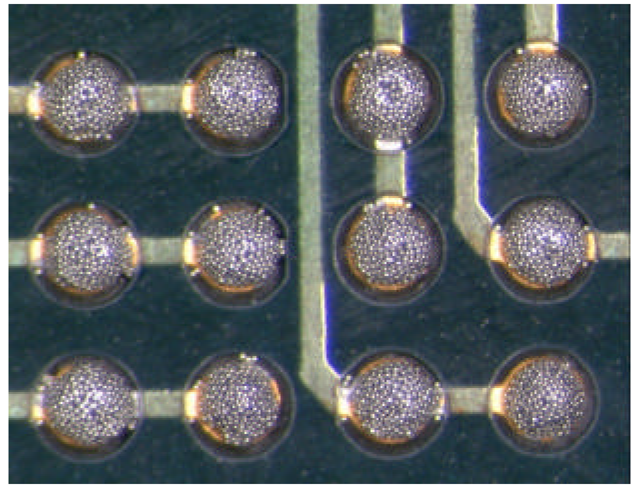

Figure 1. Solder Paste Deposits of 96.5Sn/3.5Ag Paste

Profile	Peak Temp	Time above Liquidus	Time to Peak
Tin-lead	221°C	72 seconds	256 seconds
Lead-free	246°C	81 seconds	390 seconds

Table 2. Assembly Reflow Parameters

CSP REWORK

The assemblies were reworked using a semi-automatic hot gas system. The rework system has two heaters, a top heater used for local heating of the component being reworked and an under-board heater (or bottom heater) used to heat the entire board to reduce the thermal gradient across the board. The independent pick-up tube is used for removing and replacing the components. The hot gas nozzle completely covers the component and rests on the surface of the PCB. The nozzle facilitates the flow of hot air under the component. The nozzle used for the rework of the CSPs measured 10.0 mm x 12.0 mm. Under board support is required at elevated temperatures. Four board supports were used to support the test vehicle. All the assemblies were reworked in an inert nitrogen environment.

Thermal Profiling

Thermal profiling is one of the most important steps in the rework of CSPs. An improper profile may result in the lifting of pads if the solder is not molten before removal is attempted. On the other hand, if the component is heated

