Measurements and Stochastic FEA with Application in Thermomechanical Characterization of Electronic Packages

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Abstract. The aim of this study was to validate/calibrate two tools to be able to reliably measure/predict warpage at ambient temperature, especially for ball grid array (BGA) electronic packages. The tools used in this study were a high-precision microscope and a finite-element model. First, the authors calibrated the microscope by comparing the obtained results with the results obtained with a shadow moiré machine (considered as reference) and then the finite-element model was calibrated to the microscope. The numerical study was not restricted to a deterministic approach; a stochastic study was also performed for taking into account parameter uncertainties. The results demonstrated that both tools are reliable alternatives for thermomechanical characterization of BGA packages at room temperature. The results obtained in the finite-element model calibration phase showed the importance of adopting a probabilistic approach, at the same time proving that the elaborated warpage numerical model is a good basis for future advanced analysis such as optimization or numerical design of experiments while having reasonable investment and time-consumption costs.

Keywords*:* *BGA; FEA; microscope; shadow moiré; stochastic analysis; warpage.*

1 Introduction

Electronic packages provide two main functions for integrated circuits (ICs), i.e. mechanical protection and electrical interconnection between ICs and electronic systems. There are several variants of electronic packages, among which ball grid array (BGA) packages. BGA packages are exposed to several temperature phases during assembly, leading to mechanical deformation of the package from the ideal state of flatness, i.e. warpage [1]. This is caused by a mismatch of the coefficient of thermal expansion (CTE) of the various materials composing

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these packages. Package warpage is typically temperature-dependent and when this phenomenon is excessive, it can cause solder short or non-wetting during the solder ball attachment reflow process as well as during the board mounting process [2]. For this reason, designers should predict package warpage before prototyping to get reliable products at the end [3].

The shadow moiré technique [4] is the most efficient and widely used technique to measure package warpage vs. temperature variation (especially the reflow temperature profile) [5]. However, a shadow moiré machine is a huge investment (> 200 k$), especially considering that in some cases warpage only needs to be evaluated at room temperature. An alternative is to subcontract measurements for each new design to a third-party supplier, but this may still be too expensive (~1K$) for one package sample. Then, inevitably, performing a design of experiments (DOE) incurs a prohibitive cost [6].

The authors looked at ways to work around the use of a shadow moiré machine for thermo-mechanical characterization of BGA packages using two tools that have the potential to measure and predict package warpage: a high-precision microscope (HPM) and a finite-element analysis (FEA) model performed with ANSYS Mechanical software. However, both tools need calibration to ensure that they provide reliable results. To achieve this goal, the following steps were performed. Firstly, calibrating the microscope by comparing its results against those of a shadow moiré machine (performed by a subcontractor for 4 BGA packages). Secondly, calibrating the ANSYS FEA model to the HPM without restriction to only a deterministic study but also performing a stochastic study by integrating design parameter uncertainties (especially the epoxy mold compound properties). Note that all considerations/assumptions for the simulation (elasticity, Cu trace modelling, CTE estimation for polymers) are highlighted in this work.

2 Aims of the Study: Calibration of HPM and ANSYS Warpage Model

The first part of the study was aimed at calibrating the HPM to ensure its capability of accurately measuring the warpage of BGA packages at room temperature. As a matter of fact, warpage measurement at room temperature can be performed by any equipment capable of measuring terminal deviation from coplanarity with accuracy within ±10% of the specified deviation [7]. The authors hypothesized that a HPM can potentially be used for warpage measurement at room temperature. Nevertheless, accurate measurements are required as a reference for the calibration (via comparison). The second part was the calibration of a warpage model developed via ANSYS to ensure its capability to accurately estimate warpage. For the simulation-based analysis, an

ANSYS model for warpage calculation was performed. At first sight, the model gives credible results. However, to validate it we should compare the obtained results with validated measurement results (as reference).

3 BGA 10×10 mm^2

Both the measurements and the simulations were done for a BGA package with size 10×10 mm^2 of which the parameters are presented in Figures 1 and 2, Tables 1 and 2.

