

Low-warpage molding compound development for array packages

Due to the singulation and soldering processes required during package assembly, device warpage after molding is a critical issue for array packages. Warpage is greatly affected by package geometries, such as dimensions of the matrix block, pad, die, and passive components, as well as the molding compound properties. One set of molding compound properties may generate very low warpage in one array package, but unacceptable warpage in another. To achieve minimum warpage in all geometry variations, molding compound properties have to be tuned for each package. For this paper, modifications to a successful molding compound A (MC A) were performed systematically. The curing shrinkage and Tg of the molding compounds were adjusted, while other major properties kept consistent. Warpage of array blocks/strips built with modified molding compounds was measured by a shadow Moiré method to correlate warpage with molding compound properties. Finite element analysis (FEA) was performed to predict and correlate the effects of mold compound properties on warpage.

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Introduction and background investigation

Warpage is one of the major concerns when manufacturing BGA, CSP, POP and QFN-based array packages because obtaining and maintaining a reasonably flat package is critical to successful singulation and board level soldering processes. Warpage is introduced into a package during the curing and cooling of adhesives like mold compounds. Once the gel point is reached, package components are bound together by the cross-linked polymer network, and no component can expand or shrink freely. Differences in chemical shrinkage and/or coefficient of thermal expansion (CTE) of package components thus can cause warpage. In a typical array package, warpage is seen in either a 'crying' face (corners facing downward) or a 'crying' face (corners facing upward) direction.

The warpage shape depends on both the geometries and properties of package components as well as process conditions. Most often, the package geometry is predefined in the design phase and difficult to change. Likewise, process conditions are usually based on industry standards and existing manufacturing infrastructure, thus altering the process would be relatively costly due to the additional qualification and capital investment that would likely be required. Therefore, the only feasible and cost-effective route to adjusting package warpage is to modify the materials properties of package components. Molding compounds, the largest materials component in packages, usually dominate the cause of warpage. Molding compounds are composite materials composed of resins, hardeners, fillers, catalysts, coupling/release agents, and a small percentage of other ingredients. It is meaningful to control package warpage through manipulating materials properties, such as Tg, CTE and curing shrinkage, of molding compounds. The materials formulation percentages can be modified accordingly to affect these properties. CTEs of molding compounds are largely controlled by filler contents, such as percent loading of silica fillers. Curing shrinkages are dominated by polymerization methods and curing kinetics. Tg properties are usually dependent on the stiffness

of polymer chains, chain lengths, and free volume between the chains.

For this paper, modifications to a successful molding compound A (MC A) were performed systematically. In previous studies, MC A showed very small warpage in one package but showed unacceptable results in others. Finite element analysis was used to investigate the differences. The results revealed that warpage was die size, package size and molding compound property dependent. Variations in die and package geometries could warp the package into either 'smiling' or 'crying' face direction, but warpage can be counter-corrected by altering specific mold compound properties such as CTE and percent shrinkage. The modeling analysis provided a guideline for the prediction of key property trends required to efficiently control warpage in various array packages.

The modifications to MC A were formulated with a newly developed flexible resin and hardener. By varying the amounts of flexible resin/hardener, the cure shrinkage and Tg of MC A is adjusted and other major properties remained constant. Warpage characteristics on a typical BT substrate array package were altered accordingly, properties of the modified versions were measured against MC A for comparison and warpage was measured using a shadow Moiré method to correlate warpage with mold compound properties.

Experiments and model setup

MC A modified versions were formulated in two series. In the first series, both flexible resin and hardener from 10% to 50% at 10% intervals were added. In the second series, only the flexible hardener was added, but at the same percentage intervals as in series one. The molding compounds were prepared by dry blending the ingredients followed by melt-mixing, extrusion into sheet form, fine-grinding into powder, then palletizing into pre-forms.

Standard transfer molding techniques were used to fabricate various test specimens for TMA, DMA, shrinkage, and molded array strip for warpage. Warpage measurements were made by high sensitivity shadow moiré method, an optical method that measures topography of the surface of a solid object and its deviation from a planar surface.

