WARPAGE REDUCTION FOR FLIP-CHIP UNDER-FILL ASSEMBLIES

Robert L. Hubbard
Lambda Technologies, Inc.
Morrisville, NC, USA
bhubbard@microcure.com

Pierino Zappella
Henkel Corporation
Rancho Dominguez, CA, USA

ABSTRACT

Mechanical stress in flip-chip (FC) 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. The component co-planarity must meet or be below the JEDEC standard. This work describes the combination of unique low-temperature multi-step curing profiles with the use of Variable Frequency Microwaves to produce lower warpage components both on the die side of the package as well as on the board carrier side. This lower warpage is maintained even after three sequential lead-free solder reflow conditions. Statistical data supports this increased co-planarity by Shadow Moiré measurements at various stages of processing from as-received parts through prebake, cure, and three-times reflow. Typical co-planarity improvements in the 12 to 65 percent range is observed and verified by confirmation sample sizes used for microwave cured parts and conventional box oven cured parts. Thinned die and reduced thickness substrate boards showed the most warpage improvement with VFM. Two under-fill chemistries (anhydride and hybrid) show the same effect despite lower cure temperatures and faster cure cycle times. The mechanisms responsible for the improvements in mechanical properties of the under-fills are discussed.

Key words: Flip-chip, under-fill, warpage, microwave

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 stresses have been created with the increasing 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 package reliability and co-planarity.

Standard convection heat curing is a sequence of heat transfer from either coils or infra-red emitters to 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 molecular dipoles in the adhesive and their subsequent dielectric loss to molecular rotations [3]. This direct increase in the entropy of the system at each molecular dipole site causes more rapid collisions of reacting molecules at the proper reaction orientation at a effective lower bulk temperature of the material.

Microwave curing has a selective nature. Only materials that have available, polarizable electrons and the 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 absorb the 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 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 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 of VFM processing but there hasn't been much interest in under-fill curing until recently [4].

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 (Figure 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 [5]. 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 lower as well.

Figure 1

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 doubled the shear strength by 50% compared to standard convection oven curing [7].

In a study of the curing of polyamide amine / epoxy mixtures, it was found that at a lower temperature only the VFM cured material showed higher elongation and lowered modulus [8]. There was an indication of structural modification with VFM that was not found at the same low temperature with convection heating.

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 lower temperature advantage of VFM cure might be nullified for this reason.

The objective of this work 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 study is underway to determine the chemical and morphological nature of this effect.

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 IR sensor. A fiber-optic contact probe on the bottom of the substrate was also monitored. A ramp rate of 30ºC/min brought the part to soak temperature with a control of +/- 1 ºC 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 on the back of the die.

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 Moire' (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 three hours to complete the cure of any epoxy material within the substrate.

Tg measurements were made by DSC, TMA, and TGA depending on the samples. DOE analyses were done with MiniTAB and Stat-Ease software.

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, 20mm x 20mm silicon dice with solder ball arrays were combined with 40mm x 40mm BT substrates (Tg = 155°C) of 0.59mm 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 slow ramp to 165°C followed by a soak at 165°C for 30 minutes.

A series of convection oven cure profiles were undertaken to determine whether a lower temperature cure with convection would decrease the final warpage after reflow cycles. Figure 2 shows the adjustments in time that were made when the cure soak temperature was reduced. Half of the runs were intentionally under-cured somewhat. Run 8 is the standard cure profile with the standard 3°C/min ramp rate.

	Temperature	Time	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

Figure 2: Convection cure of FP4527

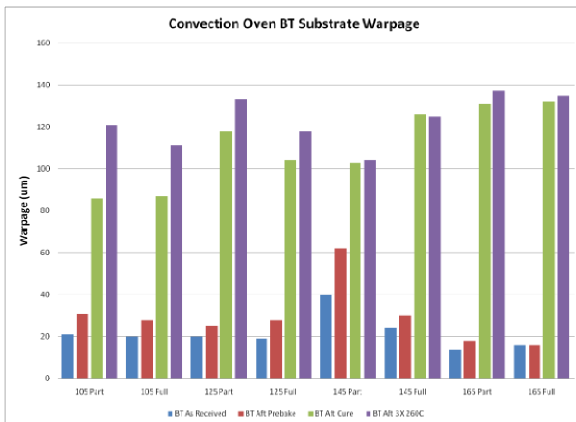

Figure 3: BT Substrate Warpage with Convection

It can be seen in Figure 3 that 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 silicon die warpage data is shown in Figure 4.