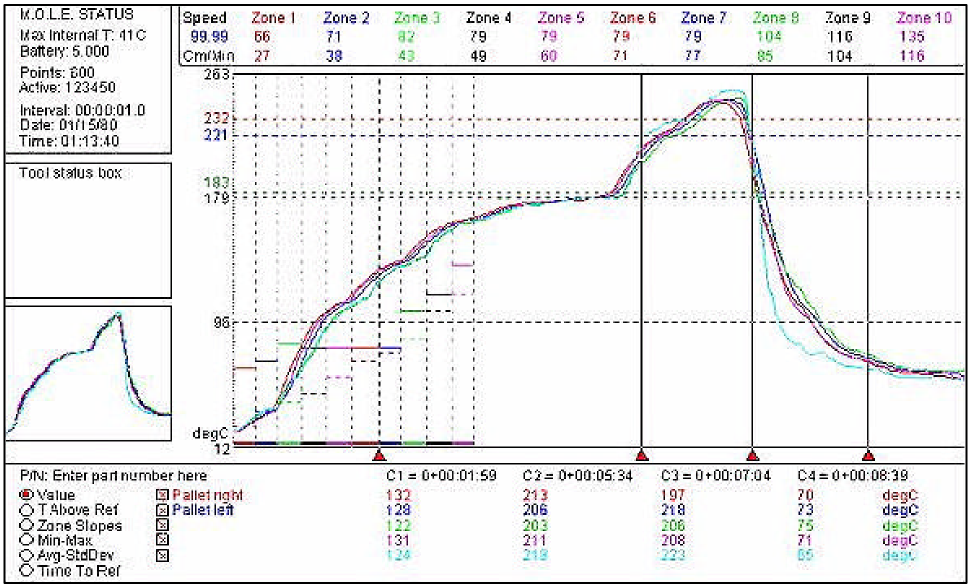

Figure 2. Lead-free Reflow Profile

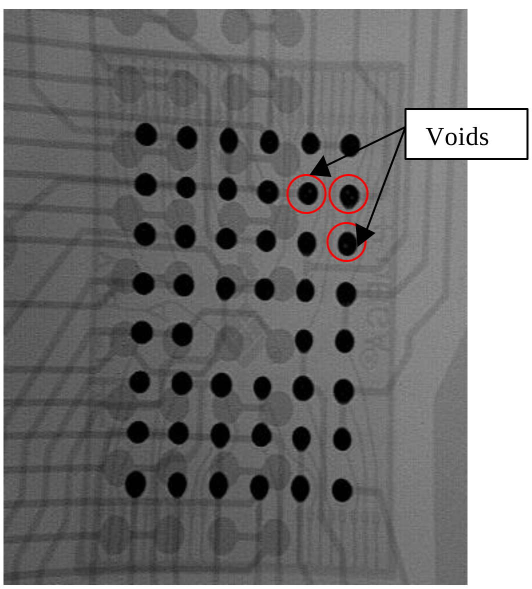

Figure 3. X-ray Image of Package B Assembly

extensively, damage can occur to surrounding components on the PCB. When replacing the CSP, a suitable thermal profile ensures that the component and board are not overheated and all the solder balls are reflowed [1].

The rework removal and replacement profiles are similar to the assembly reflow profile. The main challenge is to duplicate the assembly profile in the rework station. It is necessary to monitor the temperatures at critical locations on the assembly to ensure that the temperature of the solder joints, the temperature difference across the site, and the temperature of the adjoining components are monitored [3].

K-type thermocouples, 3.0 mils in diameter, were used for thermal profiling. To monitor the solder joint temperature of the component being reworked, holes were drilled in the PCB pads prior to assembly and then the components were assembled. Thermocouples were then inserted into these holes from the bottom side of the PCB and secured using UV-cure adhesive. Five thermocouples were used for thermal profiling. Figure 4 shows the locations of the five thermocouples and the rework setup. The locations of the five thermocouples are as follows:

- Center solder joint of the component being reworked;
- Corner solder joint of the component being reworked;
- Top of the component being reworked;
- Bottom side of the board under the component being reworked;
- Corner solder joint of the component adjacent to the one being reworked.

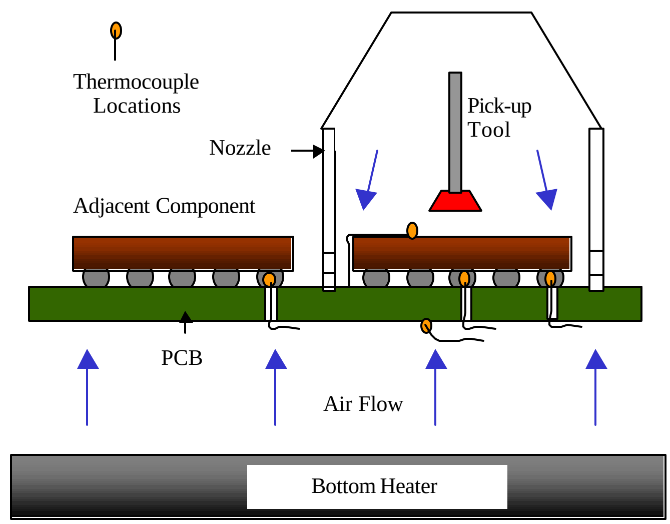

Figure 4. Thermocouple Locations

The assembly profile was developed using a ten-zone reflow oven. It is difficult to duplicate the profile used for assembly on the rework station due to different heating strategies and limitations of the rework station. Ramp rates were limited to 1.7°C/sec on the rework station. The rework profile developed on the rework station is shown in Figure 5. The reflow parameters of the profile developed on the rework station is given in Table 3.

The profile on the rework station was developed using the system software. The software is capable of adjusting the top and bottom heater temperatures such that the temperature measured by a particular thermocouple follows a certain profile. The thermocouple in the center joint of the component being reworked was used as the reference thermocouple. The software adjusted the top and bottom heater temperatures such that the center solder joint temperature followed the assembly reflow profile set by the operator. A profile that approximated the input profile settings was developed for the rework operation.

Profile	Peak Temp	Time above Liquidus	Time to Peak
Tin-lead	227°C	75 seconds	310 seconds
Lead-free	250°C	90 seconds	410 seconds

Table 3. Rework Reflow Parameters

It is evident from the comparison of the assembly and rework reflow parameters that there are significant differences between the two. Excess time above the liquidus temperature promotes excessive intermetallic growth. However, the rework station could not achieve the ramp rates required to duplicate the assembly reflow profile. The reflow profile in Figure 5 and the tin-lead rework reflow profile were used in the component removal and component replacement processes.