Finite element models were built according to experimental package size and materials properties. A full model of the array package was built as shown in *Figure 1*. To simplify the model and match the experiment, only two components, molding compounds and BT substrate, were presented in the model. The substrate was 18.65 x 6.0 x 0.2 mm. The single mold block was 5.2 x 4.4 x 0.8 mm. The package warpages at room temperature were calculated with ALGOR 3-D linear static analysis. Molding compounds were treated as isotropic. The BT substrate was treated as orthotropic, with different CTEs in X, Y and Z direction. Stress free temperature was assumed to be at 175 °C, which was the curing temperature of molding compounds. In the analysis, all the bondings were assumed to be perfect and there were no delaminations in the package. Package warpages were measured on top of molding compound in the height difference between package corner and package center. Warpage was defined as positive when the shape was in ‘crying’ face and negative when the shape was in ‘smiling’ face.

DMA (dynamic mechanical analysis) results showed that Tg decreased as the percentage of flexible resin and hardener increased, as shown in *Figures 2 and 3*. Increasing the flexible hardener had more direct impact in lowering the Tg as compared to the combination approach (*Figure 4*). The data suggests that the addition of a flexible hardener was more effective in lowering the overall cross-linking density of the cured network. The lowered cross-linking densities were also reflected by modulus results at 260°C in which addition of both flexible resin and hardener yielded a much higher modulus, an indication of higher cross-link density, as compared to flex hardener only versions as shown in *Figure 5*.

In TMA (thermal mechanical analysis) results, CTE1 & CTE 2 were not affected by either the addition of flexible resin/hardener or the hardener-only approach (*Figure 6*). The results suggest that the CTE is dictated more by the total percent filler content rather than resin variations as in such highly filled system (88% filler contents for both series).

The analysis of curing shrinkage showed that shrinkage increased as the percentage level of flexible resin/hardener increased. The flexible hardener versions showed similar results as the combination versions within the 30% range, but had much higher shrinkage in the 40-50% range (*Figure 7*).

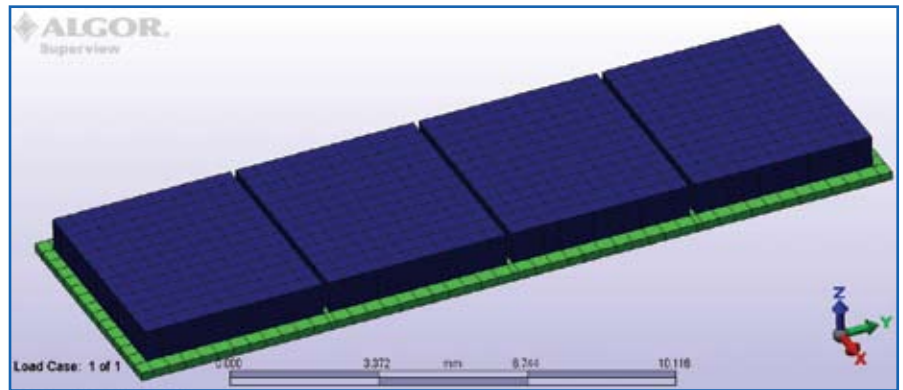


Figure 1 - A 3-D model of the molded array package.

Table 1. Series 1 of modified MC A with varied % flex resin & hardener.

| Series 1 | MC-A | 1A | 1B | 1C | 1D | 1E |
|-------------------------|-------|-------|-------|-------|-------|-------|
| % Filler | 88 | 88 | 88 | 88 | 88 | 88 |
| % Flex Epoxy | 0 | 10 | 20 | 30 | 40 | 50 |
| % Flex Hardener | 0 | 10 | 20 | 30 | 40 | 50 |
| CTE1, ppm | 9 | 12 | 11 | 11 | 11 | 12 |
| CTE2, ppm | 35 | 29 | 37 | 31 | 35 | 35 |
| Tg by DMA | 189 | 209 | 196 | 187 | 177 | 168 |
| Modulus @ RT, Gpa | 12.6 | 12.3 | 13.1 | 11.4 | 12.8 | 12.6 |
| Modulus @ 260°C, Mpa | 1420 | 1700 | 1400 | 1200 | 1140 | 1110 |
| % Shrinkage | 0.054 | 0.034 | 0.022 | 0.033 | 0.051 | 0.081 |
| Warpage, strip, mm | 1.1 | 1.61 | 1.10 | 1.08 | 0.77 | 0.86 |
| Warpage, single gap, um | 263 | 140 | 110 | -225 | -315 | -400 |

