# Alternative Methods in Measuring BGAs for Thermal Warpage

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## Abstract

Warpage determination for ball grid array (BGA) packages require measurement of the surface containing solder balls. Balls can be sheared, and the surface painted. Surface damage can alter the substrates surface causing local distortions. With packages becoming smaller and thinner, physical shearing of solder balls is becoming impractical. Alternatively, paint can be applied without physically removing the balls. Balls are removed digitally in a rigorous process of pattern matching through numerous acquisitions obtained to recreate the reflow profile. Alternative methods to obtain warpage values without having to remove balls or paint the BGAs surface are explored. The first method examines measuring the unpainted ball side through Digital Fringe Projection (DFP) and digitally removing balls based on pixel saturation. The second method measures the packages unpainted top side through Shadow Moiré (SM) and correlates a warpage value to the ball side.

Making a valid comparison between top and bottom surfaces will require understanding how warpage impacts the components through multiple repeat thermal cycles and optimizing run conditions to obtain equivalent coplanarities over temperature profiles between DFP and SM. Due to the difference in data density between these two methods, comparable smoothing parameters must be selected to ensure optimal data quality and equivalent area comparison. This paper assesses how well the top and bottom surfaces correlate to each other and explore how factors such as physical dimensions or top side features may impact results.

## Introduction

Measuring BGA warpage over temperature is a common industry practice to ensure reliable surface mount connections. This can be done in early product development, as a failure analysis step, or as outgoing or incoming quality assurance. The process of measuring BGA samples for thermal warpage is subject to industry standards from both JEDEC, in JESD22-B112C and JEITA ED7306.[1][2] Additionally, these standards establish allowable warpage values based on ball size and ball pitch, for the JEDEC standard, pass/fail further established in JEDEC SPP-024.[3] Standard practice in these standards for measuring BGA warpage is to remove the solder balls in order to measure only the substrate surface. However, as both ball size and package thickness decrease, the practicality of removing solder balls without altering the sample shape has become increasingly challenging.

Industry studies around component warpage are not uncommon as in studies from Samsung, Nokia, Intel, SPIL, and NXP.[4][5][6][7][8] These studies focus specifically on the shadow moiré technique and provide effective examples of how and why to measure the thermal warpage of complements like BGAs.

Determining warpage of BGAs can be challenging due to factors like surface preparation, size, or data processing. The solder balls can be physically sheared, which can potentially damage the substrate surface and alter the local surface topology, as shown in Figure 1. Additionally, physical forces from the ball shearing process applied to thin substrates have the potential to physically warp the surface prior to temperature exposure. Shearing may leave residual solder at or below the surface level, reflecting light more brightly than the surrounding area. Even when the solder is completely removed, light still reflects more brightly off the copper or gold pads beneath it. If samples are measured at this point, post processing requires digitally masking these areas, a similar process as if the solder balls were not removed. Applying a coat of white paint maintains consistent surface brightness and mitigates noise due to damage caused by the shearing process. However, ball removal alters the sample composition, potentially affecting warpage and thermal mass.

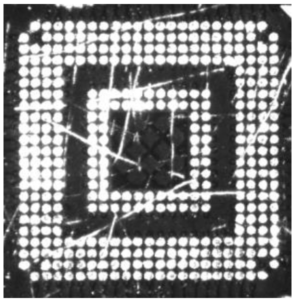

**Figure 1. Damaged BGA from Physical Shearing of Solder Balls**

Alternatively, paint can be applied to the surface while the solder balls are still intact. Post processing requires digitally selecting a region of pixels that encompasses the solder ball and scanning the entire image looking for matching areas. Processing time is dependent on the number of pixels for both the solder ball region and the full image. Searching for a 14 x 14 pixel area in a 750 x 750 image will take a greater amount of time than a 14 x 14 pixel area in a 500 x 500 image. Solder balls must be removed from all acquisitions taken throughout the thermal profile. This can be accomplished either by repeating the previously described process for each individual image or by masking multiple images using the ball location from a single reference image. As samples expand, contract, or shift during the thermal profile, the masked regions may become misaligned. Careful attention is required to ensure the correct areas are masked for each temperature.

The methods presented in this paper eliminate the need for solder ball shearing and painting. However, the primary advantage to these methods is the simplified data processing and time savings associated with it. The first method focuses on analyzing the ball side using DFP, while the second method involves measuring the top surface with SM and correlating the data with that from the ball side.

## Experimental Methodology

*Metrologies*

Shadow Moiré is an optical metrology technique based on the geometric interference between physical grating and its shadow projected on a sample surface. A white light source passes through the reference grating, which is composed of clear, low CTE glass with a patterned chrome film on the underside, at an angle of approximately 45°, forming a grating shadow on the sample. This shadow will be distorted by the out-of-plane shape of the surface as shown in Figure 2. A camera positioned above captures a series of dark and light fringes, with each successive fringe representing a height variation of the sample surface. It is the recommended choice for continuous surfaces. SM uses 12-bit gray scale depth, allowing for data to be gathered on unpainted samples.

