Comparison of Advanced Package Warpage Measurement Metrologies
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Abstract
The metrology used to characterize, measure, and present the dynamic warpage of electronic packages as a function of temperature has become a critical tool in the electronics industry. Existing JEDEC standard JESD22-B112A lists the four metrologies of shadow moiré, digital fringe projection, confocal and digital image correlation. Each of these has distinct advantages and disadvantages depending on the required use model and application. A series of identical measurement scenarios was applied to each metrology in an attempt to establish constructive comparisons of capability and use across specific tools commonly used for each metrology today. Key parameters targeted in these evaluations included field of view (FOV), oven capabilities, measurement preparation and software capabilities. The intent is not to declare a best tool but rather to provide comparative aspects across the metrologies and tools for those considering a specific use model.

1. Introduction

Figure 1 Dynamic warpage measurement metrologies. (a) thermal/shadow moiré; (b) digital fringe projection (DFP); (c) confocal technique (d) 3D digital image correlation (DIC);

A key challenge within the advanced electronics packaging industry is the need to characterize and evaluate package warpage across the wide range of package geometries and fabrications in use today. Packages have become even more varied in size, joint density, construct, and symmetry. Packaging can range from 90mm BGA (ball grid array) substrates with in excess of 4500 joints to 3.5mm Chip on Wafer substrates with 0.2mm balls on a 0.35mm pitch. Die geometry can vary from a single symmetrically located die to more complex 2.5/3D die configurations in asymmetrical arrangements. Organic and ceramic substrate constructs can interface with an array of underfill and overmold materials. The transition to RoHS compliant products has driven higher reflow temperatures, more rigid and brittle constructs than their SnPb predecessors. All of which can complicate the dynamic surface contour changes between the respective surfaces of packages and PCBs (printed circuit boards) as a function of the high temperatures common to SMT electronics manufacturing.

There are currently a number of commercially available tools based on the targeted metrologies capable of quantifying and plotting the dynamic contour changes of packages as a function of temperature as stipulated in JESD22-B112A [1]. This paper focuses on a few specifically designed to measure warpage through the elevated SMT reflow temperatures as high as 260C or more. They employ metrologies based on thermal/shadow moiré [2]-[3], digital image correlation (DIC), digital fringe projection (DFP) [4] and more recently a confocal technique with high temperature measurement capability [5] as shown in Figure 1. Thermal shadow moiré utilizes light interferometry techniques to quantify the elevation of a given surface. DFP uses phase shifting line pattern projection to process the topography. Confocal uses a pinhole-array and Z scanning mechanism to quantify the elevation of a given surface as an array of focus points. 3D DIC utilizes a pair of calibrated cameras to track the speckled surface of interest using triangulation techniques. For dynamic warpage purposes, captured images from a pair of cameras through an oven’s glass window can potentially cause some light diffraction which may induce measurement error. The sample preparation and the need of prior calibration can pose some technical challenges for this assessment in addition to recommended usage for qualitative vs. absolute measurements [6]-[7]. Hence, the 3D DIC metrology was not included for this assessment.

2. Methodology and Approach
As stated above, different warpage metrologies may have advantages in efficiency, accuracy, and scalability depending on the scope or specifics of a given measurement demand. The overview of the key characteristics of each of the three metrologies considered in this discourse is tabulated in Table 1. Each of the metrologies stated here was associated to a different tool supplier within the scope of this assessment. The intent in defining the regime to be employed by each participating metrologies user was to enable a neutral comparison of each platform’s capabilities in addressing variants in the set of key parametrics, in relation to surface warpage as a function of temperature as described in the following subsections.

