Elevated Temperature Measurements of Warpage of BGA Packages

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Biography

David Garrett is a Senior Research Scientist for Amoco Electronic Materials, Plaskon Division. He received his BA in Chemistry from DePauw University and his PhD in Physical Organic Chemistry from Indiana University. He has over 25 years of experience in the polymer research and product development at Owens Corning and Amoco Polymers. He holds nine US patents and has numerous publications. He joined Plaskon in 1995 when it became affiliated with Amoco. Dave has been very active in the Society of Plastics Engineers and is a founding member of a new division of that Society, the Advanced Polymer Composites Division. He has held many offices in that Division including Chairman.

Abstract

Warpage is a critical parameter in BGA packaging. Too much warpage can create stress on the solder ball joints and lead to reliability failures of the packages. For convenience, most warpage measurements are carried out at room temperature. However, the warpage behavior of the BGA package during the reflow process and during thermal cycling can be quite critical to its performance, since these conditions may induce additional stresses. Amoco Electronic Materials and Electronic Packaging Services, Ltd., Co. have jointly developed a technique using shadow moiré interferometry measurements to accurately monitor warpage under real-time, solder reflow temperature conditions. This presentation reports some of the results of this development program.

Background

Control of package warpage is one of the more important criteria for producing quality Ball Grid Array (BGA) products. Excessive warpage can lead to incomplete ball bonding (opens) and reliability problems. JEDEC has set an upper limit specification for package coplanarity at 8 mils across the package. The BGA assembly houses and end users have established operating limits much lower than this industry specification.

Warpage essentially occurs when there is a thermal mismatch between the various components that make up a BGA package (*i.e.* the substrate, the molding compound and the silicon chip). Several have proposed that another type of stress occurs in the package as the epoxy molding compound (EMC) polymerizes[1,2]. This stress has been labeled as chemical shrinkage. Most polymers do undergo some shrinkage as they polymerize; however, in highly filled systems such as EMC's this chemical shrinkage is negligible. Attempts to back calculate this shrinkage using the measured value for mold shrinkage and the part's coefficient of linear thermal expansion (CLTE) gave chemical shrinkage values of zero.

Other molded packages such as SOIC's, DIP"s, PLCC's, QFP's, etc. have these same thermal stresses, but, because they are molded on both sides of the substrate, these stresses will not show up as warpage but as stress fields. These stress fields may induce package cracking and delamination. A common way to estimate package stress is through an empirical formula (*equation 1*) called the Stress Intensity Factor[3].

$$\sigma = (\alpha_{EMC} - \alpha_{IC}) \bullet E_{EMC} \bullet \Delta T \qquad (eq\ 1)$$

where:

σ = internal package stress
α_{EMC} = CLTE or alpha of the EMC at T
α_{IC} = CLTE of the silicon chip at T
E_{EMC} = Young's modulus of the EMC at T
ΔT = glass transition temperature of EMC - measuring temperature(T)

This equation was developed to help assess stress cracking in standard packages. It is a standard tool in developing low stress molding compounds.

BGA packages are only molded on one side of the substrate. Because of this configuration there is a direct way to measure package stress, by monitoring the warpage. Since this warpage affects downstream processing and reliability of the package, warpage is a very critical parameter for BGA packaging.

Through classical engineering principles[4] we can characterize warpage by treating a BGA package as a bimetallic strip. The equation for the curvature of a bimetallic element is given in *equation 2.*

$$w = \frac{3(\alpha_s - \alpha_c)(T_m - T)(t_s + t_c)d^2}{4t_s^2\{(4 + 6\,t_c/t_s + 4(t_c/t_s)^2 + (E_c/E_s)(t_c/t_s)^3 + E_s/E_c(t_s/t_c)\}} \quad (eq\ 2)$$

where:

w = warpage
α_s and α_c = CLTE's of substrate and molding compound at T
t_s and t_c = thickness of substrate and molding compound
E_s and E_c = moduli of substrate and molding compound at T
Tm = molding temperature
T = testing temperature
d = width of molding compound

The major differences between *equation 1* and *equation 2* are that *equation 2* takes package size into account and the moduli terms in *equation 2* have a more complex relationship than the linear relationship of *equation 1. Equation 2* assumes good adhesion between the EMC and substrate.

