

Effects of Material Properties on Top PoP Package Warpage

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Abstract

In recent years, Package on Package (PoP) is an increasing high density package solution for package stacking technology in various device manufacturing applications. Especially, top package with stacked memory packaging system connected to a bottom logic packaging system via solder joint is representative PoP configuration. To guarantee the assembly yield and reliability of the solder joint between the top package and bottom package, mechanical compliance between these two packages is crucial during package stacking. Therefore package warpage needs to be understood and controlled to meet the assembly yield target. As the complexity of the package configuration increases by thinner package thickness, higher number of stacking dies and large package size, the warpage control within the target requirement is very challenging, especially when the material behaviors of substrate, die, molding compound and die attach film are different and also changing as a function of temperature. Therefore, the material property of key component in top PoP package plays a crucial role in warpage performance. Among key components, the thermo-mechanical properties of molding compounds is very important and mainly determine the warpage level of the Top package at room temperature and the warpage behaviors during the reflow high temperature profile for the board level assembly with bottom package. Among various material properties, the chemical cure shrinkage, coefficient of thermal expansion and storage modulus for the molding compounds are determining factors on the temperature dependant warpage control of top PoP package. In this paper, the effects of various molding compound material properties on warpage are studied through comprehensive experiment and modeling work. The findings and results provide some clues and guideline for material property selection for warpage control in Top PoP package, which influence the PoP assembly yield and reliability.

Key words: Package on Package, warpage, SMT yield, epoxy molding compound, material property

Introduction

Recently, highly integrated 3-D packaging systems have become one of the primary electronic device/system assembly solutions to meet ever increasing requirements for small form factors, better functionality and even low cost assembly for wireless and embedded electronics applications. As a result, more attention is being paid to Package-on-Package (PoP) technology among several assembly solutions for reduced package size and high density integration. In a common PoP architecture, the bottom package is generally a logic device with a single die packaged via wire bond or flip chip, and the top package is a memory device with multiple die stacks. Compared with the bottom package, the top package structure is more complicated after consisting of NOR and NAND type flash and other RAM type memory. The interconnection between the top package and the bottom package through solder bumps by typical reflow process in Surface Mount Technology (SMT) line is very strictly controlled by non-compliance issue as illustrated in Fig.1 For high yields of package stacking and better solder joint reliability, the warpage control between the top and bottom packages is very important. The warpage at room temperature and during solder reflow process are most important. Therefore, the warpage behaviors of the top package and the bottom package should be understood and controlled in terms of the package size, materials, and interconnect density, etc. This kind of knowledge will be more important with decreasing ball pitch

and ball height in future and the package warpage control will become more challenging.

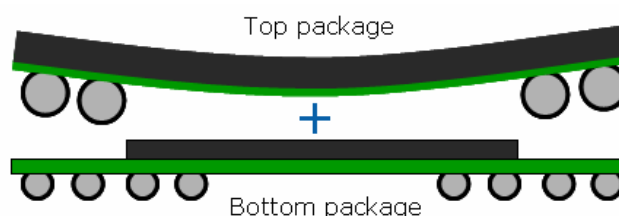


Fig. 1 Non-compliance caused by packaging warpage during packaging stacking for PoP

Many researchers discussed the package warpage study on both laminate substrate based package and lead frame based packages [1-7]. These works cover very wide topics including empirical warpage data, various modeling prediction approaches, effects of different packaging materials and design parameter studies. However, most studies were limited to package warpage at room temperature due to the feature of non-PoP type package where the main concerns are coplanarity and saw and singulation process, etc. There is also a study of PoP bottom packages, which is similar to general BGA package except the warpage requirement. For PoP top package, due to its multi-die packaging feature, the parameter studies are more difficult. For instance, there can be multiple

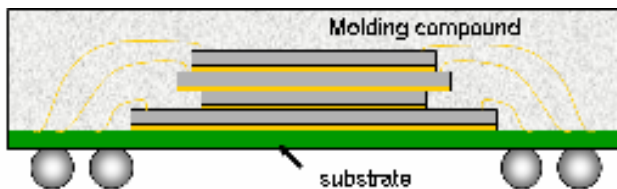
die size configurations, multiple package sizes, multiple die thicknesses, multiple package thicknesses (z-height) and multiple molding thicknesses. Due to the design complexity, sometimes, different material sets such as substrate material and molding compound are needed for different package designs to meet the same warpage requirement. Our previous group studied the impact of design parameters on packaging warpage and found the effects of package configuration design and metal line density were significant [8].

In this paper, we investigated the material contributes on warpage from PoP top package during reflow process, including molding compounds and die attach materials. We purely used experimental DOE to study the molding compound's material properties such as CTE, modulus, Tg and molding shrinkage, and the effect of die attach film materials. Then we used finite element analysis to calculate the warpage of the PoP top packages to investigate the effects of each material properties' contribute to the overall package warpages. We analyzed the correlation between warpage and some key parameters such as material properties.