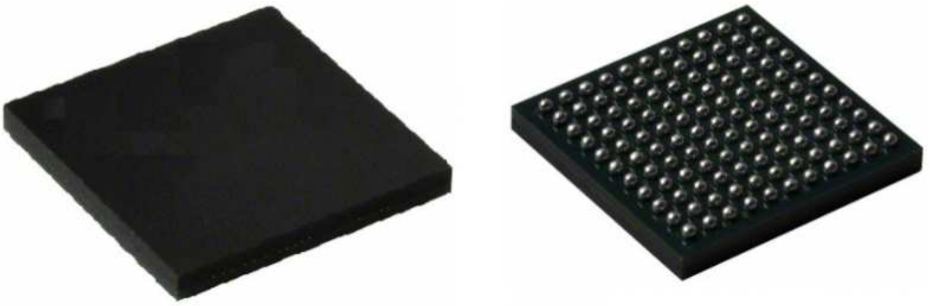

Figure 1 BGA overview.

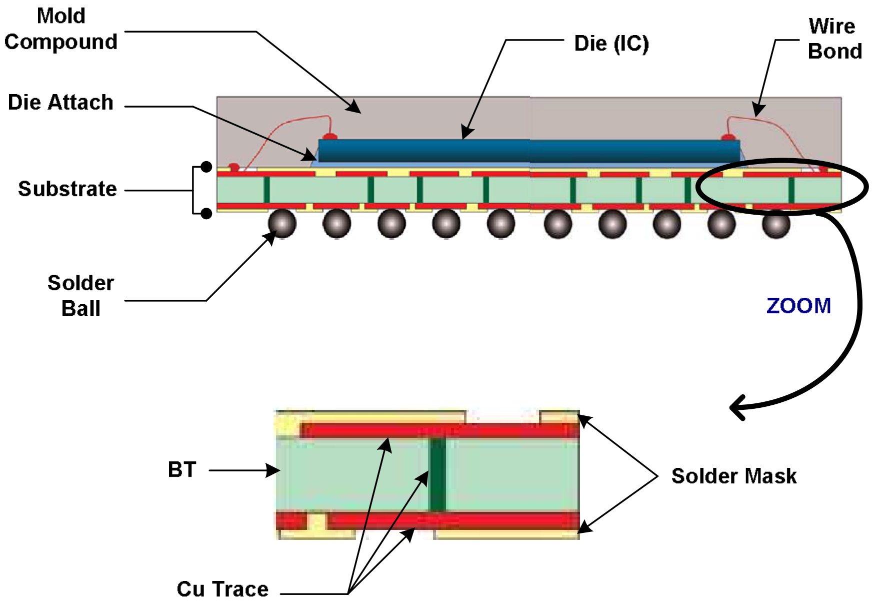

Figure 2 BGA sectional view.

Table 1 BGA dimensions.

Layer	Size (mm)	Thickness (mm)
Substrate	10 × 10	0.2
Die attach	5.16 × 4.92	0.015
Die (IC)	5.16 × 4.92	0.29
Over mold (EMC)	10 × 10	0.57
Top & bot. Cu	10 × 10	2 × 0.018
Top & bot. solder mask	10 × 10	2 × 0.007
Opening / pads	450 / 350	0.018

Table 2 BGA material mechanical properties.

Material	Poisson Coefficient	Tg (°c)	Young Modulus (Mpa)	CTE (ppm/°c)
Substrate	0.19	185	28000	CTE1x,y = 14, CTE1z = 35 - - - CTE2x,y = 5, CTE2z = 140
Die attach	0.4	42	410/60/40/70/120 @ 25/100/150/200/250°c	CTE1,2 = 48 / 140
Die	0.279	--	131000 / 130000 / 129000 @ 20 / 50 / 227 °c	2.36 / 2.89 / 3.3 / 3.61 @ -73 / 52 / 152 / 227 °c
Mold compound	0.35	120	20000 / 500 @ 25 / 215 °c	CTE1,2 = 11 / 45
Cu	0.344	--	128900	16.7
S. mask	0.467	104.8	3500	CTE1,2 = 60 / 160

4 HPM Calibration

Warpage measurement was done with the HPM and the shadow moiré machine for 4 packages (P1, P2, P3 and P4) that were encapsulated with a resin stocked in questionable conditions and for which the usage date had expired. These packages belonged to the same matrix (strip) and were sawed right after the molding process.

