Low Warpage Flip-Chip Under-Fill Curing

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***Abstract*— Mechanical stress in flip-chip assemblies continues to be a significant problem both for the reliability of the component and for the assembly of a flat component to the next board-level assembly. This paper describes the combination of unique low-temperature multi-step curing profiles with the use of variable frequency microwaves (VFM) to produce lower warpage components both on the die side of the package as well as on the board carrier side. This lower warpage compared to standard convection cure is maintained even after three sequential lead-free solder reflow conditions. Statistical data support this improved co-planarity by Shadow Moiré measurements at various stages of processing from as-received parts through prebake, cure, and three reflow cycles. Typical co-planarity improvement in the 12–65 percent range is observed and verified by confirmation sample sizes used for microwave cured parts and conventional box oven cured parts. Thinned and larger die, and reduced thickness substrate boards showed the most warpage improvement with VFM. Two under-fill chemistries show the same effect despite lower cure temperatures and faster cure cycle times. A reduction of the elastic modulus above *Tg* was found in the VFM step-cured samples which may account for the some of the reduction in stress of the under-filled packages.**

***Index Terms*— Flip-chip, microwave, under-fill, warpage.**

I. Introduction

FLIP-CHIP die attachment has gained significant use in production over the years because of its electrical performance and small form factor. Recent economic events have made flip-chip more cost competitive with gold wire bonding. As the size of the die increases beyond 20 mm on a side, the role of the under-fill adhesive becomes more critical to avoid the stress-induced cracking at the solder–ball interfaces farthest from the center of the die (neutral point). Additional vulnerabilities have been created with the increased use of low-k dielectric layers on the die surface. Under-fill materials must now meet the higher temperature requirements of no-lead solder reflow as well. The substrates are also becoming thinner with the use of core-less constructions. All of these factors challenge the formulation of adhesives to provide the thermo-mechanical properties necessary to minimize stress at the solder balls, at the dielectric layer, in the thinner substrates and during high temperature reflow cycles after the under-fill cure. An unfortunate example is the contradiction of needing a low *Tg* under-fill to protect the low-k dielectric layer but a high *Tg* under-fill to protect the solder balls [1], [2]. The two stress concerns for flip-chip in production are the co-planarity of the substrate and reliability of the die attach. Warpage in both areas needs to be minimized to reduce the initial induced strain that can affect co-planarity as well as long-term package reliability.

There have been several attempts to reduce stress in polymer materials used in microelectronics. They have focused primarily on low temperature cure and very long ramp rates to high final soak temperatures. The former sacrifices complete cure and the latter requires very long processing cycles [3]. Curing a thermoset material at lower temperatures (but higher than the *Tg*) could promise an increase in elasticity if the result was complete conversion and not vitrification. Any cure method that might result in a lower cross-link density and a decrease in elastic modulus (E') above *Tg* would decrease the stress.

Standard convection heat curing is a sequence of heat transfer from either coils or infra-red emitters to air, and then from air to the target parts, the oven walls and the fixtures. Even though microwave heating is a thermal process, the fundamental mechanism is based on the excitement of electronic dipoles in the adhesive and their subsequent dielectric loss to molecular rotations [4]. This direct increase in the entropy of the atoms at each dipole site causes more rapid collisions of reacting molecules and more often at the proper reaction orientation. The energy absorbed selectively at dipole sites results in higher "local" energy while leaving the bulk of the material at an effectively lower temperature until large chain molecular rotations begin.

Microwave curing also has a material-selective nature. Only materials that have available, polarizable electrons and some flexibility of molecular rotation will be heated. Un-cured polar polymers and doped silicon are good examples of susceptible materials. Glasses, metals and fully cured polymers do not directly absorb much radiation. In the case of a flip-chip assembly, only the under-fill and the silicon die are heated. The substrate, other components, the oven, the air and the fixtures are not directly heated. A variable frequency microwave (VFM) technology was developed to prevent the arcing of metals and to provide a uniform energy field particularly for use in microelectronics production processes. Many studies by semiconductor fabricators have shown no effect of VFM on the electrical or structural characteristics of semiconductor devices. Microwave curing of polymers has been in production use now for more than a decade with advantages of much faster cure cycles, lower temperature cure profiles and substantially lower energy expenditures. Encapsulants, glob-tops, wafer dielectric films, and flex tape bonding have taken advantage

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Fig. 1. Package CTE mis-match.

of VFM processing but there has not been much interest in under-fill curing until recently [5].

There are three reasons to believe a VFM cured under-fill material might produce lower stress and warpage.

