Challenges in Manufacturing Reliable Lead-Free and RoHS-Compliant Components

WP-CHMFGRELLDFR-2.0 White Paper

The push for lead-free or RoHS-compliant products is resulting in significant changes in packaging materials. Manufacturers of electronic equipment require materials that consistently withstand peak reflow temperatures of 240°C to 260°C. Reflow soldering at these extreme temperatures, especially after extended moisture exposure, introduces several challenges that must be solved to produce reliable products. This white paper covers some of the modifications necessary and Altera® packaging solutions available to meet reliability and usability requirements for lead-free and RoHS-compliant products.

Introduction

Plastic packages use various organic compounds for molding and die attach that have formulations consisting of an epoxy resin, filler particles, and other additives. The epoxy resin in equilibrium with the ambient atmosphere absorbs a small percentage of moisture, which turns into saturated steam during the printed circuit board reflow process. The extreme pressure from the steam and the drop in flexural strength of the mold compound and die attach materials can result in catastrophic failures of the packages. Typical failure modes of packages include encapsulant cracking, substrate cracking, severe package deformation, and delamination of one or more material interfaces. The problem is further exacerbated by the use of very large dies, which are typical of Altera devices.

This white paper covers some of the modifications necessary to meet reliability and usability requirements for lead-free and RoHS-compliant products. The test results are used to demonstrate the reliability of plastic quad flat pack (PQFP), thin quad flat pack (TQFP), ball-grid array (BGA), FineLine BGA (FBGA), and flip-chip BGA components. The results are related to the different approaches taken for different package types to successfully qualify the components to the higher reflow temperatures. For some package families, the assembly processes were improved and optimized to ensure the reliability to lead-free reflow temperatures. For some other components, new packaging materials were used to overcome the limitations of existing packaging materials.

While lead-frame and wire-bond packages can be provided as lead free, currently Altera flip-chip packages are RoHS compliant. In all cases, the BGA package balls are Pb-free. For the rest of this document, the term *Pb-free* is used to refer to the BGA solutions provided with lead-free package balls.

This white paper also presents effects of the reflow temperature on the moisture ratings of a representative member of each package family. In addition to the traditional responses such as popcorning and interfacial delamination during reliability testing, the importance of looking at the effects of absorbed moisture on the component warpage at elevated temperatures is also discussed. Absorbed moisture is known to increase package warpage. Higher warpage for large BGA components at Pb-free reflow temperatures requires monitoring at the rated moisture-sensitivity level (MSL), because it impacts the manufacturability and reliability of final assembly.

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Altera Pb-Free Solutions

Altera's Pb-free solutions are motivated by the requirements being imposed on the semiconductor and electronics industry to reduce or eliminate the use of lead. The European Waste from Electrical and Electronic Equipment (WEEE) Directive proposed restrictions on the use of Pb in electronics by 2006. In Japan, the ministry of international trade and industry has set a maximum amount of lead for automobiles (excluding batteries). While there is no legislation mandating the reduction in lead in Japanese electronic devices, the industry is actively marketing select electronic devices as lead free or RoHS compliant.

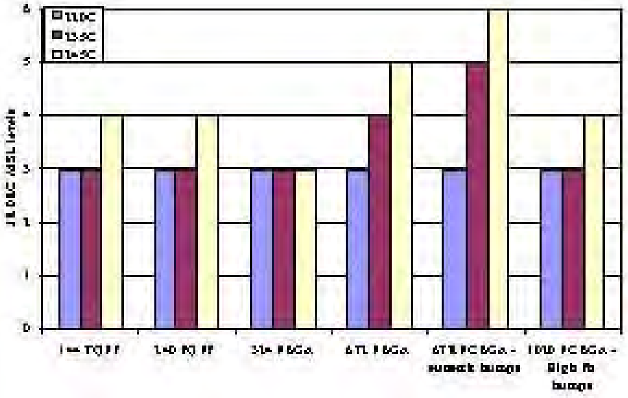
Based on these proposals and directives, Altera has proactively committed to working with its suppliers to offer Pb-free packaging solutions. There are several competing options available for Pb-free finishes. Working with assembly sub-contractors, Altera has evaluated packages with matte tin (Sn) and/or Sn-2% copper (Cu) lead finish for leaded packages, and Sn-3-4% silver(Ag)-0.5% Cu solder balls for Pb-free BGA packages. Additional testing on pre-plated nickel (Ni)/palladium (Pd) finish is also being pursued as a possible alternative finish. For the leaded packages, 12µ-thick Sn or Sn-2% Cu plating is used on standard lead frames. In addition to the change in the lead finish, the thermal robustness of the package was improved by selecting appropriate materials and processes to allow for the higher reflow temperature compatibility required for assembling boards with Pb-free solder pastes.

