

Effects of Temperature Uniformity on Package Warpage

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Abstract

Knowing how package warpage changes over temperature is a critical variable in order to assemble reliable surface mount attached technology. Component and component or component and board surfaces must stay relatively flat with one another or surface mount defects, such as head-in-pillow, open joints, bridged joints, stretched joints, etc. may occur. Initial package flatness can be affected by numerous aspects of the component manufacturing and design. However, change in shape over temperature is primarily driven by CTE mismatch between the different materials in the package. Thus material CTE is a critical factor in package design. When analyzing or modeling package warpage, one may assume that the package receives heat evenly on all sides, when in production this may not be the case. Thus, in order to understand how temperature uniformity can affect the warpage of a package, a case study of package warpage versus different heating spreads is performed.

Packages used in the case study have larger form factors, so that the effect of non-uniformity can be more readily quantified within each package. Small and thin packages are less prone to issues with package temperature variation, due to the ability for the heat to conduct through the package material and make up for uneven sources of heat. Multiple packages and multiple package form factors are measured for warpage via a shadow moiré technique while being heated and cooled through reflow profiles matching real world production conditions. Heating of the package is adjusted to compare an evenly heated package to one that is heated unevenly and has poor temperature uniformity between package surfaces. The warpage is measured dynamically as the package is heated and cooled. Conclusions are drawn as to how the role of uneven temperature spread affects the package warpage.

Introduction

Thermal warpage metrology tools are designed around the concept of emulating the thermal and physical conditions seen by a part or parts under test within the tool's own heated environment. Most commonly these tools are used to mimic the thermal conditions of a reflow profile. Warpage tests are performed over temperature on many different types of samples (packages, PCBs, sockets, connectors, wafers) within these types of thermal warpage measurement tools. Here the focus is on surface mount components, specifically BGAs, which are tested in the study. At the time of this writing, BGAs and LGAs are the only devices with industry standards defining allowable warpage levels through reflow temperatures. JEITA (ED-7306) [1] defines allowable warpage levels for BGAs and LGAs based on pitch and ball height in the case of BGAs. Similarly, JEDEC (JESD22-B112A) [2] defines the methodology for measuring thermal warpage of BGAs, which is supplemented by JEDEC SPP-024A [3], providing allowable warpage levels for BGAs based on ball pitch and ball diameter.

As BGA packages are heated, it is understood that the different materials within the BGA will expand laterally at a value that is consistent with their material properties, namely coefficient of thermal expansion (CTE). Common BGA construction includes materials with different CTE values. As the different materials are physically attached to one another, this varying lateral expansion is constrained and the CTE mismatch between the materials can cause out-of-plane shape change, or warpage. While CTE mismatch is commonly considered for warpage, the temperature differentials within the package can have similar effects on warpage. This temperature differential can be seen to some extent during the reflow process, but is affected by a number of variables. Taking the example of a large BGA with heat sink, commonly the top of the package may see higher temperature than the ball side. The actual temperature differential for a component within a reflow oven is not studied here. However, since common practices for thermal warpage measurement do not include in-situ measurements within reflow ovens, it is important to understand the effect of temperature differentials on warpage within warpage metrology equipment itself. The paper by Anselm [4] led to some of the basis for pursuing this study and discusses this potential offset between warpage metrology tool and actualities of production in regards to temperature differential. Therein production conditions are cited to have 5-10°C temperature differential and a 16°C differential is seen in the warpage metrology tool. [4] Using the latest warpage metrology equipment, temperature differentials can be more effectively controlled, allowing for a warpage comparison with temperature differentials at approximately 20°C and ≤5°C.

The Anselm paper [4] also poses questions about the parallelism or tilt of the sample to the board during reflow. An argument is made that looking at warpage of the component is not enough to understand surface mount defects such as head-in-pillow (HiP). Along with warpage, the relative tilt of the sample relative to the PCB should be tracked. Specifically, "Parallelism of

a component to the board can be affected by the center of gravity of a device or... variation in the wetting behavior of the solder joints during reflow.” [4] Later in the paper, “...wetting of the paste can place a non-uniform force distribution on the component. X/Y thermal gradients in the PCB due to Cu balance issues, routing techniques or component asymmetries can result in solder paste quadrants of a component to wet first resulting in a non-uniform wetting force on the device. If this were to occur then it is feasible that the wetting force can overcome the weight of the center of gravity causing one corner be pulled down while another corner is lifted out of a paste deposit during reflow.” [4] In this study temperature differential is used to cause solder ball collapse originating on one side of a component. The differential created in this study is exaggerated from that seen in a reflow oven on the “leading edge” of reflow. The intent is to use this study as a proof of concept to show optical measurement and reflow emulation techniques that could be used to measure and quantify tilt and top side warpage of a component during reflow heating. Practical testing of a component tilt in reflow would require real world components, boards, solder paste, stencils for paste application and a thermal warpage measurement tool capable of realistic reflow emulation.

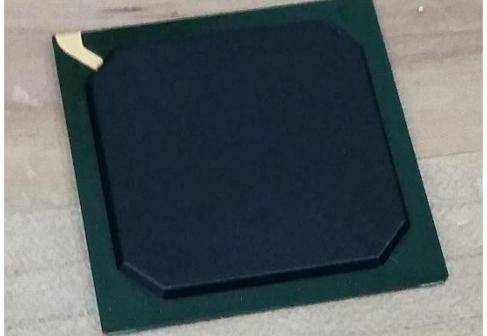
Test Methodology

BGA Warpage and Temperature Uniformity Study

The goal of this test is to measure warpage of BGA samples under different top to bottom temperature uniformity conditions.

Two BGA samples are used in the study as described in Table 1. The samples are described only generically to protect customer proprietary information. A total of 4 samples were originally considered in the study, but only 2 sets of samples showed statistically relevant information in relation to variation in warpage due to temperature uniformity differential.

