Comparing techniques for temperature-dependent warpage measurement

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Three full-field optical techniques, shadow moiré, fringe projection and digital image correlation (DIC), are used to measure temperature-dependent warpage for a PBGA package and a PCB component land site from room temperature to 250°C. The results are qualitatively similar, but imaging resolution and noise properties create offsets between coplanarity values. The paper summarizes strengths and weaknesses for each technique.

Keywords: Shadow Moiré, Fringe Projection, Digital Image Correlation, Measuring Temperature-Dependent Warpage

Introduction

Temperature-dependent warpage is an important issue for manufacturing yield and reliability in modern electronic assembly. Finer pitch interconnects limit solder paste thickness, allowing less tolerance for warpage over the full reflow soldering cycle. Developing packaging technologies, including stacked packages, stacked dies and optical interconnects, suggest future thermomechanical performance requirements will only grow tighter.

National and international standards organizations are addressing this issue. JEDEC published JESD22B112 in 2005, a specification covering measurement conditions and data presentation using thermal shadow moiré. JEITA, in Japan, has drafted a similar standard, extending it to allowed levels of thermal warpage as well as covering both shadow moiré and scanned laser triangulation technologies. JEDEC is currently revising its earlier work, extending it to more types of measurement equipment, adding a shape descriptor method, and improving the accuracy.

The objective of this paper is to compare experimental results for two samples, a PBGA package and a BGA land site on a PCB, using three full-field optical technologies: shadow moiré, fringe projection, and DIC. Different technologies can be expected to show subtle differences in results for real samples. In-plane image resolution, determined by optics, analysis algorithms, and optional smoothing filters applied to the results, is a critical differentiator. We will end with some general comments on the strengths and weaknesses of the different techniques, factors governing the optimum applications for each approach.

Experimental procedures

For comparison, we measured two samples, a PBGA package and a BGA land site on a PCB, with all three techniques under the same testing conditions. All experiments were performed in the AkroMetrix TherMoiré® PS400 as shown in *Figure 1*. The PS400 includes standard shadow moiré and thermal profiling capabilities, as well as optional Micro-Fringe Projection (MP10) and DIC add-ons.

Figure 1. TherMoiré® PS400 with MP10 and DIC set-up

The 14x14x1 mm PBGA was measured from the top surface and supported on all four edges by a custom-designed quartz sample holder. The 80x200x1.4 mm PCB array with a 14x14 mm BGA site was supported on its long edges by the support rails of the PS400. Solder mask-defined features on this surface were approximately 0.3 mm in diameter and 15 μm in height.

Samples were heated from room temperature to 250°C at 0.5°C/s, using IR radiant heating from the bottom side. Temperature data for the PBGA was taken on the bottom center of an adjacent identical sample and for the PCB on the bottom center of the sample. Three shadow moiré runs were conducted first to allow for non-repeatable initial behavior (the third run results are reported), followed by single runs with fringe projection and DIC.