The qualification data gathered demonstrates the technical capability to assemble most devices offered by Altera with process and/or material modifications. Some devices tested had very large die sizes that posed unique challenges. Not all available assembly process and materials strategies from the assembly sites were easily portable because of the very large die sizes for typical Altera devices. Various approaches were used to make the components reliable to Pb-free reflow temperatures, including the use of new materials and changes in the processes to achieve better reliability.

Verification of Moisture Sensitivity Levels

The standard Sn-Pb components without any additional modifications have been tested to the standard JEDEC surface mount simulation test to different MSLs. The components were tested to different peak reflow temperatures: 220°C, 235°C, and 245°C. While almost all components meet MSL 3 at 220°C, some of the larger components meet only MSL 4 or worse for higher temperatures (see Figure 1).

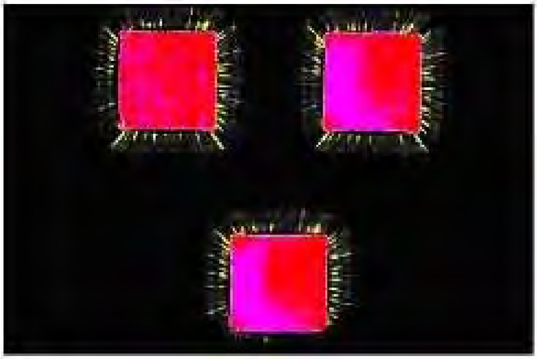
Figure 1. MSL Ratings for Standard Sn-Pb Components Tested to J-STD-020, for Different Peak



Reflow Temperatures

For peak reflow temperatures of 245°C, testing on the larger components (and larger die sizes) resulted in die surface delamination (Figure 2) at MSL 3. Degradation in moisture sensitivity was observed on each package type to different extents. Smaller TQFP, PQFP, and FBGA packages were able to withstand 245°C reflow.

Figure 2. Die Surface Delamination Observed on the Large TQFP, PQFP, and FBGA Packages Without Material/Process Modifications



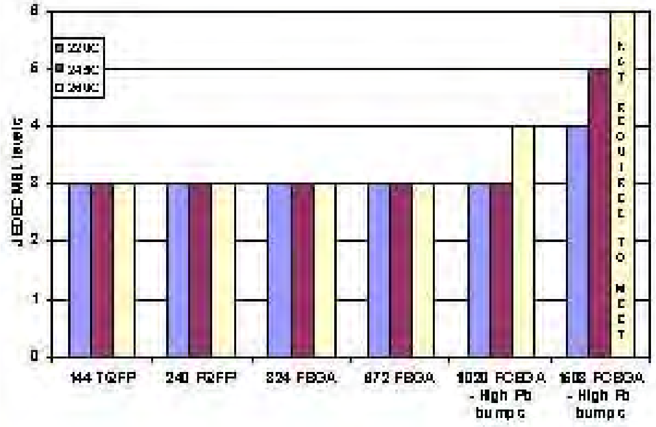
In the case of flip-chip BGAs, underfill delamination and solder smearing were observed when the solder bump composition was eutectic. When high-Pb bumps were used, no underfill delamination was observed to 245°C on all components 35 mm on a side and smaller. Figure 3 shows the underfill delamination and solder spreading/smearing observed after preconditioning with a peak reflow of 245°C when assembled with eutectic solder bumps.