Figure 2 (a) Variable FOV used in DFP and shadow moiré vs. (b) Fixed FOV used in confocal technique

**Table 1 Basic characteristic of dynamic warpage metrologies used within the scope of this study**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dynamic Warpage Metrology</th>
<th>Confocal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Considered</td>
<td>Shadow Moiré</td>
<td>Digital Fringe Projection (DFP)</td>
</tr>
<tr>
<td>Field of View (FOV in mm) pixel/mm²</td>
<td>Akrometrix (AXP)</td>
<td>Linxix TDM TT &amp; LS</td>
</tr>
<tr>
<td></td>
<td>(60x60): 144 pixels/mm²</td>
<td>(60x60): 1089 pixels/mm²; (90x90): 484 pixels/mm²; (210x210): 90 pixels/mm²</td>
</tr>
<tr>
<td>Theoretical Z Resolution per FOV:</td>
<td>0.85µm: &lt; 250 sq. mm FOV with 300LPI</td>
<td>~1.5µm: 30 to 150 sq. mm FOV</td>
</tr>
<tr>
<td>Oven Size</td>
<td>400x400mm (AXP)</td>
<td>75x75mm (TDM TT) 400x400mm (TDM LS)</td>
</tr>
<tr>
<td>Heater Setup and Ramp Rate [7]</td>
<td>Radiation heating by one-sided NIR lamps or convection heating (CRE6) Max 3°C/sec (depends on sample)</td>
<td>Radiation heating by dual-sided and dual-controlled NIR lamps Max 4°C/sec (depends on sample)</td>
</tr>
<tr>
<td>Sample Preparation Used</td>
<td>White paint</td>
<td>Need to deball</td>
</tr>
<tr>
<td>Measurement of Package with BGAs intact</td>
<td>Need to deball</td>
<td>Yes (additional post processing needed)</td>
</tr>
<tr>
<td>Data Acquisition Rate</td>
<td>Automated part tracking, batch analysis and reporting</td>
<td>Automated part tracking, batch analysis and reporting</td>
</tr>
<tr>
<td>Post Processing Capability (see supplier for specifics)</td>
<td>Automated part tracking, batch analysis and reporting</td>
<td>Automated part tracking, batch analysis and reporting</td>
</tr>
</tbody>
</table>

**Field of View (FOV)**

FOV in this discussion is the area that a given metrology can image capture at any point in time. Different use models of surface warpage applications can be concerned with measuring single samples or multiple samples at a time. Sample sizes can range from 10mm by 10mm to 90mm by 90mm or be concerned with imaging an even greater surface like PCBs [7] while later cropping down to a more specific area of interest. Consequently the FOV limitations of a given metrology is of prime consideration. Current digital imaging capability no longer tends to be a limiting factor for FOV. More often FOV is gated by the height of camera above the samples, the X-Y size of the thermal chamber, and the view angle of the samples in it. A smaller FOV may give rise to greater planar resolution and vice versa. Larger FOV can be suited for measurement of multiple units or a larger area of interest at once, while a smaller FOV requires additional measurements in predefined x-y scans to complete a unit measurement by stitching the images together. In such cases the time to capture or the resolution of the temperatures at which all data points can be collected may be affected. As stated in Table I, shadow moiré and DFP techniques used the variable FOV by adjusting objective lens while confocal technique uses a fixed FOV as shown in Figure 2. Thus FOV can determine the scalability of a metrology with respect to throughput and the kind of sample of interest.

**Theoretical Z-Resolution per FOV**

The z-resolution of each platform may vary as a function of the defined FOV, image capture device, sample height, and/or optics employed. For shadow moiré, the resolution is independent of the FOV and is controlled by a Ronchi ruled grating made from low CTE glass to cast a 2D pattern onto the sample. The typical Ronchi ruled grating has 50 to 300 LPI. The finer the grating lines are the higher the z-resolution as shown in Figure 3(a) but it does depend on the camera pixels density too to discretize the moiré fringes. However, there is a limit of working distance between the grating and the sample when high LPI is used. The DFP uses five phase shifting structured light patterns to capture the 3D topography, as shown in Figure 3(b), by processing the distorted structured light as function of elevation changes and this allows measurements to be taken from discontinuous and high depth surfaces. The DFP’s z-resolution reduces with greater FOV area due to decrease of structural light density. Confocal technique derives object surface height by calculating the peak output of the intensity response curve at focus point, as shown in Figure 3(c), for every pixel in the FOV. The z-resolution of confocal technique is subject to the objective lens NA (Numerical Aperture), which determines the width of the focus response curve, and peak position calculating method. With large NA objective lens and high accuracy interpolation technique used surrounding a very small region of predefined array of coordinates, the z-resolution can be attained at 0.1µm which has the highest theoretical z-resolution among the metrology addressed here. The time to take a single FOV in confocal technique is about 0.5s to 1s and this will impact the cost of measurement when measuring a large area of interest.
Sample Preparation Requirement

