# Cure shrinkage characterization and its implementation into correlation of warpage between simulation and measurement

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## Abstract

In this work, a new approach was proposed to characterize the cure shrinkage of EMC by using the EMC/Cu bi-layer strip specimens. The warpage of bi-layer strip was measured at different temperature using Shadow Moiré. The results show that warpage at molding temperature was non-zero and zero-warpage temperature shifted from molding temperature (175degc) to higher temperature due to cure shrinkage effect. From Timoshenko's beam theory, the cure shrinkage was calculated as 1st order approximation theoretically either from the warpage at molding temperature or from zero-warpage temperature.

The determined cure shrinkage together with thermal shrinkage obtained from TMA tests was used to predict the warpage of the different EMC/Cu strips. Good correlation was observed in the wide temperature range.

As comparison, direct measurement of the cure shrinkage was also done using long rectangular bar specimens. Cure shrinkage was determined by extracting thermal shrinkage from total shrinkage.

Cure shrinkage of 2 EMCs were characterized and then applied to PBGA matrix. Warpage of the PBGA EMC/substrate maps was measured using Shadow Moiré and simulated as well for the molding compounds (EMCs) after 3 different processes, i.e. after transfer molding (TM), post mold cure (PMC) and PMC + Reflow at 260degc for 3 times (RF260X3). Consistence between simulation and experiments was found when cure shrinkage was considered. The presented data show the necessity and importance of cure shrinkage in warpage prediction simulation.

## 1. Introduction

Epoxy molding compound (EMC) is one of the key packaging materials. Its moldability and physical properties dominate the package reliability and warpage. One of the important features of the EMC is its shrinkage when reaction between the resin and hardener takes place during molding. Such shrinkage is commonly termed as cure shrinkage or chemical shrinkage originating from cross-linking, and causes more warpage in the packages in addition to that induced by CTE mismatch among packaging materials. With strict and stringent warpage requirement of packages, such as PoP, SD and memory cards, Quad Flat Non-lead (QFN) packages and various 3D packages, accurate prediction of warpage becomes very critical, and consequently cure shrinkage comes as very important player in warpage characterization. On one hand, miniaturization and low profile of packages results in less flexibility of geometry in package design and thus more challenges in development of epoxy molding compound to meet the low warpage requirements. On the other hand, increasing mould map / panel size is used in manufacturing to improve the production efficiency and to cut costs, leading to higher panel warpage and co-planarity problems in surface mounting of packages. To conquer such situation, we are urged to develop an approach to predict the warpage precisely and the way to optimization.

Shrinkage is composed of both thermal and chemical parts, as shown in Fig. 1. The chemical shrinkage or cure shrinkage, unfortunately ignored in the most of past simulation and analysis, results in additional residual stresses in the package and consequently contributes to the warpage, therefore becomes the key for accurate simulation of warpage as addressed in refs. [1,2].

Cure shrinkage was determined by researchers, mostly from molding compound (EMC) material manufacturers [3,4], by measuring the dimensional change of disc EMC specimens. The challenges for such direct measurement come from two aspects. Firstly, accurate measurement of dimensional change is difficult as cure shrinkage is normally small; Secondly, cure shrinkage such measured, even if it is accurate, is composed of both elastic and plastic parts in which only elastic parts contributes to warpage [5]. In fact, it is very hard to distinguish elastic cure shrinkage from total cure shrinkage, and this part really depends on a lot of factors such as composition of EMC. In this circumstance, we propose a new approach to characterize cure shrinkage in this work.

In the new method, EMC/Cu bi-layer strip specimens were used to measure warpage at different temperatures. After molding EMC onto Cu substrate, zero-warpage temperature, initially at molding temperature, shifted to a higher temperature due to cure shrinkage, while the warpage at molding temperature is no longer zero. Then the cure shrinkage can be calculated either from the warpage at molding temperature or from

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zero-warpage temperature by using Timoshenko's bi-layer beam model.

As comparison, direct measurement of the cure shrinkage was also illustrated using long rectangular bar specimens. This will be discussed in section 4. For the case studied here, a correction factor of about 0.6 must be introduced so as to extract elastic cure shrinkage from total cure shrinkage.

To further illustrate the effect of cure shrinkage on warpage of general packages, a series of tests were conducted for PBGA maps molded using 2 EMC materials onto substrate without inclusion of die. Warpage was measured using Shadow Moiré and simulated at 3 different conditions, namely after transfer molding (TM), post mold cure (PMC) and PMC + Reflow at 260degc for 3 times (RF260X3). The FEA simulation results corresponding to different processes with or without consideration of cure shrinkage were compared to demonstrate the cure shrinkage effect. Results show that a good and consistent agreement between simulation and experiments was achieved when cure shrinkage was considered in simulation.

## 2. New approach for cure shrinkage characterization

Cure shrinkage refers to volumetric reduction of the EMC before and after curing. The total shrinkage of EMC follows the profile in Fig.1.