Component Removal

The assembled components were removed using the rework profiles discussed earlier. Package A was removed using the tin-lead rework profile and Packages B and C were removed using the lead-free rework profile. The software on the rework station offers a number of semi-automated sequences that can be employed to perform the main rework processes. The "Remove Zero Force" is one such sequence, wherein after the component to be removed, the nozzle, and pick-up tube are aligned manually using the prism vision system, the rework station executes a predetermined sequence of operations for component removal. The nozzle comes down, covers the component, and rests on the surface of the PCB. The top and bottom heaters heat the rework site as per the rework profile developed for that particular component. At the end of the reflow stage of the profile, when all the solder joints are molten, the pick-up tube descends and picks up the component.

After the CSPs were removed, the rework sites were studied and the height of the residual solder was measured. There was no instance of any pad rip-off (or pad lifting) or solder mask damage. The residual solder height ranged from 4.1 mils to 10.8 mils with a mean of approximately 6.0 mils. The values are the result of the measurement of 192 pad locations taken over all three package types. There was no apparent trend observed that differentiated the tin-lead and the lead-free solder residues.

Site Redressing

The residual solder on the reworked site has to be removed to obtain a flat surface for the placement of the new component. The lack of a flat surface can result in open joints, odd-shaped joints, and component displacement during soldering of the new component. Hence, it is important that a consistent amount of solder be left on the pad and the surface is flat for successful component replacement.

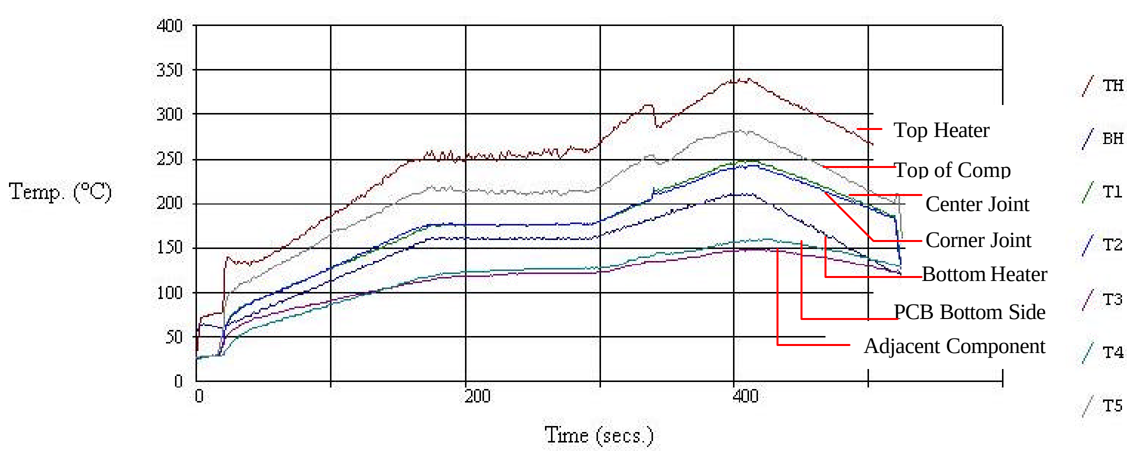

Figure 5. Rework Reflow Profile

Site redressing is the most operator-dependent step in the rework process [1]. Some of the redressing techniques require the operator to be highly proficient to avoid any damage to the PCB. Some of the common issues encountered during site redressing are solder mask damage and pad rip-off [4]. Two site redressing techniques were evaluated, the solder iron and braid method and the use of a roughened copper coupon.

The soldering iron and braid technique is crude and highly operator dependent. A flux impregnated copper braid is placed on the residual solder and heated using a soldering iron. The residual solder melts and wicks up to the copper braid thus leaving a thin layer of solder on the PCB pads. Care should be taken to ensure that the integrity of the board is not compromised in any way. The width of the solder wick and the tip of the soldering iron are to be chosen carefully. Inappropriate size of the solder wick and soldering iron tip may damage the solder mask and rip the pads off the PCB [5]. In the copper coupon method, a copper coupon roughly the size of the site is sanded using a 240-size grit paper and placed manually on the site with the residual solder. Flux is applied to both the site and the copper coupon. The removal sequence is run on the rework machine using the reflow profile developed for removal and replacement. When the residual solder melts, the solder wets to the copper coupon and is removed with the coupon. This method of site redressing is more repeatable and less dependent on the operator. However, the amount of residual solder left on the site after redressing is more than the amount left by the soldering iron and braid method. A drawback of this method is that the board has to undergo an additional reflow cycle as compared to the soldering iron and wick method.