Table 1 – BGA Samples

Generic Name	Dimensions (mm)	Solder Balls	Sample Type	Quantity Tested	Top-Side Image
27mm BGA	27x27x1.7 (0.3mm thick substrate)	0.5mm Diameter / 0.8mm Pitch	PBGA	9 samples	
35mm BGA	35x35x1.7 (0.4mm thick substrate)	0.6mm Diameter / 1.0mm Pitch	PBGA	9 samples	

Testing parameters generally followed guidelines within JESD22-B112A. [2] In addition, the following parameters were kept as controls through the test:

- Parts were measured with ball side facing up, with no solder balls
- All samples were “fresh,” having not seen a reflow cycle
- No sample prebake was used
- Sample surfaces were painted with white high temperature paint
- Data was measured from 30°C to 250°C and back to 30°C
- Sample support consisted of a clear, 2mm thick, production Quartz glass plate
- Shadow moiré measurement technique
- Average heating rate was approximately 0.5°C/sec though slightly slower in Δ20°C reflows and slightly faster in Δ5°C reflows

Temperature uniformity and sample type were the only independent variables for the test. Sample type is already covered in Table 1. The test plan for temperature uniformity was to use a multi-zone IR heating oven including inner and outer bottom heater zones, as well as an independently controlled top heater. The system and oven including top IR heaters are a patent pending concept which uses a combination of short wave IR bulbs and dark ruby quartz tubes to filter out visible light and drive IR energy through the grating glass of the shadow moiré setup to the sample top. The goal was to reach approximately a 20°C temperature differential at the 250°C max reflow temperature in the “non-uniform” reflow and maintain a $\leq 5^\circ\text{C}$ total sample temperature variation for the “uniform” reflow. Achieving the non-uniform reflow was accomplished by disabling the top heating zone, focusing heat on the central bottom heater, and using a short working distance between sample and grating. The uniform reflow was achieved by using the top heating zone, focusing heat more toward the outer bottom heater, and using a “lower while heating” feature to increase sample to grating working distance until measurement.

Results for the warpage study are quantified using 3S Warpage as well as 3D renderings of the surface for qualitative analysis. 3S Warpage is a newer gauge choice defined with magnitude equal to coplanarity and sign determined in two steps. [5] First, the Signal Strength of the surface is calculated.

$$\text{Signal Strength} = \frac{ex^2 + fn^2}{4 * \text{Coplanarity}} \quad (1)$$

where $m = \#$ of pixels in x and $n = \#$ of pixels in y, and e and f are respectively the x^2 and y^2 coefficients of a 2nd order polynomial fit of the surface. If Signal Strength is less than 25%, then the shape is considered transitional, meaning that it cannot be clearly called positive or negative in direction. In this case, the 3S Warpage is reported as TX, where X is the coplanarity. If Signal Strength is greater than 25%, then the sign is determined using the same method as JEDEC Full-field Signed Warpage, using the same variables as equation (1).

$$-(em^2 + fn^2) \quad (2)$$

Here, the numerical value of the equation is thrown away and only the sign is kept.

BGA Tilt and Solder Ball Collapse

The goal of this test is to validate a testing approach for measuring both topside warpage and tilt of a BGA sample that is being soldered to a PCB. Additionally, the test serves as a point of reference for the effect of lateral temperature variation on the collapse of solder balls past their liquidus temperature. The study does not factor in other mechanical forces that would realistically play into BGA reflow assembly but instead focuses on tilt as a result of temperature variation.

The 35mm BGA described in Table 1 is used for the study. In this case the sample is tested with solder balls on and in a “live bug” or balls down position. One BGA is used for tracking temperature and two samples are tested for warpage and tilt across two different thermal runs and fresh sample sets. The BGA is placed on a piece of 2mm thick, Production Quartz glass with the top of the glass painted black. The black painted glass surface serves two purposes. The black paint is used to absorb IR energy, thereby heating the glass and conducting through to the solder balls of the BGA. Additionally, the glass serves as a relatively flat and thermally stable reference surface that acts as a rather flat “PCB”. Neither component surface is painted or prepared in any way, to be more realistic to a production scenario.

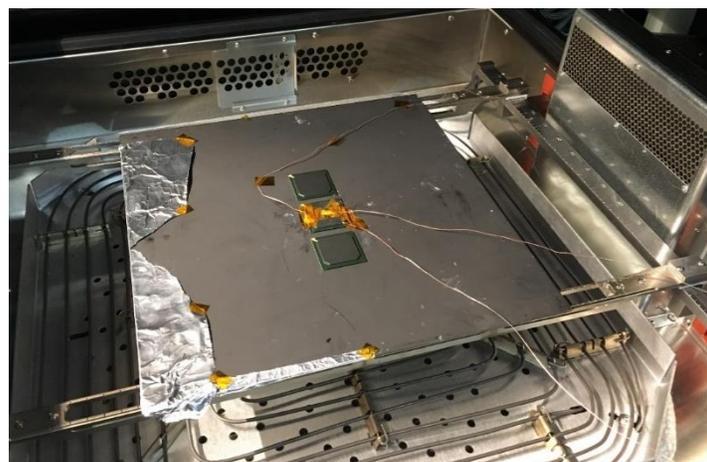


Figure 1 - Setup for Tilt and Solder Ball Collapse Test

Figure 1 shows an image of the setup for this test. To create a lateral non-uniformity of approximately 20°C, a piece of tinfoil was attached to the underside of the black glass so that it covered approximately ¼ of the portion of the glass directly beneath

the BGAs. This tinfoil served to block the transfer of IR energy to one side of the test BGA, thereby creating a temperature differential between the two sides. Heat was supplied from the central lower heater and the top heater, and the output of the lower heaters was set to about 55% of maximum power. This low power provided a controlled degree of non-uniform lower heating. Focusing the lower heating on the center also served to maximize non-uniformity, since the IR heating was applied directly to the bottom of the black glass. Meanwhile, the top heaters supplied equal heating to the top of the part, preventing the lateral non-uniformity from becoming excessive. The balance of these factors, especially oven power and tinfoil coverage, was determined via repeated uniformity testing with a dummy part. As Figure 1 shows, thermocouples were placed on three locations on the part during both initial dialing and actual testing. Two thermocouples on the sides of the part measured the key lateral temperature differential, while a third in the center ensured that the differential was expressed as an even gradient through the part.

The shadow moiré technique used for data acquisition is not traditionally used for surfaces with sudden discontinuities in height, as would be seen between the glass surface and BGA topside. However, software advancements have allowed interpretation of this data set as a whole. In this case the glass surface will be used as the reference plane and the topside of the BGA will be plotted for both warpage and tilt of the surface over temperature. Techniques using shadow moiré and discontinuous surfaces are described further in “Measuring Die Tilt Using Shadow Moiré Optical Measurements; New Techniques for Discontinuous and Semi-Reflective Surfaces” [6] and will not be fully defined here.

Results for the BGA top side shape relative to the reference glass are quantified by providing 3S Warpage and calculating the angle of the component surface relative to the substrate surface. The equation for calculating the angle between the component and substrate is fairly simple geometry:

$$Tilt\ Angle = \sin^{-1}\left(\frac{a-b}{L}\right) \tag{3}$$

where a is the z-value at the higher of the diagonal end points, b is the z-value at the lower of the diagonal end points, and L is the length of that diagonal based on user specified image dimensions. Only the surface on the molded top of the BGA will be used for 3S warpage and angle calculation, even though the glass is used as a reference plane. Data will also be presented via 3D surface renderings and horizontal centerline 2D plots. Finally, in order to separate the surface warpage from the tilt of the BGA relative to the glass, a 1st order polynomial surface fit is applied to the data sets. The 1st order polynomial data will primarily show the relative tilt of the surface.