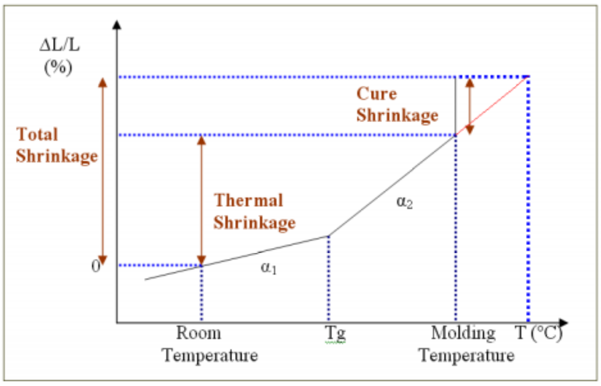


Fig. 1: Shrinkage in EMC at different temperatures

It can be seen from Fig.1 that total shrinkage includes two parts, thermal shrinkage due to temperature change and cure shrinkage due to cross-linking, i.e.:

Cure shrinkage (CS)
= Total shrinkage (TS) – Thermal shrinkage (ThS) (1)

Different ways have been proposed to determine cure shrinkage. Ken Oota [3] from Sumitomo studied various Epoxy molding compounds (EMCs), and found a very strong correlation between total cure shrinkage and free volume of materials, and a linear relationship between cure shrinkage and free volume was obtained. Similar relationship was also validated in M. Ogata's work [4]. Cookson also investigated the dependence of cure shrinkage upon Tg and other parameters. In general, cure shrinkage was in a range of 0.06% to 0.35% for most green molding compound. This extra shrinkage results in additional warpage esp. at low temperature including room temperature and must be quantified so as to understand warpage extensively.

Experimental determination of cure shrinkage is quite challenging since the length change induced by cure shrinkage is of small percentage. Direct measurement of specimen's dimension change faces 2 bottlenecks: (1) accuracy and (2) the fact that, of the total cure shrinkage, only elastic cure shrinkage which is retained after solidification of EMC, contributes to warpage.

Here we propose an indirect approach to determine cure shrinkgae by using a bi-layer specimen. The specimen is prepared by molding the EMC onto a substrate made of a known material. Since cure shrinkage comes to play after molding, the bi-layer strip specimen will warp when cooling down from molding temperature to room temperatue. Practically, cure shrinkage after being fully cured is of more interest as this should be consistent parameter of any given EMC. Theoretically, measuring warpage at room temperature is already able to chracterize the cure shrinkage, however, to ensure accuracy and provide consistent data, cure shrinkage can be determined based on the warpage data in a wide range of temperatue using Shadow Moire. Since cure shrinkage is extracted by substracting thermal shrinkage from total shrinkage, accuracy of cure shrinkage is affected by thermal property data, and a group of warpage data at various temoperature points will help minimize the errors and improve accuracy. A substrate material with significant difference CTE from EMC is preferred so that the warpage can be measured with high accuracy.

As 1st order approaximation of warpage prediction of bi-layer strips, Timoshenko's bi-layer beam model can be applied assuming the strip is a thin beam. When temperature changes from $T_o$ to $T$, it will deform due to different expansion of two layers, causing warpage w as in Fig. 2. The bowing curvature can be expressed as follows [7,8] when the deflection is not large:

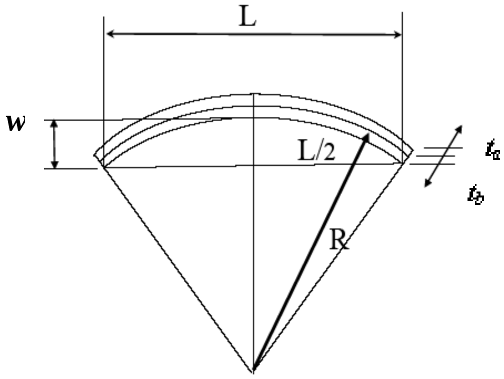


Fig.2: Geometric analysis of a warping bi-layer beam

$$\frac{1}{R}-\frac{1}{R_o}=\frac{6(1+p)^2(\Delta L_b-\Delta L_a)}{t\left[3(1+p)^2+(1+pq)\left(p^2+{}^{1}\!/_{pq}\right)\right]} \qquad (2)$$

where $\Delta La = \alpha_a$ (T-To), and $\Delta L_b = \alpha_b$ (T-To) are total shrinkage of layer a and layer b, respectively. $1/R_o$ is initial curvature of the strip at $T_o$ ($\mu m^{-1}$), $1/R$ is Curvature of the strip at T, $\alpha_a$ and $\alpha_b$ are the effective CTE of low and high expansion materials (ppm/°C), $q = E_a/E_b$, where $E_a$ and $E_b$ are the Young's Modulii of the two materials, $p = t_a/t_b$, with $t_a$ and $t_b$ the thickness of the bimorph layers and $t = t_a + t_b$, the total thickness of the strip.

