

Advanced assessment of thermal stress related failure modes occurring during the assembly of high pin count BGAs on PCBs

Michael Hertl, Diane Weidmann
INSIDIX, 24 rue du Drac, F-38180 Seyssins, France
e-mail: michael.hertl@insidix.com, phone: +33-4.38.12.42.80

Abstract

When addressing failure modes and reliability problems of high pin count circuits, the coplanarity of the solder balls is of major importance. In fact those components with more than several hundreds of solder balls only operate correctly if each single ball is correctly soldered.

On the other hand, those components are in general critical in terms of thermo-mechanical behaviour. They are often used for heavy calculation purposes, and therefore generate a significant amount of heat during operation. Additionally, the mechanical structure is complicated, involving apart the die itself several laminated routing layers. All those laminated materials (silicon, copper, different kinds of routing layer substrate, mould compound, etc.) are characterized by different CTEs (coefficient of thermal expansion). Therefore each temperature variation of the component will inevitably generate internal stress and thus deformation of the entire component.

An important amount of thermo-mechanical stress, and thus deformation, occurs during the reflow solder process. Due to the process heat up to 260°C the coplanarity failure of the ball array may become such important that a part of the solder balls is not touching at all the PCB at the moment of solder solidification. Or the contact between single balls and the PCB might be weak, and the resulting connection of this ball will cause a permanent reliability risk during the product's life time. Therefore, with increasing dimension and increasing pin count, coplanarity validation of the balls at solder temperature becomes a key issue for high pin count component reliability.

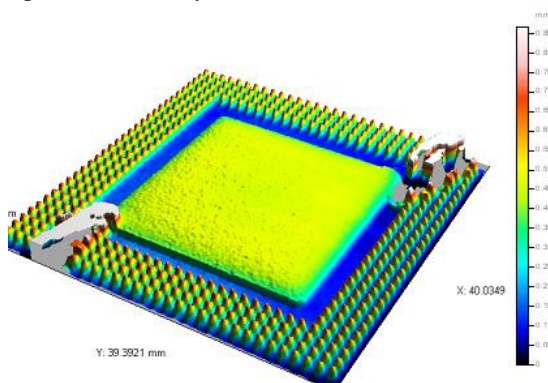


Fig. 1: High resolution 3D topography obtained on a high pin count BGA.

In the present paper we will introduce Insidix' new Topography and Deformation Measurement (TDM) system, specifically designed for high resolution easy to operate coplanarity measurements on high pin count BGAs during reflow solder cycles, with temperature gradients up to +3°C/s / -6°C/s in a temperature range from 25°C to 300°C. Applications on different high pin count BGA components and related assemblies will be discussed (see Figure 1).

Experimental set-up

The experimental set-up is shown in Figure 2. The electronics component or assembly to be studied is illuminated by structured light on its surface. The stripe pattern is more or less deformed by the sample's surface structure. The resulting image is captured by a CCD camera.

Thermal stress generation is available by top and bottom heating and cooling elements. The sample temperature is monitored by up to 4 thermocouples. User defined temperature profiles with heating gradients up to +3°C/s and cooling gradients down to -6°C/s may be imposed to the sample, within a temperature range from -60°C up to +300°C.

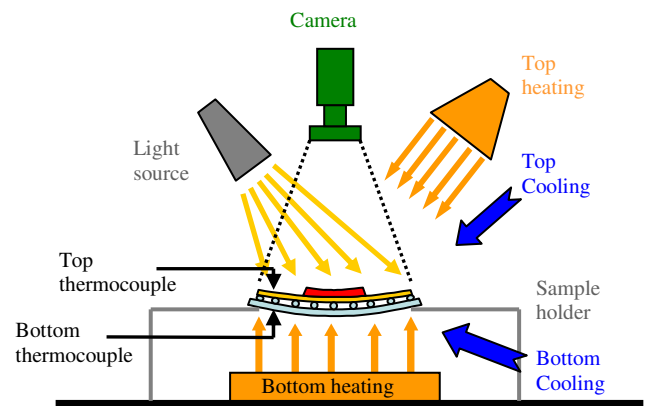


Fig. 2: Sketch of the Topography and Deformation Measurement (TDM) set-up.