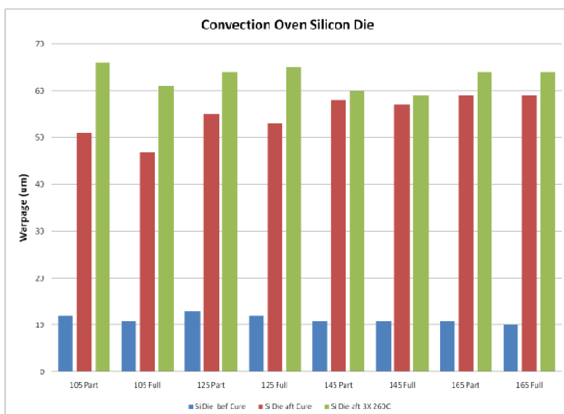

Figure 4: Silicon Die Warpage with Convection

Once again there is lower die warpage initially at lower temperatures but after three reflows the advantage is lost. The best convection profile for this material was a 45 minute ramp to 145°C and soak for 22 minutes.

The VFM trials were performed as a sequence of four cure temperatures with varying soak times. The designed experiment used the four soak times as the primary variables. Earlier experiments have shown that ramp times before and between soaks were not significant in either the extent of cure or in warpage. The ramp times were set to 30°C/min to avoid any generated voids from being trapped in the matrix. This is still ten times faster than the convection ramp rates. The cooling ramp was the 2-3 minute time it took for the materials to return to room temperature (oven ambient) after the last soak.

The VFM cure profiles (Figure 5) were developed by evaluating the extent of cure from VFM at each of the individual temperatures.

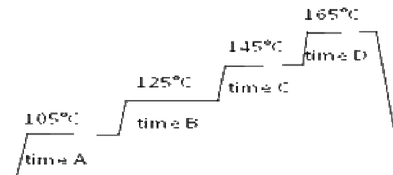

Figure 5: VFM DOE Variables

It was found that the most significant variable from the DOE was the time at 105°C with a smaller but significant effect of the time at 145°C (Figures 6 and 7). This was the case for both the minimum warpage of the BT substrate as well as the silicon dice. 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 for this material was a 40 minute soak at 105°C followed by an 8 minute 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.

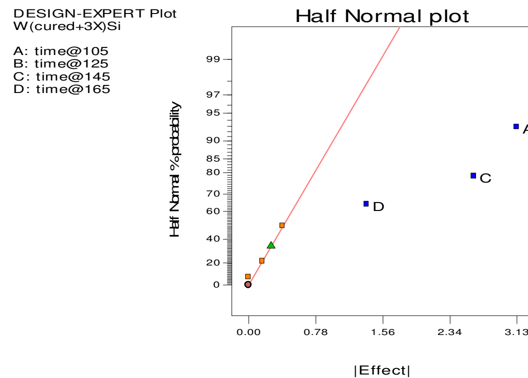

Figure 6: Effects of VFM Cure on Silicon Dice

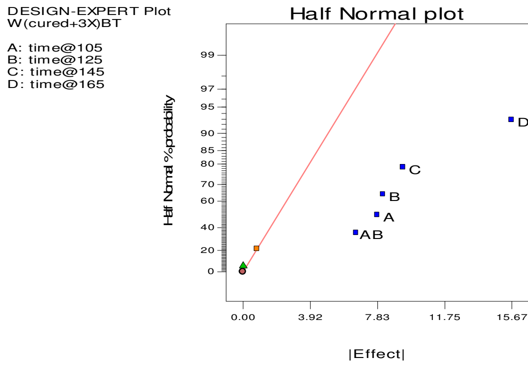

Figure 7: Effects of VFM Cure on BT Substrate

Confirmation trials were performed using standard and optimized convection profiles and the VFM profile (not optimized) from the previous experiments. Twelve parts each were assembled with results shown in Figure 8 including post-cure 3X reflow processes at 260°C.

	BT(cure)	BT(reflow)	Si(cure)	Si(reflow)
Conv.(std)	124um	114um	59um	61um
Conv.(opt)	124um	120um	58um	60um
VFM	95um	103um	45um	53um
Change	**-24%**	**-14%**	**-24%**	**-13%**

Figure 8: Warpage Confirmation Results

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 study so a second commercial under-fill material of a different class of epoxy chemistry was evaluated using the same substrates and dice as before.