Please note the above equation is for an ideal bi-layer beam simply supported at both ends, while deflection is small without external mechanical force applied. Assuming initial curvature is zero ($1/R = 0$), the deflection at the mid point can be given as [7]:

$$(R-t_2)^2 = (R-w-t_2)^2 + \left(\frac{L}{2}\right)^2 \tag{3}$$

The radius of curvature after deflection is:

$$\frac{1}{R} = \frac{8w}{L^2 + 4w^2 + 8wt_2} \tag{4}$$

Provided that the deflection and the thickness are less than 10% of its length, $8wt_2$ and $4wd^2$ can then be neglected, therefore:

$$w = \frac{L^2}{8R} \tag{5}$$

Combining Eq. (2) with Eq. (5), we have:

$$w = \frac{3(1+p)^2 L^2 (\Delta L_b - \Delta L_a)}{4t\left[3(1+p)^2 + (1+pq)\left(p^2 + \frac{1}{pq}\right)\right]} \tag{6}$$

From Eq. (6), total shrinkage of the EMC (material b) can be derived from warpage, when Young's modulus, CTE and the thickness of substrate and EMC are given. Especially at molding temperature we have:

$$CS = \frac{4t\left[3(1+p)^2 + (1+pq)\left(p^2 + \frac{1}{pq}\right)\right] w_m}{3(1+p)^2 L^2} \tag{7}$$

Where $W_m$ is the warpage at molding temperature, CS refers to cure shrinkage.

On the other hand, zero warpage temperature, Tz, will be shifted to a higher temperature due to cure shrinkage. Theoretically, cure shrinkage can also be determined from zero warpage temperature shifted from 175degc to Tz as follows:

*CS*= (Effective CTE of EMC – CTE of substrate) * (Tz – molding temperature)
= Difference of expansion between EMC and substrate (Cu here)
≈ ($\alpha 2$ - $\alpha_{Cu}$) * (Tz – Molding T), if Tg< molding T. (8)

## 3. Experimental set-up of bi-layer beam system

Cure shrinkage causes additional warpage of the bi-layer system. Warpage should be zero at molding temperature, usually 175degc, provided there is no cure shrinkage. However, zero warpage temperature will be shifted to a higher temperature due to cure shrinkge. This can be addressed in Fig. 3.

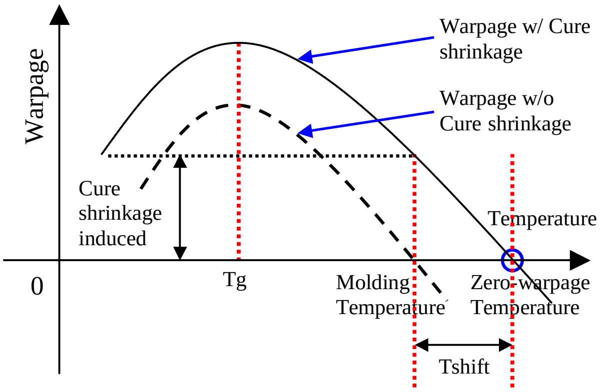


Fig. 3: Warpage of the bi-layer beam with and without cure shrinkage

It can be seen that warapge at molding temperature and zero warpage temperature are 2 characteristic data for cure shrinkage determination. A more elaborated way to cure shrinkage calculation is to use warpage in a wide range of temperature and best fitting the data to derive cure shrinkage. For this purpose, a series of tests were deisgned to measure cure shrinkage.

### *3.1 Experimental design of bi-layer beam system*

To charactrerize cure shrinkage of EMCs, we designed EMC/Cu bi-material strips by molding 2 selected molding compounds onto copper strips, then the warpage of the bi-layer stripe was measured at different temperature. The specimen diemsions are shown in Fig.4.

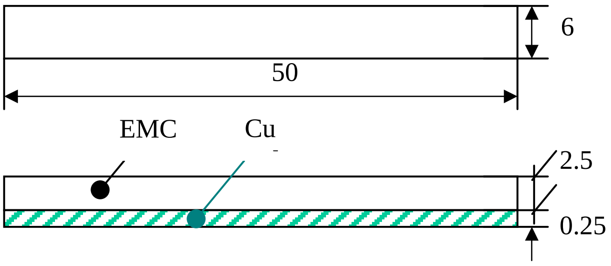
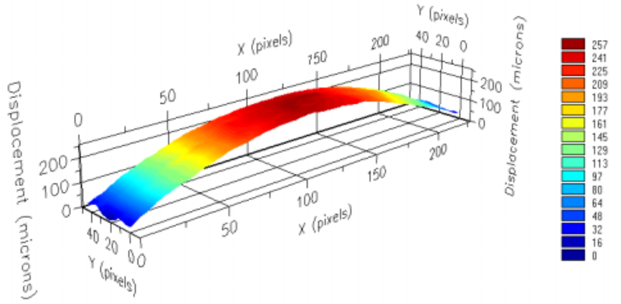