1) The uniform bulk heating of VFM should be expected to cure the material in all directions equally. This should reduce the radial stress difference between the edges of the die and the center as found with conventional heating [5]. The uniform heating at both surfaces (die and board) also promotes improved adhesion from the onset of cure.
2) The difference in expansion (and especially contraction) of the silicon die and organic substrate during cure is known to produce significant warpage (Fig. 1). Since the substrate is not directly heated by VFM, that differential shrinkage is less than half that normally found [6].
3) It is well known that a lower final cure temperature will produce a lower total shrinkage during cooling of epoxy materials [6]. Since the adhesive can be cured at lower temperatures with VFM (to the same extent of cure and Tg), the expected shrinkage should be lower and the expected induced strain should be lower as well.

A fourth potential contributor to lowered stress has been suggested in a study of the curing of polyamide amine/epoxy mixtures [7]. It was found that at a lower temperature only, the VFM cured material showed higher elongation and lowered modulus. There was an indication of structural modification (by Fourier transform infrared) with VFM that was not found at the same low temperature with convection heating. The suggestion was that lower cross-link density was the cause of lowered stress.

A study using a commercial under-fill (Henkel FP4527) found that VFM curing at lower temperatures and faster times doubled the die radius of curvature (lower stress) and increased the shear strength by 50% compared to standard convection oven curing [8], [9].

It is important to note that any further thermal processing of parts that had been cured at lower temperatures should reset the shrinkage to correspond with the expected shrinkage at the highest temperature. The use of multiple solder reflows at 260 °C for BGA parts would be a common example of this. The low temperature advantage of VFM cure might be nullified for this reason.

The objective of this paper is to determine whether the lower warpage of under-fills can be maintained even after succeeding solder reflows and whether this effect is found in more than one under-fill chemistry. An additional objective is to determine whether a chemical and morphological advantage of VFM cure contributes to the lower stress and warpage.

II. Experimental

VFM curing was done on a Lambda Technologies Microcure 2100–700 system. Ambient gas control or vacuum was not required. Four-thousand ninety-six frequencies were cycled between 5.8 and 7.0 GHz every 0.1 seconds for a residence time of 25 μs at each frequency. Part temperature was controlled in a closed-loop feedback system by measurement with a calibrated non-contact infrared sensor on the back of the die. A fiber-optic contact probe on the bottom of the substrate was also monitored. A ramp rate of 30 °C/min brought the part to soak temperature with a control of $+/-1$ °C for the programmed time. The cool time was usually about 2–3 minutes since the chamber air was at room temperature during the tests. Power was automatically adjusted to maintain the programmed temperature profile as measured through the back of the die.

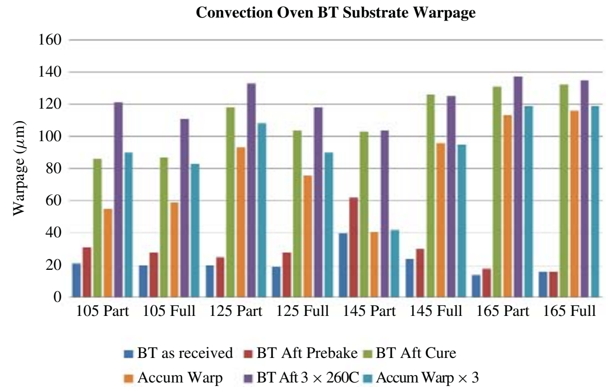

Fig. 2. BT Substrate warpage with convection cure.

The test parts include a variety of dice and substrates as described in each section below. The convection oven was a Despatch LAC model. Shadow Moiré (Akrometrix) measurements were made by spraying white paint on the die and substrate sides and using the interference patterns to determine co-planarity from center to corners. All of the BT laminate substrates were treated to a preliminary prebake of 165 °C for 3 h to complete the cure of any epoxy material within the substrate.

Tg measurements were made by differential scanning calorimeter (DSC), thermal mechanical analysis (TMA), and dynamic mechanical anaylsis (DMA) depending on the samples. DOE analyses were done with MiniTAB and Stat-Ease software.

III. Results

The first phase was to reproduce the results described above for a commercial under-fill (Henkel FP4527) and to determine whether the improved warpage remained after three high-lead (260 °C) solder reflow steps.

In these tests, 20 mm × 20 mm silicon dice with solder ball arrays were combined with 40 mm × 40 mm bismaleimide triazine (BT) substrates (Tg = 155 °C) of 59 mils thickness including solder mask. A dispense of 105–110 mg of FP4527 was dispensed in a star pattern and the dice were pressed into the underfill until the gap was closed. The standard cure profile for this material is a 3 °C/min ramp to 165 °C followed by a soak at 165 °C for 30 min.