4.1 HPM Equipment

An HPM is a semi-automatic vision measurement system that allows conducting non-contact measurements for control of geometric parts and profiles. It is a compact machine equipped with a high-resolution charge coupled device (CCD) camera, automatic zoom, specific lighting and image processing algorithms.

4.2 HPM Warpage Measurements at Room Temperature

The procedure adopted by the authors to carry out the measurements was as follows: for each package, the measurements were done in 3 different positions (to eliminate the risk of imperfect HPM table planarity) by measuring the package corner heights ($Z_{i\,=\,1,..4}$) assuming that the height origin is the package bottom center surface. For each package, the warpage is simply the average of the package corner height $\left(\mathrm{Warpage} = \left(\sum_{i=1}^{4} Z_i\right)/4\right)$. The results were as shown in Table 3.

Table 3 HPM results.

Package	Warpage (μm)
P1	95
P2	96
P3	99
P4	108

4.3 Shadow Moiré Technique

With the shadow moiré technique, a solid object surface topography can be measured, i.e. its deviation from a planar surface. Figure 3 shows a schematic of the technique. Measurements are made by placing a sheet of low expansion quartz glass etched with equally spaced parallel lines parallel to the sample.

A beam of white light is then directed onto the glass and the etched lines on the glass create a shadow on the top surface of the sample. When the sample (electronic package, printed wiring board, …) surface is inclined or curved, a moiré pattern is produced by the geometric interference between the etched lines on the glass and the shadows of those lines on the sample's surface. If the sample is flat and parallel to the grating, there is no warpage and no moiré pattern is produced. The warpage, W, can be calculated from the following Eq. (1):

$$W = N.p/\left(tan(\theta) + tan(\beta)\right) \tag{1}$$

where N is the fringe order, p is the pitch of the grating, θ is the angle of illumination, and β is the angle of observation. The highest sensitivity that shadow moiré can practically reach with this approach is ±2.5 (μm) [8].

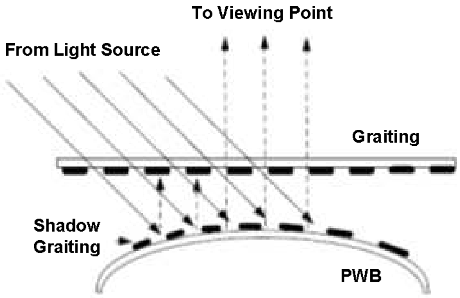

Figure 3 Schematic of the shadow moiré technique.

4.4 Shadow Moiré Warpage Measurement at Room Temperature

As mentioned in the introduction, the main goal of this study was to get around using a shadow moiré machine (the reference tool) during the design and prototyping phase of electronic packages because it is a large investment. Indeed, the HPM has the potential to measure warpage but it must be calibrated first based on reliable reference measurements. Therefore, we decided to order the reference warpage measurements from a subcontractor, who performed them using a shadow moiré machine while respecting the recommendations of the Joint Electron Device Engineering Council (JEDEC). The shadow moiré results for the same packages inspected in Section 4.2 are presented in Figure 4.

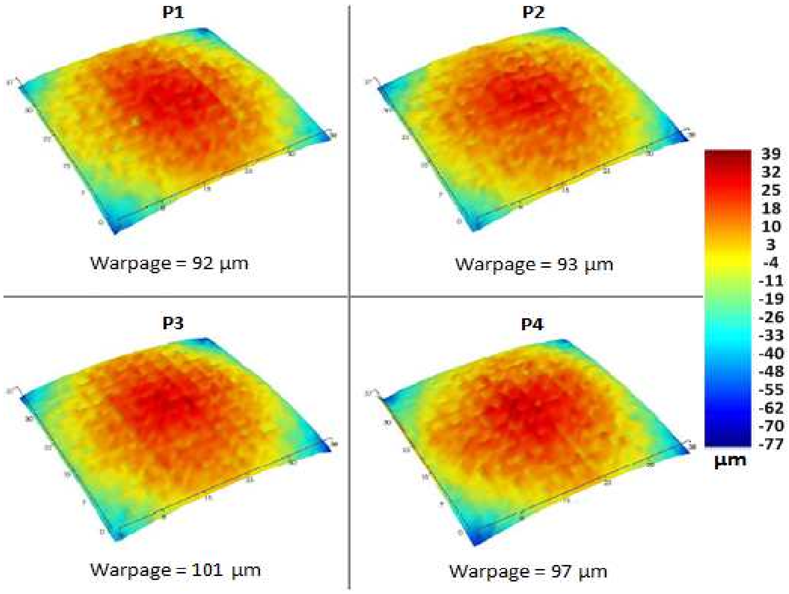

Figure 4 Shadow moiré results for the 4 samples.