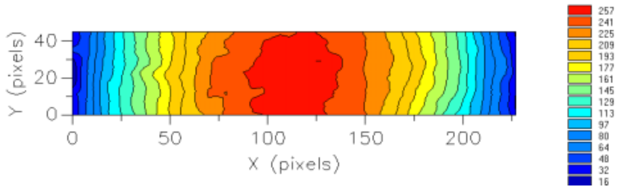
Fig. 4 Dimensions of bi-layer specimen

### *3.2 Warpage of bi-layer strips at different temperatures*

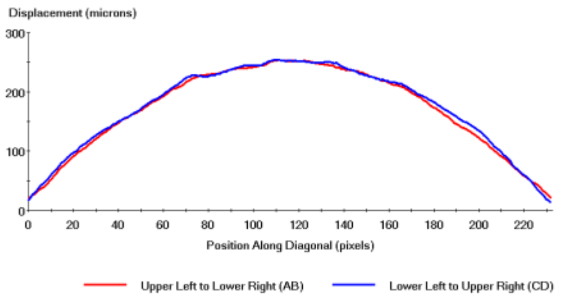
Warpage in a temperature range from room temperature to 260degc was measured using Shadow Moiré. The EMC was post mold cured for 4 hours before tests. Fig. 5 shows a typical 3D contour obtained from Shadow Moiré. 4 or more samples in each case were tested to reproduce data. The detailed results are listed in Table 1 and plotted in Fig.6.



a. 3D contour



b. Contour lines



c. 2D diagonal extraction

Fig.5. Typical Shadow Moiré warpage plots @ 28degc

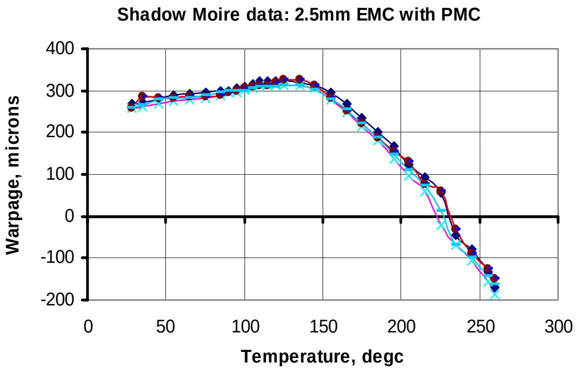


Fig. 6. Warpage versus temperature measured for 2.5mm EMC

Table 1: Warpage results at selected temperature

| T, degc | S1 | S2 | S3 | S4 | Average |
|---|---|---|---|---|---|
| 28 | 268 | 259 | 258 | 257 | 261 |
| 35 | 273 | 262 | 287 | 264 | 272 |
| 45 | 278 | 267 | 282 | 277 | 276 |
| 55 | 289 | 274 | 281 | 281 | 281 |
| 65 | 291 | 279 | 285 | 282 | 284 |
| 75 | 294 | 283 | 287 | 288 | 288 |
| 85 | 299 | 289 | 290 | 296 | 294 |
| 90 | 300 | 296 | 295 | 299 | 298 |
| 95 | 305 | 296 | 300 | 300 | 300 |
| 100 | 310 | 302 | 304 | 300 | 304 |
| 105 | 317 | 307 | 308 | 304 | 309 |
| 110 | 321 | 311 | 312 | 308 | 313 |
| 115 | 324 | 314 | 314 | 309 | 315 |
| 120 | 323 | 312 | 318 | 309 | 316 |
| 125 | 323 | 314 | 326 | 312 | 319 |
| 135 | 320 | 312 | 326 | 314 | 318 |
| 145 | 314 | 304 | 313 | 302 | 308 |
| 155 | 296 | 280 | 283 | 279 | 285 |
| 165 | 269 | 250 | 252 | 254 | 256 |
| 175 | 236 | 215 | 221 | 220 | 223 |
| 185 | 201 | 182 | 187 | 186 | 189 |
| 195 | 167 | 137 | 154 | 146 | 151 |
| 205 | 124 | 95 | 129 | 110 | 115 |
| 215 | 93 | 58 | 78 | 73 | 76 |
| 225 | 57 | -22 | 59 | 14 | 27 |
| 235 | -46 | -68 | -31 | -67 | -53 |
| 245 | -80 | -107 | -88 | -100 | -94 |
| 255 | -134 | -157 | -126 | -144 | -140 |
| 260 | -171 | -185 | -149 | -162 | -167 |