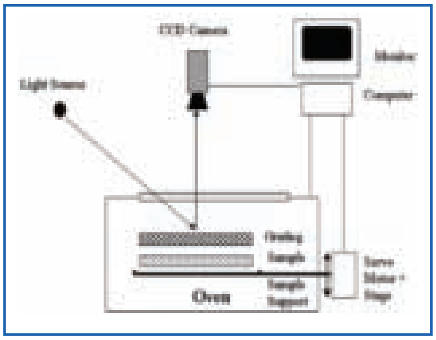

Figure 2. Shadow moiré configuration

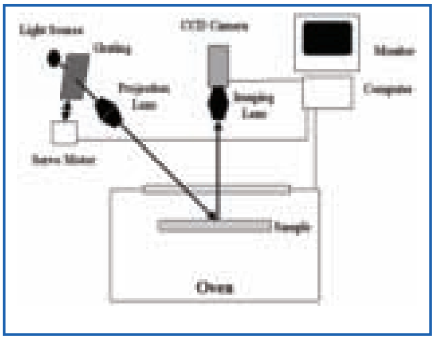

Figure 3. Fringe projection configuration

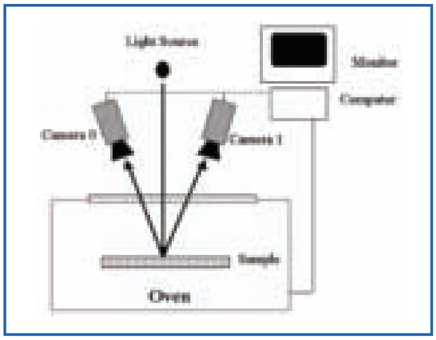

Figure 4. Digital image correlation configuration

Shadow moiré

Shadow moiré uses geometric interference between a reference grating and its shadow on a sample to measure relative vertical displacement at each pixel position in the resulting interference pattern image. It requires a Ronchi-ruled grating (alternating clear and opaque lines of equal thickness and constant pitch imprinted on a high temperature, low CTE glass), a white line light source at approximately 45 degrees to the grating, and a camera perpendicular to the grating. Its optical configuration integrated with the heating chamber is shown in *Figure 2*. A technique, known as phase stepping, is applied to shadow moiré to increase measurement resolution and provide automatic ordering of the interference fringes from high to low[1]. This technique is implemented by vertically translating the sample relative to the grating.

The samples were prepared with a light coat of high temperature white spray paint to increase the signal-to-noise ratio. A 300 line per inch grating with out-of-plane resolution of 0.85 microns was used for both samples. The PBGA images were 162x164 pixels and the PCB BGA site images were 156x156 pixels, both giving an XY imaging resolution of approximately 12 pixels/mm.

Because the out-of-plane resolution is primarily a function of grating pitch in this configuration, shadow moiré can be scaled to relatively large samples without resolution loss. However, this technique is limited as sample size decreases, especially below 10 mm. When camera image pixel pitch approaches one-half the grating pitch, the resolution of the reference grating lines introduces an aliasing error in the displacement data. If a finer pitch grating is used to achieve higher magnification without resolving grating lines, this approach will be complicated by reducing the working distance between sample and grating created by the Talbot effect[2, 3].

Fringe projection

Similar to shadow moiré, fringe projection is also a non-contact, full-field optical technique for out-of-plane and topography measurement[4]. Fringe patterns can be generated digitally by a computer controlled LCD/DMD or by projecting white light through a physical grating. In this study, the latter method is used with a sinusoidal transmittance grating placed close to the light source. The normal of the grating plane has a 45-degree angle with respect to the sample. The fringe pattern on the grating is projected onto the sample surface through a set of projection lenses. A camera above the sample acquires the distorted fringe patterns, which are then used to calculate the relative vertical displacement at each pixel position from its reference plane. *Figure 3* shows the configuration of the fringe projection system. Phase stepping similar to that of shadow moiré is performed by shifting the grating along its grating plane instead of vertically translating the sample. Data analysis is also similar to that for shadow moiré.

Since the camera needs to resolve the projected fringes on the sample surface for data analysis, a thicker and more uniform coat of white spray paint was applied onto the sample surface to increase the signal-to-noise ratio. A 151 line per inch grating was used for both samples, resulting in an out-of-plane resolution of 3 µm. The PBGA images were 990x950 pixels and the PCB BGA site images were 971x968 pixels, both giving an XY imaging resolution of approximately 70 pixels/mm. At high magnifications, the optical paths of both the projected and observed fringe pattern are subject to distortion by air density variations due to convective currents. An external fan was used to reduce convective air currents between the camera lens and oven window to reduce this effect.

The out-of-plane resolution of this technique is dependent on the grating pitch and the ability to project the fixed grating lines onto a certain sample field of View (FOV). Smaller grating pitch and/or smaller FOV yield finer out-of-plane resolution. When sample size drops to 10mm or smaller, out-of-plane resolution is comparable to shadow moiré and its XY imaging resolution is significantly better.

Digital image correlation

Digital image correlation, or DIC, is an optical method for measuring both in-plane and out-of-plane displacements of an object surface[5]. A high contrast, random speckle pattern is applied to the surface of interest. Two cameras are mounted above the oven, viewing the sample from different angles as shown in *Figure 4*. Images are captured from both cameras simultaneously. Software identifies the same point on the surface from both perspectives, using pattern recognition of the speckles within a small pixel window. Using the principle of stereo triangulation, the spatial position of the pixel window relative to the cameras is determined in 3D space. Stepping the pixel window across the sample, both in-plane and out-of-plane displacements can be mapped out.