The time and complexity of required sample preparation can be more or less critical depending on the resource needed as well as potential interaction with the sample itself. Sample preparation may include removal of solderballs, surface painting or other surface processing to enable effective measurement. The method and force needed to remove the BGA balls can substantially deform the package and hence induce unwanted noises if not executed with care. Figure 7 shows a mechanical deball tool and a coat of heat resistant white paint laid on the sample used in shadow moiré metrology. Alternately soldering techniques to effect removal of solderballs can be used as long as the heat transferred does not alter the behavior of the package unknowingly. Painting in shadow moiré optimizes the contrast of fringes presented, so the need to or not to paint can depend on the reflectivity of the target surface which can impact the measurement quality. Like shadow moiré, DFP measurements may or may not require a deballing process and a coat of white paint depending on the fringe contrast obtained and the capability of the software to extract warpage data. However, the quality of the DFP measurement can be impacted as a result of potential shadow cast by any protruded features and reflective surface that can add in the raw data for further data smoothing processes. In contrast, the confocal technique does not required any sample preparation and the sample can be measured at vicinity of the predefined array of coordinates. This could reduce the density of the data generated from confocal. In all these metrologies, the surface reflectivity can impact the measurement.

Number of Samples Per Run

![Figure 6](image6.png)

(a) shadow moiré - top: small convective heating chamber (CRE6); bottom: a large oven to accommodate more sample (AXP). (b) Insidix DFP. (c) Confocal – JEDEC tray size

Ramp Rate and Repeatability of Thermal Stimulus

The ramp rate and repeatability of heating to reduce the temperature gradient across the measured sample can be determined by the heating profile used as well as the efficiency of the heat transfer mechanism be it radiant, convection, and/or conductive as shown in Figure 4 for the respective metrology setup. The heating chamber design employed has to work seamlessly with the imaging system in order to produce reliable dynamic warpage images. Adding soak time can reduce temperature gradients across the package, at the expense of increasing the thermal run time. The ability to closely replicate the typical SMT reflow profile as shown in Figure 5 can be a subject of interest to understand the real dynamic warpage of the package and board. The thermal run time and time to peak temperature of a given heating chamber can be influenced not only by the temperature ramp rate but the imaging time that adds sequentially. So total run time per data point will likely be longer for the confocal technique depending on the number of interval readings. Shadow moiré and DFP can capture images under continuous ramps and often achieve higher ramp rates than confocal. Confocal with its longer dwell times to complete image scans often yields tighter temperature gradients top to bottom across the samples.

![Figure 5](image5.png)

Figure 5 Excerpt from IPC TM-650 2-6-27 Typical Reflow Profile Specs for Peak Temperature of 260C

![Figure 4](image4.png)

(a) Insidix DFP heating chamber (top & bottom heating)

(b) Takaoka Confocal Heating Chamber (top and bottom with convection)

(c) Akrometrix shadow moiré convective (CRE6) and radiation module

Figure 4 Schematic drawing of heating chamber used in DFP, confocal and shadow moiré.
The number of samples per run is determined by the heating chamber size, FOV and the thermal capability. Figure 6 shows the representative sample arrangement for each metrology. The shadow moiré unit employed in this study has two types of thermal fixturing. It has the option of a central chamber for larger samples and/or trays of samples, as well as a small convective fixture (CRE6) for small to medium samples nested within the larger chamber. The DFP used in this study has a single chamber with a fixturing beam to secure the samples. While the confocal tool designed their stage based on a JEDEC tray size of 322.6 mm x135.9 mm. Confocal requires samples be arranged in an orderly or fixtured manner to allow the stage to index precisely for data acquisition and measurement.