TABLE I
CONVECTION CURE OF FP4527

	Temp (°C)	Time (min)	Cure
1	105	45	Under
2	105	90	Full
3	125	30	Under
4	125	60	Full
5	145	22	Under
6	145	45	Full
7	165	15	Under
8	165	30	Full

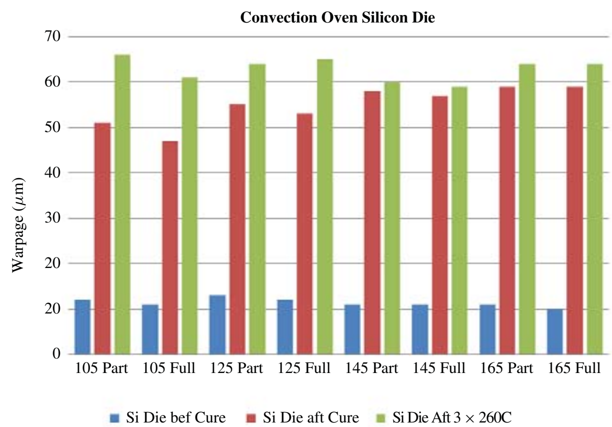

Fig. 3. BT Silicon die warpage with convection cure.

Run	Block	Factor 1 A:time@ 105 min	Factor 2 A:time@ 125 min	Factor 3 A:time@ 145 min	Factor 4 A:time@ 165 min
1	Block 1	0	0	8	4
2	Block 1	40	10	8	4
3	Block 1	40	0	8	0
4	Block 1	40	10	0	0
5	Block 1	0	10	0	4
6	Block 1	20	5	4	2
7	Block 1	0	10	8	0
8	Block 1	20	5	4	2
9	Block 1	0	0	0	0
10	Block 1	40	0	0	4

Fig. 4. VFM cure DOE variables.

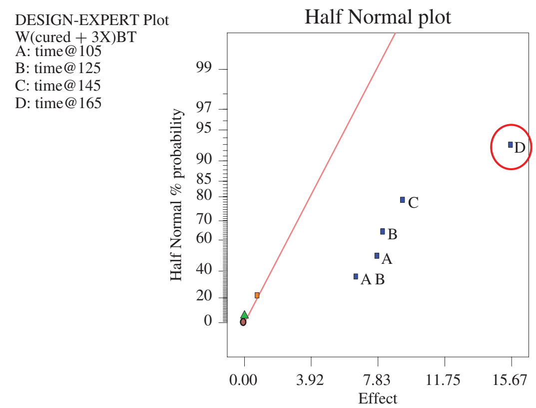

Fig. 5. Effects of VFM cure on BT warpage.

A series of convection oven cure profiles were undertaken to determine whether a lower temperature cure with standard convection heating would decrease the final warpage after reflow cycles. Table I presents the adjustments in time that were made when the cure soak temperature was reduced. Half of the runs were intentionally under-cured somewhat to replicate the unintentional under-curing sometimes found in practice [10]. Run 8 is the standard cure profile with the standard 3 °C/min ramp rate. *Note that warpage data are cumulative from the previous process step*.

It can be seen in Fig. 2 that for FP4527 the lower temperature convection cures resulted in lower initial BT warpage but after three reflows the warpage increased to about the same level as the high temperature cures. The partial cures were fully cured after the three reflows but did not have significantly different BT warpage than the full cures before reflows. The practical use of a partial under-fill cure is limited to parts that would all see a subsequent high temperature process.

The die warpage for the FP4527 under-filled packages is shown in Fig. 3. Once again there is lower die warpage initially at lower temperatures but after three reflows the advantage is lost. An improved convection profile for this material was a slow ramp to 145 °C and soak for 22 min.

The VFM trials were performed as a sequence of four cure temperatures, 20° apart with varying soak times (Fig. 4). The designed experiment used the four soak times as the primary variables. Earlier experiments have shown that modest changes in ramp times before and between soaks were not significant in either the extent of cure or in warpage. A more thorough evaluation of ramp rates is under study. The ramp rates were set to 30 °C/min which is known to avoid any generated voids from being trapped in the matrix with a faster ramp rate. This is still 10 times faster than the convection ramp rates. The cooling period consisted of 2–3 min time it took for the materials to passively return to room temperature (oven ambient) after the last soak. The time chosen for each soak was developed by evaluating the extent of cure with VFM at each of the individual temperatures and decreased to allow for the cure times at other temperatures and times.