Table 2. Series 2 of modified MC A with varied % flex hardener.

| Series 2 | MC-A | 2A | 2B | 2C | 2D | 2E |
|-------------------------|-------|-------|------|------|-------|-------|
| % Filler | 88 | 88 | 88 | 88 | 88 | 88 |
| % Flex Epoxy | 0 | 0 | 0 | 0 | 0 | 0 |
| % Flex Hardener | 0 | 10 | 20 | 30 | 40 | 50 |
| CTE1, ppm | 9 | 11 | 10 | 11 | 11 | 12 |
| CTE2, ppm | 35 | 45 | 38 | 42 | 41 | 34 |
| Tg by DMA | 189 | 180 | 171 | 161 | 154 | 147 |
| Modulus @ RT, Gpa | 12.6 | 13.5 | 12.4 | 11.3 | 13.5 | 13.3 |
| Modulus @ 260°C, Mpa | 1420 | 1100 | 850 | 775 | 790 | 730 |
| % Shrinkage | 0.054 | 0.011 | 0.02 | 0.03 | 0.026 | 0.049 |
| Warpage, strip, mm | 1.7 | 1.02 | 0.96 | 0.88 | 0.60 | 0.46 |
| Warpage, single gap, um | 263 | 206 | 187 | -223 | -290 | -330 |

These results suggest that the addition of a flexible hardener in the 40-50% range could induce more cure shrinkage than that of the combination approach, since CTE-induced thermal shrinkage was quite negligible for all these versions as shown in the above CTE results.

Package warpage was measured in two ways. First, a high sensitivity shadow moiré method was used to measure the warpage of the single mold cap. Results revealed that the single mold cap warpage was in the ‘crying’ face direction and became more pronounced as the percentage of flexible resin and hardener increased. Both series shared the same trend and warpage value. In the second test., the

entire strip was measured by subtracting the four corner heights of the strip from the center height. The strip’s warpage was found to be in ‘crying’ face direction and decreased as the percentage of flexible resin and hardener was increased. Both trends showed that low Tg and high curing shrinkage would force the package warpage into the higher, ‘crying’ face direction.

These results indicate that warpage can be impacted by the addition of flexible hardener or a combination of flexible resin and hardener. Tg and shrinkage were identified as the factors that have the greatest influence on warpage, either on a single mold cap or an entire strip. Because there was little variation in CTE values,

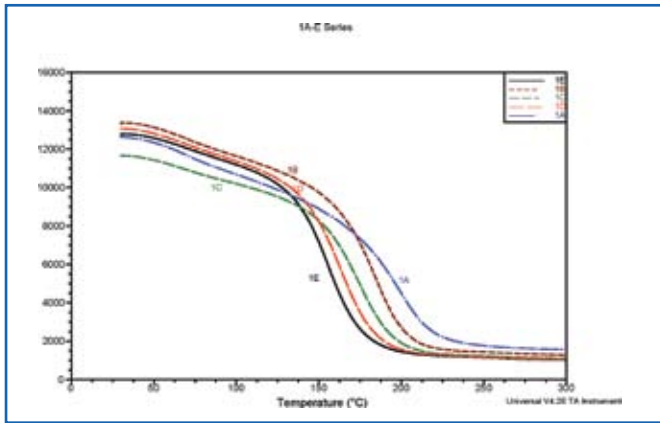


Figure 2. DMA of MC A modified with varying % flexible resin & hardener.

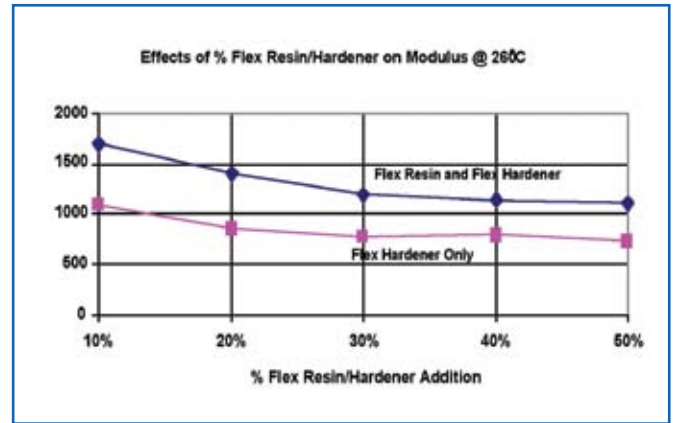


Figure 5. Effects of % flexible resin and hardener on modulus @ 260°C.