BGA Warpage and Temperature Uniformity Study Results

The temperature profiles for the 5°C and 20°C top to bottom temperature uniformity reflow profiles are shown in Figures 2 and 3 below. The top/bottom temperature uniformity of these reflow profiles was optimized with a couple of preceding reflow profile runs. Figures 2 and 3 are typical examples of the reflow profile runs. Thermocouple Process 1 is attached to the molded side of the BGA and Process 2 is on the ball side, which is on top of the part in this dead bug setup.

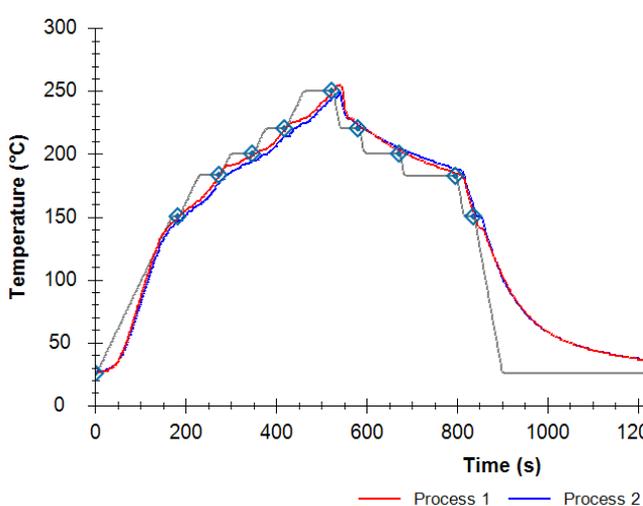


Figure 2 – Reflow w/ 5°C Top/Bottom Uniformity

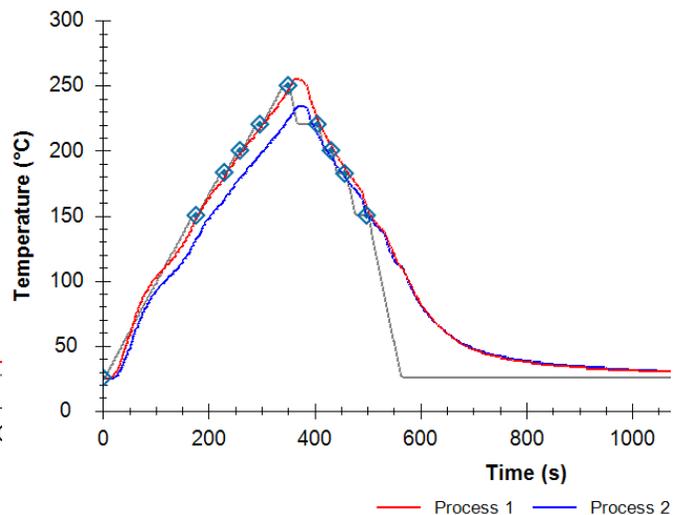


Figure 3 – Reflow w/ 20°C Top/Bottom Uniformity

Actual temperature uniformity values used in the study for measurements at the peak temperature were between 3°C and 7°C for the “5°C” run and gradually more uniform at the lower temperature points.

Similarly, for the “20°C” run the temperature non-uniformity at peak temperature was as high as 24°C also showing lower variation at lower temperatures, particularly on the cooling side of the profile. The temperature uniformity was certainly variable through the full run, maximizing near profile peak, so the 5°C and 20°C labels are used for simplicity in discussing the results.

27mm BGA Warpage Results

3S Warpage Values for the 5°C and 20°C runs are shown in below in Figures 4 and 5.

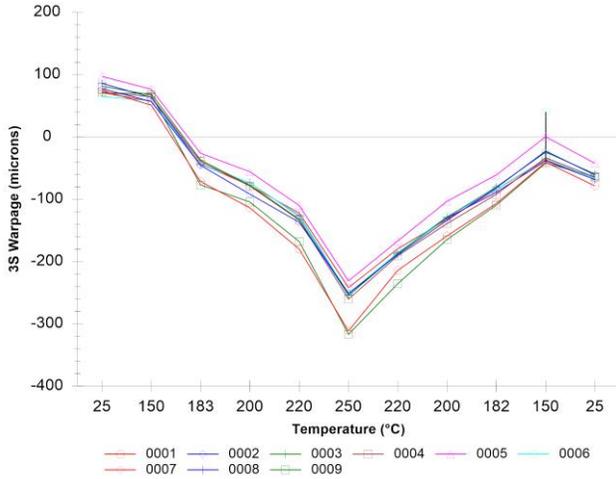


Figure 4 – 3S Warpage at 5°C Uniformity

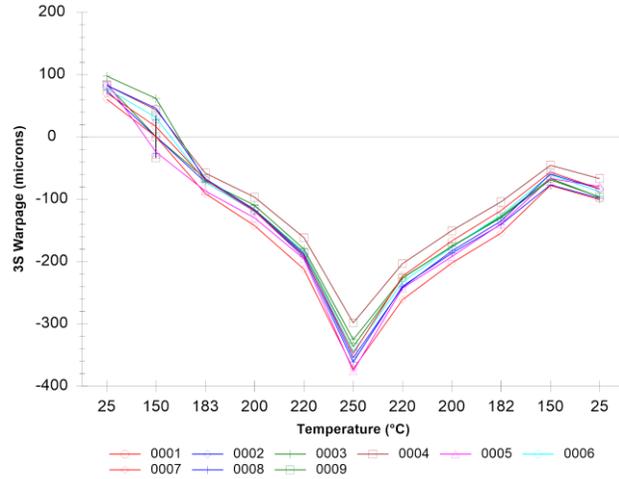


Figure 5 – 3S Warpage at 20°C Uniformity

As expected some sample to sample variation is seen, thus data is also summarized by averaging coplanarity at each temperature across all 9 samples used in each test. Figure 6 shows this data.