## 4. Correlation with Timoshenko's bi-layer model

From the experimental results obtained in a temperature range from room temperature to 260degc, the cure shrinkgae can be determined using Timoshenko's beam theory as first order approximation following Eqs. (7) and (8). That is 0.135% for the selected EMC. The cure shrinkage can also be obtained by best-fitting the experimental data in the temperature range selected (i.e. from room to high temperature). In implementation of cure shrinkage into warpage prediction, there are two alternative ways. Firstly, we can convert cure shrinkage into additional coefficient of thermal expansion (CTE), and combine it with thermal shrinkage to form an effective CTE which is temperature dependent; secondly, we can simply shift the reference temperature in ANSYS from molding temperature to zero-warpage temperature for warpage calculation. While temperature shift due to cure shrinkage actually can be obtained in two ways, one from the cure shrinkage at molding temperature and the other directly from $T_0$ where zero-warpage occurs as in experiemnts. The two methods should give the same results. However, since Shadow Moire will face accuracy challenges at $T_0$, accurate zero-warpage temperature determination will inevitably contain sometimes big errors of +/- 10degc. To improve this it is suggested to use Timosheno's beam model, as in Eq. (7), for the first order approximation to calculate cure shrinkage from the warpage at molding temperature, and further based on the CTE over molding temperature to determine the temperature shift.

$$\text{Tshift} = \text{CS} / (\alpha_{\text{EMC}} - \alpha_{\text{Cu}}) \qquad (9)$$

Expansion of the EMC is the addition of thermal expansion plus cure shrinkgae by taking 175degc as reference temperature, or equivalently the expansion with starting temperature of 175degc (molding temperature) + Tshift in Eq. (9) due to cure shrinkage. With that consideration, the correlation between beam model prediction and actual measurement was done and shown in Fig.7.

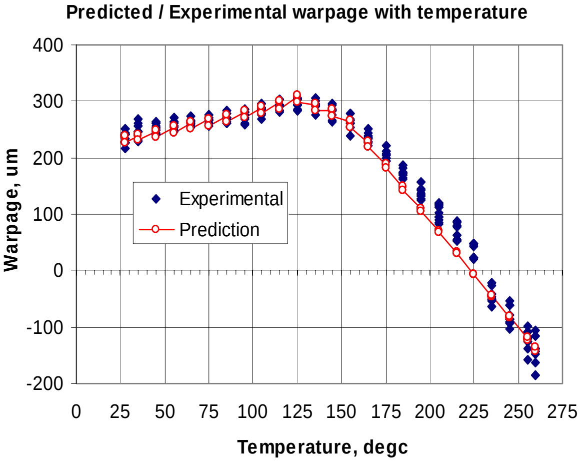


Fig.7. Correlation based on Timoshenko's beam model

It is notable that thermal shrinkage /avergae CTE of EMC is very critical in the determination of the cure shrinkage induced temperature shift. The commonly used α1, α2 and Tg to calculate thermal shrinkage causes errors, especially around Tg, and therefore deviation of prediction and measurement. What is even worse is that the errors are dependent upon testing method set-up. To ensure consistent correlation and accurate cure shrinkage characterization, it is recommeded to use complete TMA curve of the EMC to calculate shrinkage.

## 5. Direct measurement of cure shrinkage

Other methods for cure shrinkage characterization have been used before. Ken Oota [3] used a thin molded disc to determine cure shrinkage by measuring its dimension change before and after cooling down, which is total shrinkage, and the calculated thermal shrinkage using TMA data. The difference between total and thermal shrinkage is considered as cure shrinkage. As comparison, similar measurement was done, however, using rectangular stripes. Due to geometric effect of the bar and Poisson effect and constrained by the precision of the measurement tools, direct measurement using rectangular bar was not accurate. The cure shrinkage such determined was used as reference only.

Considering conversion of EMC from liquid to solid state, a correction factor of about 0.6 was introduced to consider the contribution of elastic cure shrinkage to warpage [6]. Taking this into consideration, the determined cure shrinkage by such way was 0.15%, fairly agreeable with that obtained from our new method.

## 6. 3D FEA analsyis on PBGA maps and correaltion

To further illustrate the necessity of cure shrinkage in simulation and analysis, we applied the cure shrinkage data obtained for other 2 different EMCs following above methodology to warpage prediction of actual PBGA matrix. The objective is to extrapolate the cure shrinkage results to actual product to verify its effectiveness.

The test matrix was prepared by molding EMC onto substrate of 35mmX35mm without die attached. 2 EMC materials were selected. The reason to use such EMC / substrate matrix is to eliminate the effect of geometrical and material effect of other components on warpage. Therefore, the results were expected to be more applicable. Warpage of the samples after 3 different processes, namely after transfer molding (TM), post mold cure (PMC) and PMC+ReFlow at 260degc for 3 times (RF260X3) were measured using Shadow Moiré facility at room temperature.