Figure 3. Underfill Delamination and Solder Spreading/Smearing Observation with a Preconditioning Peak Reflow of 245°C when Assembled with Eutectic Solder Bumps

To improve manufacturability, Altera prefers to achieve MSL 3 rating for all components. To achieve this rating, some modifications and different approaches were necessary for each package type. Requirements from various industry groups call for qualification of the components to peak reflow temperatures of 245°C to 260°C, depending on the component size.

For TQFP and PQFP packages, a new mold compound and a new die-attach material had to be used to avoid package failures due to interfacial delamination and popcorning. Part of the improvement comes from the lower moisture absorption rates for the new materials. In addition, mechanical simulation models indicate that these materials result in lower warpage for the components through the entire reflow temperature range, thereby resulting in lower stresses at all interfaces. Using the new material set, a JEDEC MSL rating of 3 can be achieved for all TQFP and PQFP packages. In all cases, the standard lead frames were used, and the Pb-free plating was matte Sn or Sn-2% Cu. Figure 4 shows MSL ratings with improvements to the material and assembly process flow. Most components meet MSL 3 to 260°C peak reflow temperature.

Figure 4. MSL Ratings with Improvements to the Materials and Assembly Process Flow

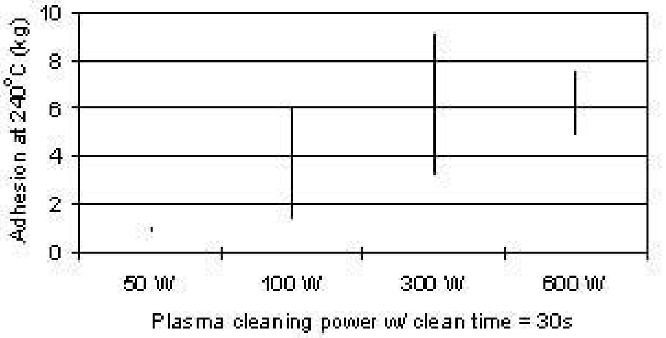


In the case of all FBGA packages, the mold compound and die attach used for the standard Sn/Pb assembly could be used with some minor variants. All devices tested in 19 mm or smaller FBGA packages devices could meet JEDEC MSL 3 for reflow temperatures of 245°C. However, for larger FBGA packages and for peak reflow temperatures above 245°C, die surface delamination was observed and additional modifications were required. All devices had a polyamide coating on the die surface. In the absence of the polyamide coating, the MSL rating of 3 would not be possible because of the very large die sizes.

Two process changes were made to improve the adhesion of the mold compound to the die surface. Optimized pre-mold bake and die-surface plasma cleaning steps were included to improve the adhesion of the mold compound to the die surface. It is believed that the surface roughening needs to be optimized to ensure good adhesion. With these improvements, a JEDEC MSL rating of 3 was possible for all Altera devices in a FBGA package.

Some published reports indicate that a AUS5 solder mask is not rated to the peak reflow temperatures required for Pb-free packages. For that reason, substrates were verified with AUS5, AUS303, and AUS308 solder masks. During testing, no failures related to the solder mask were observed for all tested combinations. Figure 5 shows data from a sub-contractor showing improvement in the mold compound adhesion to the roughened die surface (with polyimide coating) as a function of the plasma cleaning power for constant time.

