Methodology for Predicting BGA Warpage by Incorporating Metal Layer Design

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Abstract
This paper presents a methodology to predict warpage of ball grid array packages (BGAs) that takes into account details of metal designs in the multi layered substrate. Composite theory along with local homogenization methods are used to resolve the distribution of material properties in each layer of the substrate that enables an efficient simulation model with moderate computational size. Associated procedures have been implemented and tested for finite element simulation tool. Verification examples were prepared to demonstrate the warpage predictions on BGA packages. Key substrate parameters including package mold compound shrinkage during post mold cure and the resultant impact on deformation behavior and mechanical reliability of BGA assemblies. A comparison of simplified homogenization methods and representative unit cell models of multi layered composite structures are discussed and show the significance of incorporating detailed metal layer design in simulation model for accurate warpage prediction.

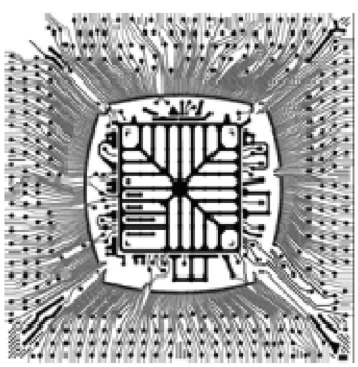
Key words
BGAs, composites, ECAD, MCAD, thermomechanical, warpage.

I. Introduction
In BGA packages, the thermal mismatch of the different materials in the multilayered substrate gives rise to package warpage. The details of the metal pattern in the substrate has significant influence on the package warpage behavior during package manufacturing and in use conditions. Previous modeling approaches do not typically consider the complex details of the metal design and this can lead to inaccuracy in the warpage prediction. This paper describes a novel methodology for warpage prediction of BGAs taking into account details of the metal pattern by bridging the electronic computer-aided drafting (ECAD) and mechanical computer aided drafting (MCAD) interface. Also, this method has no limitations as far as total number of metal layers present in the substrate layer stack-up (2, 4, or more layers).

The design procedure for metal patterns in a BGA substrate is carried out using ECAD tools. By exposing layer by layer in the ECAD viewer, image files are captured with high pixel density to define complex design details. Image files are then divided into set of square blocks. Copper and resin are identified for each square block via image processing and are assigned defined numerical values. This is repeated for each layer. The entire stack-up pattern can be captured in the table format that can easily be transferred into finite element simulation tool. With the structural layered elements imported into a commercial finite element simulation tool with the metal design table, composite theory is applied along with a local homogenization procedure to resolve the distribution of material properties in each layer of the substrate. This method enables accurate warpage prediction with moderate computational size. Results from this method have been validated with measured warpage data using the Thermo-Moiré technique over the thermal reflow profile (25^0C to 250^0C). The chemical shrinkage of mold compound (EMC) during post mold cure (PMC) and the impact onto deformation behavior of the package will be discussed. This new modeling procedure is compared with simplified homogenization methods and representative unit cell models of multi layered composite structures [1].

II. Substrate Metal Design Modeling
Complex metal design in BGA substrate layers can easily be

modeled and analyzed by connecting the ECAD and MCAD interfaces. In this work, the ECAD tool was implemented to generate the metal design in substrate layer. With the ECAD image viewer, the metal layer designs were captured into an image format (e.g. jpg) that can be analyzed in image processing software. Fig. 1(a) shows a representative substrate metal layer converted into bi-chrome (black and white) image using image processing software. This step was carried out to clearly distinguish the metal from the surrounding resin material. The image file was then divided into a set of square blocks and each square block designated with a pre-defined numerical value (metal =1 and resin = 0). The same steps are performed for each individual metal layer and the entire substrate stack-up pattern was captured in a tabular format that can easily be transferred into a finite element simulation tool. Layered structural solid elements available in commercial finite element codes were used to model the substrate layers by conjoining the previously generated table that contains metal design details in a numeric code. Fig. 1(c) shows the representative metal layer modeled in finite element simulation tool using SOLID 186 element type that is a higher order 3-D 20-noded solid element that exhibits quadratic displacement behavior. In Fig. 1(c), only metal elements are exposed and the resin elements are hidden. Material properties are assigned to each element based upon a grid reference.