The thermal and mechanical properties of the selected EMCs were characterized on TMA and DMA facilities after above mentioned 3 different process conditions, i.e. after transfer molding (TM), post mold cure (PMC) and PMC+ReFlow at 260degc for 3 times (RF260X3). The data were then used as inputs for simulations to investigate how the material properties, e.g. CTE and modulus as well as chemical shrinkage, affect the warpage behavior. Octant models as shown in Fig. 8 were applied. The substrate with effective molding area of 31mmX31mm was modeled as Solder mask + core BT-Cu + solder mask tri-layer structure. In one part, the total shrinkage was applied to FEA analysis of the EMC/substrate system, i.e. cure shrinkage was considered; while in another part the test platform was simulated using only thermal shrinkage data without consideration of cure shrinkage. The obtained results were then compared to demonstrate the contribution of cure shrinkage to warpage.

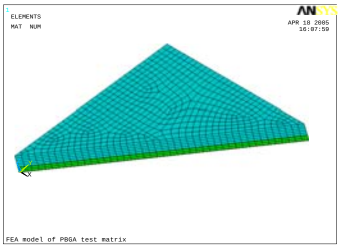


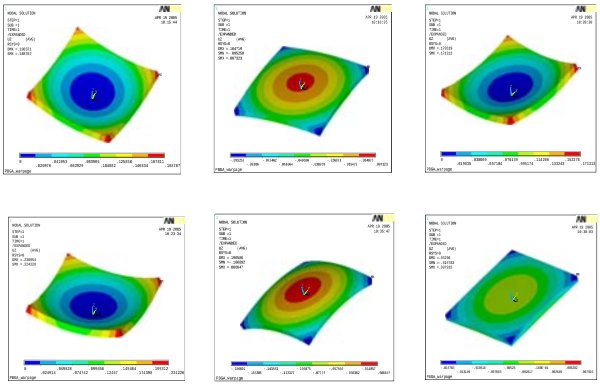
Fig.8. FEA model of test PBGA matrix

The simulation results after 3 different processes for the 2 selected EMCs were shown in Figs. 9-11, where in each of the Figures, the upper 3 plots are for EMC-1, while the lower 3 plots for EMC-2. Fig.9 shows the warpage contours when cure shrinkage was not considered and thermal shrinkage was deduced using Tg, α1 & α2; whereas for Fig.11 the results taking cure shrinkage into account and using thermal shrinkage data directly derived from TMA measurement. The difference between Fig.9 and Fig.10 is that the latter using thermal shrinkage directly from TMA curve.

Figures. 12 to 14 compare Shadow Moiré results and FEA simulation data for the cases in Figs. 9-11. It is clearly seen that:

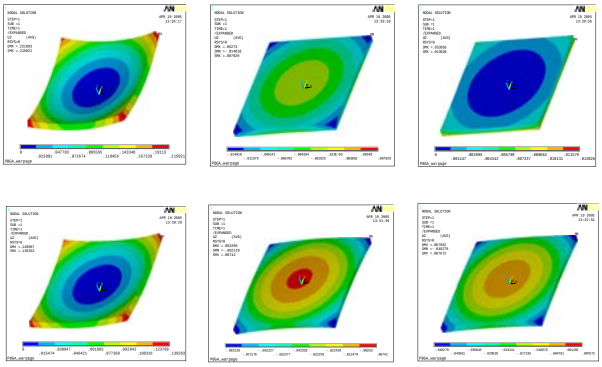
(a) When no cure shrinkage was considered, and traditional Tg, α1 & α2 values used in simulation, the correlation is very poor, as shown in Fig. 12, the trend and warping pattern after different process can not be predicted;

(b) If thermal shrinkage data were derived directly from TMA test, the trend between simulation and measurement could be greatly improved, however, a tremendous discrepancy of warpage values was seen, as in Fig. 13;



After TM PMC TM+PMC+RFX3

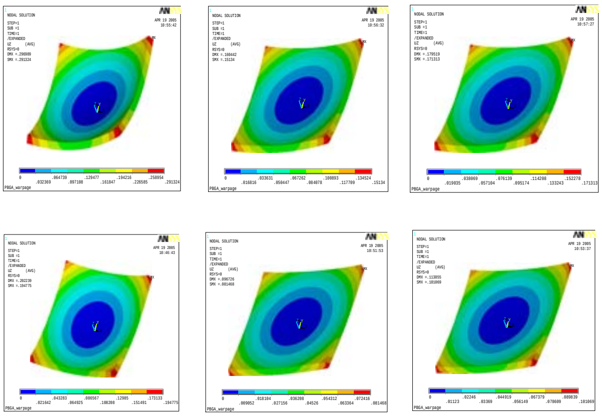
Fig.9. Warpage contour in PBGA - No CS, Tg, α1 & α2 used as simulation inputs



After TM PMC TM+PMC+RFX3

Fig.10 Warpage contour in PBGA - No CS, using thermal shrinkage from TMA curve

(c) With cure shrinkage inclusion and application of TMA thermal shrinkage data, the correlation was perfect for both EMCs and after all various process conditions, as in Fig. 14.