**Post Processing Capability and Time**

The acquired raw topology data may need to be subjected to additional processing to extract the final result. The time required to process the images and measurements into finite numeric tables, graphs and graphical 3D surface and diagonal sectional view plots within the accompanied software is of interest. Figure 8 shows typical results that can be generated for each metrology. All of them can generate 3D contour plot and tabulated results with clear assignment of convex (+) and concave (-) shape assignment as defined in JEDEC and IPC [11],[7]. Cropping of interest area within the FOV images may be done manually or automated by software as needed for both shadow moiré and DFP when a larger FOV was used to capture multiple sample surfaces at once. Both these required human interaction with the accompanied software. As for confocal, the contour plot and tabulated data were generated automatically with minimal human interaction once the recipe creation has been established prior to measurement. There are embedded software automation and data smoothing processes that can be done to alter post processing time, results and ease of use, but that is beyond the scope of this paper. The ease of use and processing times are software and supplier specific, not necessarily metrology specific.

3. Evaluation and Result

**Table II DOE Legs for Evaluation**

<table>
<thead>
<tr>
<th>Leg</th>
<th>Sample</th>
<th>Test Description</th>
<th>No. of Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concave lens</td>
<td>Measurement against a known concave flatness value</td>
<td>1</td>
</tr>
<tr>
<td>2A</td>
<td>V with balls removed</td>
<td>Dynamic warpage using the fastest ramp SMT heating profile</td>
<td>4</td>
</tr>
<tr>
<td>2B</td>
<td>V with balls removed</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>W</td>
<td>Typical retrow profile simulation with greater interval readings</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>V with balls</td>
<td>Measurement of dynamic warpage with balls</td>
<td>4</td>
</tr>
</tbody>
</table>

A common document defining four types of imaging and measurement actions along with an identical set of samples to process, was supplied to each of the participating metrology suppliers to carry out the four measurement Legs listed in Table II. Each of the metrology suppliers were allowed to perform all of the protocol steps based on their best known practice and all measurements were carried out at their respective facilities. The sample sets included a concave lens and two types of flip chip ball grid array (FCBGA) as indicated in Table III. The number of sample used was intended to vary the FOV of each tools. Sample V and W packages were included due to their differences in thermal mass as well as their availability at the time of evaluation. Having different thermal mass packages enabled the evaluation of heating chamber capabilities employed by each metrology in Leg 2 and 3. Leg 2A/2B was intended to affirm or dispell the assumption that the thermal ramp rate applied had negligible effect on measured warpage at any given temperature. The time taken in each step of the measurement was recorded for further analysis later to understand the measurement throughput time.

**Table III Test Specimens and Package for Evaluation**

<table>
<thead>
<tr>
<th>Type</th>
<th>Sample Description</th>
<th>Size (mm)</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Known standard</td>
<td>Concave lens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCBGA – Bare Die V</td>
<td>with balls</td>
<td>25x27</td>
<td></td>
</tr>
<tr>
<td>FCBGA – Lidded W</td>
<td>without balls</td>
<td>~42.5x42.5</td>
<td></td>
</tr>
</tbody>
</table>

**Leg 1: Fused Silica Concave Lens**

**Table IV Concave lens flatness measurement**

<table>
<thead>
<tr>
<th>Metrology</th>
<th>Lens code</th>
<th>Measurement (um)</th>
<th>Theoretical Flatness (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confocal</td>
<td>SPC037</td>
<td>670.3</td>
<td>668</td>
</tr>
<tr>
<td>DFP</td>
<td>KPC064</td>
<td>1024.6</td>
<td>1025.6</td>
</tr>
<tr>
<td>Shadow moiré</td>
<td>SPC037</td>
<td>661</td>
<td>662</td>
</tr>
</tbody>
</table>