The most significant substrate warpage reduction was related to the lowest cure temperature (105 °C) although the other step time at 145 °C was statistically significant (Fig. 5). Note that the highest soak time is above the Tg of the BT. The under-fill cure process may be significantly affecting the properties of a not fully cured BT substrate.

It was found that the most significant variable for the die warpage data was the time at 105 °C with a smaller but significant effect of the time at 145 °C (Fig. 6). Once again there was no effect on warpage from the fast ramp rates. Room for further improvement in warpage appears to be in even longer times for the lowest temperature soak. The best VFM cure profile from this experiment was a 40 minute soak at 105 °C followed by an 8 min soak at 145 °C. No further experiments were done to optimize this nor were there experiments to evaluate even lower temperature soak steps in the profile. In each trial the completion of cure after the four soak profile was confirmed by Tg.

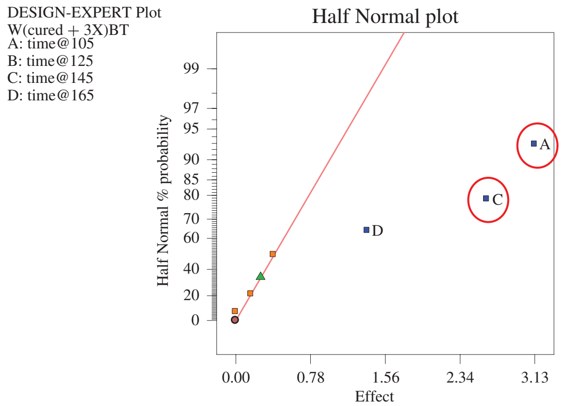

Fig. 6. Effects of VFM cure on die warpage.

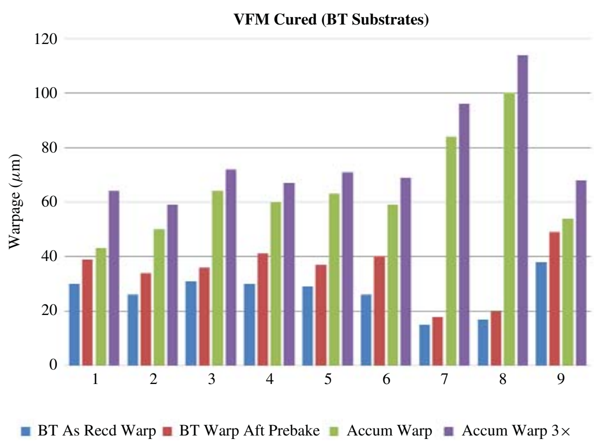

Fig. 7. Warpage results on BT substrates after cure.

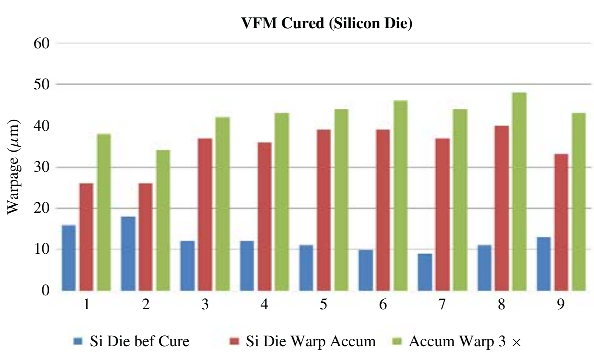

Fig. 8. Warpage results for silicon die side.

The results for BT warpage are compared in Fig. 7. The convection warpage data are included for both the standard cure and the "optimized" convection cure. For this material there is an advantage to use the lower temperature convection cure, but it comes at a price of 3X increase in cure time. The VFM cure is shorter and achieves substantially lower warpage.

The warpage measurements for the silicon die side are compared in Fig. 8. It can be seen that the "optimized" convection cure does not substantially improve warpage but the VFM cure does. It should be pointed out that the cycle time for an UF cure includes all heating ramps and cooling steps. The total cure cycle for the standard convection cure was

TABLE II

Warpage Confirmation for FP4527

	BT (Cure)	BT (Reflow)	Si (Cure)	Si (Reflow)
Conv.(std)	94 μm	82 μm	47 μm	49 μm
Std. dev.	11 μm	13 μm	0.8 μm	1.5 μm
VFM	64 μm	72 μm	33 μm	41 μm
Std. dev.	14 μm	15 μm	1.7 μm	1.8 μm
Change	**−32%**	**−12%**	**−30%**	**−16%**

Run	Block	Factor 1 A:time@ 65 min	Factor 2 A:time@ 85 min	Factor 3 A:time@ 105 min	Factor 4 A:time@ 145 min
1	Block 1	20	20	5	15
2	Block 1	5	35	10	5
3	Block 1	35	5	0	25
4	Block 1	35	35	10	25
5	Block 1	5	5	0	5
6	Block 1	35	35	0	5
7	Block 1	35	5	10	5
8	Block 1	5	5	10	25
9	Block 1	20	20	5	15
10	Block 1	5	35	0	25

Fig. 9. Multi-step DOE profile for UF8830.