The primary obtained information consists of high resolution 3D topography images of the entire assembly, as shown in Figure 1. The high depth of view (up to 32 mm) of the optical set-up allows to acquire all relevant levels of virtually every component or assembly simultaneously, as for example PCB, BGA substrate and BGA top surface. For each pixel, the (x,y,z) coordinates are absolutely known. After acquisition, software zoom on each level is possible and will reveal detailed surface information on a μm scale.

Application 1: Component warpage

Too strong component warpage during the solder process is a regularly seen potential root cause for failures like opens or bad quality solder joints. Therefore it is important to qualify critical parts, such as in particular high pin count BGAs, in terms of maximum warpage during the entire thermal profile.

Figure 3 shows the top and bottom side of a 30 × 30 mm BGA with 548 solder balls. The aim of the first part of the present study is to check the coplanarity of this sample under reflow solder temperature conditions.

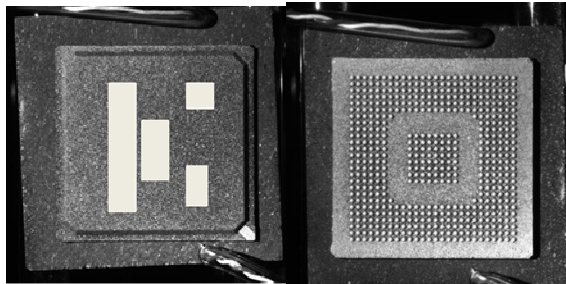


Fig. 3: Top and bottom view of the BGA under study.

For doing so, the sample is placed in the TDM system, and a temperature profile identical to the projected solder profile is programmed. The sample temperature is monitored by 2 thermocouples, which are placed in the near vicinity of the sample, on the graphite made sample holder. The programmed temperature profile is shown in Figure 4, together with the measured one during a typical experimental run. It can be seen that the programmed profile is very well followed, even during the steep heating up and cooling down respectively at the beginning and the end of the run.

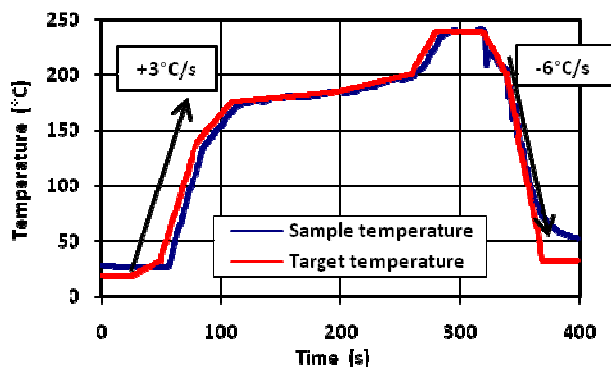


Fig. 4: JEDEC type reflow temperature profile, applied to the BGA in the TDM system.

Simultaneously to the running temperature profile, snapshots of the 3D sample surface topography are taken. Figure 5 shows the top side sample topography at room temperature. The same images are obtained at selected higher temperatures, up to 240°C. A diagonal 2D profile is extracted along the diagonal of the full 3D image, and the amplitude of this diagonal profile is automatically calculated. In the top view experimental set-up, the amplitude of this diagonal profile is considered as an easily accessible measure of the component's warpage. In

this way, top side warpage values are obtained at the following temperatures: 30°C – 100°C – 180°C – 220°C – 240°C – 220°C – 200°C – 180°C – 100°C – 30°C.