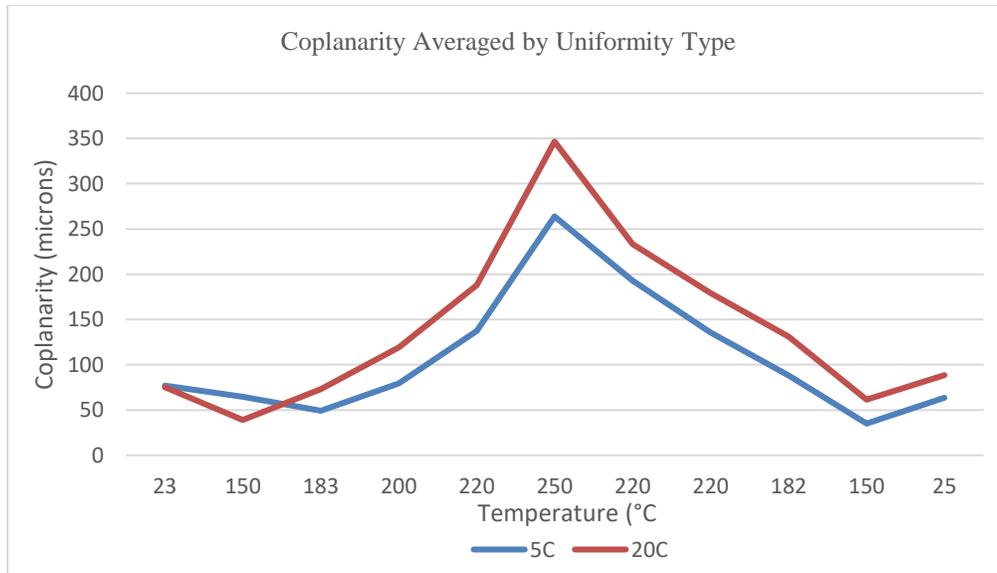
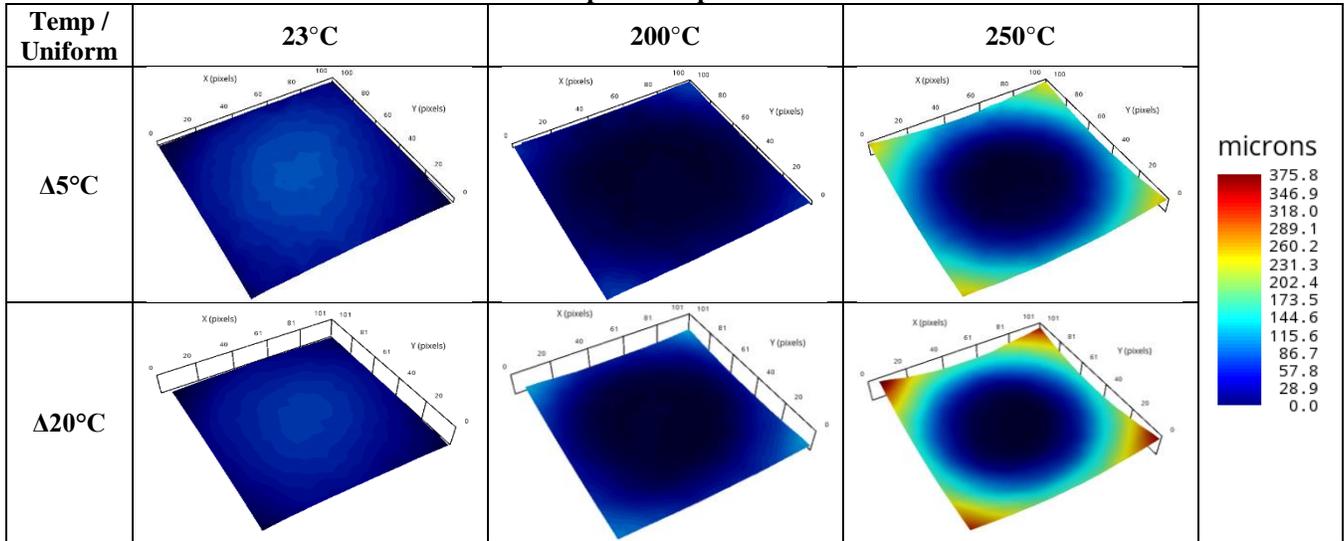


Figure 6 – Average Coplanarity for each 27mm BGA Reflow Run

Showing 3D renderings of all samples, across all temperature, and profiles types is impractical for this report. However, representative examples of 3D warpage shapes are summarized in Table 2.

Table 2 – 3D plot examples of 27mm BGA



35mm BGA Warpage Results

3S Warpage Values for the 5°C and 20°C runs are shown in below in Figures 7 and 8.

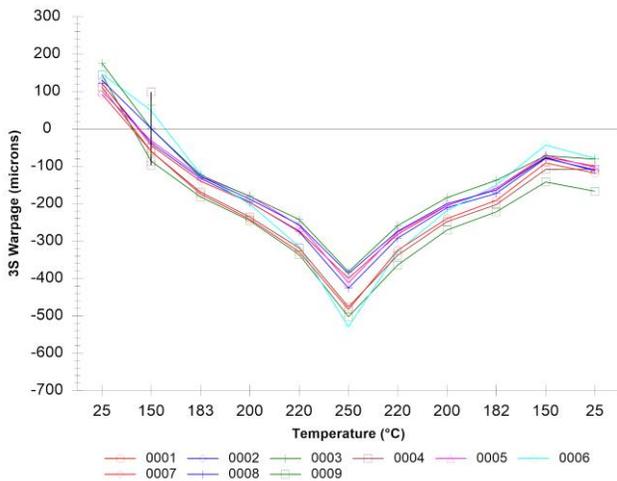


Figure 7 – 3S Warpage at 5°C Uniformity

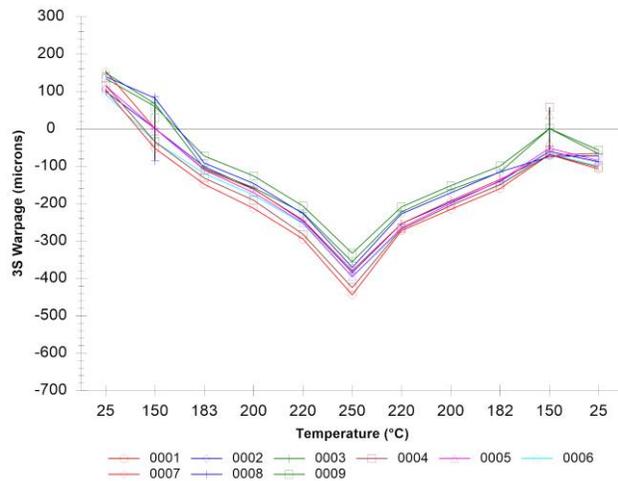


Figure 8 – 3S Warpage at 20°C Uniformity

As before some sample to sample variation is seen and data is summarized by averaging coplanarity at each temperature across all 9 samples in Figure 9.