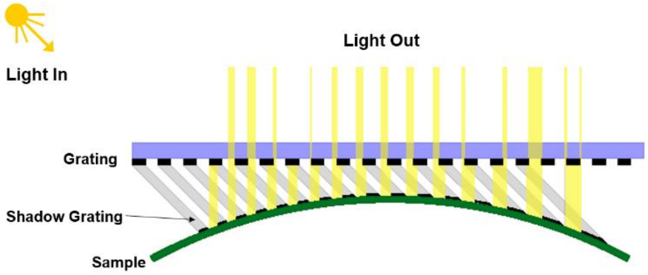

**Figure 2. Shadow Moiré Technique**

Digital Fringe Projection is another optical metrology technique that measures surface contours by projecting fringes onto a sample with a digital projector and observing the resulting fringe distortion. Unlike SM, the fringes in DFP do not directly indicate height changes. Instead, the height variation is determined by comparing the distortion of measured fringes to those of a reference plane. This volumetric calibration means that each point within the volume, in which the calibration is performed, has a unique value. The fringe change relative to that of the reference plane can be determined by subtracting the reference plane phase map from the sample surface phase map. A simple DFP diagram is shown in Figure 3. The DFP uses 12-bit gray scale depth, allowing for data to be gathered on unpainted samples.

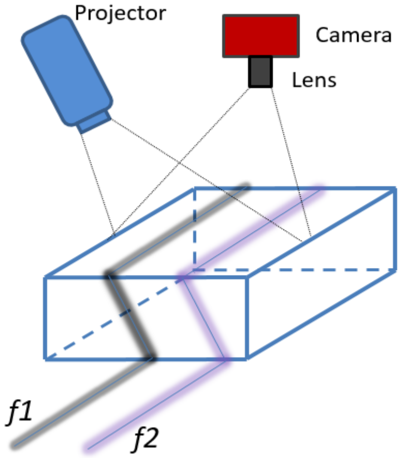

**Figure 3. Digital Fringe Projection Technique**

The resolution from SM measurements can be as low as 500 nm. This technique has low measurement noise and has a higher throughput than DFP. Additionally, data processing is generally faster for continuous surfaces compared to those with distinct features. The grating location being within close proximity to the sample can potentially cause a temperature variation between the top and bottom surfaces. Modifying heating rates can mitigate this. The camera zoom is limited by resolving the grating lines. A NIST-traceable, calibrated two-step block of known height is used to determine the height per fringe, or fringe value. The fringe value is specific to the grating size and camera configuration and is constant across the measurement field of view (FOV) due to the system geometry.

DFP has minimal limitation in terms of data density, allowing smaller pixel sizes number. This is advantageous to show more surface detail or measure small features of a sample surface. DFP is better suited to resolving fine surface features on smaller samples, such as solder balls. However, the measurement resolution gets worse as FOV increases, increased data density can lead to more noise, there is an increased sensitivity to diffraction due to air density differences in the oven, and it lacks submicron z-resolution. [9] The reference plane is determined by measuring an alumina flat. Resolution is dependent on the FOV.

*Devices Under Test*

This study used four different samples, all smaller and thinner BGA style devices, aligning with the focus of this study. Each BGA is assigned a number, with sample details provided in Table 1. A deeper analysis was conducted on the BGA 1 samples to further refine the correlation between top and bottom warpage.

**Table 1. Dimensions, Ball Diameter, and Ball Pitch of Tested BGAs**

| | Dimensions (mm) | Ball Size (mm) | Ball Pitch (mm) |
|---|---|---|---|
| BGA 1 | 8.0 x 8.0 x 0.85 | 0.19 | 0.28 |
| BGA 2 | 12.4 x 15.0 x 0.70 | 0.52 | 0.69 |
| BGA 3 | 14.0 x 14.5 x 0.75 | 0.17 | 0.25 |
| BGA 4 | 12.4 x 12.4 x 0.50 | 0.30 | 0.38 |

*Analysis Methodology*

BGAs were placed in an oven for 24 hours at 115 °C, prior to testing. Samples were analyzed using a thermal profile similar to Figure 4, where BGA 1 and 4 had a peak temperature of 230 °C, and BGA 2 and 3 had a peak temperature of 260 °C. Bottom surface measurements were performed on the Akrometrix AXP 2.0 measurement tool with a DFP

3 module, with resolution between 2 – 3 µm. Top side measurements were performed on an Akrometrix AXP 3, using a 300 lines per inch grating, with 0.5 µm resolution. All BGAs were supported on a piece of dark heat-resistant glass.