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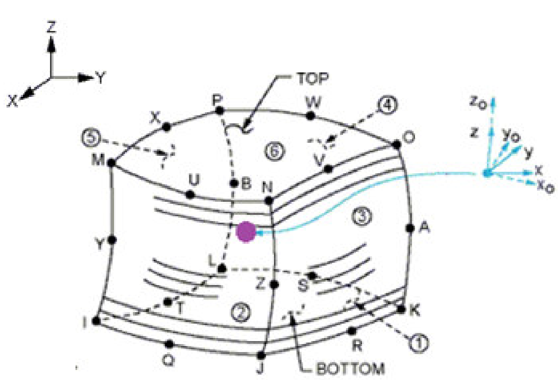

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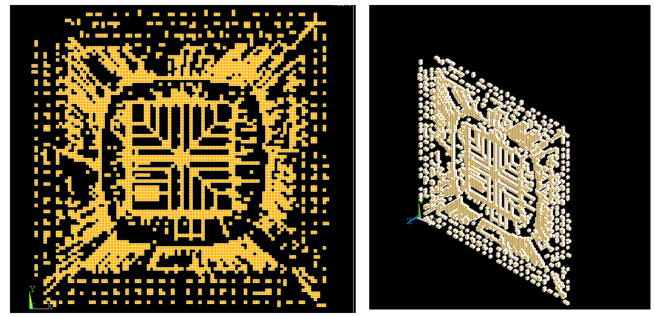
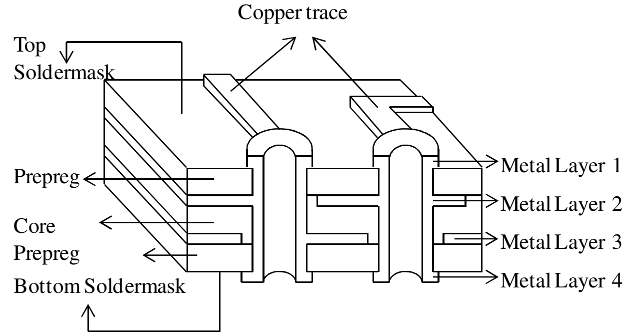


(c)

Fig. 1(a) substrate metal layer converted into bi-chrome image using image processing tool (b) SOLID 186 layered structural solid elements in finite element commercial tool (c) metal layer modeled in the finite element commercial tool using structural layered element type

A 4 layer substrate was considered for modeling package warpage. Fig. 2(a) shows the representative block of typical 4 layered substrate that comprises: the top solder mask layer, the first metal layer, prepreg, second metal layer, the core, third metal layer, prepreg, fourth metal layer and finally the bottom solder mask layer. Fig. 2(b) shows the 4 metal layers with corresponding copper percentage of a BGA substrate used to model package warpage.



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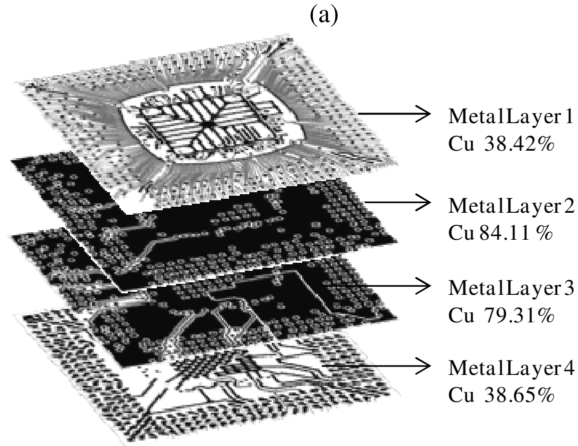


(b)

Fig. 2 (a) Representative block of a 4 layered substrate (b) 4 metal layers with corresponding copper percentages

III. Material Constitutive Behavior

Material properties are one of the primary parameters that drive the mechanical models. It is important to use appropriate material definition for each component in a package structure. Epoxy mold compounds (EMC) are thermoset polymers that are viscoelastic in nature. It is essential to consider the viscoelastic behavior whenever an accurate stress/displacement model is required. Stress relaxation experiments in the frequency domain were performed on the molding compound that is same material used in BGA package. A thermorheological model was assumed from the master curve of relaxation modulus using time-temperature equivalence assumption.