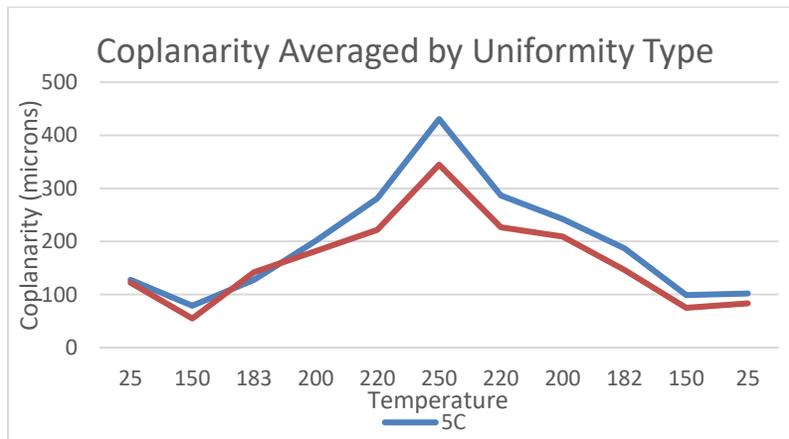
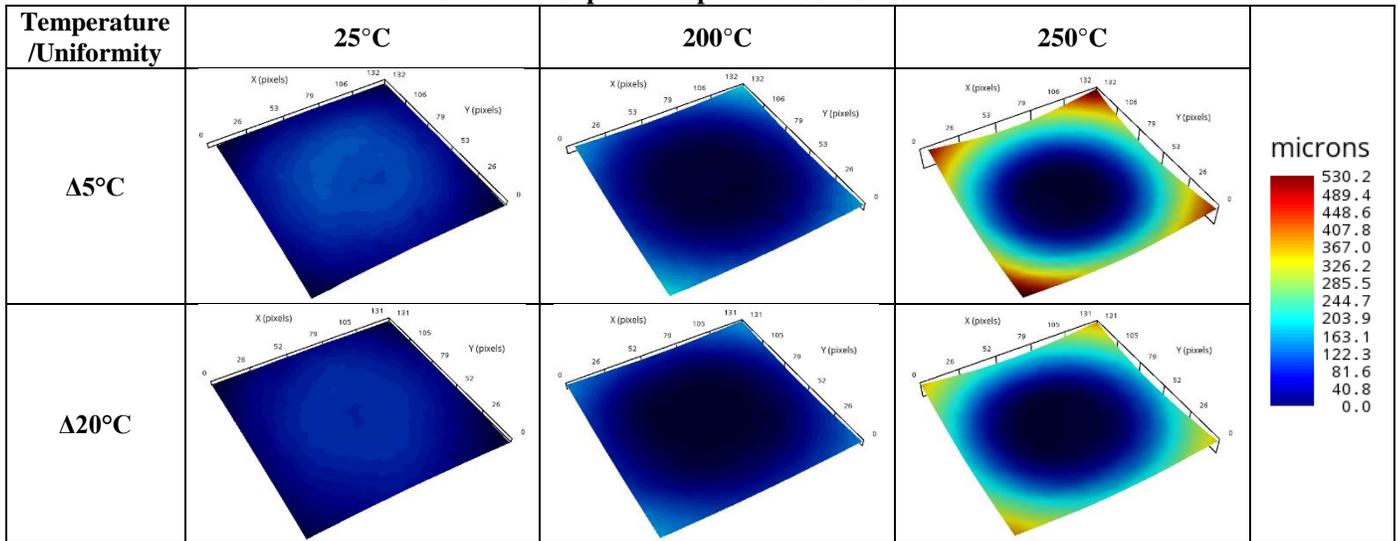


Figure 9 – Average Coplanarity for each 35mm BGA Reflow Run

Representative examples of 3D warpage shapes are summarized in Table 3.

Table 3 – 3D plot examples of 35mm BGA



BGA Warpage and Temperature Uniformity Study Discussion

The most intriguing detail of the warpage results is that while the package construction appears similar between the two parts externally and warpage values follow a similar trend, the effects of top to bottom temperature uniformity work in completely opposite ways for the two samples. For the 27mm BGA the higher temperature variation leads to higher warpage levels at maximum temperature. However, for the 35mm BGA the complete opposite happens in that warpage levels are highest when the temperature is more evenly balanced from top to bottom. Though some sample variation is seen the overall trend is consistent in both samples to conclude that the two thermal conditions influence warpage in both negative and positive ways, depending on the sample.

In an attempt to further understand the differences in warpage conditions for the two samples a test of surface strain and CTE is run for the top (molded side) and bottom (substrate side) of both the 27mm and 35mm BGAs. Here the balanced heating ($\Delta 5^\circ\text{C}$) was used. This measurement is done using the Digital Image Correlation (DIC) technique, which is commonly used for calculating material CTE by measuring surface strain over temperature. Figure 10 shows CTE over temperature of both mold and substrate side of the two sample types.

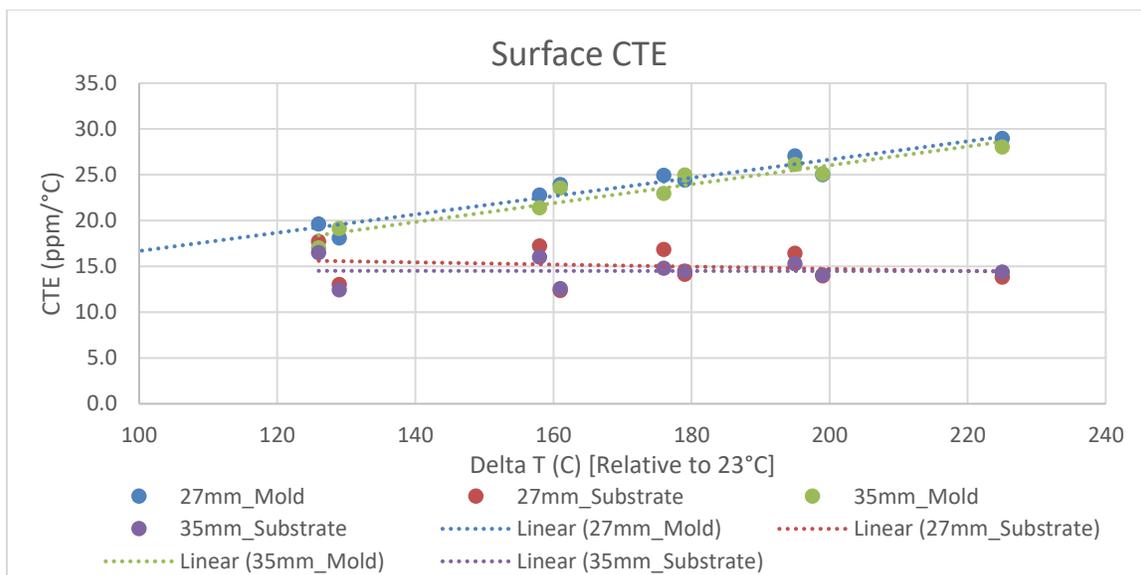


Figure 10 – CTE values over temperature of molded and substrate surfaces of 27mm and 35mm BGAs