TABLE III

DSC Cure Comparisons for UF8830

	Tg (°C)	ΔH (J/g)	% Cure
Un-cured		98.25	0
Convection	106	0.11	99.9
VFM	102	0.19	99.8

90 min and the total cure cycle for VFM was 53 min. The die sizes for these trials were 20 mm × 20 mm × 0.77 mm. No further optimization was performed on the VFM results for lack of materials.

Confirmation trials were performed using the standard convection profile and the VFM profile from the previous DOE experiment. Twelve parts each were assembled with the results shown in Table II including post-cure 3X reflow processes at 260 °C.

A second phase of the work was to determine if the improved warpage with VFM was specific to one under-fill or more general. Direct modification of under-fill components was not possible for this paper so a second under-fill material, UF8830, of a different chemical class was evaluated using the same substrates and dice as before. The standard convection cure for this material is a 35-min ramp to 150 °C, hold at 150 °C for 2 h and let cool.

A multi-step profile DOE was run as shown in Fig. 9 to determine the significant soak temperature effects on warpage.

It is important to compare equivalently cured samples when making comparisons of thermo-mechanical properties. The heats of reaction of cured and un-cured UF8830 resins (Fig. 10) are presented in Table III. The lower *Tg* for the VFM sample is seen to be insignificant with respect to % cure.

In the VFM multi-step cure profile experiment, there was a strong interaction between the 85 °C and 145 °C temperatures

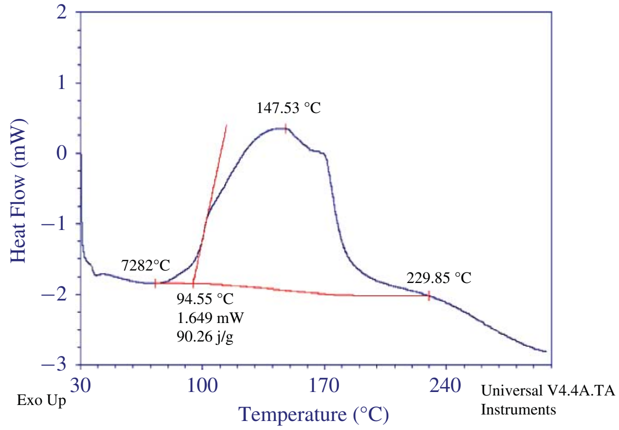

Fig. 10. DSC of un-cured UF8830.

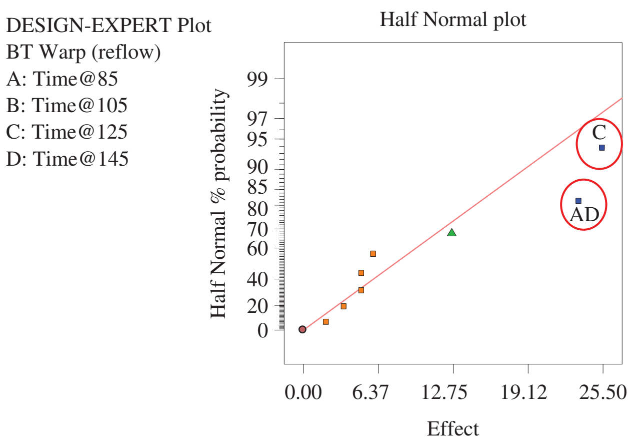

Fig. 11. Effects of VFM cure on BT substrate.

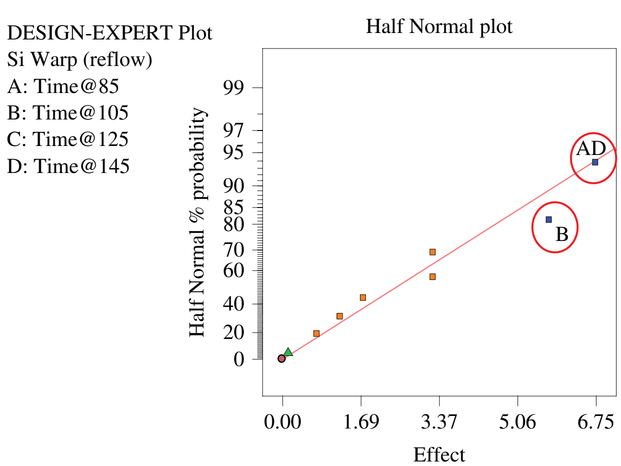

Fig. 12. Effects of VFM cure on silicon dice.