The soldering iron and braid method was performed on different boards before employing the method for this study. However, many of the sites redressed using this method showed some signs of damage. The most common damage that occurred was to the solder mask.

The copper coupon method of redressing was found to be more repeatable and did not result in any solder mask damage. The wetting of the lead-free residual solders to the copper coupon was not as good as the wetting of the tin-lead solder. The peak top heater temperature was increased to 340°C from the previous 325°C to promote wetting. A significant increase in the amount of residual solder removed was observed, but it was still less than the tin-lead solder. Initially, the copper coupon was shifting inside the nozzle due to its small size and the gas flow. The “Zero Force Removal” sequence was modified to a “Force Removal” sequence in which the pick-up nozzle applies a force of 50.0 grams, and holds the coupon in place until the end of the soak stage. At the end of the soak stage, the pick-up tube releases the coupon and moves up by 40.0 mils. This holds the coupon in place and successfully removes a significant portion of the residual solder.

The solder remaining on the pads after redressing using the two methods was measured using a laser profilometer. The height of the solder remaining on the pads ranged from 0.4 mils to 2.2 mils with a mean of approximately 1.1 mils in the case of the soldering iron and braid method. The copper coupon redressing technique left behind a greater quantity of solder, ranging from 1.7 mils to 3.0 mils with a mean of approximately 2.4 mils. Figure 6 shows the height of solder over the PCB surface before and after redressing for the tin-silver-copper alloy.

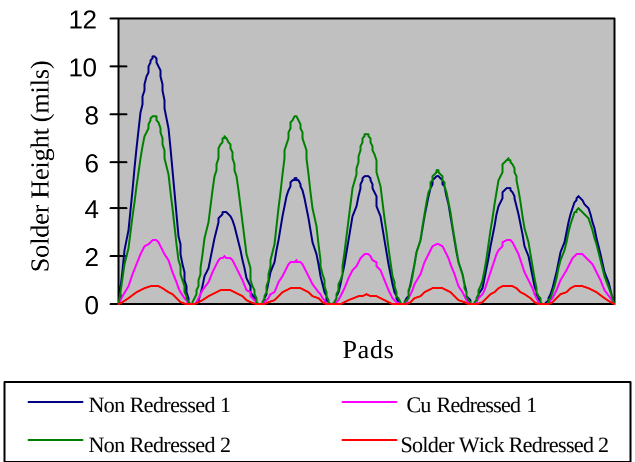

Figure 6. Height of Solder Residue Before and After Redressing (in mils)

Flux Application and Component Replacement

The replacement of the component is a very challenging task. The CSPs are very light in weight and can move inside the nozzle during the soldering process resulting in defects. In addition, the use of a flux-only replacement process may not offer the amount of tackiness required to hold the component in place during the soldering process. The top heater airflow was reduced from 100 SCFH (Standard Cubic Feet per Hour) to 50 SCFH (low airflow) in an effort to keep the component from moving during the soldering process. However, even with the use of low airflow rates, solder joints were not formed. Flow rates lower than 50 SCFH could not be obtained on the rework station. Hence, modifications to the “Zero Force Place Release Reflow” sequence of the rework station was modified to a “Force Place Release Reflow” sequence.

The application of flux to the component involves the screening of a thin layer of tacky flux on to a flat metal plate using a “doctor” blade. The gap in the “doctor” blade determines the thickness of the flux film on the metal plate. The component to be replaced is then placed in the thin film of flux. The corresponding PCB site is fluxed with the same tacky flux using a thin brush. The component is then picked up from the metal plate by the pick-up tube and aligned with the PCB site. After final alignment using the prism vision, the pick-up tube comes down and places the component on to the PCB. As a modification to the original sequence, the pick-up tube was made to exert a force of 50.0 grams on the component and hold it in place until the end of the soak stage. At the end of the soak stage, the pick-up tube releases the component and moves up by 40.0 mils and the rest of the reflow cycle continues. At the end of the reflow cycle, the component is soldered on to the PCB. This modification to the original replacement sequence worked well with all the packages. A flux depth approximately one-half the solder ball height was used for the replacement process. A flux depth of 4.0 mils was used for Packages B and C, and 5.0 mils for Package A.