A linear regression is added to each data set. Also note that the x-axis is in temperature differential from room temperature and not absolute temperature. The conclusion drawn from Figure 10 is that the two samples have no tangible differences in CTE of their corresponding surfaces. The molded surface expands more and gets hotter, thus differences in overall expansion are greater when temperature difference is also greater. Differences in lateral expansion lead to warpage and as such the conclusion from the DIC results and possibly FEA simulation may be that even heating will cause lower warpage. Actual warpage testing proved this is not always that case. The comparison of CTE of mold versus substrate for the package is an oversimplification of the expansion of the entire sample as both contain other materials including a silicon die with a low rate of expansion, known to be around 3-3.5ppm/°C in these temperature ranges. [7]

In search of answers for differences in the package warpage, one of each sample was cut in half to find the package die. Both packages were single die with similar thickness. However, the 35mm BGA had a die that was nearly twice as large in X and Y. It is unclear whether the die size or other differences in package construction led to the different warpage behaviors.

BGA Tilt and Solder Ball Collapse Results and Discussion

The proof of concept for topside measurement of BGAs during reflow is provided by a combination of these results and previous studies on concepts of using shadow moiré data for discontinuous surfaces. [6] Using the setup from Figure 1, shadow moiré images are taken of the BGA in a live bug position resting on black glass. In this case the black glass is acting as a flat PCB surface. Traditionally, shadow moiré is unable to measure neither the height change between the BGA molded area and surrounding BGA substrate, nor the height change between the surrounding BGA substrate and black glass. However, new software approaches [6] based on some initial height estimates can be used to measure the height of all of the sudden height changes while using the shadow moiré technique. The molded surface with surrounding glass is shown as measured with shadow moiré in Figure 11. The approximate heights of the molded surface are confirmed with a Digital Fringe Projection (DFP) technique in Figure 12, which has the inherent ability to measure step heights, but has limits to larger field of view in the iteration used in this testing. [8] In this case the step height from molded surface to surrounding glass was measured as 2234 microns by shadow moiré and 2174 microns for DFP on two different samples. For the purpose of measuring relative tilt of the data with shadow moiré, the absolute height is actually not required. The DFP measurement is more for a sanity check.

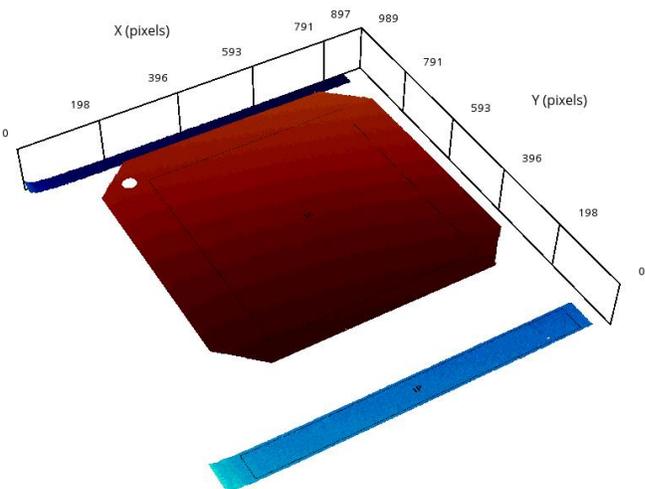
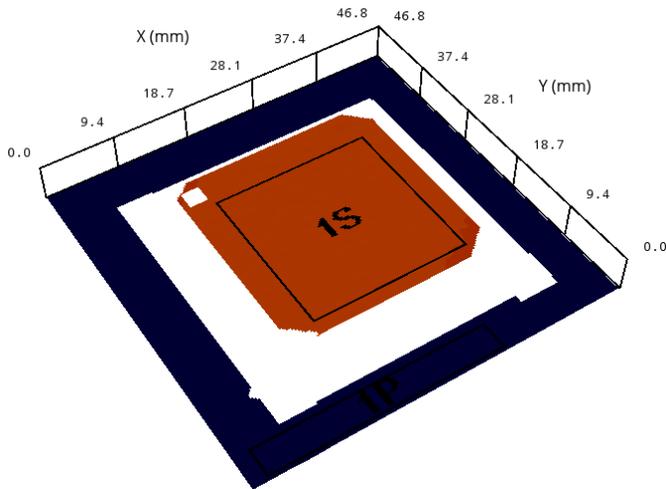


Figure 11 – Molded surface and surrounding glass, SM

Figure 12 – Molded surface and surrounding glass, DFP

The results of measuring the molded top surface on glass were primarily dominated by warpage of the package itself and not the settling or tilting of the package on the glass. Keep in mind that the overall movement or tilt of the package may be more significant in actual soldering situations. The two thermal runs each include two samples designed for even top and bottom heating but higher temperatures on the right side of the sample versus the left. The controlling thermocouples were swapped from left to right between the first and second profile in order to have the sample reach higher overall temperatures and see the effects on tilt. Thus, process 1 is on the left side in reflow 1 (Figure 13) and right side in reflow 2 (Figure 14).

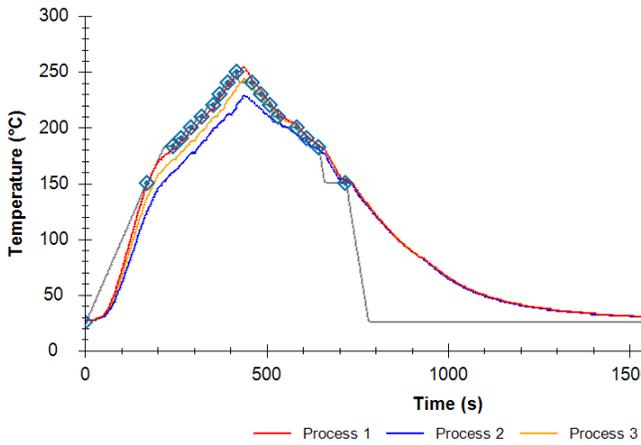


Figure 13 – BGA Tilt Study Reflow 1

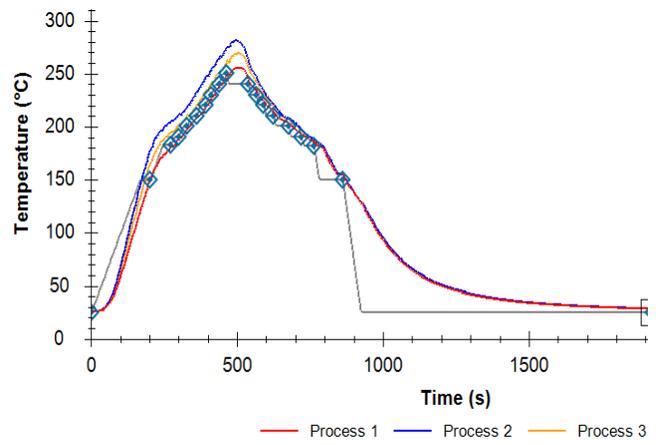


Figure 14 – BGA Tilt Study Reflow 2

3S Warpage is shown in Figure 15 and the angle of tilt in Figure 16 for four total samples over two thermal cycles. This data is shown on a reference plane relative to the underlying glass, although the warpage of the sample is the dominant factor to the overall shape and tilt.