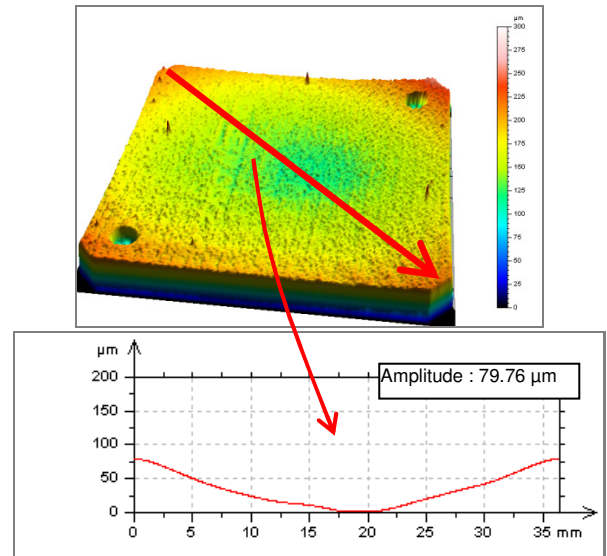


Fig. 5: Top: BGA top surface topography. The color scale indicates absolute heights from 0 to 300μm. Bottom: 2D profile extraction following the BGA diagonal (as indicated).

The procedure shown above allows fast and easy measurement of the warpage vs. temperature characteristic of the bottom side of any given component. In general, it can be assumed that the bottom side warpage follows the top side warpage, so that the results obtained on the component top side reflect with sufficient accuracy the bottom side warpage, where the solder balls are.

However, direct bottom side measurements nevertheless are often interesting: Some more analysis work is necessary, due to the presence of the solder balls. But in contrast, detailed height information can be obtained for each single solder ball, at all temperatures from room temperature up to maximum solder cycle temperature. Figure 6 shows the bottom side topography of the BGA shown in Figures 3 and 5.

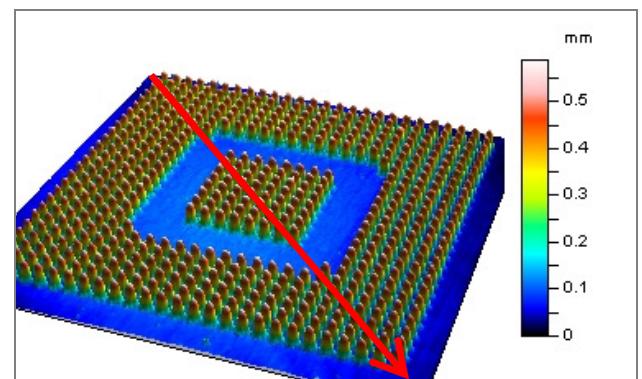


Fig. 6: Bottom side topography of the same BGA as shown in Fig. 5, with all solder balls in place. Again, 2D diagonal profiles are extracted following the indicated red arrow.

2D diagonal profiles are extracted from the bottom side topography, in the same way as from the top side one. Figure 7 shows some of them.