In the modified "Force Place Release Reflow" sequence, the pick-up tube releases the component and moves up before the solder starts reflowing. The continuous application of force during the reflow stage of the profile will affect the shape of the solder joint formed and promote solder bridging, hence it was ensured that the pick-up tube broke all contact with the component after the soak stage. The presence of the pick-up tube over the component during the pre-heat and soak stages may also restrict the self-centering capability of the solder alloy [6].

X-ray Inspection and Cross-sectional Analysis

The reworked samples were visually inspected and then probed for electrical continuity. All the reworked samples were electrically good and had resistance values similar to the assembled samples. The reworked samples were x-rayed to observe any bridging or excessive void formation. The reworked assemblies showed good solder joint formation and no significant voids were observed. Figure 7 shows the x-ray image of the reworked assembly of Package B.

Three of the reworked samples of each package were cross-sectioned to study the shape of the solder joint, the wetting of the solder around the pads, and the standoff. The cross-sections represented one non-reworked sample, one sample reworked using the soldering iron and braid redressing technique, and one sample reworked using the copper coupon redressing technique for each package. The standoffs measured using the cross-sections were compared to the standoffs measured using the laser profilometer. Table 4 shows the standoff measurements of the non-reworked and reworked packages measured using the laser profilometer and cross-sections.

The laser profilometer readings are the average of nine packages with four scans per package. The laser profilometer readings were lower than the standoffs measured using the cross-sections. The standoff obtained after rework was less compared to the standoff prior to rework due to the flux-only rework process employed. The standoff of the lead-free packages reworked using the solder iron and wick site redress method were approximately 0.5 mils to 0.8 mils lower than the packages reworked using the copper coupon site redress method.

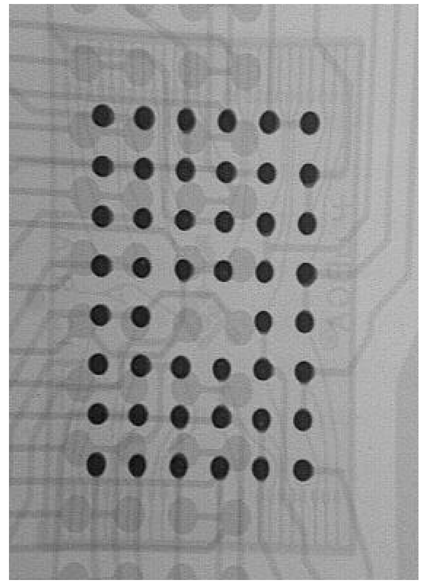

Figure 7. X-Ray Image of Reworked Packages B

	Package A		Package B		Package C	
	C/S	LP	C/S	LP	C/S	LP
Assembly	4.70	4.6	5.33	5.18	5.21	5.05
Rework (Solder Iron)	-	-	4.19	3.91	4.43	3.98
Rework (Copper Coupon)	4.07	4.04	4.89	4.70	4.91	4.78

Table 4. Standoff Measurements in mils (C/S: Cross-sections, LP: Laser Profilometer)

The cross-sections of the non-reworked packages showed good pad wetting and collapse of the solder joints. However, some instances of voiding were observed. Figure 8 shows the cross-section of a non-reworked Package B (tin-silver-copper) solder joint.

The cross-sections of the reworked packages also showed good wetting around the pads. However, except for Package A, which had taller solder balls of eutectic tin-lead, the lead-free packages did not show the same extent of collapse as compared to the non-reworked assemblies. In addition, the cross-sections of the reworked lead-free packages showed some degree of misalignment of the component to the PCB pad. This may be due to the modified component replacement process that was employed. However, this misalignment was not observed in cross-sections of Package A. The packages reworked using the copper coupon site redress method showed better solder joint shape than the packages reworked using soldering iron and wick site redress method. This may be attributed to the fact that the amount of solder left on the PCB pads after site redressing is significantly more in the case of copper coupon redressing. Figure 9 shows the cross- section of a Package A solder joint reworked using the copper coupon site redress method. Figure 10 shows the cross-section of Package B, reworked using the soldering iron and wick method. Figure 11 shows the cross-section of Package C, reworked using the copper coupon site redress method.