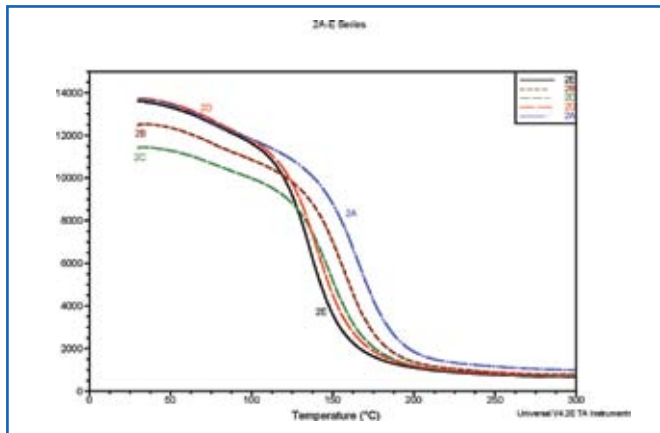


Figure 3. DMA of MC A modified with varying % flexible hardener only.

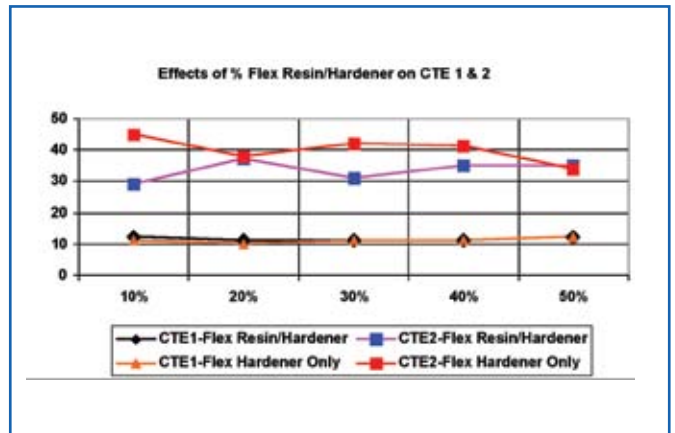


Figure 6. Effects of % flexible resin and hardener on CTE.

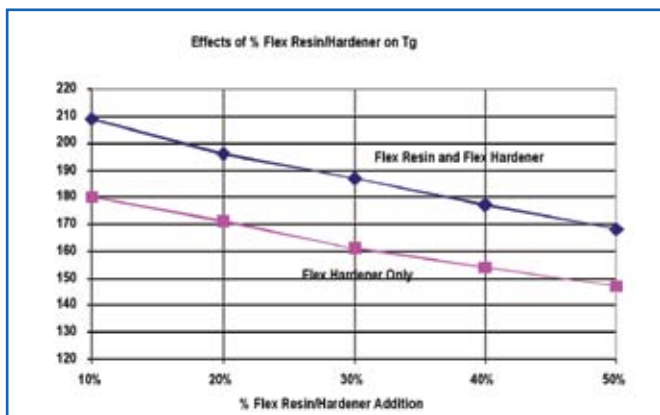


Figure 4. Effects of % flexible resin and hardener on Tg.

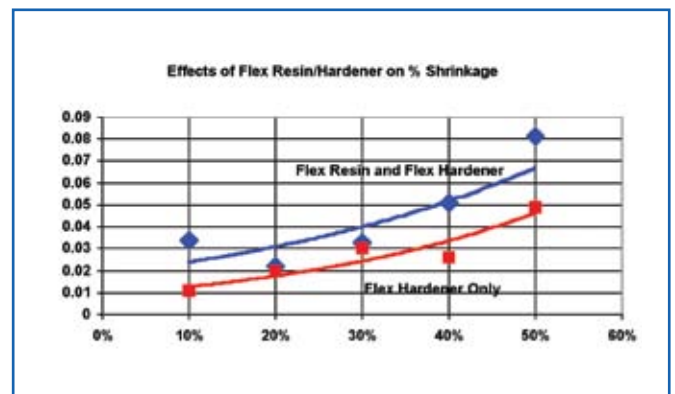


Figure 7. Effects of % flexible resin and hardener on shrinkage.

the effect of CTE was negligible in this study.