4.5 Shadow Moiré Results vs. HPM Results

Comparison of the results, presented in Table 4, showed that there is a correlation between the HPM results and shadow moiré results. Indeed, the error average is less than the minimum accuracy of ±10% as recommended by JEDEC [4]. Therefore, it can be stated that an HPM can provide reliable measurements regarding package warpage.

Table 4 Shadow Moiré results vs. HPM results.

Package	**Warpage at room temperature (µm)**		
	Shadow Moiré	**HPM**	**Error %**
P1	92	95	3.3
P2	93	96	3.2
P3	101	99	2.0
P4	97	108	11.3
	Error average %		5

5 ANSYS Warpage Model Calibration

To reduce costs in the BGA design stage, the package deformation at ambient temperature (20° C) just after the cure molding process, which is characterised by a temperature of 180° C, can be simulated. To achieve this, an ANSYS numerical model was developed to reflect the warpage phenomenon as faithfully as possible. However, it was not possible to model resin viscoelastic behaviour, resin pre-heating, the post-mold cure process nor the sawing process. Not modelling all physical considerations and/or adopting simplifications can potentially lead to mismatch between simulation results and measured results.

5.1 Simplifications

5.1.1 Elasticity

In this case, the material properties of polymers like epoxy mold compound (EMC) were considered linear elastic. Although EMC is viscoelastic in nature, such property data are not readily available from suppliers. Characterization of viscoelasticity in a laboratory for each EMC incurs prohibitive costs (equipment and time). To palliate this, ‘effective CTE’ is introduced in the next paragraph, which provides a reasonable estimation of polymer behaviour [6].

5.1.2 Polymer CTE

The CTE plays a major role in package warpage. It is the ratio of thermal strain ε by temperature variation unit. Knowing that the CTE $\alpha = \alpha(T)$ strongly depends on temperature, especially in the case of polymers, the strain can be written as in Eq. (2):

$$\varepsilon = \int_{T_1}^{T_2} \alpha(T)dT \tag{2}$$

The CTE can be regarded as a bilinear property around the glass transition temperature, T_g, so it can also be written as in Eq. (3):

$$\varepsilon = \int_{T_1}^{T_g} \alpha(T)dT + \int_{T_g}^{T_2} \alpha(T)dT \tag{3}$$

where:

T_1: initial temperature (180 °C)
T_2: final temperature (20 °C)

Knowing that

$$\alpha(T < T_g) = \alpha_1 \text{ and } \quad \alpha(T > T_g) = \alpha_2,$$

we get Eq. (4):

$$\varepsilon = \alpha_1(T_g - T_1) + \alpha_2(T_2 - T_g), \tag{4}$$

finally obtaining Eq. (5):

$$\varepsilon = \alpha_{\mathrm{eff}}(\mathrm{T}_2 - \mathrm{T}_1) \tag{5}$$

where in Eq. (6):

$$\alpha_{eff} = \left(\alpha_1(T_g - T_1) + \alpha_2(T_2 - T_g)\right)/(T_2 - T_1) \tag{6}$$

For the warpage simulation, the effective CTE (for each polymer) was calculated using Eq. 6, where Tg falls in the simulated temperature range.

5.1.3 Cu Trace FEA modelling

Putting the Cu trace onto a substrate is normally performed by the package design engineer via a routing software program (Cadence in our case). The question asked by an FEA engineer is: should the Cu trace and conductive vias be modelled in a package warpage finite-element model? Two methods were inspected:

Method 1: Modelling all package elements faithfully

1. Exporting the Cu trace to ANSYS:
   The BGA's 10×10 mm^2 Cu trace (designed in Cadence) was exported to CST (electromagnetic analysis software) via a macro, the geometry was saved as *.SAT file (standard exchange format), the last file was opened in

SolidWorks (CAD software) and saved as *.IGS file (another standard exchange format), which can be opened in ANSYS. Figure 5 shows the Cu trace geometry in ANSYS.