If you apply *equation 2* to a "typical" BGA molding compound and substrate (see **Table I**), the following trends can be estimated:

Warpage will decrease with:

- A reduced temperature difference (higher measuring temperature or lower T_m.)
- A close match of the CLTE's of the EMC and substrate
- Smaller package width (major effect)
- Increased thickness of the EMC (major effect)
- Increased modulus of the EMC (minor effect)
- Decreased modulus of the substrate (minor effect)

The warpage will invert (change sign) if the measuring temperature is above the T_m or if the alpha 1 of the EMC is smaller than the alpha 1 of the substrate. At T_m the package will be in a "no stress" state and warpage should be zero. It makes good logical sense that at the temperature at which the components are introduced to each other, there would be no thermally induced stresses. The only stresses at this temperature would be a result of the polymerization of the epoxy novolac material. This shrinkage has been labeled as "chemical shrinkage" and is outside the scope of either *equation 1* or *equation 2.*

Table I. Physical properties of components of a "typical" BGA package

property	EMC	BT substrate	IC
alpha 1 (ppm)/ °C	14	15	4 - 5
alpha 2 (ppm)/ °C	57	9.0	---
glass transition temperature (°C)	225	154	---
room temp Young's modulus (GPa)	10.3	17.9	105.9
thickness (mm)	0.69	0.33	0.45
width (mm)	24	--	8.3
mold temp (°C)	175		

The value of T_m is the subject to some debate. In this discussion we have assumed that T_m is the mold temperature of the package. Many argue that there is minimal stress on the package above the glass transition temperature of EMC so that warpage and stress will only occur below the T_g[5]. The reasoning is that the modulus above the T_g is so low that the EMC becomes very compliant. The molding compound used in this model actually shows a nearly linear loss in modulus by DMA from 10.5 GPa to 2 GPa over a temperature range of 25°C to 240°C (*Figure 1*). At no point within the testing range does this material become compliant.

BGA packages have a third component within the package, the IC, which presents two new interfaces where warpage can occur. The theoretical profiling of this package now becomes quite complicated. We have calculated the effect of the IC on package warpage using *equation 2* and found it has minimal effect. This was done by treating all three interfaces (IC-substrate, IC-EMC, EMC-substrate) independently and then adding the contribution of each to the total warpage. The inclusion of the IC does, however, change the "effective" width, d, of the calculations since it blocks out the center area of the package.

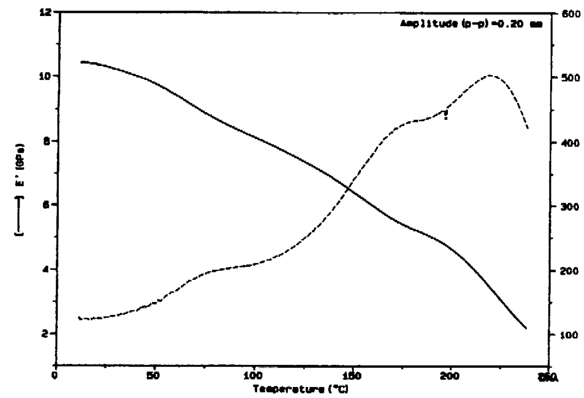

Figure 1. Dynamic Mechanical Analysis of SMT-B-1™

In general, warpage measurements of BGA packages are run at room temperature. However, package warpage and coplanarity should be more critical at soldering temperatures where flatness is necessary to get strong solder bonds. The objective of this study was to measure package warpage under a temperature profile similar to reflow soldering conditions in order to learn more about the geometric changes the package undergoes during thermal cycling. This study would also offer the opportunity to verify the various theories on warpage.

An additional complication in assessing the theoretical warpage with temperature is that both components, the substrate and the molding material, have glass transition temperatures within the testing range. At the T_g the CLTE of the material changes and the modulus usually changes thus complicating the calculation.

Data

Five different molding materials were transfer molded onto a BT substrate having a 8.30 mm x 8.30 mm x 0.45 mm dummy die. The BT substrates were all plasma cleaned in Argon plasma using optimized cleaning conditions. The mold temperature was 175°C. The materials were all post cured at 175°C for five hours. The molded packages were scanned for delamination by C-SAM. All the packages showed good adhesion by this test method.

These molding compounds are all commercial grade material designed for BGA applications. They come from four different manufacturers; the first two, SMT-B-1™ and 146.408, being from Plaskon. Some of the physical properties of these materials are given in **Table II**. All properties were measured on the same test equipment using the same test methods.