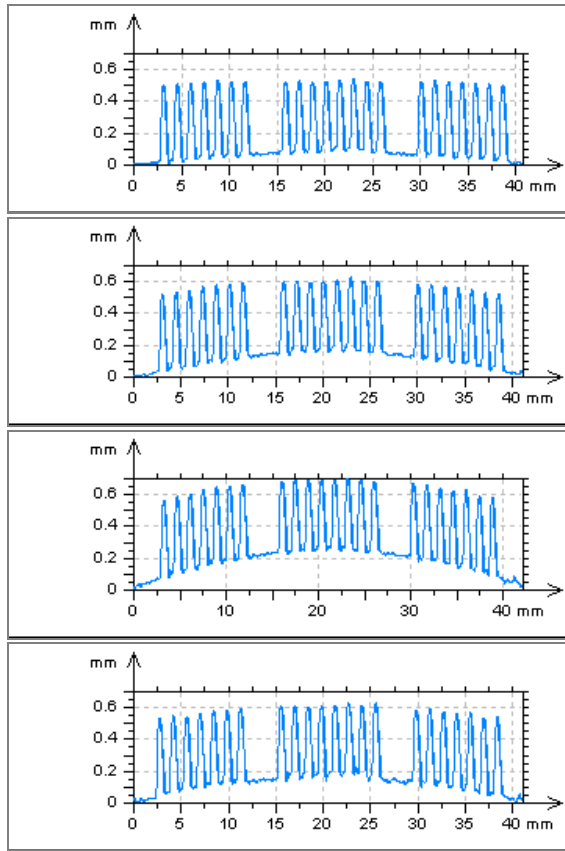


Fig. 7: From top to bottom: 2D diagonal profile on the BGA bottom side, obtained respectively at 30°C – 100°C – 180°C – 240°C.

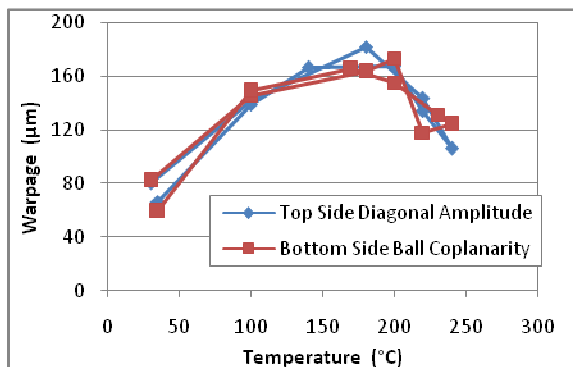


Fig. 8: Warpage vs. temperature behavior of the component, extracted either as top side 2D diagonal profile amplitude, or as bottom side lowest-to-highest ball distance difference.

The profiles shows relatively limited warpage at room temperature, which is consistent with the component top side result shown in Figure 5. Then, with increasing temperature, the bottom side warpage increases, and takes its maximum value of about 170 µm at a temperature of 180°C. At higher temperatures, the component relaxes

slightly, to show a warpage of about 120 µm at the maximum temperature of 240°C.

The important advantage of this type of bottom side analysis is that now the absolute distance between the top level of the highest and the lowest solder ball can be extracted, which is the key value for failure analysis and reliability analysis concerning the solder process. If this distance is too high, either at least one of the balls will not touch the PCB at all during soldering, or the contact between at least one ball and the PCB will be so weak that bad solder joint quality will result.

Figure 8 shows a summary of the warpage results, for both top and bottom side measurement, at various temperatures. At most temperatures two data points are indicated, one corresponds to the topography obtained during heating, the other one to the topography obtained during cooling down.

The results are:

- Top and bottom side analysis indicate the same sample warpage, for all analysed temperatures.
- The maximum warpage occurs at 180°C, with an absolute value of 170 µm.
- The warpage behaviour is reversible, that means when cooling down, the warpage measured at a given temperature is the same as during the heating up phase.

This result offers the process development engineer the opportunity to exactly know the warpage behaviour of components to be soldered before actually doing the solder process. Components with too important warpage can easily be identified.

Application 2: Component – PCB stress transfer

Component warpage analysis prior to soldering, as shown in the previous section, is only the first step towards a full understanding of potential reliability problems of assemblies. The next step concerns the study of the interaction between component and PCB, once the assembly process is done.

Figure 9 shows a full field image of the topography of an entire assembly, including a BGA of the same type as the one analysed in the previous section. This type of acquisition can give information concerning the stress interaction between component and PCB. For this purpose we check the deformation characteristics between different temperatures of the component alone, and the component assembled onto different types of PCBs.

Figure 10 shows relative deformation images $\Delta z(x,y)$ of the BGA top surface, acquired on the BGA alone (top line), and the BGA assembled onto 2 different PCBs (middle and bottom line). Each image shown in Figure 10 is the result of a pixel-by-pixel topography difference calculation $\Delta z(x,y) = z(x,y,T_{final}) - z(x,y,T_{initial})$. This representation facilitates the identification of deformation behaviour differences of the 3 components in different conditions of assembly.