The relaxation modulus E(t) is defined as

$$E(t)=\frac{\sigma(t)}{\varepsilon_0}=E_\infty+\sum_{k=1}^{n}E_k e^{\frac{-t}{\tau_k}} \quad (1)$$

that is the Prony series representation [2]. In (1), E_∞ is the final modulus and $E_0=E_\infty+\sum_{k=1}^{n}E_k$ is the instantaneous modulus and E_k,τ_k pairs are Prony pairs.

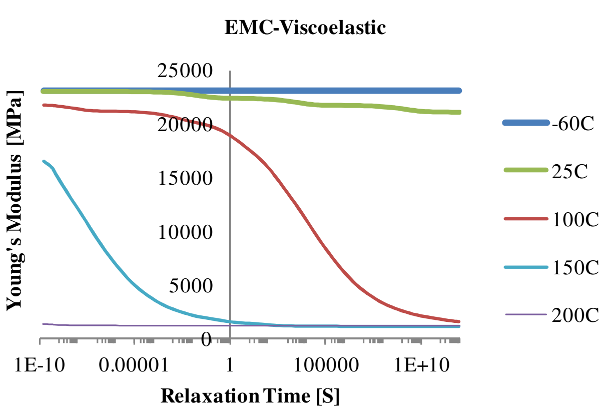
Also, Williams-Landel-Ferry (WLF) functions used for shift factor

$$\log a_T(T)=\frac{C_1(T-T_R)}{C_2+T-T_R} \quad (2)$$

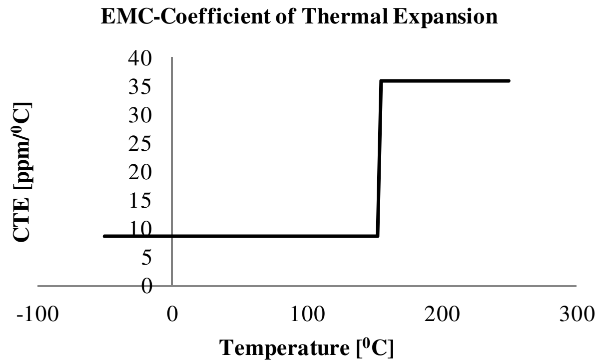
where C_1 and C_2 are material constants.

Prony pairs were extracted from the model and also material constants from WLF function and implemented in the finite element tool.

Fig. 3(a) shows the stress relaxation moduli of epoxy mold compound as a function of time at five isothermal temperatures. Fig. 3(b) plots the co-efficient of thermal expansion over a wide range of temperature with the glass transition temperature for the mold compound with step definition.



(a)



(b)

Fig. 3 (a) Stress relaxation moduli of an epoxy mold compound as a function of time at multiple isothermal temperature (b) CTE of EMC as a function of temperature

In EMCs, the curing process transforms the resin into a plastic by cross-linking. Molecular chains react chemically, linking into a rigid, 3-D structure. During this process, a small percentage of chemical shrinkage occurs as shown in Fig. 4 (point B to D) and this information is incorporated into the finite element model to further improve warpage prediction. In this work, chemical shrinkage of EMC was applied in the FE code by updating the stress-free-temperature for EMC body. The typical chemical shrinkage value for EMC is around 0.05% and the corresponding EMC stress-free-temperature can be obtained as follows:

$$EMC_{Stress-free-temperature}$$
$$=Package_{stress-free-temperature}+\left(\frac{0.05\%}{CTE_{EMC@>Tg}}\right) \quad (3)$$

The stress-free-temperature for the rest of the package material will be at 175^0C that corresponds to the temperature of EMC during the mold transfer step.

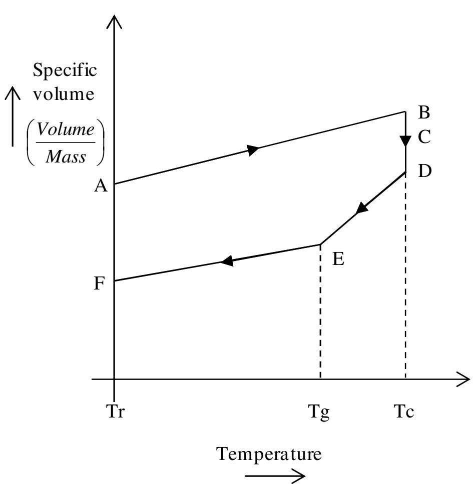


Fig. 4 EMC shrinkage data definition

Where AB is the volume change of compound from room temperature (Tr) to curing temperature (Tc); BD is the reaction shrinkage under Tc, C is the gel point; DF is the Physical shrinkage including shrinkage above Tg (DE) and shrinkage below Tg (EF); AF is the shrinkage ratio