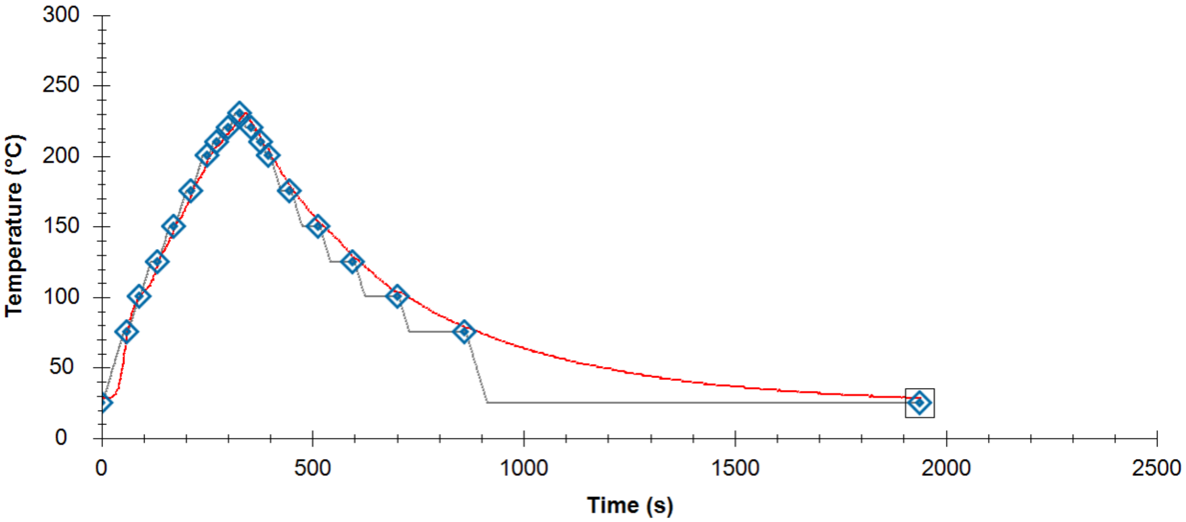

**Figure 4. Example Thermal Profile Applied During Testing**

Samples were tested three times each with both DFP and SM to determine if there was any kind of degradation with repeat thermal runs. The results were observed to be consistent, starting and ending with the approximately the same coplanarity values. This would indicate the peak temperature used is not high enough to alter the sample.

*Surface Brightness Processing of Ball Side Data Measured by DFP*

This method looks to remove the solder balls by identifying them based on their grayscale values. Images are 12-bit, meaning the grayscale values range from 0 to 4095, or black to white. Prior to beginning an analysis, the surface brightness is adjusted to both illuminate the unpainted surface and saturate the ball pixels. Figure 5 shows a side –by-side comparison of a sample with saturated solder balls and the detection of their pixels. Attention should be given to the edges of the highlighted regions to notice the entire ball region is not selected. To account for this, the masked regions are expanded to remove the balls completely.

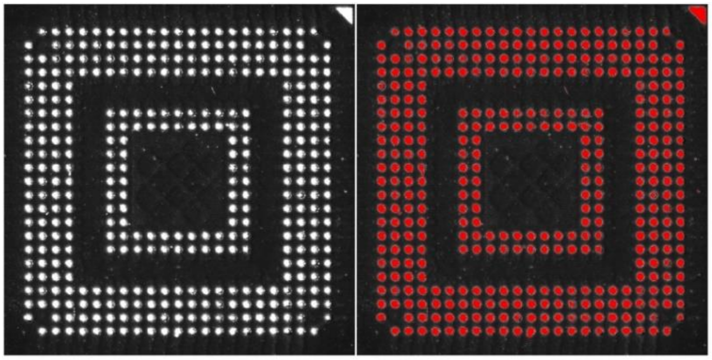

**Figure 5. Masking by Pixel Saturation of Solder Balls on BGA 1**

Once the balls are removed, further data processing is performed, including plane rotation, noise removal, and smoothing. Smoothing is an important step and will be covered in more detail below. Figure 6 shows a comparison of the same BGA at room temperature painted and processed using a function known as feature detection and not painted using the surface brightness feature. Feature detection is a software function that identifies repeating patterns based on height and shape, allowing them to be categorized automatically and, in this case, removed from the data set.

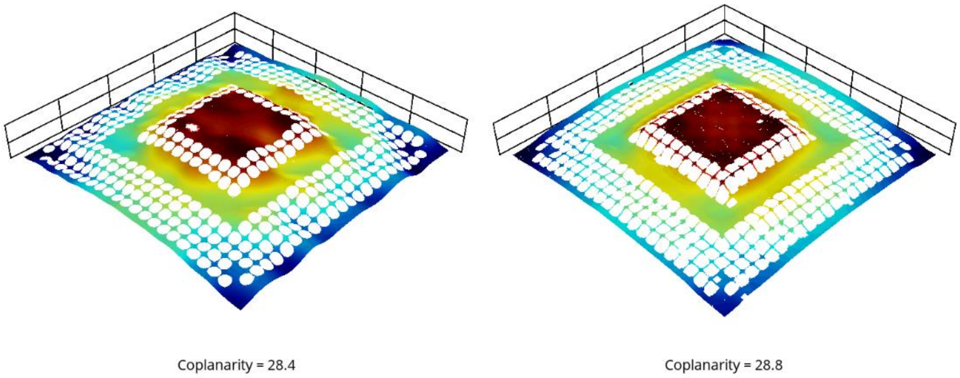

**Figure 6. Processing Using Feature Detection (Left) Versus Pixel Saturation (Right) of BGA 1**

*Correlating Top and Bottom Surface*

This method aims to correlate the top surface of BGA1, measured with SM, to the bottom surface, measured with DFP. Figure 7 displays the top and bottom surface of the BGAs average values during a thermal profile, using a software feature known as Interface Analysis. This software orients two separately acquired data sets in the same space based on orientation metadata tracked when the individual acquisitions are acquired. The ball side is located on top. It is evident that the topography of both surfaces warp in the same direction throughout the thermal profile.