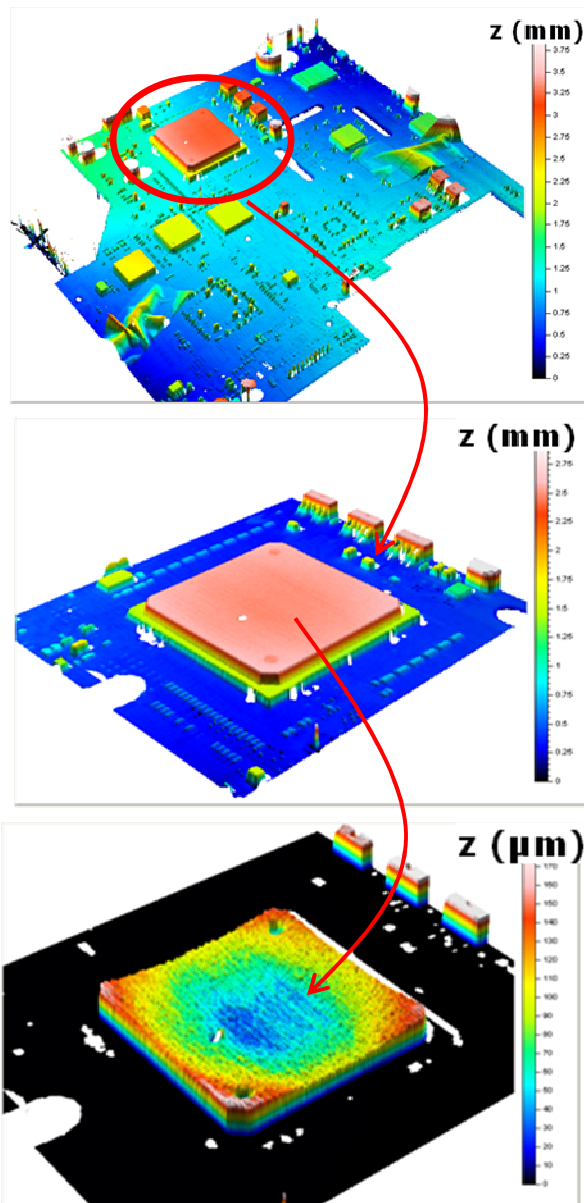


Fig. 9: Full field acquisition of a fully assembled PCB (top), and successive (numerical) zooms on the BGA included in the assembly. Note that the zoom images are obtained by data analysis only, without any further acquisition done on the assembly. The μm -scale details shown in the 3rd image on the BGA top surface are already included in the large (overview) image on top. Only the height scale changed between these two images.

The following can clearly be seen:

- The deformation characteristic of the component alone is clearly different from the one of the component assembled.
- Similarly, for the two different assemblies, the component does not behave in the same way for the same kind of temperature variation.
- For example, in case of the component alone, increasing the temperature from 30°C to 240°C makes the component centre decrease

in height with respect to the component corners (first line, central image). In contrast, for identical temperature variation, in case of the same component assembled onto PCB type B, the centre of the component increases in height with respect to the component corners (third line, central image).

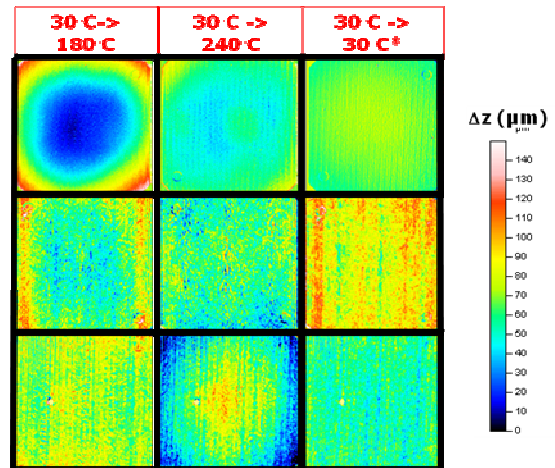


Fig. 10: Deformation characteristics of the BGA alone (first line), the BGA assembled on a PCB type A (second line), and the BGA assembled on a PCB type B (third line).