For Silicon, elasticity values provided in the frame of reference of a standard (100) silicon wafer [3] are:

$$E_x = E_y = 169GPa; E_z = 130GPa$$
$$\nu_{yz} = 0.36; \nu_{zx} = 0.28; \nu_{xy} = 0.064;$$
$$G_{yz} = G_{zx} = 79.6GPa; G_{xy} = 50.94GPa$$

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} 194.5 & 35.7 & 64.1 & 0 & 0 & 0 \\ 35.7 & 194.5 & 64.1 & 0 & 0 & 0 \\ 64.1 & 64.1 & 165.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 79.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 79.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 50.9 \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \quad (4)$$

(in GPa)

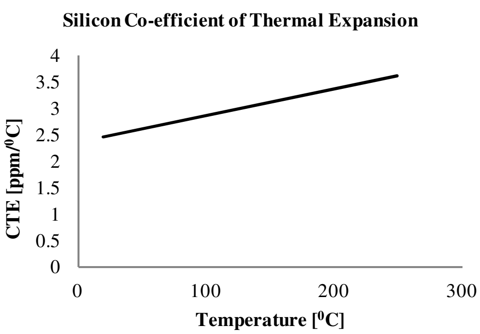
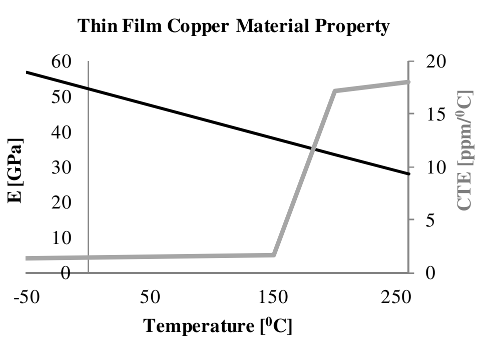


Fig. 5 CTE of Silicon Die as a function of temperature

Fig. 6(a)-(e) shows the material property information for the remaining materials in the BGA package. Apart from EMC, the remaining materials were assumed to be linear-elastic temperature dependent.



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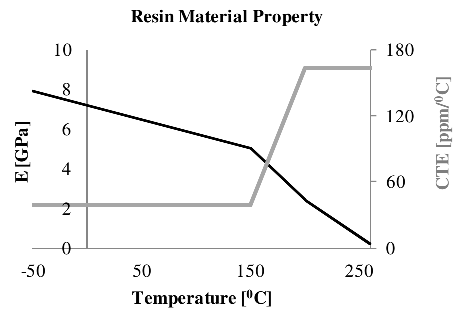

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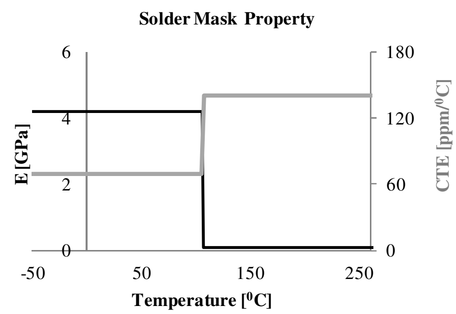

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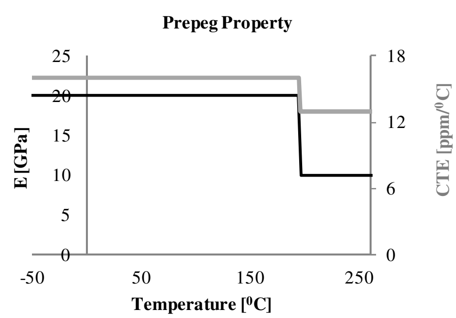