Figure 5. Data from Sub-Contractor Showing Improvement in the Mold Compound Adhesion

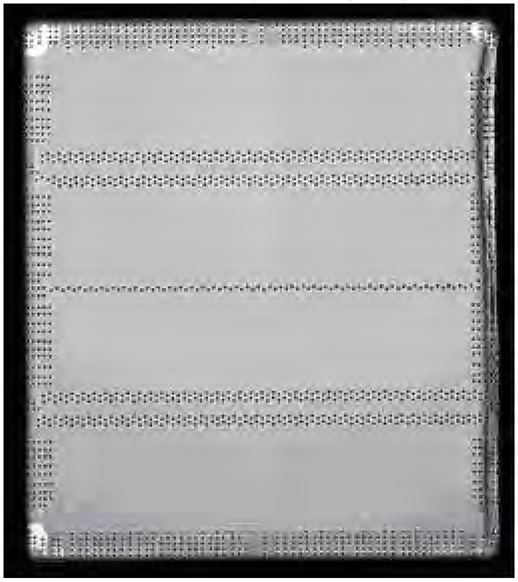


Flip-chip BGAs are by far the most difficult packages to achieve JEDEC MSL 3. Even if no failures were observed after preconditioning, often the components failed after 500 cycles of temperature cycling condition B stress. The typical failure mode was underfill delamination at the die corners. The use of 20-mm and larger die sizes with 6000 or more solder bumps adds additional complications. The selection of the correct choice of materials is important to achieve MSL requirements while keeping the coplanarity of the components within manufacturable levels.

During initial testing, it was obvious that eutectic Sn/Pb solder bumps could not be used for reflow temperatures exceeding 225°C because the hydrostatic pressures in the underfill cause the molten eutectic solder to smear along the surface of the die. This problem is so severe that the components can only survive the reflow in dry condition. For this and other reasons, Altera chose to use high-Pb bumps and eutectic pre-solder for all products.

The overall composition of the bumps meets the European requirement of >85% Pb in the solder bump joints to be exempt for the time being. The softer nature of the high-Pb bumps means that the tensile loading at the solder joints has to be minimized. Otherwise, the cyclic loading could result in pumping effects at the high Pb to eutectic Sn/Pb interface, thereby causing voiding and solder joint opens. Figure 6 shows the die corner delamination seen on large die flip chips with the old bill of materials. This failure mode was seen both for 220°C and 245°C reflow.

Figure 6. Die Corner Delamination Seen on Large Die Flip Chips with the Old Bill of Materials



In order to minimize the tensile and shear stresses at the solder joints, a new set of materials was chosen for the underfill, thermal compound, and lid attach adhesive. Simulation models were used to identify most optimal material properties. The materials chosen for building the Pb-free (external only) flip chips would allow rating most of the flip-chip BGAs to JEDEC MSL 3. For the very large die (23 mm on a side) and package sizes (40-mm body), only JEDEC level 5A can be achieved at 245°C at this time, even with improvements.

Is 260°C Peak Reflow Temperature Necessary?

In addition to the standard component-level testing, components for each package type were mounted on PCBs at Solectron Corporation to verify the solder joint reliability using a ten-zone production reflow oven. The oven was purged with nitrogen during the reflow process, and the reflow profile was optimized for each device separately. Kester 256-LF, an alkaline noclean flux, was used for mounting all three devices. Components were mounted both with and without a nitrogen ambience to estimate the lowest temperature at which the components can be mounted. The reflow profile used for surface mount of 780 pin flip-chip BGA package includes a peak reflow temperature of 236°C, devices were mounted in air, and a 70-s time above the melting point.

Figure 7 shows the reflow profile used for the surface mount of a 780-pin flip-chip BGA package. In addition to the standard board assembly, a rework assembly was also studied for the Pb-free components. *(1)* The peak temperature required for the board assembly of the large components can be as low as 235°C even when mounted in air.