These results clearly show the stress transfer between component and PCB in an assembly. The more the component behaviour in case of the assembly differs from the behaviour of the component alone, the higher is the interaction between component and PCB.

Application 3: Component – PCB CTE mismatch

This chapter introduces a failure mode related to CTE (coefficient of thermal expansion) mismatch between the PCB and the components soldered onto it. If these CTE's are too different, then each temperature variation on the assembly leads to strong in-plane stress transfer between components and PCB.

Quantitative in-plane deformation analysis of components and assemblies have been done once again on the BGA presented in Figure 3 and two different assemblies including this component, by applying the digital image correlation (DIC) technology. Briefly, for doing DIC, a thin layer of white spray is applied to the sample surface, which gives the sample surface a granular structure with typical grain sizes in the order of a few μm . Applying white light under an angle of about 45° to the sample will generate a random light/shadow (grey scale) structure on the sample. Two digital images (photographs) of the sample are then taken at two different temperatures. Finally, a numerical algorithm correlates the two different grey scale structures of the images, in order to identify displacement vectors characterizing the in-plane deformation of the sample between the initial and the final temperature.

Figure 11 shows the result in case of the BGA alone, for a temperature increase from 35°C to 200°C. Note that the measurement is applied to the BGA bottom side, with all solder balls in place.

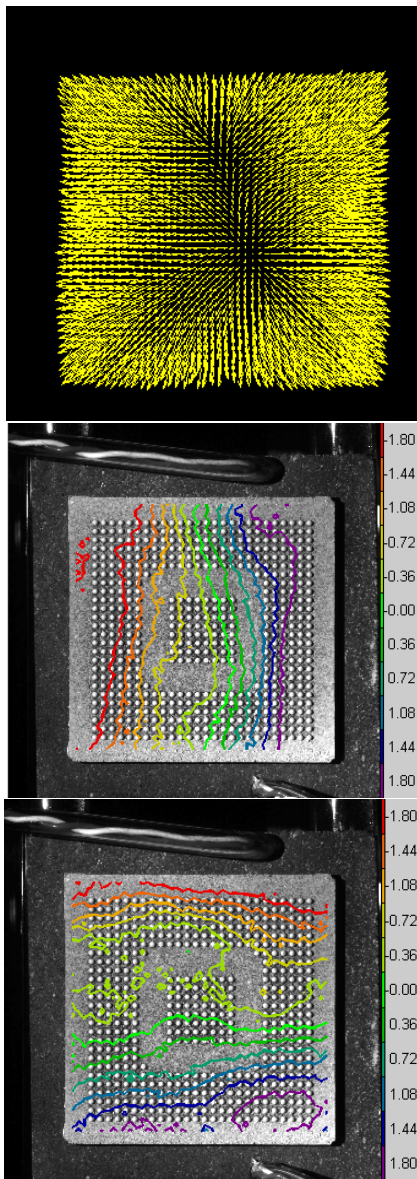


Fig. 11: In-plane deformation analysis of the BGA alone, for a temperature increase from 35°C to 200°C. Top: Qualitative vector displacement field. Quantitative iso-displacement line analysis in x- (centre) and y- (bottom) direction. Each iso-displacement line combines all pixels that undergo the same displacement (either in x- or y-direction) for the given temperature variation.