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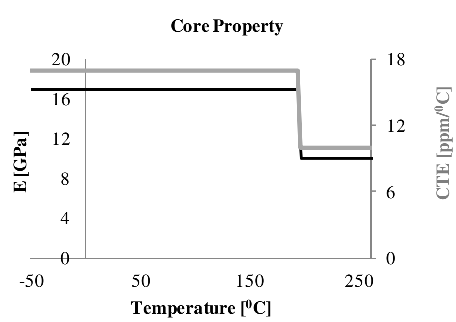


(e)

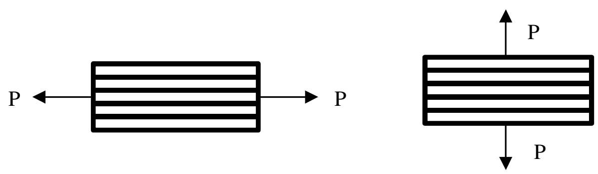
Fig. 6 (a) Material properties of thin film copper as a function of temperature; (b) Material properties of resin as a function of temperature; (c) Material properties of solder mask as a function of temperature; (d) Material properties of prepreg as a function of temperature; (e) Material properties of core as a function of temperature

IV. Simplified Substrate Modeling Approaches

Based upon current complexity in the metal design pattern it is convenient to implement the simplified micromechanics approach to calculate the effective material properties for substrate layers containing the metal design with surrounding resin materials. In this work, two methods (a) homogenization method (b) representative unit cell model yielded isotropic properties of metal design layers based upon percentage of copper and resin present. Warpage results with these two simplified methods were compared with a more sophisticated modeling method that considers metal design details [7].

(a) Homogenization method

This method applies micromechanics concepts to determine the engineering constants of metal layers in substrate [5]-[7].



(a) (b)

Fig. 7 A unidirectional fiber-reinforced composite layer with loading along longitudinal (a) and transverse (b) directions

$$E_{II} = E_{cu}V_{cu} + E_{\mathrm{Resin}}V_{\mathrm{Resin}} \qquad (5)$$

$$E_{\perp} = \frac{E_{cu}E_{\mathrm{Resin}}}{E_{cu}V_{\mathrm{Resin}} + E_{\mathrm{Resin}}V_{cu}} \qquad (6)$$

$$\nu_{II\perp} = \nu_{cu}V_{cu} + \nu_{\mathrm{Resin}}V_{\mathrm{Resin}} \qquad (7)$$

$$\nu_{\perp II} = \frac{E_{\perp}}{E_{II}}\nu_{II\perp} \qquad (8)$$

$$CTE_{II} = \frac{CTE_{cu}E_{cu}V_{cu} + CTE_{\mathrm{Resin}}E_{\mathrm{Resin}}V_{\mathrm{Resin}}}{E_{cu}V_{cu} + E_{\mathrm{Resin}}V_{\mathrm{Resin}}} \qquad (9)$$

$$CTE_{\perp} = (1+\upsilon_{cu})CTE_{cu}V_{cu} + (1+\upsilon_{\mathrm{Resin}})CTE_{\mathrm{Resin}}V_{\mathrm{Resin}} - CTE_{II}\upsilon_{\mathrm{II}\perp} \qquad (10)$$

Where, E= Young's modulus, ν = Poisson's ratio, CTE=co-efficient of thermal expansion, 11=longitudinal direction, $\perp$ =transverse direction, major direction= $II\perp$, minor direction= $\perp II$.

If the metal design orientation is considered to be random then the effective modulus in all directions can be considered to be the average of E_{II} and $E_{\perp}$, similarly CTE and Poisson ratios can be updated

$$E_{Compound} = \frac{E_{II} + E_{\perp}}{2} \qquad (11)$$

$$CTE_{Compound} = \frac{CTE_{II} + CTE_{\perp}}{2} \qquad (12)$$

(b) Representative unit cell (RCU) model

This method is the extension of homogenization method that derives material properties that describe the entire structure by defining a representative cell of the structure. This cell must satisfy the definition of a parallelepiped for all the simulations [1], [8]. This condition insures that the model stays repeatable and becomes very important when defining the boundary conditions. Also, this cell must consider all the features that influence the physical properties of the structure.