Figure 7. Reflow Profile Used for Surface Mount of 780-Pin Flip-Chip BGA Package

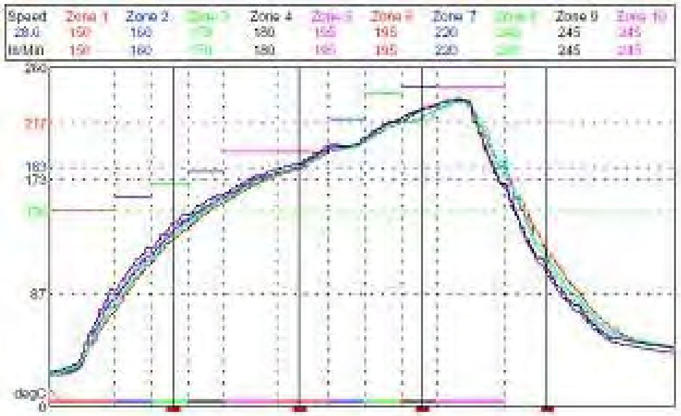
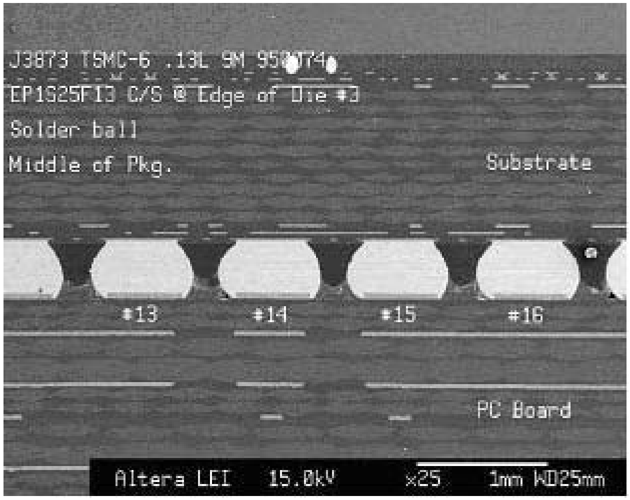


Figure 8 shows the cross-section of a 780-pin flip-chip BGA device, showing good collapse of the Pb-free solder joints for a peak reflow temperature of 235°C. From the cross-section, it is clear that large components can be mounted at temperatures as low as 235°C. Even assuming a variation of about 15°C across a large board, it is feasible to mount a wide range of components at peak temperatures not exceeding 250°C at any point on the board, so requiring all components to be reflowed at 260°C puts an enormous and unnecessary burden on component suppliers.

Figure 8. Cross-Section of a 780-Pin Flip-Chip BGA Device Showing Pb-Free Solder Joints



Whisker Growth on Leaded Packages

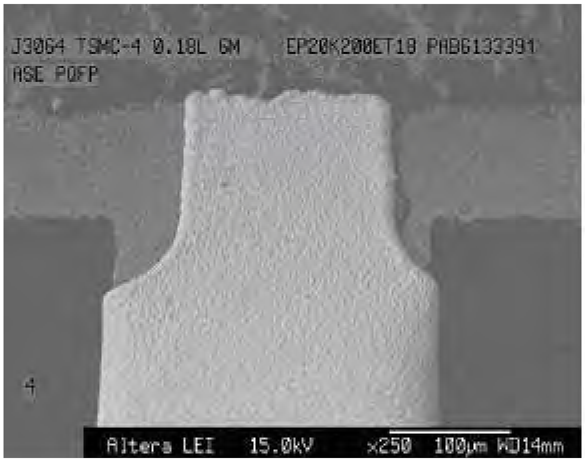
Several reports have been published on pure tin finishes being susceptible to the spontaneous growth of single crystal structures known as *tin whiskers*. Tin whiskers can cause electrical failures, ranging from parametric deviations to catastrophic short circuits. Although the tin whisker phenomenon has been reported and studied for decades, it is still a potential reliability hazard, particularly when equipment is subject to long-term storage before use. There have been several attempts to develop a reliable test to accelerate the growth of these whiskers, but, so far, all results appear to be applicable for a specific plating process.

In the absence of a test method for acceleration of the tin whisker growth, Altera chose to look at components stored at room temperature for extended periods of time to verify the tin whisker growth phenomenon. The same five units were observed after assembly, 30-days storage, 180-days storage, and 450-days storage. In addition to inspection of components stored at ambient conditions, inspection was performed on five components after completion of the reliability tests (preconditioning, biased humidity, and autoclave). In all cases, 20 leads were checked at 20X, 100X, and 250X magnification.