Finite element analysis

Finite element analysis was performed to compare the warpage in each modification. Because of the different flexible resin and hardener percentages, the shrinkage and Tg of the cured product

changed accordingly, with these variations also introducing changes in package warpage. For this simplified two-layer system, the warpage depends on the final dimensional difference (ΔL) between the BT substrate and the molding compound, as the mold compound cured and both cooled down to room temperature. The dimension change from 175 °C cooling

to room temperature (RT) was illustrated in Figure 10. For the BT laminate, there was no phase transition and CTE change, and the dimensional change was a straight line (Figure 10). The final dimensional change for molding compounds was related to curing shrinkage, Tg and CTEs above and below Tg. The green line in Figure 10 illustrates this three-section

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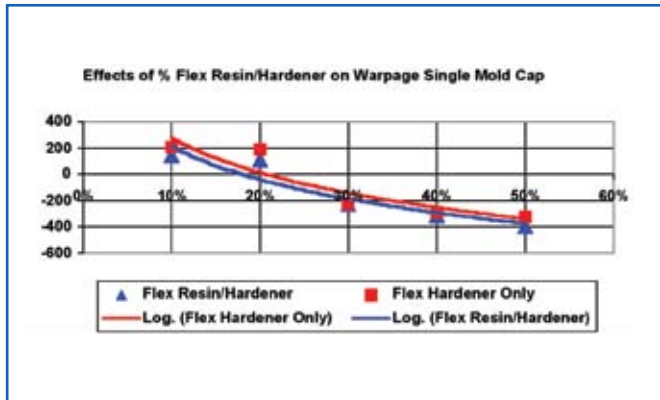


Figure 8. Effects of % flexible resin and hardener on warpage @ single mold cap.

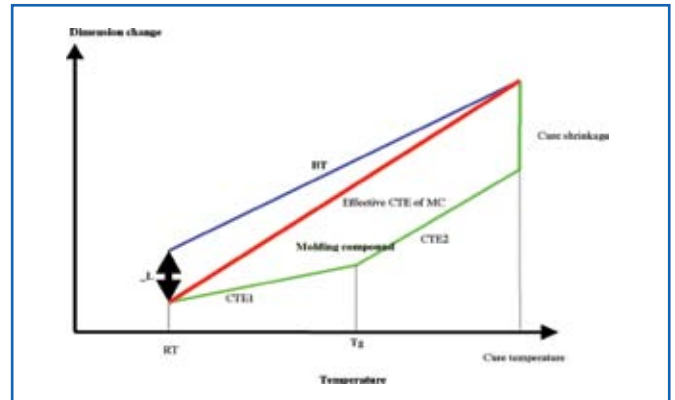


Fig. 10 Dimension change of BT and molding compound vs. temperature.

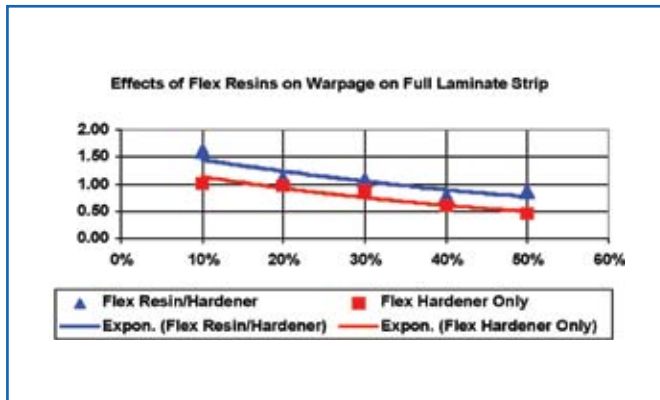


Figure 9. Effects of % flexible resin and hardener on warpage @ entire strip.