The SPC037 and KPC064 concave lenses were chosen as thermally stable and precisely contoured elements to act as standards of sorts. Metrology users leveraged the specific standard that they already had in house. The coefficient of thermal expansion is ~0.55ppm/°C. The curvature of the lenses are precisely produced and so should present minimal variation across temperature [7]. Each participant was to measure their lens warpage up to a peak temperature of 260°C. Table IV shows the result obtained from measurement compared to theoretical flatness given by lens supplier. The flatnesses measured were within ~2 to 3 um from theoretical value which is within tool precision.
expectations [7]. For DFP and shadow moire metrology, the level of smoothing can affect the reported measured value. Since a fused silica concave lens has near zero thermal expansion coefficient, the flatness of the concave region was measured at elevated temperature. Figure 9 shows the results for three metrologies. The confocal tool, which has the highest resolution, accuracy and repeatability, shows the steady increase of lens flatness as the temperature increase while DFP and shadow moiré methods showed more like a saw tooth trend behavior. This could be due to the paint applied and relative lower repeatability but still meets the repeatability tolerance expectation in [7].

Leg 2 A & B: Fast Ramp and Typical SMT Reflow

The intent of this leg was to allow each tool to demonstrate both their heating chamber capability to perform at a faster ramp rate without doing isothermal measurement (required per industry standard [7]) compared to an actual SMT reflow process while capturing the dynamic warpage of the package. A secondary goal was to affirm or dispell the claim that thermal ramp rates have negligible effect on the measured warpage of a structurally intact package at any given temperature. Figure 10 and Figure 11 show the respective thermal profile and dynamic warpage behavior for Leg 2.

For Leg 2A, both the shadow moiré and DFP temperatures can be ramped up to the peak while capturing data points at arbitrary defined temperature intervals as fine as 10°C. Virtually no dwell time demonstrated. Due to the scanning nature of the confocal metrology the scanning of four complete samples could gate the fastest ramp rate of their heating chamber. Consequently their chosen approach to a fast ramp rate was to measure three data points starting from room temperature then at the peak temperature and finally the room temperature upon cooling. The time taken to ramp to peak temperature and cool down to room takes about 2500s for the confocal tool compared to ~750s to ~850s for the shadow moiré and DFP system respectively. The temperature difference between the top and bottom side of package for shadow moiré seems higher compared to the other two metrologies. This can be due to higher ramp rate used in the small convection chamber (CRE6) and so temperature equilibrium cannot be achieved quickly but the cooling rate of CRE6 seems faster compared to a bigger chamber. Both
the confocal and DFP demonstrated the most minimal delta temperature between top and bottom sample surfaces. This could be attributed to the fact that they employed topside and bottomside heating sources; and the longer period of time to scan/measure required in confocal. Also the DFP actually triggered imaging based on a top bottom temperature gradient of 0.1°C at each temperature data point. For Leg 2B which uses a slower ramp rate, both DFP and shadow moiré demonstrated smooth temperature ramps up to the peak and then cool down with minimal temperature delta observed between top and bottom sides of the package. The complete cycle times were 850s and ~1200s for shadow moiré and DFP respectively. DFP took slightly more time due to a higher number of interval readings captured (every 10°C) and a self imposed requirement to achieve a gradient of 0.1°C top to bottom. Note that for actual industry use, caution is needed for the number of data points captured on a unit that prolong the total measurement [7]. Again the scanning nature of confocal under a fixed FOV can limit the frequency of interval readings but also achieved tighter top to bottom temperature gradients as a result. Thus confocal chose to capture 17x data points with each FOV measurement taking about 0.5 to 1.0s and each unit requires nine FOV measurements. Hence the reflow profile generated by confocal approach was inevitably stepped when multiple interval warpage measurements were needed.

As for dynamic warpage data for Leg 2A and B shown in Figure 11, all warpage measurement obtained from these metrologies were within expected ranges. Both confocal and DFP seem to show more agreement in warpage value for both room temperature and peak temperature irrespective to the reflow profile used in Leg 2A and 2B. While for shadow moiré, the room temperature and peak temperature warpage seems to demonstrate ~20um and ~40um lower value respectively. This might be attributed to higher surface detail captured from the 300LPI grating, the temperature gradient or the remelting of solder residue remaining from the deballing process or the nature of the sample itself. Also the results for these specific evaluates and samples indicate that there was little sensitivity to the ramp rates used.