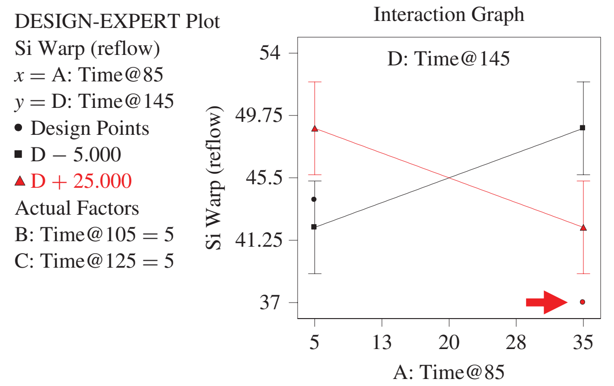

Fig. 13. DOE profiles for VFM.

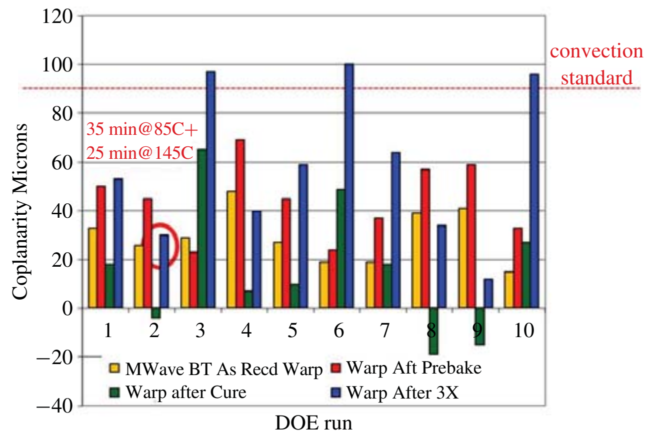

Fig. 14. BT substrate warpage for UF8830.

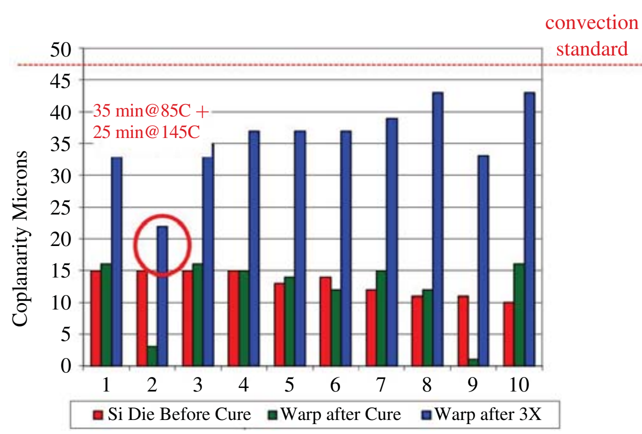

Fig. 15. Silicon warpage for Epoxy B.

for both the BT substrate warpage and the silicon die warpage (Figs. 11 and 12). Once again the lowest soak temperature is a common thread with respect to package warpage as well as higher temperature interactions.

In this case there is an interaction that favors either long or short times at both extreme temperatures (Fig. 13). Since it is unlikely that 5 min soaks at 85 °C and 145 °C would thoroughly cure the under-fill, the best conditions would combine 35 min at 85 °C and 25 min at 145 °C. In fact the best warpage results for the BT and silicon dice were at these settings (with 5 min at the other two temperatures—highlighted with arrow). The intermediate temperatures are significant but smaller. No further optimization experiments were conducted for lack of material.

No improvements in the standard convection warpage data were found by reducing the cure temperature. Warpage data for the BT substrates cured with standard convection and the VFM DOE profiles are compared in Fig. 14. Most of the trials had

TABLE IV
CONFIRMATION RESULTS FOR UF8830

	BT (Cure)	BT (Reflow)	Si (Cure)	Si (Reflow)
Conv. (std)	69.5 μm	87.1 μm	35.2 μm	46.7 μm
S.D.	13.5 μm	18.4 μm	3.2 μm	2.8 μm
VFM	36.4 μm	76.5 μm	16.6 μm	37.5 μm
S.D.	14.6 μm	18.0 μm	3.0 μm	3.6 μm
Change	**−48%**	**−13%**	**−53%**	**−20%**

TABLE V
BT WARPAGE OF THIN ASSEMBLIES

	BT(cure)	2 days	BT(3X reflow)
Conv.(std)	611.3 μm	523.8 μm	744.8 μm
VFM	75.0 μm	98.8 μm	141.5 μm
Difference	**−88%**	**−81%**	**−81%**

dramatically reduced warpage and some conditions actually caused the BT substrates to change from concave to convex (before 3X reflow).