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

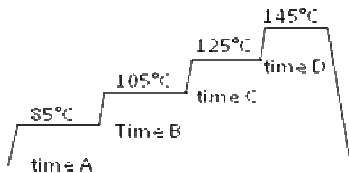

Figure 9: Multi-step DOE Profile

There was a strong interaction between the 85°C and 145°C temperatures for both the BT substrate warpage and the silicon die warpage (Figures 10 and 11). Once again the lowest soak temperature is a common thread with respect to package warpage as well as higher temperature interactions.

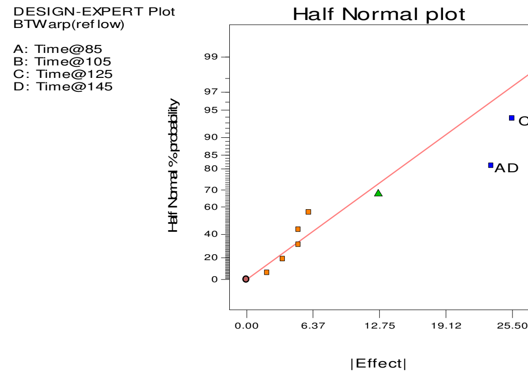

Figure 10: Effects of VFM Cure on BT Substrate

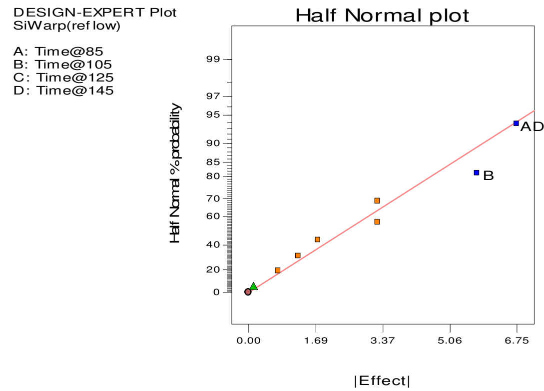

Figure 11: Effects of VFM Cure on Silicon Dice

In this case there is an interaction that favors either long or short times at both extreme temperatures (Figure 12). Since it is unlikely that 5 minute soaks at 85°C and 145°C would thoroughly cure the under-fill, the best conditions would combine 35 minutes @ 85°C and 25 minutes @ 145°C. In fact the best warpage results for the BT and silicon dice were at these settings (with 5 minutes at the other two temperatures – highlighted with arrow). The intermediate temperatures are significant. In a parallel study the nature of the chemistry and thermo-mechanical properties of VFM cure at these four temperatures are being investigated.

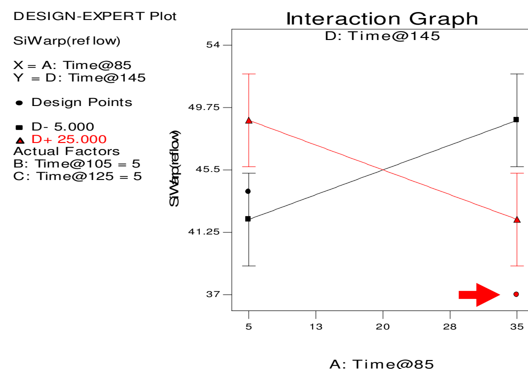

Figure 12: Significant Temperatures for VFM

Confirmation runs were made with the standard convection cure of 35min. ramp to 150°C + 120min 150°C soak and the VFM run #2 of 35min@85°C + 5min@105°C + 5min@125°C + 25min@145°C. 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 (Figures 13-15). The flexural moduli and CTEs were also the same.