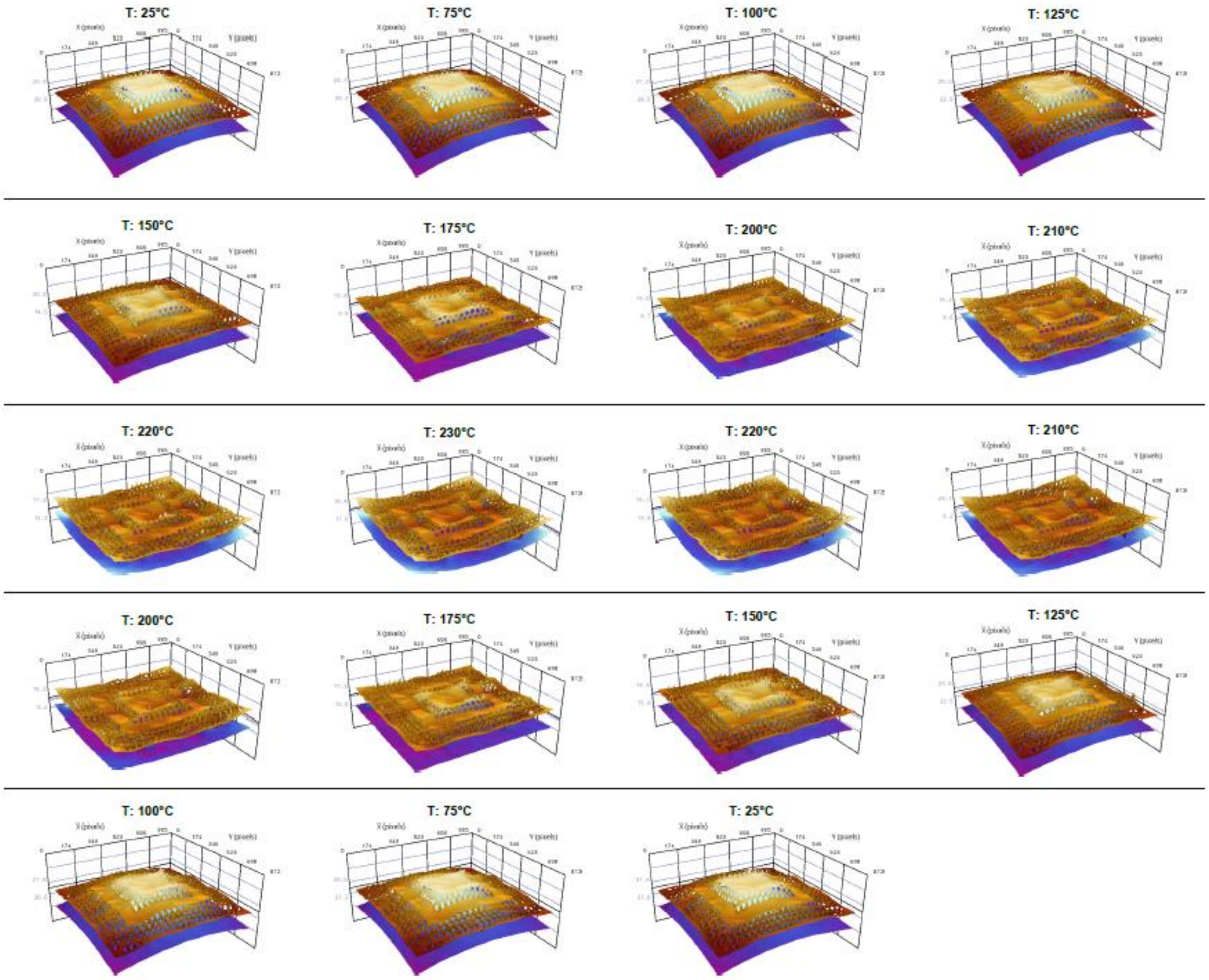

**Figure 7. BGA 1 Bottom and Top Surface Topography Throughout Thermal Profile**

Successfully correlating top surface values will require collecting bottom surface data and applying equivalent data processing.

*Smoothing*

Defining equivalent smoothing parameters for both SM and DFP is crucial for accurately determining correlation between top and bottom surfaces. Smoothing is achieved by applying a least squared fit across a matrix of pixel values, or kernel. Post processing of the bottom surface leaves small substrate regions located in between regions of empty data from where solder balls were digitally removed. A large kernel size is needed to extend across multiples sets of these regions to ensure accurate averaging.