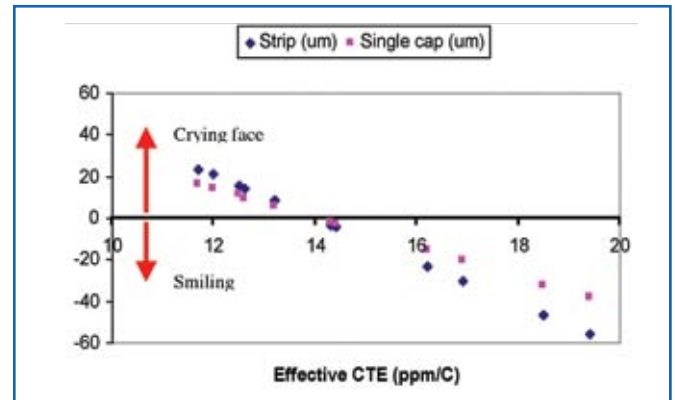


Figure 11 - Warpage calculated by finite element analysis.

Table 3. Summary of finite element analysis.

| MC | Modulus (G Pa) | CTE1 (ppm/C) | CTE2 (ppm/C) | Tg (° C) | Shrinkage (%) | Effective CTE (ppm/C) | Strip warpage (um) | Strip experiment (mm) | Single cap warpage (um) | Single cap experiment (um) |
|------|----------------|--------------|--------------|----------|---------------|-----------------------|--------------------|-----------------------|-------------------------|----------------------------|
| 1A | 12.3 | 12 | 29 | 209 | 0.034 | 14.3 | -3.5 | 1.61 | -2.3 | -140 |
| 1B | 13.1 | 11 | 37 | 196 | 0.022 | 12.5 | 15.4 | 1.1 | 11 | -110 |
| 1C | 11.4 | 11 | 31 | 187 | 0.033 | 13.2 | 8.3 | 1.08 | 5.7 | -225 |
| 1D | 12.8 | 11 | 35 | 177 | 0.051 | 14.4 | -4.5 | 0.77 | -2.8 | -315 |
| 1E | 12.6 | 12 | 35 | 168 | 0.081 | 18.5 | -46.7 | 0.86 | -32.2 | -400 |
| MC A | 12.6 | 9 | 35 | 189 | 0.054 | 12.6 | 14.4 | 1.7 | 9.3 | -263 |
| 2A | 13.5 | 11 | 45 | 180 | 0.011 | 11.7 | 23.6 | 1.02 | 16.4 | -206 |
| 2B | 12.4 | 10 | 38 | 171 | 0.02 | 12 | 21 | 0.96 | 14.1 | -187 |
| 2C | 11.3 | 11 | 42 | 161 | 0.03 | 16.2 | -23.2 | 0.88 | -15.8 | -223 |
| 2D | 13.5 | 11 | 41 | 154 | 0.026 | 16.9 | -30.1 | 0.6 | -20.6 | -290 |
| 2E | 13.3 | 12 | 34 | 147 | 0.049 | 19.4 | -55.8 | 0.46 | -38.4 | -330 |

change. To fit into the finite element linear analysis, the effective CTE was calculated using Equation 1.

$$\text{Equation 1} \\ \text{CTE}_{\text{effective}} = [(T_g - RT) \times \text{CTE}_1 + (T_{\text{cure}} - T_g) \times \text{CTE}_2 + \text{cure shrinkage}] / (T_{\text{cure}} - RT)$$

The dimensional change of the molding

compound is presented in a straight line (in red. Figure 10) with the effective CTE. This equation should not be applied to cases with Tg higher than curing temperature. The finite element results are summarized in Table 3 along with experimental warpage results. As the percentage of flexible hardener and epoxy increased, system Tg decreased and curing shrinkage

increased. The effective CTEs were therefore increased. The relation between calculated array warpage and effective CTE is summarized in Figure 11. Warpage in the 'crying' face (Figure 12) direction gradually decreased along with the increase in effective CTE. After approaching zero warpage, the warpage changed into 'crying' face (Figure 13) and gradually increased in

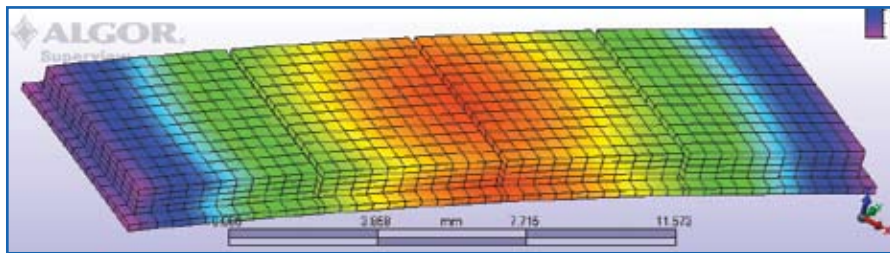


Figure 12 - A typical crying face warpage calculated by finite element analysis.