**Leg 3: Typical SMT Reflow and Higher Unit Counts**

Similarly to Leg2, Leg 3 performed the measurement using twelve samples of higher thermal mass package (sample W). Shadow moiré supplier arranged the sample in 2x6 array with FOV of 136x1315mm while DFP supplier used a smaller FOV (210x210mm) with 3x4 array to optimize the resolution by having a tighter square area. Confocal supplier arranged the sample in 2x6 array too but the FOV is fixed. Figure 12 shows the temperature profile obtained during the measurement cycle by each of the metrologies. The thermal profiles for DFP and shadow moiré were continuously heating up and cooling down while confocal showed a stepped heating and cooling profile as explain before. The time taken to complete the 17 interval measurements were 11477s (~191mins) for confocal. This is attributed to the number of scans needed using the fixed FOV. The shadow moiré took about 980s (~16mins) to complete 47 interval measurements while DFP took 1523s (~25mins). The delta temperature between the top and bottom of the package is higher (~20°C) in shadow moiré metrology and this again may indicate that the temperature ramp can be too aggressive or it could be due to lack of top side heating element. It’s possible

![Figure 12 Temperature profiles for (a) Takaoka-confocal (b) Insidix-DFP and (c) Akrometrix-shadow moiré. (Top graphs show the delta temperature of the sample; Bottom graphs show the absolute temperature).](image)

![Figure 13 Dynamic warpage as a function of temperature for Leg 3 obtained from Takaoka-confocal, Insidix-DFP & Akrometrix-shadow moiré (AXP)](image)
that the temperature delta can be reduced by the addition of side heating elements or dwelling to reduce the temperature deltas.

The corresponding dynamic warpage data is shown in Figure 13. The range of warpage obtained seems reasonable between the expected value. Since sample W was a package with an integrated heat spreader, the dynamic warpage magnitude seems to not be changing but the shape of the package does. However there were differences among the metrology in terms of range of warpage obtained and this was highly due to the sample provided. The confocal’s dynamic warpage data seems smoother over the temperature while the shadow moiré and DFP system demonstrated more of a saw tooth curve. This is attributed to the higher accuracy and repeatability of confocal technique which focuses on small area around the vicinity of BGA for the warpage quantification rather than entire surface area. Both shadow moire and DFP metrologies employed smoothing algorithms to process the raw data which the level of data smoothing used requires further validation against a higher accuracy tool, such as confocal metrology, to ensure representable smoothing parameters can be obtained.

**Leg 4: Dynamic Warpage Measurement on Package w/ BGAs**

In some cases, there is a need to measure the dynamic warpage of a given package with BGA solderballs intact. The reasons could be the deballing process can be too labor intensive, the need to reuse the package for subsequent evaluation, to avoid potential damage to the ultra thin package, and etc. Hence this experiment was to understand how each metrology handles a non-contiguous surface such as a substrate with solderballs intact. In this case, shadow moiré cannot handle non-continuous surfaces without suffering unwrapping anomalies. However, a confocal approach can suit this demand perfectly as it was designed with the intent to measure packages with BGA intact without the need of manual processing. As for DFP, the use of structured fringes and the relevant software capability can allow the measurement to be performed on packages with BGA and then the use of software to digitally analyze the data to obtain both substrate warpage and BGA coplanarity independently. This digital processing subject to skill in aligning the array of BGA coordinates to the measured surface data to extract the necessary warpage magnitude. Figure 15 shows the results of dynamic warpage for both confocal and DFP. The plotted dynamic warpage behavior from both were within the expectation even though there was potential noise being captured and sign (concave and convex) inversion by using DFP.