Pixels located near the edge are ignored by ($n$-1)/2, where $n$ is the kernel size. If these edge pixels are not discarded, the fitting process can cause the edge z-values to fluctuate more drastically than reality. Removing these pixels cause a slight decrease in the physical dimensions of the sample. Consequently, determination of equivalent smoothing parameters is not only dependent on ratio of kernel size to pixel dimensions between DFP and SM images, but also on the physical dimensions being reported. The number of pixels present in the DFP images are 855 x 855 and SM are 92 x 92.

## Results

### *Unpainted Bottoms*

Figure 8 shows the results for six of BGA 1, both in unpainted and painted conditions. Each line represents an average of three separate runs, with green indicating unpainted BGAs and red indicating painted BGAs. The two sets display a similar overall pattern. However, unpainted samples show a higher standard deviation, averaging 2.57 µm, compared to 1.81 µm for painted samples. It was observed that the solder balls on the unpainted BGAs reflected light, creating secondary fringe patterns that increased noise in each measurement. While smoothing can help reduce some of this error, it does not fully eliminate it. The painted BGAs do not exhibit this issue because the solder balls' reflectivity matches that of the surface.

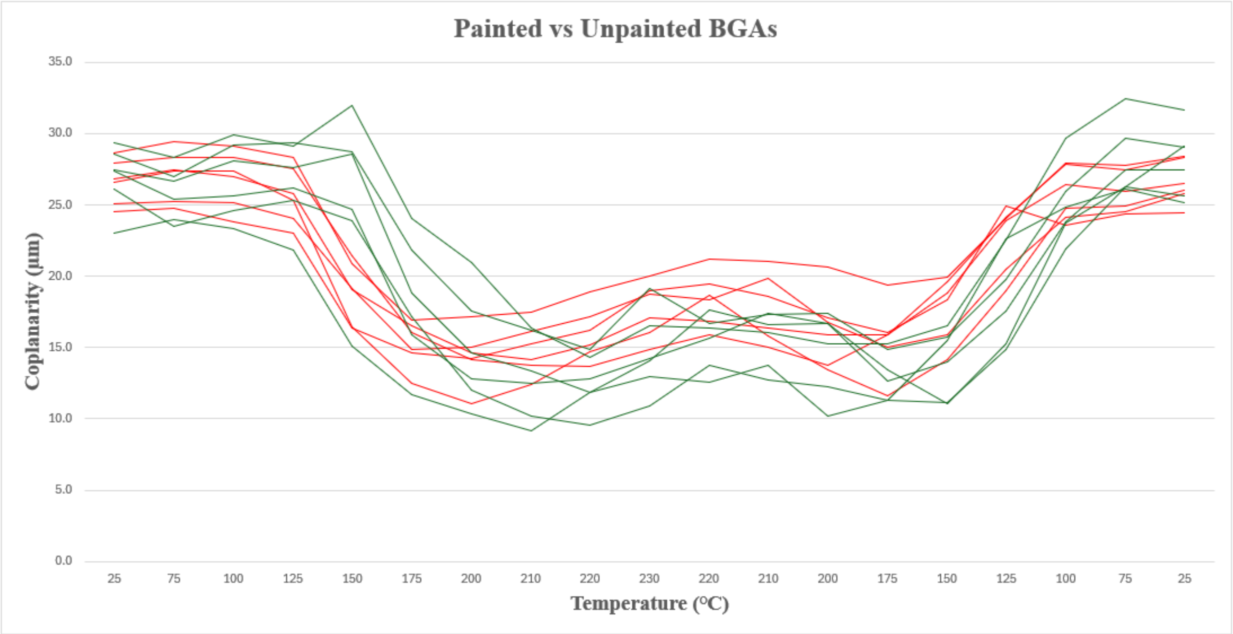

**Figure 8. Coplanarity over Temperature Profile of Painted (Red) Versus Unpainted (Green) for BGA 1**

A total of 342 acquisitions were collected across six samples, 19 temperature points, and three repeat analyses. Digitally removing solder balls on the painted BGAs using the feature detection option took approximately three and a half hours, whereas solder ball removal on the unpainted BGAs using surface brightness masking took less than 10 minutes. In other words, post processing of the unpainted BGAs took less than five percent of the time needed for painted BGAs.

Unlike detecting solder balls based on pixel regions, there is no matching or calculations being performed when removing pixels based on grayscale values. This means removal of these pixels are relatively instantaneous. Processing all acquisitions within a thermal profile can be performed in a fraction of the time it would have required. In addition, this feature can be applied statistically to each individual acquisition based on the deviation from the mean. Compared to feature detection, this is not only faster but does not suffer from masked regions becoming misaligned. The surface brightness feature is not a replacement for feature detection. It cannot be used with painted BGAs nor give any information about ball height.