In our experiment, the samples were prepared with a thin uniform coat of high temperature white spray paint, followed by black spray paint throttled to create a random speckle pattern. A stereo angle of approximately 20 degrees was set between the two cameras. The FOV was adjusted to be 45x34 mm, leading to an out-of-plane resolution of 1 µm. The 14x14 mm sample areas comprised 434x434 pixels. A 21x21 pixel window was set for the PBGA component, setting the effective XY imaging resolution as 1.5 pixels/mm, while a 9x9 pixel window was set for the PCB BGA site, setting the effective XY imaging resolution as 3.4 pixels/mm. An external fan was also used to reduce convective air currents during heating and cooling.

Achieving optimum performance from DIC measurements is critically dependent on the size distribution of the speckles and pixel window size. Speckles should be

3 to 5 pixels in diameter and random in position. Larger or smaller speckles can add noise to the measurement. Pixel window size must be large enough so that unique pixel configurations can be obtained. However, the positional coordinates are averages over the pixel window, which reduces XY imaging resolution of this technique.

Experimental results and discussion

Warpage variation with temperature was qualitatively similar for all three techniques. *Figure 5* shows warpage along the diagonal cross-sections for the PBGA top surface, concave at room temperature and convex at 250°C. *Figures 6a and 6b* show the coplanarity vs. temperature for the three techniques for the PBGA and PCB, respectively. The PBGA warpage shows an inversion of the warpage around 200°C, with minimum coplanarity around this temperature. The PCB shows relatively little effect below 200°C, above which it grows approximately 10 µm more concave. In both cases, the curves show a range of coplanarity values of about 10 µm.

The problem in comparing results across techniques lies in the definition of the coplanarity gauge. Coplanarity is the difference between the highest and lowest displacement values in the full-field data set, with respect to a least-squares fit reference plane. As a result, it is extremely sensitive to statistical extrema in the data set. Coplanarity includes contributions from the substrate warpage, surface features, and noise. In practice, many procedures for routine calculation of coplanarity call for filtering or truncation of statistical outliers in the data set, in order to achieve acceptable levels of reproducibility.

The presence of surface features, such as copper traces and solder pads (as well as extraneous features from surface damage and coating defects), contributes to the coplanarity value, to the extent that the XY imaging resolution of the technique does not average out these features. *Figure 7a* shows the shadow moiré results for the PCB component land site at room temperature, with a complex pattern of solder pads and other features. To illustrate the effect of XY imaging resolution, *Figures 7b and 7c* show the central portion of this pattern as measured by fringe projection and DIC, respectively. Fringe projection shows much finer resolution of the pattern, as expected, which should translate into higher coplanarity values since the height of the fine structure is subject to less spatial averaging.