Figure 9 shows a matte Sn finished lead (the coarse grains give the finish a matted appearance), and Figure 10 shows a Sn-2%Cu finished lead, both for devices stored at room temperature for 450 days and with plating thicknesses of 12µ. No whisker growth was observed in any of the cases. From the observations, it appears that by controlling the plating process, the lead-frame material, and the plating thickness, it is possible to avoid tin whiskers.

Figure 9. High Magnification View of a Matte Sn Finished Lead on a PQFP Device

Figure 10. High Magnification View of a Matte Sn-2%Cu Finished Lead on a PQFP Device



Component Warpage at Pb-Free Reflow Conditions

Component warpage plays a critical role in the manufacturability of very large BGA components. A paper presented by Shook et al. (2) shows that ingressed moisture increases the warpage even further. In this case, all of the large BGAs used flip-chip interconnections.

Altera studied the warpage behavior of large flip-chip devices with and without subjecting the packages to moisture loading. Flip-chip BGAs typically have the highest warpage at room temperature and tend to flatten out at reflow temperatures. There was approximately 10% difference observed in the measured warpage at room temperature between the dry and moisture-soaked devices. At reflow temperatures the warpage continued to be higher for the device soaked in moisture. Subsequent C-SAM analysis showed no delamination in the package. In addition, components have reduced warpage upon bake and are indistinguishable from the dry components. These observations are consistent with the observations made by Shook et al. However, in no case was the warpage above the internal specification of 8 mils.

Figure 11 shows the warpage measurements on a 33-mm package after 192 hours of moisture soak at 30°C and 60% RH. The peak warpage of 5.6 mils was observed at room temperature (top). At reflow conditions the warpage was stable at ~2 mils (bottom). No delamination was observed. Similar results were observed on a 27-mm wire-bonded FBGA package.

Figure 11. Warpage Measurements on a 33-mm Package after 192 Hours of Moisture Soak at 30°C and 60% RH