### *Top and Bottom Correlation*

The data collected from painted BGA 1 is used in this painted versus unpainted comparison. The top surface, left unpainted, was measured using SM across the same 19 temperature points, with three repeat analyses. Figure 9 presents these results, with orange lines representing the bottom surface measurements measured with DFP and purple lines representing the top surface measurements measured with SM. The thin lines show an average of the three individual runs, and the thick line shows an overall average of the surface. The maximum difference in coplanarity between the top and bottom surface is 4.8 microns, which falls within the cumulative error range of both techniques.

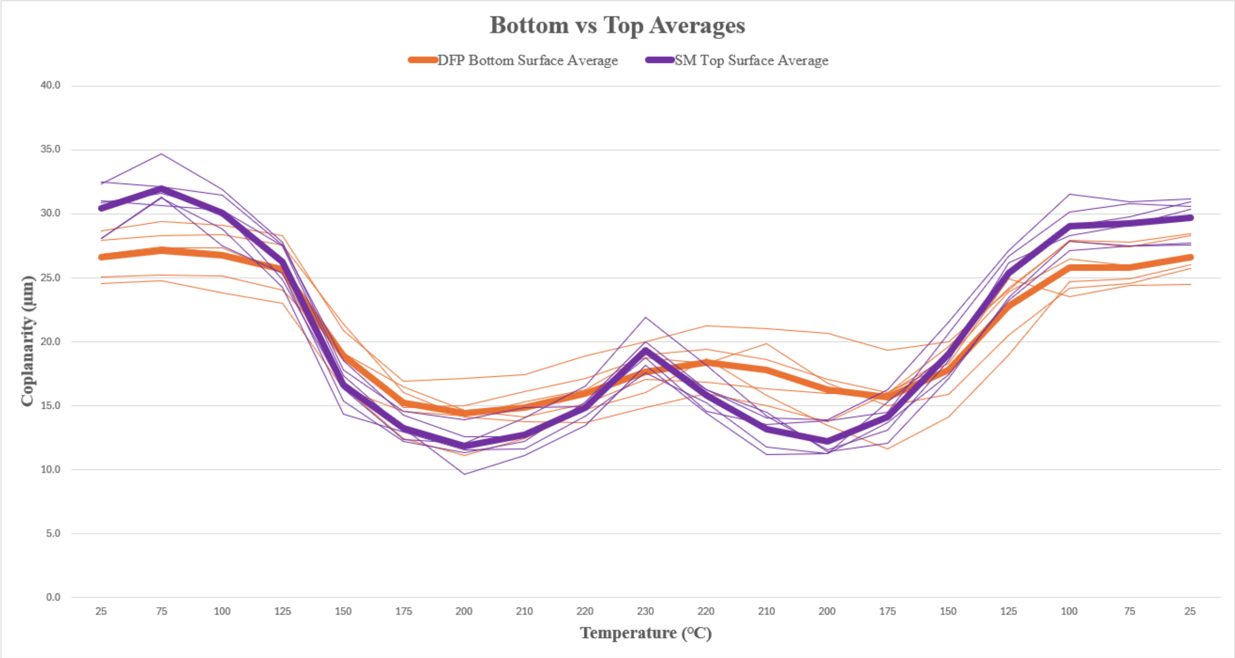

**Figure 9. Coplanarity over Temperature Profile of Painted Bottom Surface, using Digital Fringe Projection Versus Unpainted Top Surface, using Shadow Moiré, for BGA 1**

One potential source of variation may be thermocouple placement. The BGAs are analyzed with solder balls intact, so placing the thermocouple over the bottom surface could be problematic. Instead, it is placed on the top surface for the bottom side measurement. This setup may lead to the bottom surface measurement being taken at a slightly different temperature than reported, potentially causing a slight shift in data.

Another possible source of variation is the lack of a reference dataset to confirm that surfaces are being processed correctly and that all sample BGAs are in good condition. Without this, it is difficult to ensure that any observed outliers are not due to a compromised BGA. If one of the outliers is in poor condition, it could contribute further to the variation in the results.

Additional BGAs were tested, where the unpainted bottom surface was measured with DFP, while the unpainted top surface was measured with SM. Each sample surface was only analyzed once. The bottom surface was processed using the surface brightness technique. A more accurate comparison might have been achieved by painting the bottom surface and comparing it with the unpainted top surface. Figure 10 displays the averages of BGA 2, Figure 11 displays the averages of BGA 3, and Figure 12 displays the averages of BGA 4.