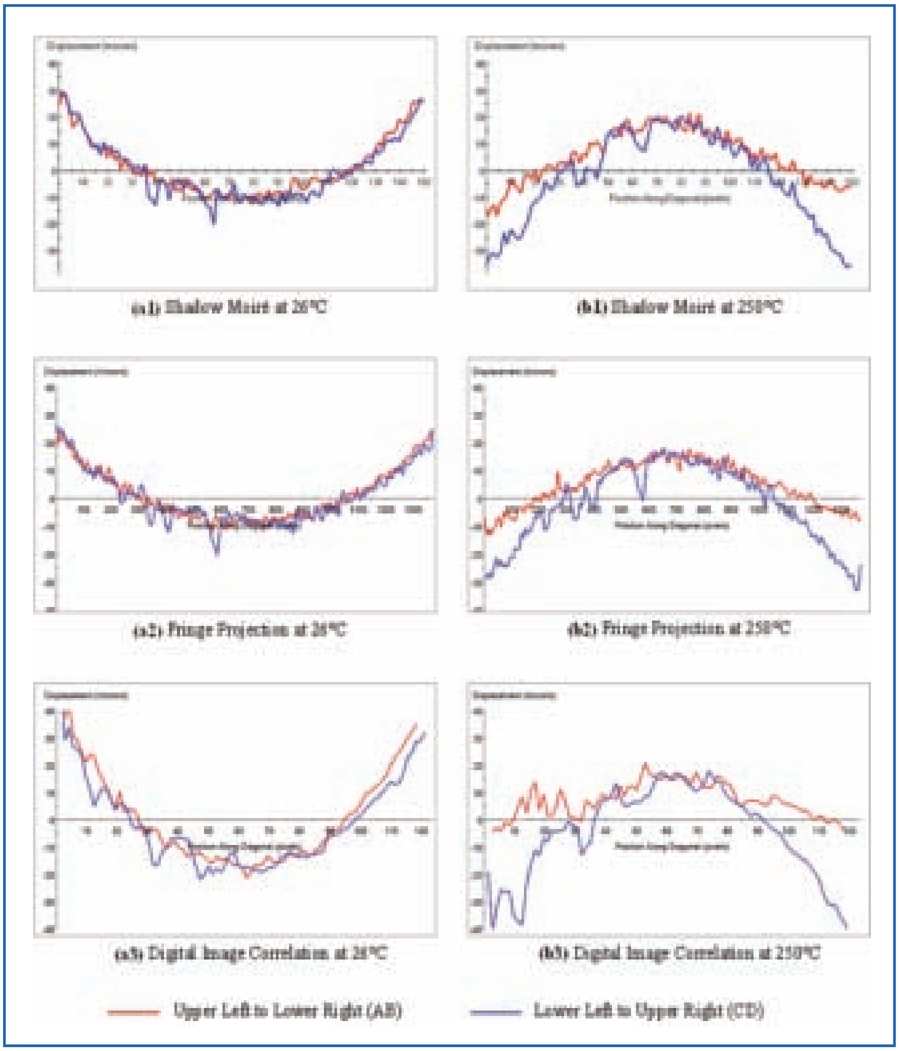

Figure 5. Diagonal plots of a 14mm PBGA at 26°C and 250°C

Conclusions

Experiments on the 14mm samples in this paper demonstrate that all three techniques have the capability of measuring temperature-dependent warpage. While the technical specifications described are characteristic to our experimental configurations, each technique has general strengths and weaknesses that may make it optimal for individual applications.

Shadow Moiré

+ Robust
+ Out-of-plane resolution independent of field of view
- Magnification limited by grating line resolution
- Adjacent grating affects sample thermal behavior

Fringe Projection

+ Better XY imaging resolution
+ Variable grating pitch possible
- Out-of-plane resolution scales with field of view
- More sensitive to vibration and thermal air currents

Digital Image Correlation

+ In-plane strain measurement capability
+ Simple hardware with high speed data acquisition
- Out-of-plane resolution scales with field of view
- Poorer XY imaging resolution
- Sample preparation more complex

This summary suggests some favorable applications, e.g. shadow moiré for large samples, fringe projection for small samples, DIC where in-plane strain is important. However, all three techniques are expected to be widely used for a wide variety of samples, making full consideration of specific technique characteristics critical to the interpretation and comparison of results.

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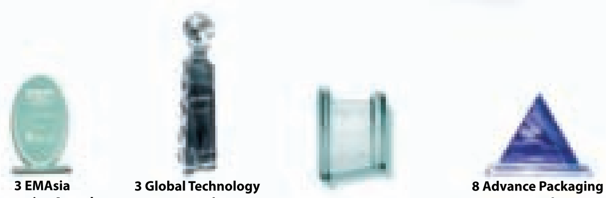

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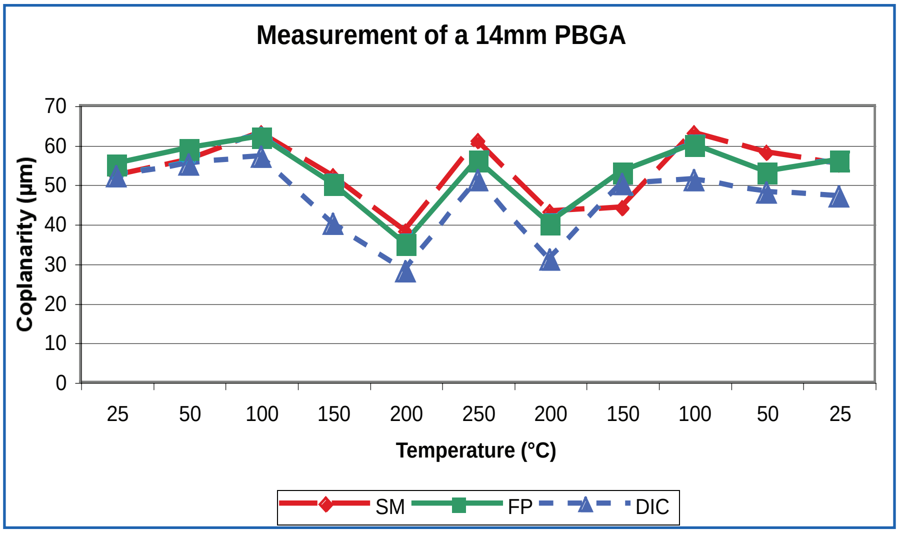