Warpage on these molded parts was measured by Electronic Packaging Services, Ltd. Co. using shadow moiré measurements[6]. These measurements are made by coating the part with a reflective paint and placing a sheet of low expansion quartz glass etched with equally spaced parallel lines parallel to the sample. The density of the grating lines for these measurements was 300 lines/inch. A beam of light is then directed onto the quartz glass and the lines create a shadow on the top of the BGA package (*Figure 2*). When the sample is curved or warped a moiré pattern is produced by the geometric interference between the etched lines on the quartz and the shadow of those lines on the surface. A typical fringe pattern is shown in *Figure 3*. If the surface is flat and the two surfaces parallel, then no fringe patterns are produced.

In order to measure the warpage at elevated temperatures, the sample and quartz grating were placed in an ir-heated oven having appropriate windows for focusing the light and measuring the fringe patterns. The oven was heated from room temperature to 240°C at a controlled rate to simulate the reflow soldering process. The time to reach maximum temperature was 500 sec. At various pre-established temperatures the moiré fringe patterns were quantitatively analyzed for the amount of sample warpage. These measurements can be graphically displayed in various ways as illustrated in *Figure 4* and *Figure 5*.

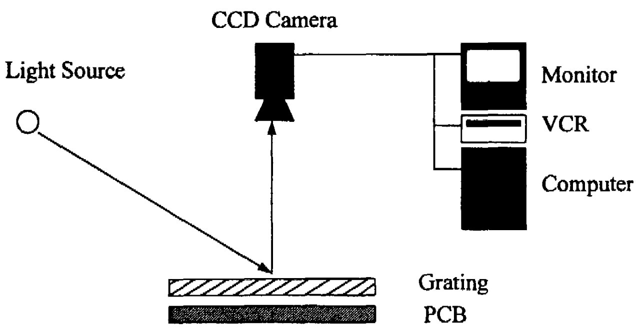

Figure 2. Shadow Moiré setup/configuration

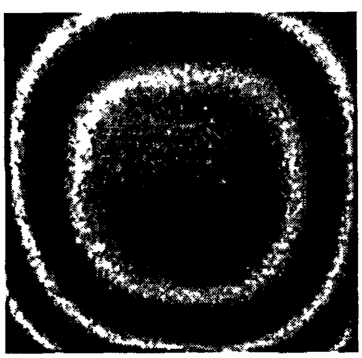

Figure 3. Typical moire fringe pattern for BGA's

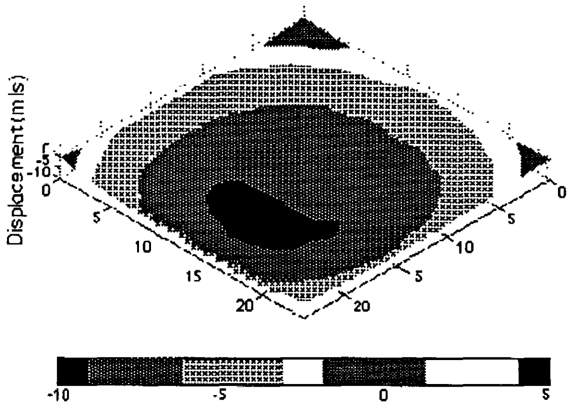

Figure 4. 3-D plot of shadow moiré data

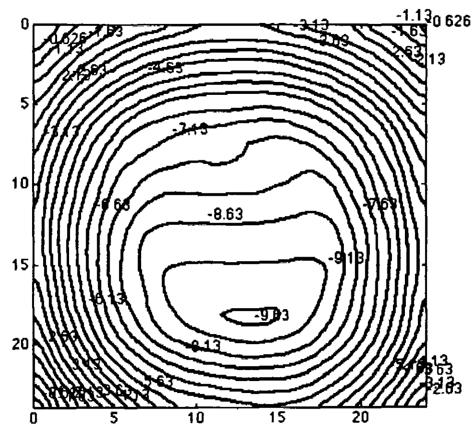

Figure 5. 2-D contour plot of shadow moiré data

In analyzing the moiré data, we treated it as if we were measuring warpage using an optical technique. That is, the displacement was measured at the center of the package and at the four corners. The average displacement of the four corners minus the center displacement was the calculated warpage. By convention concave warpage is negative and convex warpage is positive. All measurements were taken on the top side of the package. The moiré data showed in all our samples that maximum warpage did not occur at the center of the package but usually near the edge of the chip. We elected to use the center point / corner points analysis technique in order to be consistent with other measuring techniques and

to reduce the analysis time and difficulty. Three packages of each material were tested with remarkably good reproducibility. Two sets of data were collected during the cooling cycle as well at the final room temperature to determine if any hysteresis occurred in the heating and cooling procedure. A difference in warpage might indicate that the package had been damaged (delamination) during the heating cycle or that the rate of heating played a role in introducing warpage (i.e. uneven heating). Within experimental error, no hysteresis was observed for any of the samples. The data for all five samples are plotted in
Figure 6.