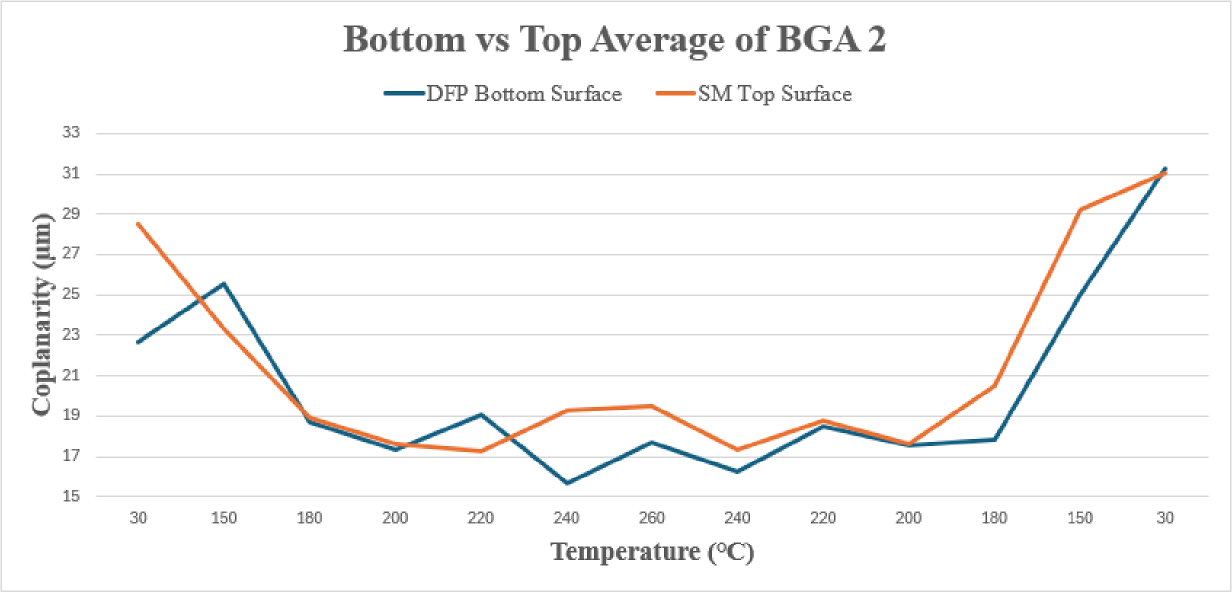

**Figure 10. Coplanarity over Temperature Profile of Unpainted Bottom Surface Versus Unpainted Top Surface of BGA 2**

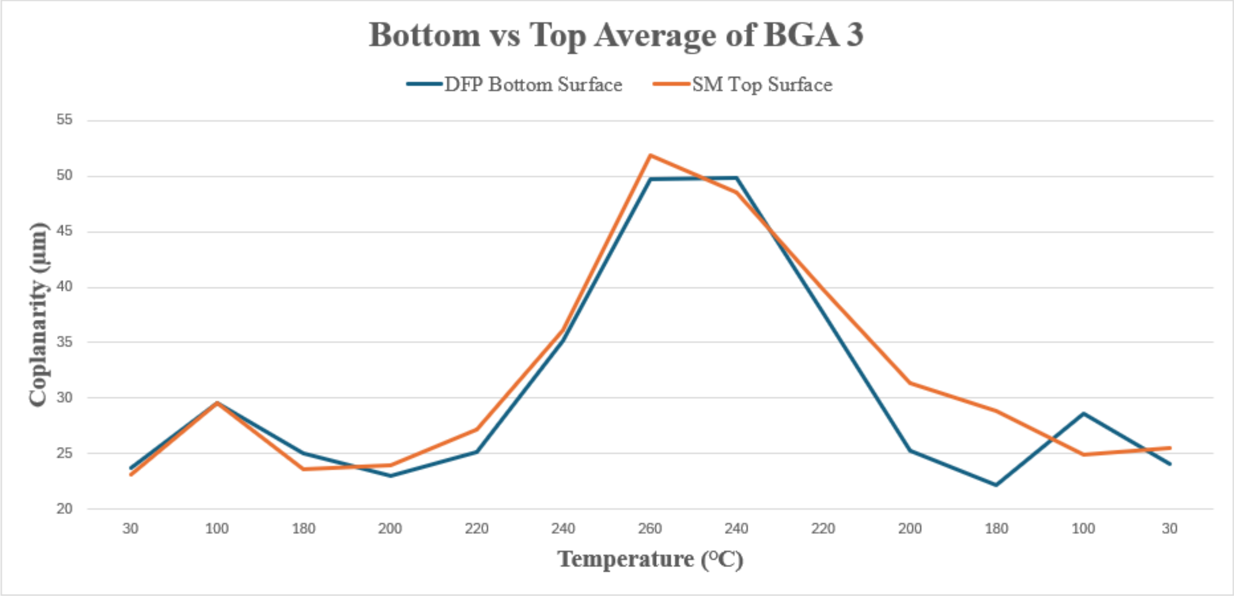

**Figure 111. Coplanarity over Temperature Profile of Unpainted Bottom Surface Versus Unpainted Top Surface of BGA 3**

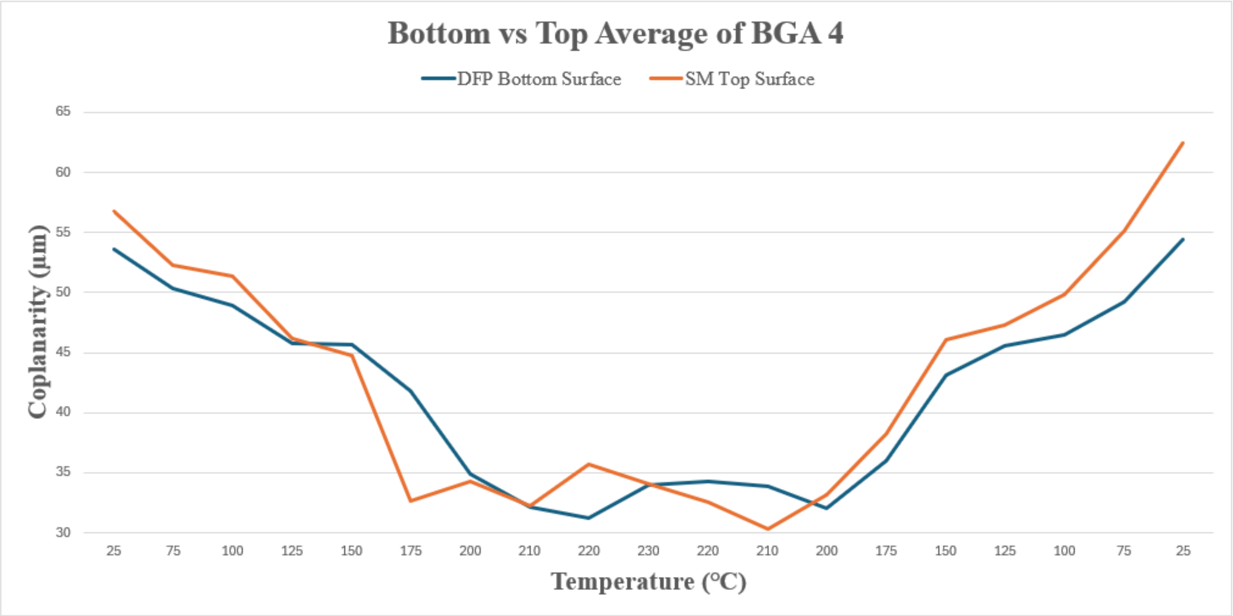

**Figure 122. Coplanarity over Temperature of Unpainted Bottom Surface Versus Unpainted Top Surface of BGA 4**

The overall trends of the surface averages for both the top and bottom generally follow a similar pattern. Applying paint to the bottom surfaces may have reduced the variation between the two surfaces, as seen on the bottom surface of BGA 2 and BGA 3. The top surface of BGA 4 is distinct from the other BGAs since the top surface is not composed entirely of a mold compound, but instead includes pads on the surface. In this case, painting the top surface will most likely provide better quality data.

The most effective approach to correlating the two surfaces is to first use DFP to measure the painted ball side, allowing for accurate bottom side topography determination. While painting is not necessary, improved correlation between the two surfaces may be observed. Next, the top surface can be measured using SM to establish equivalent processing steps, particularly smoothing. Once comparable results are achieved, top surface analyses can be used as an alternative to measuring the ball side.

**Discussion**

*Application specific approach*

The removal of solder balls for BGA thermal warpage testing remains the industry standard, and no general recommendation is made here to replace this method for all sample types. A sample-specific threshold is needed to determine when these newly presented approaches are appropriate. Larger, thicker samples are expected to show greater mismatch between top and bottom shapes and have few issues with ball removal, making the standard approach effective. The samples in this study were selected for their package body thickness (0.50–0.85 mm) and serve as practical examples for the alternative method presented here. Thus, samples with less than 0.85 mm thickness are suggested as a starting point for these alternative methods, requiring additional industry feedback needed to refine guidelines. Additionally, a minimum solder ball size could serve as a rule for cases where effective ball removal becomes impractical.