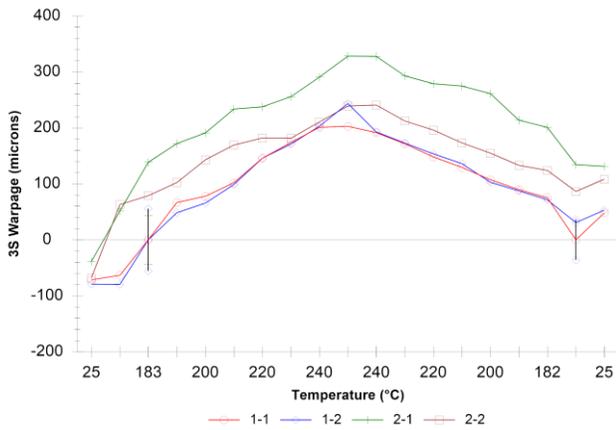


Figure 15 – Tilt Study 3S Warpage

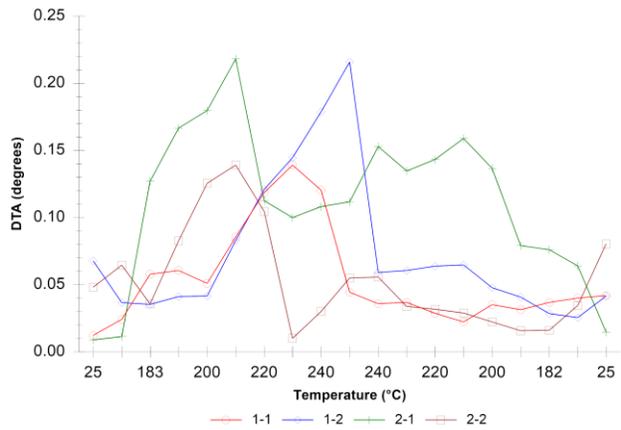


Figure 16 – Tilt Study, Tilt Angle

The warpage matches with the overall trend on the substrate side of the sample from the top to bottom temperature uniformity study. Overall it is difficult to interpret the tilt angle information clearly. It seems the samples did not follow a very clear tilting mechanism as the solder began to liquefy. Higher tilt numbers can generally be seen around liquidus temperatures, but the overall trend is unclear. However, there is an inherent issue with using this gauge for tilt from left to right along the sample as the gauge is based on tilt along the diagonal, using center and corner points. Examples of the molded BGA surface on the glass references plane are shown at room and maximum temperature in Figure 17 and Figure 18.

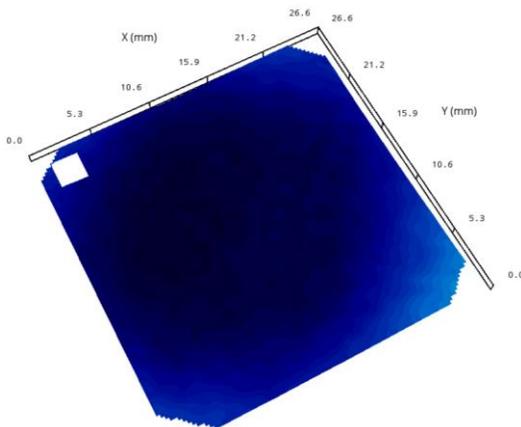


Figure 17 – Tilt Study 25°C Warpage

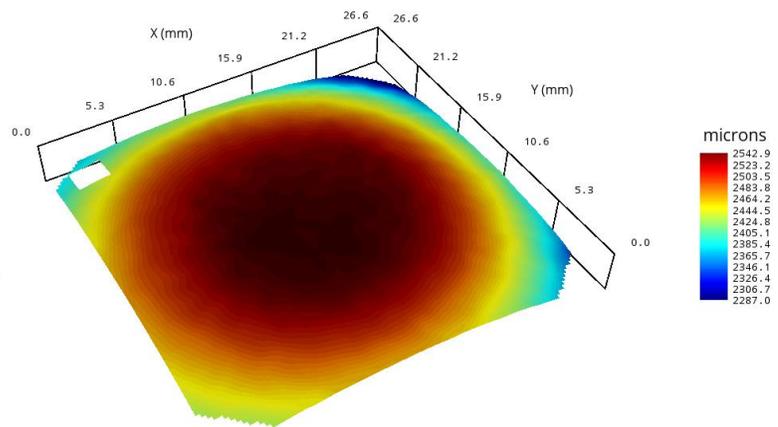


Figure 18 – Tilt Study 250°C Warpage

To further understand the BGA tilt, its molded surface, while still on the reference plane of the surrounding glass, is fit to a 1st order plane. This removes the warpage of the surface and leaves only the relative tilt between the molded and glass surfaces. Using the 1st order surface, horizontal centerline plots are extracted from one of the sample data sets. The horizontal centerline plot is a 2D line plot from left to right on the sample, shown in Figure 19. While interpreting these plots, keep in mind that the absolute height from glass to BGA is not necessarily accurate for these surfaces. Instead, line plot tilt change is the focus here. Additionally, since the 2nd reflow run is used, listed temperatures are representative of the colder left side of the sample. As a result, solder liquidus will appear to be seen early.