The die warpage results with UF8830 are compared in Fig. 15. The multi-step trial 2 was substantially better and also showed decreased warpage before reflow. Pin-grid array parts would be expected to benefit the most from this cure profile since they would not necessarily see high temperatures after the under-fill cure.

Confirmation runs were made with the standard convection cure of 35 min ramp to 150 °C + 120 min 150 °C soak and the best results VFM run of 35 min at 85 °C + 5 min at 105 °C + 5 min at 125 °C + 25 min at 145 °C as discussed above. The extent of cure of the convection cured and VFM cured materials were both determined to be 100% (within measurement error) by Tg from DSC, TMA, and DMA.

There were 10 parts for each cure process using the same 59 mils thick BT substrates but with only 15 mm square dice available (Table IV). Since the smaller dice would not represent the same warpage improvement, the actual results of VFM 20 mm dice would be even better. Note that the BT standard deviations are significantly higher than the die which was generally the case. Finding substrates with consistently low variation in bow was difficult.

Additional experiments were performed with UF8830 to determine the reduction of warpage with VFM on parts that were more representative of modern PBGA packages. The silicon dice were 20 mm square but thinned to 75 μm and the BT substrates were 47 mm × 30 mm but only 200 μm thick. The die had a large array of solder bumps. There was an additional wait step of two days inserted between the cure of the under-fill and the 3X lead-free reflow steps. This wait step was meant to determine whether there could be a relaxation of the cure stress with time between processes. Four assemblies each were made with standard convection and VFM multi-step curing profiles as described above. A significant stress relaxation after cure can be seen in Tables V and VI but the stress has increased beyond the original level after solder reflow. There was significantly less stress for the VFM cured parts even after reflows.

TABLE VI
DIE WARPAGE OF THIN ASSEMBLIES

	Si (cure)	2 days	Si (reflow)
Conv.(std)	324.8 μm	355.3 μm	426.5 μm
VFM	102.0 μm	56.8 μm	255.5 μm
Difference	**−69%**	**−84%**	**−40%**

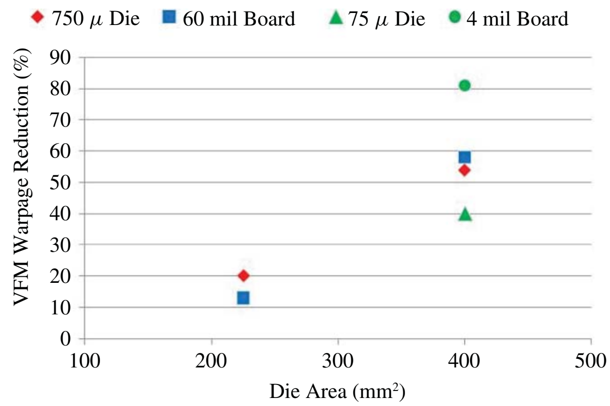

Fig. 16. VFM warpage reduction versus die size.

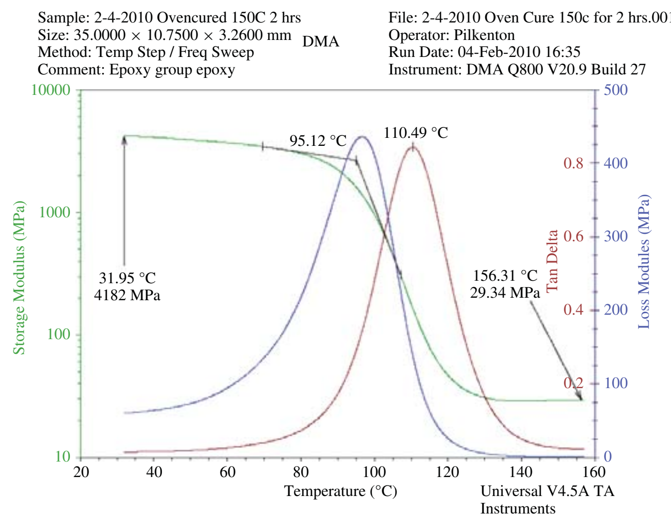

Fig. 17. DMA of UF8830—convection cured.

The improvement in warpage reduction was also found to be related to the die size (Fig. 16). There is also an indication that thinner dice will exhibit more warpage improvement with VFM curing.