The qualitative displacement vector field indicates isotropic expansion of the component. The quantitative iso-displacement line images allow to easily calculate the CTE of the component, as an average value for the given temperature range. In the present case, an average CTE of 20×10^{-6} 1/K can be calculated for the component alone, for the given temperature range.

Figure 12 shows the result of the same measurement, applied to assembly type A, including the BGA as one of

its multiple components. For the assembly, for the same temperature variation as used for the BGA alone, a CTE of 12×10^{-6} 1/K is obtained.

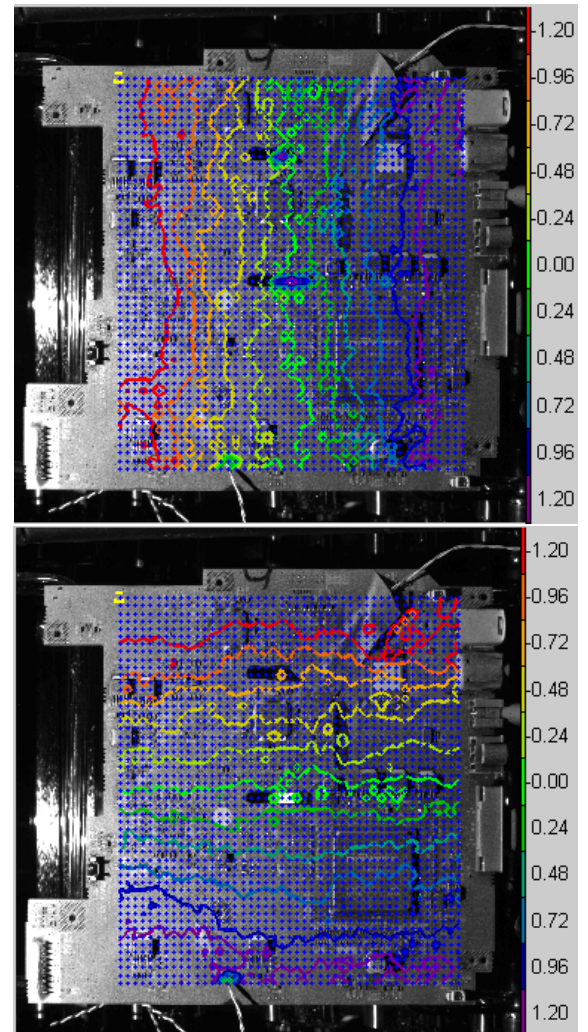


Fig. 12: In-plane deformation analysis applied to an entire, fully equipped assembly. Initial temperature: 35°C; final temperature 200°C.

This result shows that even at room temperature, without any temperature variation, permanent stress is applied onto the BGA's solder balls: During the solder process, the solder balls become solid at about 215°C. Then, while further cooling down, the BGA is forced to shrink together with the assembly, thus with a CTE of 12×10^{-6} 1/K. However, as a component alone, the BGA would shrink with a CTE of 20×10^{-6} 1/K. Thus the presence of the PCB hinders the BGA from shrinking corresponding to its material characteristics, and all forces necessary for keeping the BGA from higher shrinking are transmitted via the solder balls.

Conclusions

A new experimental tool, TDM, has been presented to analyse component and assembly surface deformations, which allow to deduce information about underlying stress build-up in electronic samples.

TDM has been applied to visualize out-of-plane (z) topographies and deformations of a BGA alone, top and bottom side, and of assemblies featuring this BGA as one of their multiple components. In a second experiment, significant variations concerning the in-plane deformation under temperature variation have been shown for component and assembly (CTE mismatch).

These results significantly increase the characterisation panel of the assembly concerning failure risks during the solder process, and reliability expectations of the assembly during its operation at the customer.

References

1. M. Hertl, D. Weidmann, A. Ngai, "An Advanced Reliability Improvement and Failure Analysis Approach to Thermal Stress Issues in IC Packages," *Proceedings of the 16th IPFA*, Suzhou, China, July 2009, pp. 28-32.