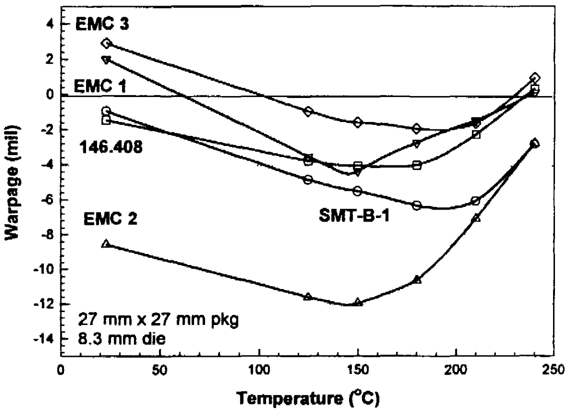

Figure 6. Temperature vs warpage curves for BGA packages

Discussion

The shape of the plots in *Figure 6* are quite similar. They all start at room temperature with a negative slope and then change dramatically at some temperature to a positive slope. This change occurs at a different temperature for each material and is related to the glass transition of the specific EMC. The most intriguing result is that the data do not fit either the warpage model or the strain intensity factor model. Both models predict that zero warpage would occur at a temperature related either to the glass transition temperature or the molding temperature of the material. The data, however, indicate that the package has the greatest concave warpage at or near its Tg. The mathematical models only account for the effects of thermally induced stresses created by the thermal mismatch of the package components. If we want to maintain the validity of the models, a reasonable way to explain this discrepancy is to assign residual stresses to the packages which are not thermally dependent. The source of this residual stress is not obvious. It is currently popular to invoke chemical shrinkage as a shrinkage component of EMCs. The epoxy/hardener resins used in EMCs will shrink during polymerization, however, attempts to measure the contribution to shrinkage of these highly filled materials have led to values below the detectable limits of the test method. Since the resin is a 10% - 15% component of the molding compound, it is easy to understand why its shrinkage contribution is marginal. Stress can also be introduced into a package through the molding process. Such process variables such as clamping forces, uneven curing due to thermal transport through the molding material, irregular heating across the mold plates, minor sticking of the part in the mold, all can contribute to stresses and subsequent warpage. To illustrate the effect processing may have on warpage, *Figure 7* shows the importance of optimizing the in-mold cure time to minimize warpage for several SMT-B-1™ variants.

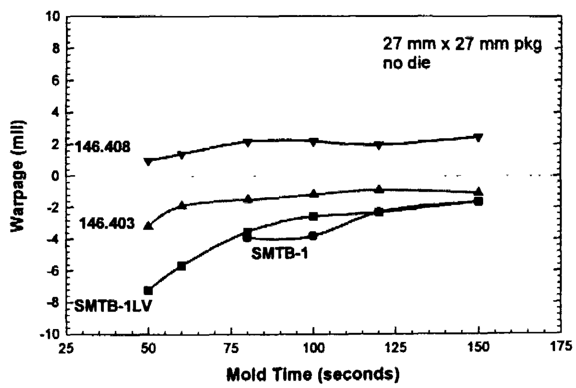

Figure 7. The relationship of warpage to molding time

How well does the warpage equation (*eq. 2*) modified with a temperature independent, residual stress term fit the experimental data? For the data to fit, the alpha 1's of the molding compound must always be smaller than the alpha 1 values for the substrate/IC. If not, the initial slopes of the curves would be positive for some of the packages. All the tested EMC's had alpha 1 values below that of the BT substrate, which fits this model. However, the chip should also affect the warpage and it has a very low alpha1. Since the materials on both sides of the chip have larger expansion coefficients than the chip, its affect on overall package warpage would be somewhat neutralized.

The equations would predict that the slopes of the lines should be dependent on the alpha values of the EMC. There is some indication that this relationship exists for the two Plaskon samples where we know that the chemical composition is the same. The correlation with the other packages is not clear. The confounding effect to this slope is the relationship of the modulus of the molding compound to this slope and the fact that this modulus is temperature dependent.