	DSC	TMA	DMA	CTEα1	E'
Conv.	104	89	104	34	6.3
VFM	108	84	117	33	6.8

Figure 13: Extent of Cure

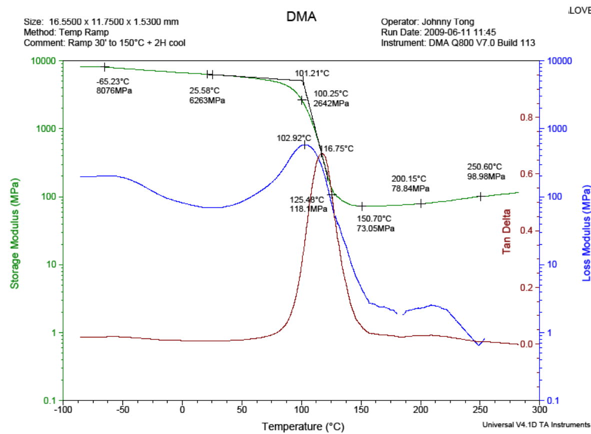

Figure 14: DMA of Convection Cure

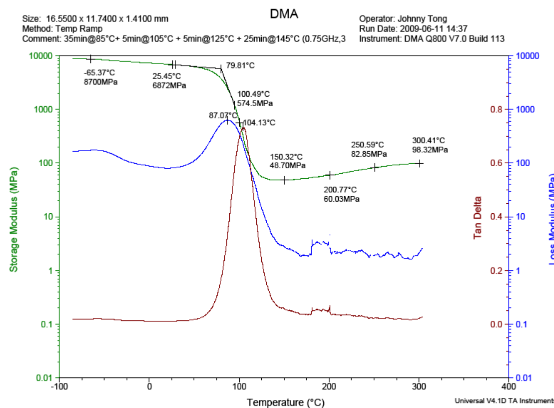

Figure 15: DMA of VFM Cure

There were 10 parts for each cure process using the same 59 mil thick BT substrates but with only 15µm square dice available (Figure 16). Since the smaller dice would not represent the same warpage improvement, the actual results of VFM run #2 are listed for comparison to the 20mm dice used in the previous experiments. Note that the BT standard deviations are significantly higher than the die which was the case in general. Finding substrates with consistently low variation in bow was difficult.

	BT(cure)	BT(reflow)	Si(cure)	Si(reflow)
Conv.(std)	105	122	49	60
S.D.	13.5	18.4	3.2	2.8
VFM	68	109	29	50
S.D.	14.6	18.0	3.0	3.6
Change	**-35%**	**-12%**	**-39%**	**-16%**
VFM #2	38	75	18	37
Change	**-64%**	**-39%**	**-63%**	**-38%**

Figure 16: Table of Confirmation Results

Additional experiments were performed with the second under-fill to determine the reduction of warpage with VFM on parts that were more representative of modern BGA packages. The silicon dice were 20mm square but thinned to 75µm and the BT substrates were 47mm x 30mm but only 200µm thick. 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 curing profiles as described earlier. A significant stress relaxation after cure can be seen in Figures 17 and 18 but the stress is increased beyond the original level after solder reflow. There was significantly less increased stress for the VFM cured parts.

	BT(cure)	2 days	BT(3X reflow)
Conv.(std)	756um	669um	890um
VFM	263um	287um	330um
Change	**-65%**	**-57%**	**-62%**

Figure 17: BT Warpage of Thin Assemblies

	Si (cure)	2 days	Si(3X reflow)
Conv.(std)	407um	355um	509um
VFM	204um	159um	357um
Change	**-50%**	**-55%**	**-30%**

Figure 18: Die Warpage of Thin Assemblies

DISCUSSION

The use of 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. 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 commercial under-fill chemistries and reached levels as high as 62% less warpage even after

3X reflows. Variation in substrate co-planarity was higher than 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. This improvement may be 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 retaining the advantage.

As a practical matter, the total multi-step cure cycle times with VFM were still shorter than the standard convection times as shown in Figure 19.

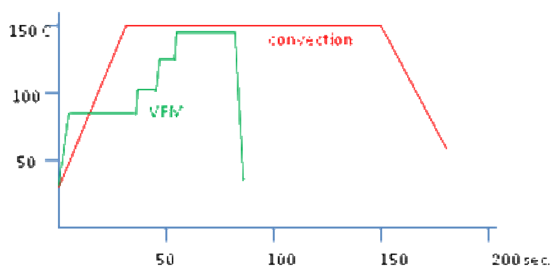

Figure 19: Total cure cycles

The reasons for this warpage improvement can be attributed to the well known characteristics of microwave heating but additional work is being done to determine if there are also chemical and morphological enhancements resulting from the low temperature VFM cure profiles [9]. Reliability evaluations are planned to determine the interaction between initial lower stress in packages with stress induced product behavior.

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