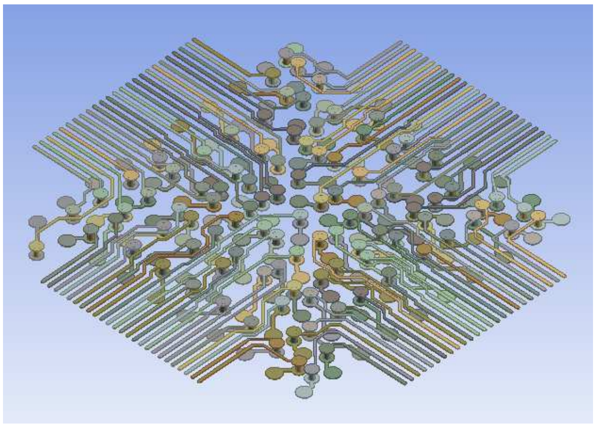

Figure 5 BGA Cu trace in ANSYS.

2. Building the package around the Cu trace:
   After exporting the Cu trace geometry to ANSYS, the next step is to insert the bismaleimidetriazine (BT), solder mask, die attach, die and molding compound to form the BGA (Figure 6).

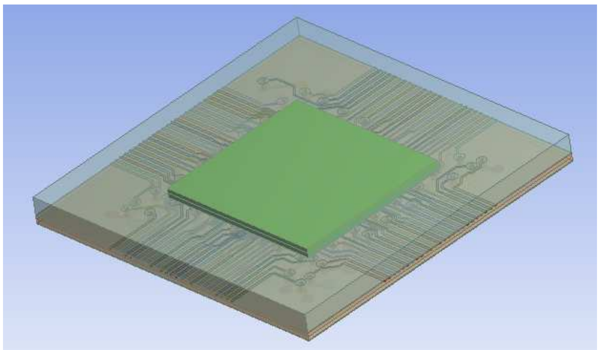

Figure 6 Faithfully modelled BGA.

3. FEA warpage analysis:
   Insufficient memory resources issues occurred when solving the warpage problem because the element number increases considerably when the Cu trace is modelled. Therefore, only a quarter of the model was modelled, assuming that there is perfect symmetry regarding the geometry. However, simulation was still slow because of the mesh generation complexity and

the high number of elements. The warpage value in this case was 26 µm (Figure 7).

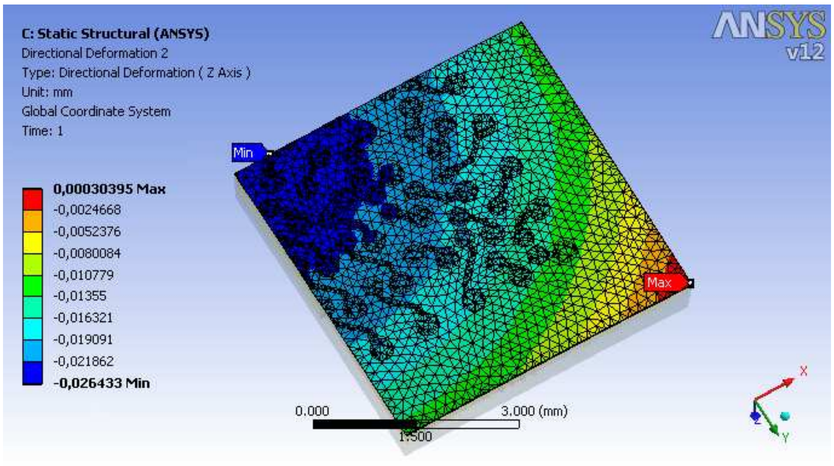

Figure 7 Faithfully modelled BGA Warpage (1/4 model).