Figure 6a. Thermal warpage of a 14_14 mm PBGA

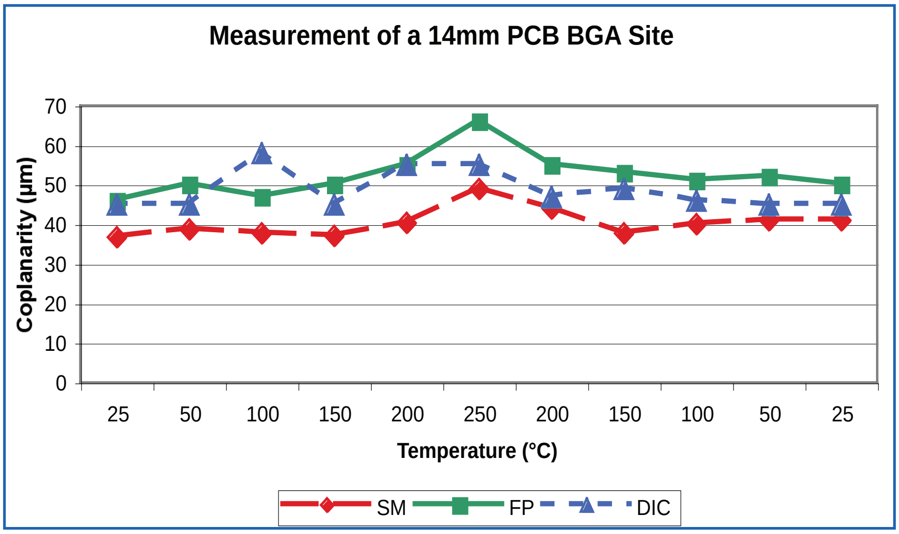

Figure 6b. Thermal warpage of a 14_14 mm PCB BGA

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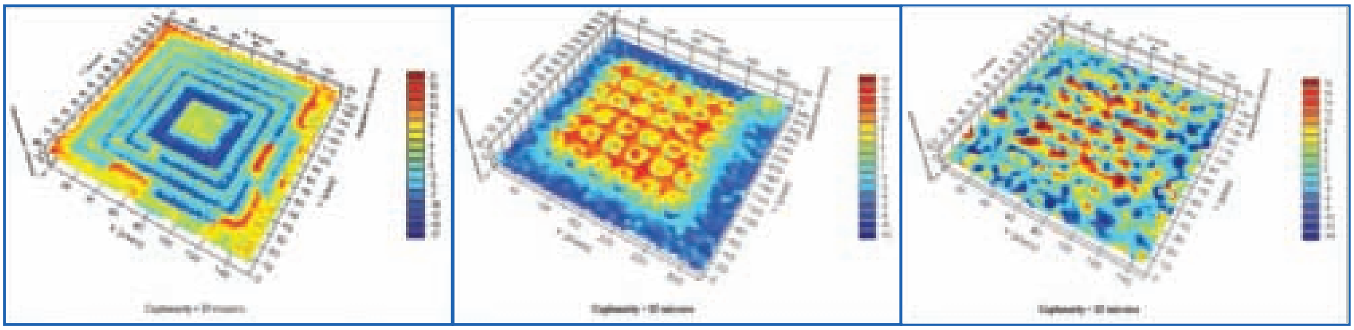

Figure 7. 3D surface plots of a 14mm PCB BGA site at room temperature (a) shadow moiré, full view (b) fringe projection, zoomed view (c) digital image correlation, zoomed view