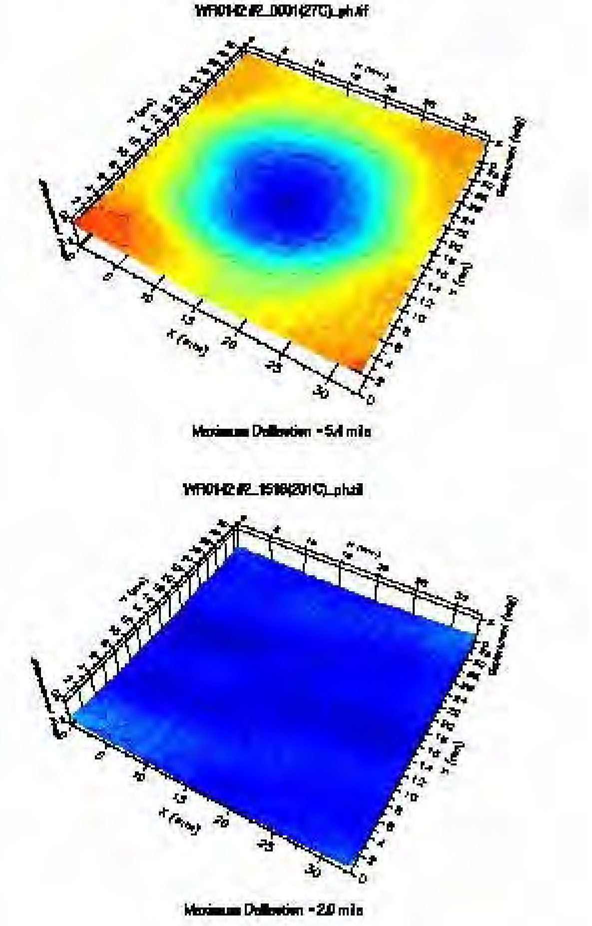
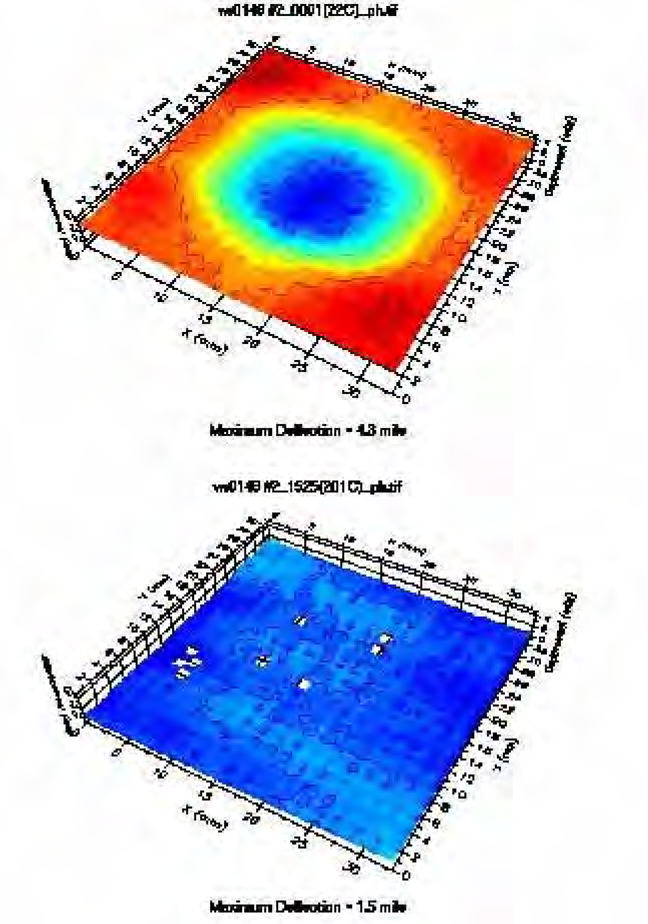


Figure 12 shows the warpage measurement on a 33-mm package in the dry condition. The peak warpage of 4.3 mils was observed at room temperature (top). At reflow conditions, the warpage was stable at ~1,5 mils (bottom). Similar results were observed on a 27-mm wire-bonded FBGA package.

Figure 12. Warpage Measurements on a 33-mm Package in the Dry Condition



Conclusion

Several years of Pb-free research have concluded that there is no drop-in solution to replace Pb-Sn solder in electronics industry. However, the industry has accepted the use of eutectic Sn-Ag-Cu for solder balls and either matte Sn or Sn-2%Cu for lead finishes. Altera tested components with these finishes to confirm that most components can be manufactured and assembled onto boards reliably.

This white paper shows that with suitable modifications of the component assembly processes and materials, it is possible to manufacture reliable TQFP, PQFP, FBGA, and flip-chip BGA package families. In addition, the requirement of 260°C reflow temperature is excessive and boards can be assembled and reworked without exceeding a peak reflow temperature of 250°C. Also, work performed on warpage on large flip-chip BGAs shows that moisture ingress may play a role in determining the MSL of the components.

References

1. *Board Assembly and Rework of Large Flip-Chip Ball Grid Array Devices*, Sam Yoon et al., Apex 2004.
2. *Impact of Ingressed Moisture and High Temperature Warpage Behavior on the Robust Assembly Capability for Large Body PBGAs*, R. L. Shook et al., pp.1823, ECTC 2003, May 27-30, 2003, New Orleans.

Document Revision History

Table 1 shows the revision history for this document.

Table 1. Document Revision History

Date	Version	Changes
July 2010	2.0	■ Changed title from *Challenges in Manufacturing Reliable Lead-Free Components* to *Challenges in Manufacturing Reliable Lead-Free and RoHS-Compliant Components* ■ Text edits.
January 2004	1.0	Initial release.