Method 2: Modelling the Cu trace with 2 full layers of copper

The substrate was modelled with 5 full layers: BT (1 layer), copper (2 layers) and solder mask (2 layers). Because of the perfect symmetry regarding the geometry, boundary conditions and loads, only a quarter model was generated to save CPU time during the simulation work. The warpage simulation result was 30µm (Figure 8) for the same assumptions, hypothesis and conditions adopted in the previous section.

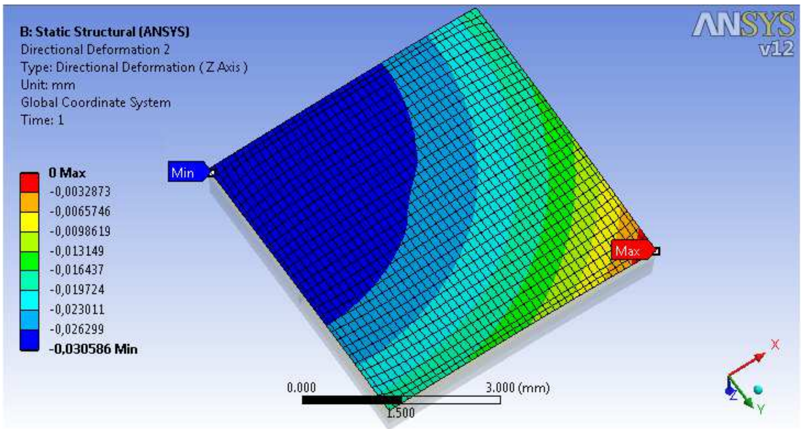

Figure 8 Warpage for BGA package whose substrate is modelled with 5 full layers (1/4 model).

Method 1 vs Method 2:

As can be seen in Table 5, there is not a large mismatch in terms of warpage when we model the Cu trace using Method 1 or 2. However, it is not easy to implement the first method: several software packages are needed (4 in the present study), it's hard to mesh the geometry, and the CPU processing is very intensive and time-consuming. Thus, it is not interesting to adopt Method 1 for advanced warpage analysis like numerical DOE or optimization. Method 2 (modelling the Cu trace with 2 full Cu layers) was thus adopted for further simulations.

Table 5 Warpage values using Methods 1 and 2.

	Method 1: modelling faithfully the Cu trace	**Method 2: modelling Cu trace by 2 full Cu layers**
Warpage (μm)	26	30

5.2 Simulation Results

5.2.1 Deterministic Analysis

In the deterministic analysis, all design parameters were assumed to be constants. Hence, nominal values were used for all inputs (dimensions, material parameters and loads parameters). The warpage value in this case was 30 μm (Figure 8).

5.2.2 Probabilistic Analysis

One of the main hypotheses in the study of mechanical systems is that the model is deterministic. That means all parameters used in the model are constants. However, experimental works show the limitations of this assumption. This is because there are always differences between what we calculate and what we measure, due mainly to the uncertainties in geometry, material properties, boundary conditions or loads, which have a considerable impact on the mechanical behaviour of the studied system. This is why it is evident to include uncertainties in simulation work [9].

The estimation of warpage moments (average and standard deviation) of a structure can be obtained by the Monte Carlo method, which is very widely used in spite of its high cost of calculation. It is used as a reference for other approached calculations [10]. ANSYS Mechanical includes a probabilistic analysis system that adopts the Monte Carlo method.

Preliminary study showed that the warpage is highly sensitive to the EMC's (resin) effective CTE. In addition, one cannot rely 100% on the material datasheet provided by the supplier. Normally, the EMC should be inspected by measuring its material mechanical properties in the lab. The warpage analysis will be non-realistic if we do not suppose that the EMC's CTE is a stochastic parameter. Therefore, warpage moments (average and standard deviation) were calculated supposing that the EMC's CTE is a normal probabilistic variable whose moments are as defined in Table 6. Stochastic analysis was performed via an ANSYS script on 800 samples. The results are presented in Table 7. Actually, warpage is highly sensitive to the EMC's CTE: 10% in EMC CTE standard deviation produces ~40% in warpage standard deviation, which shows the outlier if input uncertainties are neglected.

Table 6 Moments of Mold CTE.

	Average	Standard Deviation
Mold CTE	$\alpha_{average} = \alpha_{eff} = 23.75e^{-6}$	$\alpha_{std} = \alpha_{eff} \times 10\% = 2.37e^{-6}$

Table 7 Simulated warpage moments.