In comparing the various packages several parameters were evaluated; room temperature warpage, the maximum warpage (without regards to sign), and the maximum change in warpage (**Table III** and *Figure 8*). The room temperature warpage was taken for reference since most QC warpage measurements are taken at room temperature. The maximum warpage offers a measure of the maximum stress the package sees during soldering and the maximum change in warpage indicates the total stress that the package sees. The specific warpage at any temperature appears to be dependent on the filler content and the package configuration. The change in warpage with temperature appears to be related to the chemistry of the system.

Table III. Warpage values taken from shadow moiré measurements from 26°C to 240°C

material	RT warp (mil)	max warp (mil)	max change in warp
SMT-B-1™	-1.21	-5.69	5.38
146.408	-1.42	-4.06	4.54
EMC #1	+2.36	-4.38	6.74
EMC #2	-7.97	-11.97	8.59
EMC #3	+2.92	+3.00	5.93

SMT-B-1™ EMC is the most widely used BGA molding compound today and has been the industry standard for the last several years. It has an excellent room temperature warpage range of -1 mil to - 3 mils. However, the industry requirements have changed in the past year so that the 3 mil warpage level has become marginal. The semi-commercial product, 146.408, was developed to improve the package warpage to a level below 2 mils for most package configurations. This product shows the best set of warpage properties of all the test materials.

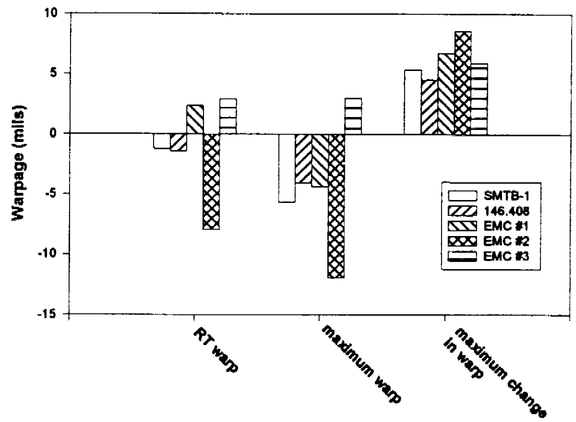

Figure 8. PBGA warpage comparisons from shadow moiré measurements.

Two of the three competitive resins that were used in this evaluation have very good room temperature warpage. These two both show positive warpage (convex) because they have high filler contents. Their maximum warpage values are also quite good. The third property listed in Table III may be the most interesting. This property is the maximum warpage change that the package undergoes as it is heated to the reflow temperature. If this change is zero then you would expect that the solder balls would see no stress as the package is cooled or thermally cycled (even if the package had some minor warpage). The lack of stress on the solder balls would lead to a high level of package reliability. The SMT-B-1™ and 146.408 show the lowest level of warpage change of the EMC's tested.

Conclusions

A test method using shadow moiré techniques has been developed to accurately profile the warpage of BGA packages under thermal exposure similar to solder reflow conditions. Five BGA packages were analyzed using this technique and demonstrated that the classical treatment of warpage did not fit the data. An additional stress seems to be apparent in all packages This stress does not appear to be related to the thermally induced stresses defined in the theoretical equations.

The thermal warpage curves give a better indication of the stresses that occur during thermal cycling and when the packages are soldered. The curves also point out the importance in product development of characterizing the entire warpage behavior rather than the just the room temperature warpage. The most important warpage characteristic for good reliability may be the maximum change in warpage over the temperature exposure range of the package.

Acknowledgments

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Table II. Physical Properties of Epoxy Molding Compounds (EMC's) Tested

property	SMT-B-1™	146.408	EMC #1	EMC #2	EMC #3
ash content (%)	77	81	90	85	84
viscosity at 175°C (poise)	88	72	112	62	49
spiral flow (cm)	77	82	81	96	86
gel time (sec)	19	12	26	20	19
tg by TMA (°C)	205	190	130	160	170
alpha 1 (ppm/°C)	14	12	9	13	15
alpha 2 (ppm/°C)	58	57	28	41	39
flexural strength ($kg/m^2 \times 10^6$)	10.5	9.8	15.3	15.9	13.0
flexural modulus ($kg/m^2 \times 10^9$)	1.41	1.55	2.96	2.30	1.23