In all the three package assemblies, Ni-Sn intermetallics were observed. The nickel-tin intermetallic layer thickness showed significant growth after rework. These intermetallics, characterized by their brittleness, can adversely affect the solder joint properties [7]. Figure 12 shows the intermetallic layer of a reworked Package C (tin-silver) solder joint.

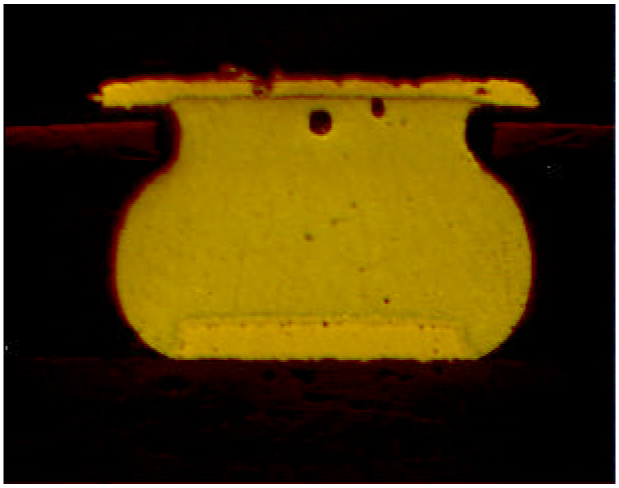

Figure 8. Non-reworked Package B Solder Joint

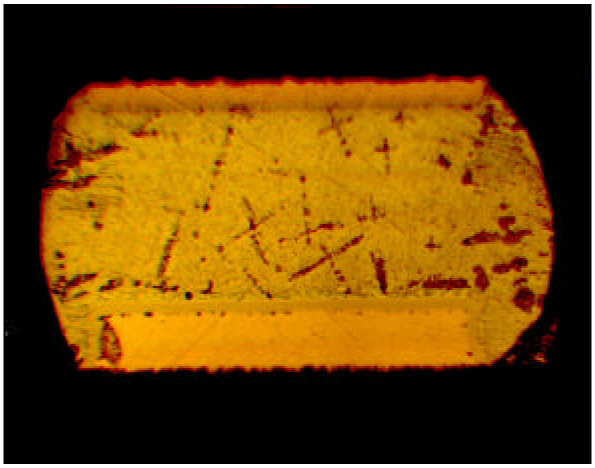

Figure 9. A Reworked Package A Solder Joint

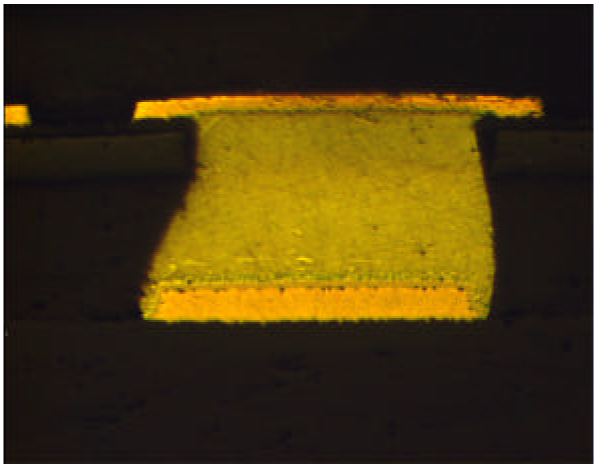

Figure 10. A Reworked Package B Solder Joint (Soldering Iron and Wick Site Redress)

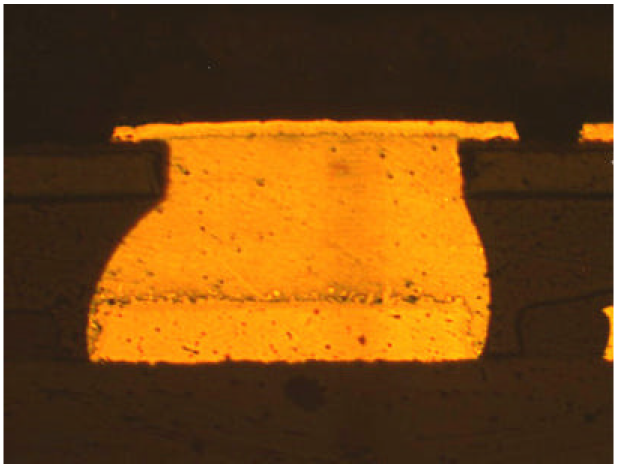

Figure 11. A Reworked Package C Solder Joint (Copper Coupon Site Redress)