	Average	Standard Deviation	Maximum (smiley)	Minimum (crying)
Warpage (µm)	30.3	13.7	69.3	12.9

5.3 HPM Results

HPM measurements were done for 15 packages (new samples), which were encapsulated with good resin (stocked according to recommendations and used before the expiration date) as opposed to the packages measured in Section 4 (HPM calibration). The results are presented in Tables 8 and 9. Indeed, the resin (EMC) was the main influencing parameter with regards to warpage: the warpage was 2 times greater when the resin was wrongly stocked and/or expired.

Table 8 Warpage measured by HPM equipment.

Package n°	Warpage (µm)	Package n°	Warpage (µm)
1	35.5	9	46.1
2	40.1	10	37.3
3	39	11	52
4	44	12	51.3
5	44	13	44.9
6	41.5	14	46.8
7	42.8	15	39.8
8	52.9		

Table 9 Measured warpage moments.

	Average	**Standard Deviation**	**Maximum (smiley)**	**Minimum (crying)**
Warpage (µm)	43.9	5.3	52.9	35.5

5.4 Simulation Results vs. HPM Results

In Figure 9, a comparison between warpage the probability density curves obtained in the measurements and in the simulation work is presented. It can be seen that there is a fairly good correlation between the two results. Thus, it can be stated that the elaborated model developed via ANSYS is able to provide reliable warpage estimations. Thus, the proposed approach is validated.

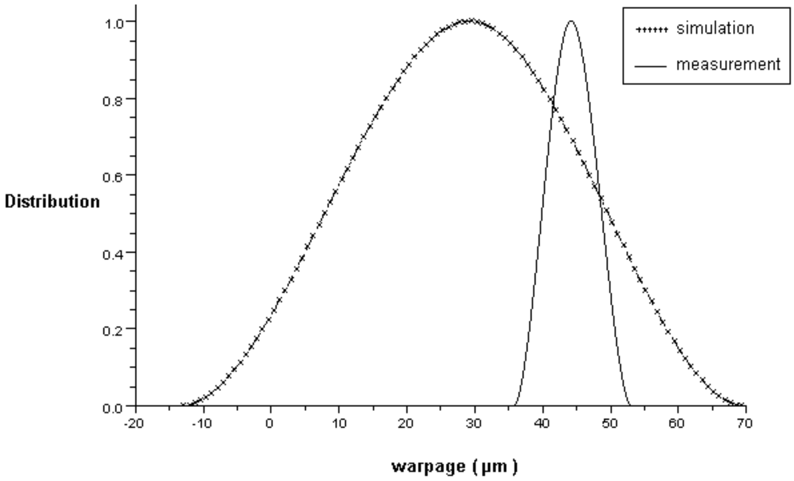

Figure 9 Simulation histogram vs. HPM measurement histogram.

6 Conclusions

The adopted methodology involved calibration of an HPM according to international standards. The epoxy mold compound used to encapsulate electronic packages is the most influencing design parameter. Indeed, in the measurement phase it was found that the warpage was two times greater when the epoxy used had been wrongly stocked and/or expired and therefore it was decided to use the epoxy material properties as random variables in the FEA model. This approach makes the simulation more realistic and allows finding a fairly good correlation between measurements and simulation. Two tools were used and validated to predict and measure BGA warpage in a non-expensive, reliable and fast way. The FEA model simulates the thermomechanical behavior of electronic packages. Thanks to this tool, DOE can be performed numerically via the FE model to obtain guidelines regarding the bill of materials and optimised dimensions to design a reliable product. Meanwhile, the HPM will allow efficient inspection of warpage in the prototyping phase.

Nomenclature

N : fringe order
p : pitch of the grating
T (C°) : temperature
Tg (C°) : glass transition temperature
W (µm) : warpage
Z (µm) : BGA corner height
α (e^{-6}/C°) : coefficient of thermal expansion (CTE)
α_1 (e^{-6}/C°) : CTE before Tg
α_2 (e^{-6}/C°) : CTE after Tg
α_{eff} (e^{-6}/C°) : effective CTE
β (rad) : angle of observation
ε : strain
θ(rad) : angle of illumination

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