After TM PMC TM+PMC+RFX3

Fig.11 Warpage contour in PBGA - CS considered, using thermal shrinkage from TMA curve

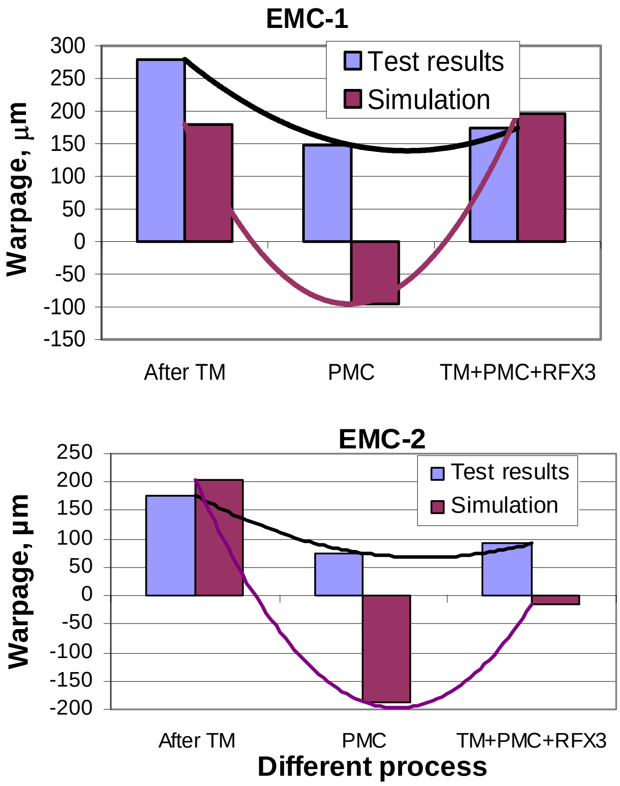


Fig. 12. Correlation between simulation and test - No CS, Tg, α1 & α2 used as simulation inputs

Modulus effect on warpage was also verified by using either DMA data or derived modulus at low and

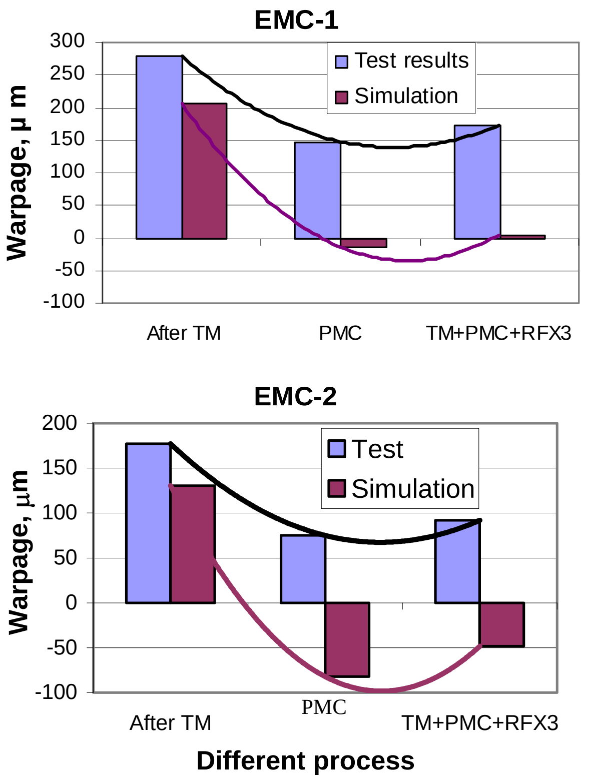


Fig. 13. Correlation between simulation and test - No CS, using thermal shrinkage from TMA