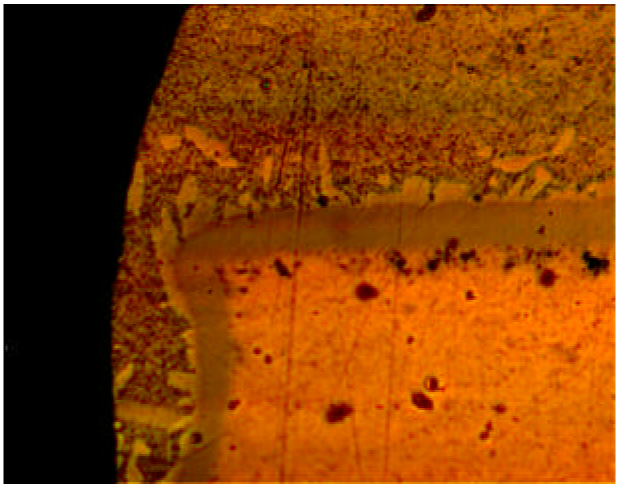

Figure 12. Ni-Sn Intermetallic Layer, Package C (Copper Coupon Site Redress)

RELIABILITY

The reworked samples are at present in Air-to-Air Thermal Cycling (AATC). The thermal cycle is a 20-minute cycle from 0°C to 100°C with 5-minute ramp and soak times. The reworked samples have completed 920 thermal cycles without any failure. Further results are awaited.

CONCLUSIONS

The fine-pitch nature of CSPs, the low standoffs, lead-free processing temperatures, and the inconsistency associated with the rework process make the rework of lead-free CSPs a challenging task. The capabilities available on the rework machine being used for lead-free CSP rework are very important. The efficiency of the heating process is dependent mainly on the heating system of the rework station and the nozzle design. In depth evaluation of the rework station is necessary prior to actual operation [8]. The main capabilities that a rework station should possess for lead-free rework should include [5]:

- The ability to handle lead-free processing temperatures;
- Efficient heating systems (top heater and under board heater);
- A vision system that can accurately place fine-pitch components;
- Hot gas airflow control;
- Flexible software for thermal profiling and editing rework sequences.

Thermal profiling is very important and efforts to measure the temperature at the solder joints should be undertaken. Component removal is a relatively simpler process. Ample board support should be provided and any damage to the PCB site should be prevented.

Site redressing is a crucial process in lead-free rework. The use of the soldering iron and wick method resulted in solder mask damage. The copper coupon redress method proved to be superior in that there was no damage to the PCB site. The main advantage associated with copper coupon redressing is that the step is no longer entirely operator dependent and is a repeatable process. However, it involves subjecting the assembly to an additional reflow cycle, which may negatively affect the integrity of the PCB site and the reliability of the assembly due to excessive intermetallic formation.

Modifications to the replacement process sequence were required to prevent the component from shifting during reflow. This modification may have adversely affected the self-centering capability of the component and hence explains the mis-registered solder joints observed in a few cases. The components being reworked often require to be baked at 125°C to remove the excess moisture and prevent any form of delamination or popcorning during reflow. The baking period depends on the moisture sensitivity level of the package. Since the CSPs used in this experiment were classified as non-moisture sensitive (JEDEC Level 1), baking prior to replacement was not performed.

No instance of bridging or electrical failure was observed. The cross-sectional analysis of the reworked samples showed good pad wetting in all cases, but the lead-free packages showed reduced collapse. The copper coupon site redress technique resulted in better solder joint shape than the soldering iron and braid method. The standoff post-rework reduced by 0.8-1.2 mils in the case of the soldering iron and braid site redress method and 0.3-0.6 mils in the case of the copper coupon site redress method.

There was an increase in intermetallic thickness after the rework process. This may be detrimental to the reliability of the reworked packages. The thermal cycling reliability results of the reworked packages are awaited.

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