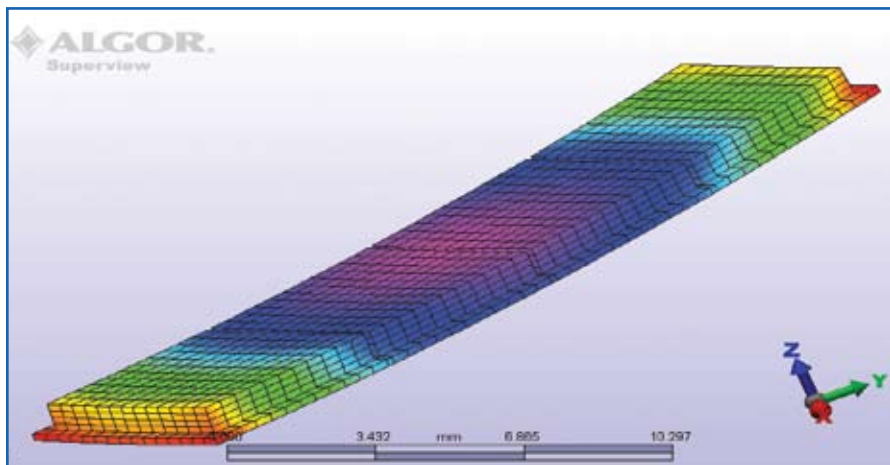


Figure 13 - A typical smiling face warpage calculated by finite element analysis.

decrease in crying face warpage and an increase in smiling face warpage as the effective CTE increased. However, the warpage values from the finite element prediction were much smaller than the experimental measurements, indicating that calibration is needed so that the necessary property change predicted by finite element analysis for zero warpage can be realized experimentally.

Conclusions

The results of these experiments and analysis show that altering the flexible resin/hardener in molding compounds can effectively change package warpage. Using a flexible hardener was very effective in lowering the Tg and increasing curing shrinkage, which were identified as key factors to array warpage. Crying face warpages can be corrected by using mold compounds with low Tg and high curing shrinkage, while smiling face warpage can be altered by using mold compounds with high Tg and low curing shrinkage. These findings are a breakthrough for effective processing of the latest generation of thin CSP and QFN array packages, essentially enabling the absolute flatness of these packages so that they can effectively pass through singulation and PCB assembly processes.

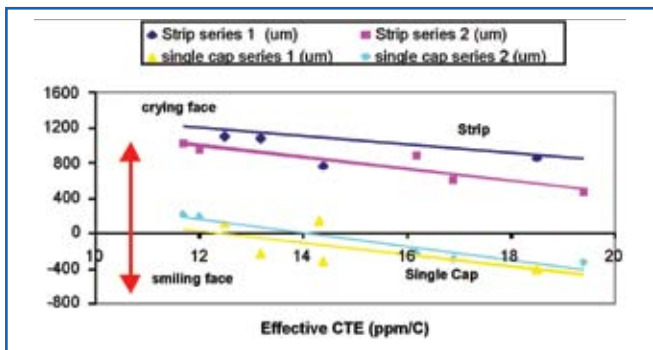


Figure 14 - Experimental warpage vs. effective CTE.

value if the effective CTE kept increasing. (Figure 14)

Experimental results showed same warpage directions for strips and single cap, with both warping in the crying face direction first then moving into the smiling face direction as the effective CTE increases. The finite element analysis also predicted that both the strip and single cap warpage should change from a crying face into a smiling face as the effective CTE increases, (the transition point for effective CTE value was approximately 14.5 ppm/C) for the FEA prediction which is in consistent with experimental single mold cap warpage. Though no transition was observed in the experimental samples with full strip warpage, the trend did follow a



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