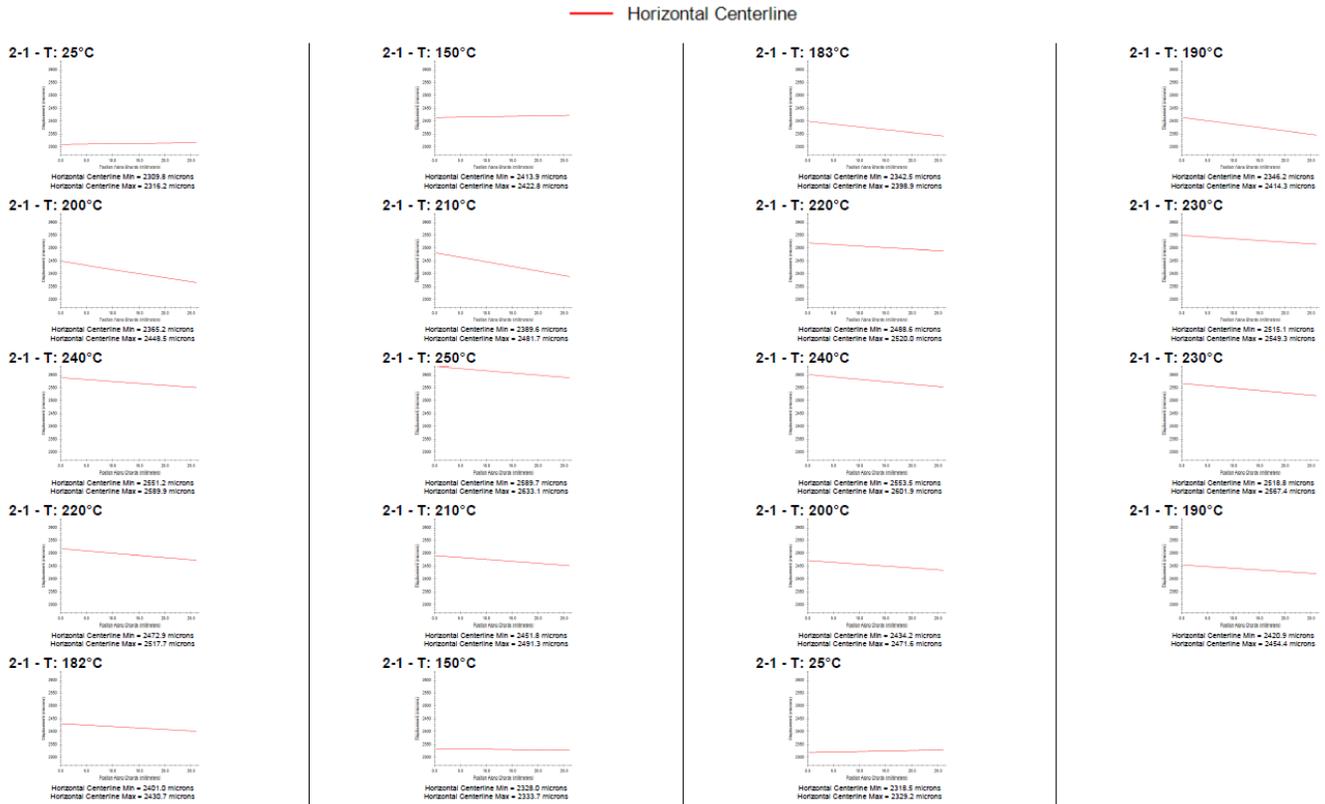


Figure 19 – Molded BGA Surface with 1st Order Fit, Horizontal Centerline Plots over Reflow Temperatures

The same data can be represented in terms of angle along the horizontal centerline in Figure 20.

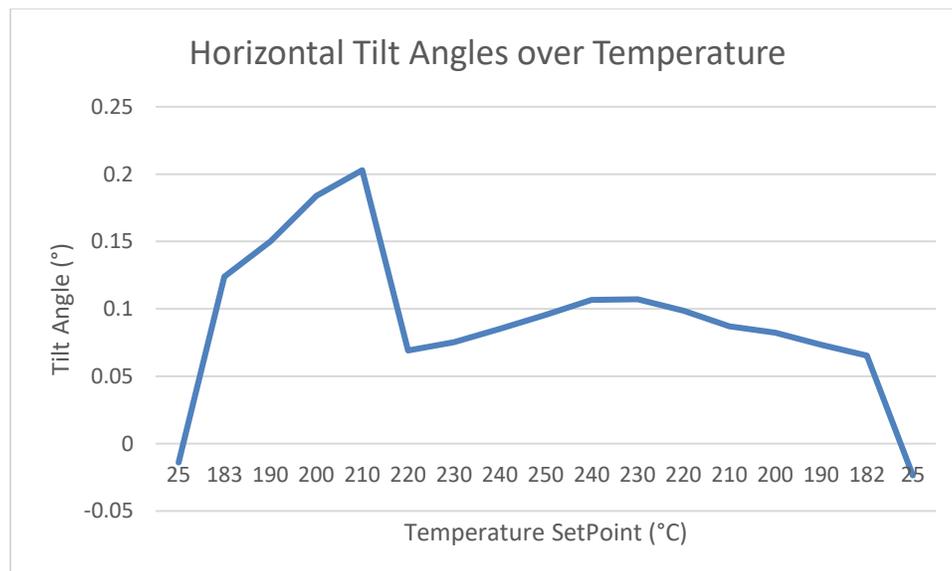


Figure 20 - Molded BGA Surface with 1st Order Fit, Tilt Angle of Horizontal Centerline

In Figure 20 the effect of a hotter right side of the BGA can be seen in the BGA tilt maximizing when the left side of the BGA is at 210°C. In this case, the right side is likely around 230-235°C and past the liquidus point of the solder. A significant reduction in the tilt is seen when the left side reaches 220°C and theoretically also softens and slightly lowers. The tilting effect on the cooling side is much less pronounced as the left to right temperature differential is reduced during the cooling cycle, though still present.

Summary

Top to bottom temperature uniformity can play a significant role in PBGA warpage at elevated temperatures. How this temperature uniformity affects the warpage seems to vary with package design. When running samples through “even” and “non-uniform” reflow cycles, two similarly constructed packages showed opposing responses to the changing thermal conditions. While it was discovered that the two PBGA samples have noticeably different die sizes, the explanation of the differences in response to temperature non-uniformity is unclear.

A viable approach to measuring the topside of surface mount packages is demonstrated using the shadow moiré technique. The measurement allows both the warpage and relative tilt of the package to the underlying PCB to be measured. The same concepts could potentially apply to other measurement techniques including Digital Fringe Projection. Testing showed that by applying heat to a leading edge of a BGA, a tilt towards the hot side could be measured, particularly after removing the effects of warpage using a 1st order polynomial fit. Package behavior in real SMT conditions is expected to be different, as other forces will be applied to the package.

Future Work

Comparison of actual thermal warpage testing to FEA simulations could potentially explain the effects on warpage caused by temperature non-uniformity. The test approach for measuring BGA tilt and solder ball collapse can be used in actual surface mount reflow attachment.

Acknowledgements

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