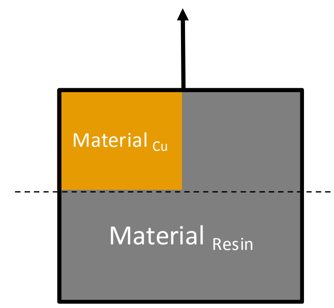


Fig.8 Representative unit cell of a metal layer

$$V_{cu} = \frac{A_{cu}}{A_{cu} + A_{\mathrm{Resin}}} \qquad (13)$$

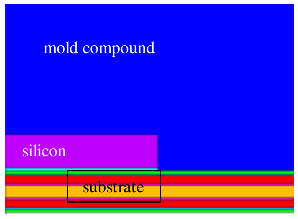
$$E_{compound} = \frac{\sqrt{V_{cu}}E_{cu}E_{\mathrm{Resin}} + \left(1-\sqrt{V_{cu}}\right)E^2_{\mathrm{Resin}}}{\sqrt{V_{cu}}\left(1-\sqrt{V_{cu}}\right)E_{cu} + \left(1-\sqrt{V_{cu}}+V_{cu}\right)E_{\mathrm{Resin}}} \qquad (14)$$

$$CTE_{compound} = \frac{CTE_{\mathrm{Resin}}\left(\sqrt{V_{cu}}-1\right)\left(E_{cu}\sqrt{V_{cu}} + E_{\mathrm{Resin}}\right) - CTE_{cu}E_{cu}V_{cu}}{E_{\mathrm{Resin}}\left(\sqrt{V_{cu}}-1\right) - E_{Cu}\sqrt{f_1}} \qquad (15)$$

Where V_{cu}= metal density percentage, $E_{compound}$ = Average elastic modulus using RCU method, $CTE_{compound}$ = Average CTE using RCU method,

V. Experimental Validation

In order to validate the modeling methodology, Thermo-Moiré warpage data of the 4 layered MAPBGA package has been considered. Fig. 9 shows the MAPBGA package information used in this study. MAPBGA packages were baked dry, solder balls removed and substrate painted white and subjected to reflow profile as shown in Fig. 11. Interpretation of Thermo-Moiré warpage data is provided in Fig. 10. In Fig. 12 shows the experimental warpage repeatability data for 5 different test samples.



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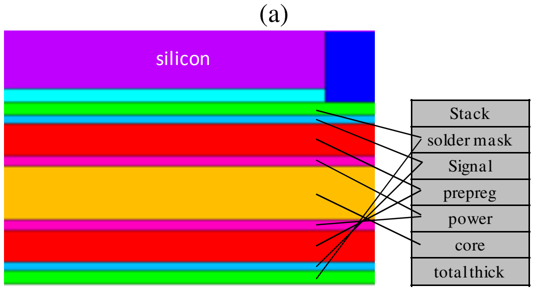


(b)