*Final Testing Methodology*

The results validate a reasonable match between bottom and top surface measurements. These results suggest that the best approach to measuring samples with dimensions similar to those in this study is simply to measure the sample topside unpainted with SM. This is the fastest and easiest approach, requiring no sample preparation, allowing for higher volume and the best resolution thermal warpage measurements, as the SM technique can be used at up to a 250 x 250mm with 0.5 µm resolution and very minimal measurement noise. This is a significant departure from the industry standard approach of measuring the attach side of the package. Thus, those skeptical of only using top side data can use the same methodologies in this study to verify a reasonable match between DFP bottom side and SM top side of balled samples in early testing, then shift to SM topside only for volume needs. In high-volume outgoing quality control, measuring complex ball-side data can increase measurement noise, time, cost, and complexity.

## Conclusion

Measuring unpainted BGAs with solder balls still intact offer a valid alternative to current methods, preserving sample integrity and avoiding surface damage that can occur with physical shearing of solder balls. As components continue to decrease in size, shearing may become impractical. Eliminating painting and extensive post processing significantly reduces time, making surface brightness processing of unpainted BGAs an efficient alternative to analyzing painted ones.

Further time savings can be achieved by eliminating both sample painting and post processing of solder balls by focusing on measuring the top surface. In cases where top surfaces with features beyond the mold compound, painting may still enhance data quality. This study demonstrates that a correlation between the top and bottom surfaces of multiple BGAs is possible.

## Acknowledgements

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