**Measurement Throughput Time**

The pre and post processing of the data obtained from each metrology and DOE legs is shown in Figure 14(a). For sample V package used in Leg 2A and 2B that has BGAs, additional deballing needed for DFP and shadow moiré which take about 10 minutes for 4 units. In this study, shadow moiré metrology conducted painting on the surface of the package for measurement to achieve optimal contrast while DFP opted for no painting. The confocal requires none of the deballing and painting. The thermal profile creation for all these metrologies were comparable. The pre-measurement setup for each tool was different hence the time taken was
significantly different. Confocal takes relatively longer time for the first measurement as the units need to be arranged in an orderly manner for proper measurement indexing but significant preparation time reduction for repetitive measurement in Leg 2B. After measurement, the analysis time noted was different among the tools which depends on the operator, software and hardware capabilities as well as the extend of manual data varification and optimizing smoothing process. So it is unclear to these authors how equivalent the actions comprising these analysis times were. As for sample W package which was without BGA attached, the time needed to deball has been eliminated which can potentially contribute 20min or more to the sample preparation time for both DFP and shadow moiré metrology. Hence the pre and post processing time needed for DFP and shadow moiré metrology can vary with the sample condition, the quantity of samples, and operator experience.

The thermal run and time to peak temperature, which is the amount of time needed for the measurement to complete the temperature cycle and to reach the peak temperature respectively, are shown in Figure 14(b). Since the warpage measurements were taken at different reading intervals, the thermal run time can be affected. However the clearest distinction was the time needed for confocal to complete the thermal run measurement and time to peak, which were linearly scaled with the number of interval readings due to it’s measuring protocol. On the other hand, both DFP and shadow moiré have lesser impact to the time to complete the measurement because they use a variable FOV to capture all the samples. If confocal is to improve the thermal run time and time to peak, the number of readings and samples loaded will need to be optimized.

5. Summary

The findings here are limited to the scope of evaluation that was implemented with existing capabilities. All these dynamic warpage metrologies which include shadow moiré, DFP and confocal technique, were able to generate the expected results and provide sub mil resolution or finer.

Shadow moiré utilizes a variable FOV without any degradation of its z-axis resolution which is gated by the density of its Ronchi grating but the camera pixel density can affect the discretization of the moiré fringes. DFP also utilizes a variable FOV but the broader the FOV width, the less dense the structured light distribution which can degrade the z-axis resolution. On the other hand, the DFP does not require continuous surfaces and so can image BGA samples without the need to remove the array of the balls from BGA samples. However, it requires skilled attention to process the data. Depends on the package condition, both removal of solder ball and white painting are the consistent sample preparation steps to consider for obtaining higher quality imaging and data. Confocal, which uses a fixed FOV and image stitching algorithm to capture the surface of interest, has constant and highest z-resolution and repeatability. It requires little or no sample preparation for package dynamic warpage measurement.

Both shadow moiré and DFP allow for close to real time imaging at numerous temperatures coupled with flexible oven chamber sizes to accommodate different sample types and arrangement. Confocal’s fixed FOV demands multiple imaging of a given sample arranged in orderly manner within the size of JEDEC tray oven compartment. This could limit the flexibility of its use models if extend beyond the realm of package measurement. In terms of the heating chamber, the temperature profile used for shadow moiré and DFP based showed it can support both rapid ramp of at least 2°C/s. The delta temperature between the top and bottom of the sample can be further reduced by optimizing the dwell time needed or reconfigure the oven. With topside heating used in DFP and confocal, the delta temperature can be kept minimal. In contrast, the confocal thermal run generated a staggered temperature profile and longer measurement time needed when multiple interval readings and samples are needed. Selectively defined the interval readings for confocal metrology can optimize the measurement cycle time.

Finally, the core intent here was not to compare specific tools or suppliers per se but rather generic metrologies. Each supplier is constantly working to enhance hardware and software capabilies of current and future models. This paper addresses the state of the tools and capabilities applied at the time of writing.

Acknowledgments

iNEMI would like to express the heartiest appreciation to the participating metrology suppliers, namely Akrometrix, Insidix and Takaoka along with the component suppliers for supporting this effort. Without the donation of their time, resources and expertise this paper would not have been possible.

References