Fig. 9 Cross section of 4 layered MAPBGA

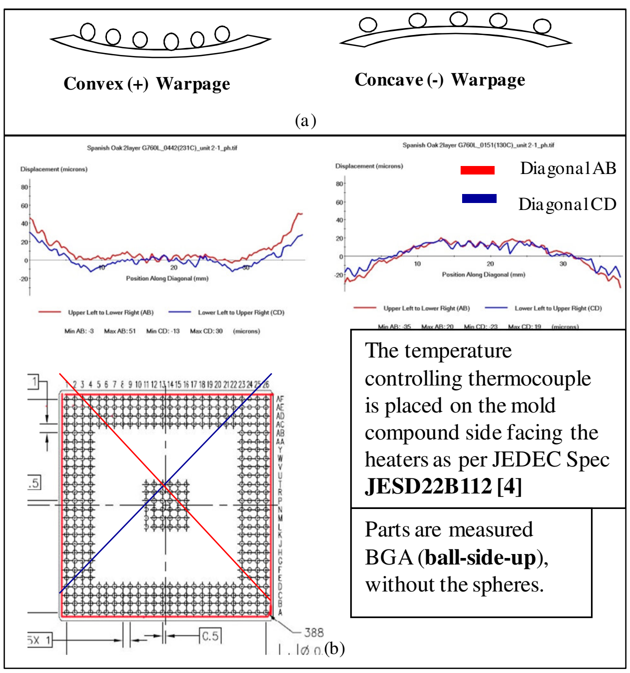


Fig. 10 Interpretation of Thermo-Moiré warpage data

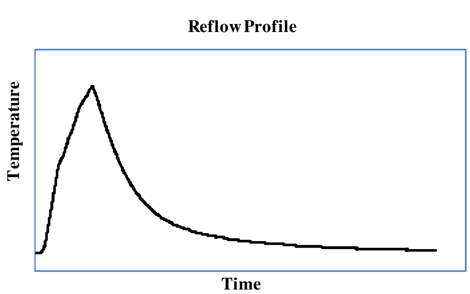


Fig. 11 Temperature profile used during warpage measurements

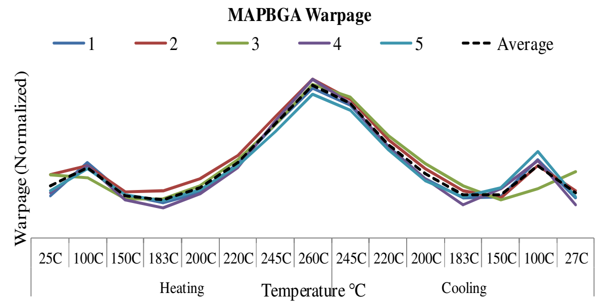


Fig. 12 Experimental warpage data for 5 test samples

The package was modeled using the metal design details in the substrate layer stack-up. Fig. 13 shows the warpage path considered in the model. Fig. 14 shows the comparison of warpage results for 3 different modeling approaches with experimental data. The detailed metal design approach captures the magnitude of the warpage and direction for the entire reflow profile that is consistent with the experimental data and two other simplified modeling techniques that fail to capture the warpage trend at higher temperatures.

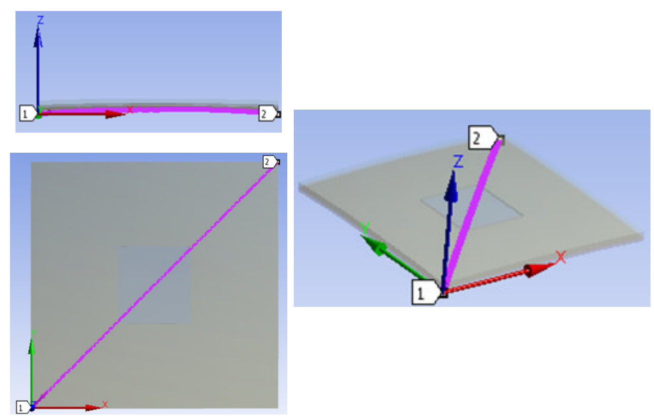
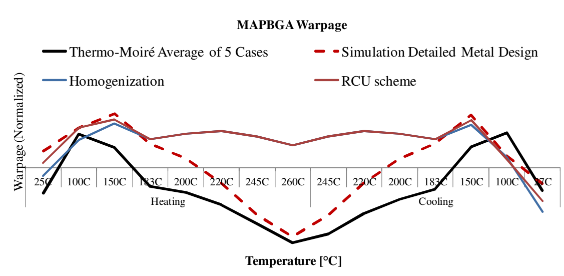


Fig. 13 Definition of warpage path in the model



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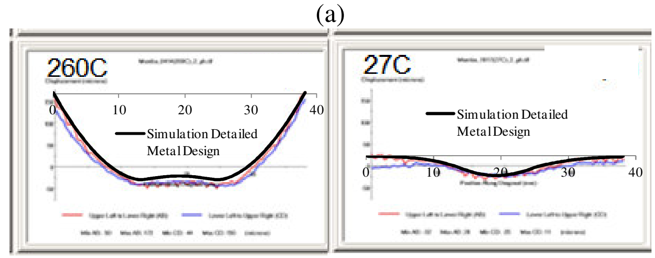

(b)

Fig. 14 (a) Comparison of warpage using 3 different modeling approaches with experimental data (b) Warpage comparison along diagonal path at discrete temperature between Thermo-Moiré and simulation with a detailed material design approach

VI. Summary and Conclusion

This work describes a methodology for predicting BGA warpage by incorporating metal layer design in a numerical code. Two simplified modeling approaches were described that are based upon micro mechanics theory. Metal layer design of the BGA substrate was modeled using a composite homogenization methodology that was validated with experimental data. This work indicates that it is very important to consider metal design detail to have accurate warpage prediction over an entire reflow profile.

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