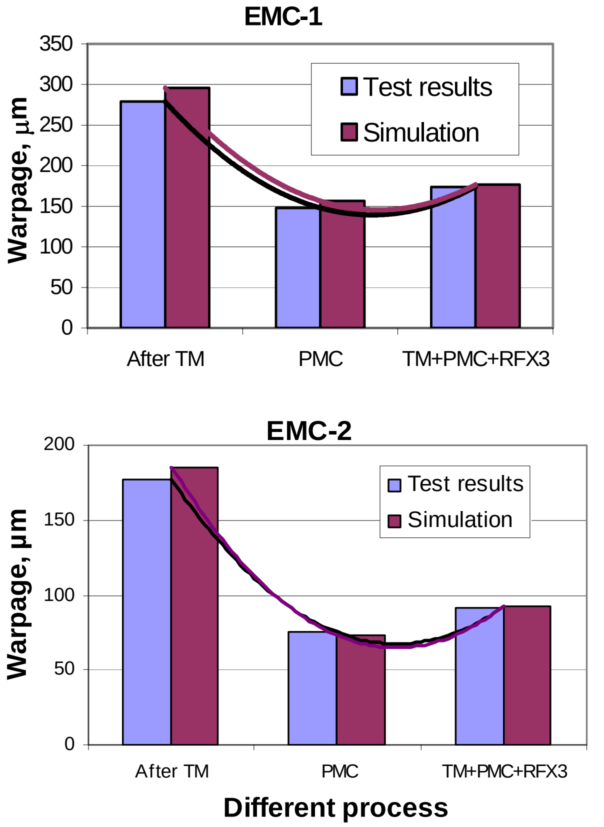


Fig. 14. Correlation between simulation and test – CS considered, using TMA from thermal shrinkage

high temperature. It was found that at low temperature it is only a second level effect. However, use of DMA data but it is recommended, especially at high temperature, where modulus is very low and maximum warpage is achieved. This is critical when high temperature warpage, for example, of PoP packages, is urging accurate characterization.

Good agreement of simulation with measurement under conditions of considering cure shrinkage and using TMA thermal shrinkage and DMA modulus data suggested the inclusion of cure shrinkage and identified the significance of correct application of TMA and DMA data. It demonstrates that accurate characterization of warpage is feasible but cure shrinkage must be considered, and material data must be reliability and properly used.

## 7. Discussion

In our new approach to characterize cure shrinkage, a simple EMC/Cu or a known material as substrate was used. Through measurement of warpage of the bi-layer beam system in a wide temperature range using Shadow Moiré, the elastic cure shrinkage of the EMC was derived by best fitting the experimental data. Material characterization data including thermal expansion (from TMA) and mechanical property (from DMA) were recommended to use to ensure accuracy of cure shrinkage determination. As 1st order approximation, elastic cure shrinkage can be obtained either from the warpage at molding temperature or from the Tshift, a temperature shift due to cure shrinkage. In summary, the procedure of cure shrinkage characterization is as follows:

a. Warpage measurement of EMC/Cu bi-layer system in a wide temperature range;
b. TMA and DMA characterization of the testing EMC;
c. Best-fitting warpage data to obtain cure shrinkage;
d. 1st order estimation of cure shrinkage using Wm, warpage at molding temperature; and Tshift, temperature shift from molding temperature to new zero-warpage temperature;
e. Verification using Timoshenko's beam model.

Compared with traditional direct measurement approach for cure shrinkage determination, our new method has high sensitivity and thus high accuracy of measurement, applicable to the whole temperature range. Besides, elastic cure shrinkage can be derived directly, whereas the plastic cure shrinkage that actually does not contribute to warpage is excluded.

Obviously, final cure shrinkage value varies with TMA and DMA data. This fact urges proper characterization of thermal and mechanical property of EMC and correct application. For TMA data, using α1, α2 and Tg will cause extra errors and should be abandoned; instead thermal shrinkage data should be applied directly to capture precisely the warpage trend.

More errors can be seen at high temperature. This partially is originated from modulus errors in DMA data. In rubber stage, modulus of EMC is very low, warpage becomes more sensitive to the modulus variation. Considering that zero-warpage temperature is at high temperature range, and moreover Shadow Moiré is not capable enough to capture the zero-warpage temperature, it is suggested to use both the warpage at molding temperature and Tshift to estimate the elastic cure shrinkage as first order approximation.

FEA analysis of the bi-layer could help clarify the accuracy of Timoshenko's beam model. That part of work can provide comprehensive comparison using 2D and 3D models and calibrate the effectiveness of beam model. The results will be presented separately in another paper due to length constrain of this paper.

For practical purpose, correlation for real packages with actual die will be significant. Theoretically, with or without die has no detriment for our new method. However, application of cure shrinkage data to real packages will be very demonstrative, and should be part of future works to further validate our method.

In our work, cure shrinkage is considered for fully cured EMC. No efforts have been put into shrinkage at different curing stages that were studied, e.g. in Ref. [9, 10]. This is conforming to actual industrial practice where post molding cure is usually one of the processes to ensure full-cross-linking in EMC and thus stabilized property of EMC.

## 8. Conclusions

1) New method to characterize cure shrinkage / total shrinkage of EMC was presented by measurement of warpage of bi-layer beam in a wide temperature range. Simple estimate of the cure shrinkage was initiated. As first order approximation, Timoshenko's beam model provides a good correlation.
2) Advantages of this new method are proposed. Firstly, it characterizes directly the elastic cure shrinkage; and secondly, it has higher accuracy than other direct measurement methods.
3) Cure shrinkage of 3 molding compounds was characterized. The cure shrinkage data of 2 EMCs were applied to PBGA matrix. It was illustrated clearly that accurate warpage prediction could be achieved when cure shrinkage data was applied and both TMA and DMA data were properly adopted.

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