The next question was whether there was a contribution to warpage reduction due to a morphological or chemical change when VFM curing was used. One method of reducing stress in a thermoset is to increase the chain lengths by lowering the network cross-link density [6]. Lowered cross-link density can be identified by lowered elastic (storage) modulus (E') above the Tg (the rubber state). The moduli (storage, loss, Tan δ) of UF8830 are shown in Fig. 17 after standard 150 °C cure in a convection oven for 2 h.

The moduli of UF8830 after VFM cure at 35 min at 85 °C + 5 min at 105 °C + 5 min at 125 °C + 25 min at 145 °C are

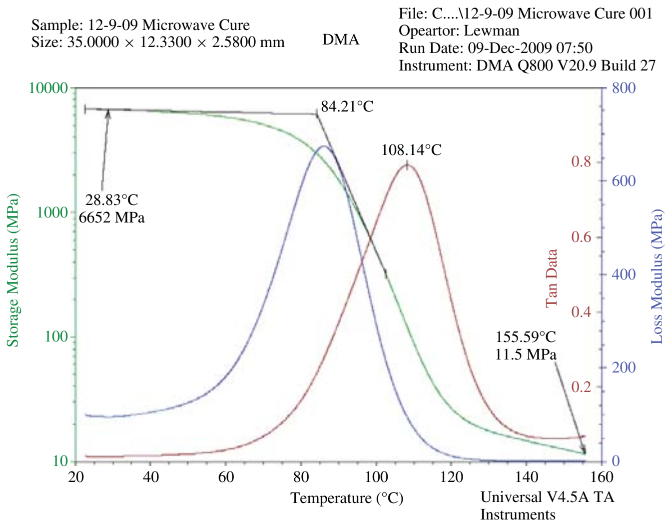

Fig. 18. DMA of UF8830—VFM cured.

TABLE VII
UF8830 ELASTIC MODULUS COMPARISONS

	Tg **(°C)**	E′ (>**150 °C**)
Convection	110	29 MPa
VFM	108	11 MPa

shown in Fig. 18 and the data for the two samples are summarized in Table VII. The much lower E' (above Tg) with the VFM cure indicates that a lowered cross-link density is created with a lower temperature multi-step microwave cure. The Tg values of the two samples are within measurement error.

IV. DISCUSSION

The use of a lower temperature under-fill cure in a convection oven did not substantially decrease either the warpage of the substrates or the silicon die in flip-chip packages especially when package processing continued with three reflow steps. In contrast, the use of multi-step low temperature VFM cure of the same under-fills was very effective in improving substrate co-planarity and reducing silicon die warpage in flip-chip packages. The improvements with VFM cure were found with two different under-fill chemistries and reached levels as high as 62% less warpage even after 3X reflows. Variation in substrate co-planarity was higher than that with silicon dice but the improvements were more dramatic as well. Silicon die warpage was reduced with VFM curing by as much as 30% after 3X reflows. For packages such as pin grid arrays that do not see additional thermal excursions, the BT and die warpage reductions can be as high as 65% and 50%, respectively. As the substrates and dice became thinner the warpage improvements became more dramatic. The stress decreases rapidly for dice with areas larger than 200 mm^2. These improvements become more useful as die are thinned and core-less substrates become more common. There was an initial relaxation of the warpage after cure but additional thermal processing increased the final warpage in all cases with VFM cured parts retaining most of the stress reduction.

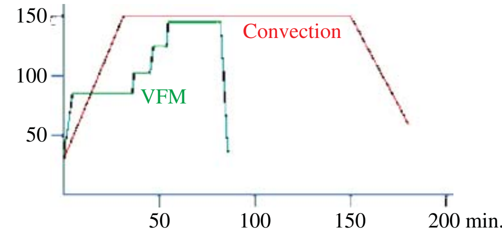

Fig. 19. Total cure-cycle time UF8830.

As a practical matter, the total multi-step cure cycle times with VFM were still shorter than the standard convection times as shown in Fig. 19. Further improvements in warpage were indicated as possible for both of these materials by the models derived from the designed experiments without changes to the formulations.

The reasons for this warpage improvement can be attributed to the well-known characteristics of microwave heating (uniformity, selectivity, low temperature cure) but there appears to be a contributing factor of decreased cross-link density with the VFM cure profiles. Additional work is being done to determine the exact chemical nature of this enhancement in stress reduction during low temperature VFM cure of model compounds [11]. These investigations may help explain the previously documented component reliability improvements found from the use of VFM cure profiles. An understanding of the relationship between time-at-temperature and cross-link morphology could produce general rules for microwave thermoset cure. A better understanding of microwave curing mechanisms could also lead to further improvements in the design of low-stress thermoset materials as they have with thermoplastic materials [12].

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