Experimental and Analysis

Package and Material Description

Fig. 2 shows the general PoP top package structure, which consists of the substrate, the molding compound and the silicon die stack. The main driving force for package warpage is CTE mismatch between the molding compound and substrate. Although the silicon die stack volume contributes the warpage amount, the CTE mismatch between molding compound and substrate drives package warpage since they are temperature dependant material properties and easier to deform compared with silicon. For the package configuration, the specifications for die stacking, die size and package dimension are summarized in Table 1.



CTE mismatch between molding compound and substrate mainly drives the package warpage

Fig. 2 PoP top package configuration for warpage study

Item	Description
PKG Dimension	15x15mm
PKG Height	Max. 1.20mm
Mold Cap Thick.	0.6 mm
Substrate Thick.	0.13 mm
Die Thickness	75um

Table 1. Specification for PoP top package configuration

For the material variation, we used six different molding compound materials (MC-A, MC-B, MC-C, MC-D, MC-E and MC-F), which have different material characteristics as

shown in Table. 2. MC-A, B and C have large filler size and low filler content, but MC-D, E, and F have smaller filler size and high filler content.

Property	MC-A	MC-B	MC-C	MC-D	MC-E	MC-F
DOE Leg	0	1	2	3	4	5
Filler Size (Max; um)	high	high	high	low	low	low
Filler Content (wt%)	low	low	low	high	high	high
Tg (°C)	medium	medium	high	medium	low	low
CTE1 (ppm/°C)	high	high	high	medium	low	low
CTE2 (ppm/°C)	medium	high	high	medium	low	low
F. Modulus @RT (GPa)	low	high	high	low	low	high
F. Modulus @260 (MPa)	low	medium	medium	high	low	low
Mold Shrinkage (%)	high	high	high	low	high	low

Table. 2 MC material properties used in this study

Package Warpage Measurement and analysis

We used shadow moiré technique to characterize the package warpage as a function of temperature. Quantification of the warpage variation is done by checking the warpage contours on the surface of the package in dead bug (solder lands facing up) position at each temperature during reflow process, and plotted the warpage curves in whole temperature range. 6 units per leg were measured inside the Thermo-Moire Analysis tool where the units were subjected to simulated reflow profile with a peak temperature of 260C. The measurements were taken on the surface of the package without actual solder balls. The signs of the warpage and smiling or crying warpage are defined as shown in Fig. 3.

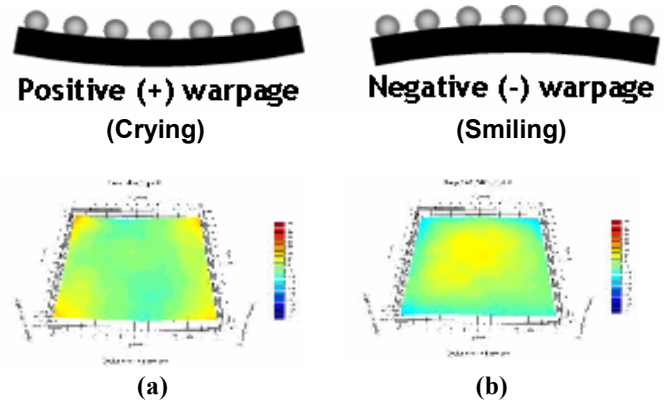


Fig. 3 Definition of warpage sign and moiré 3-D contours for (a) positive warpage and (b) negative warpage

Warpage Modeling

The package warpage is affected by the mold compound properties, silicon die volume fraction, substrate thickness and package geometry. The focus here will be on mold compound properties. The dimensional changes in mold compound are result of two independent effects: Thermal shrinkage and Cure shrinkage. Thermal shrinkage is a result of mold compound CTE1 and CTE2 as well as modulus above and below Tg. Cure shrinkage is a result of polymer cross linking, also to a small degree the mold compound modulus can affect cure shrinkage.

The major criterion for end customer using the POP package is the warpage value at solder reflow temperatures because this is when the solder joint is forming. Some customers also require warpage limitations from room temperature to the reflow temperature to ensure adequate flux coverage.

Total package warpage at any given temperature will be the combined effect of thermal shrinkage and cure shrinkage as shown in Fig. 4. Cure shrinkage always results in -ve warpage and the thermal shrinkage results either +ve or -ve warpage depending on the CTE mismatch and mold compound modulus. The positive or negative warpage of the package is determined by the competing effects of cure shrinkage and thermal shrinkage. The package warpage requirements can be met by selecting a mold compound that has required materials properties such as CTE1, CTE2, modulus and % of cure shrinkage.

Modeling Methodology

We performed the warpage modeling work to characterize the effect of material property on the warpage level of the package. To analyze the effect of each property, a base case package is modeled with assumed mold compound properties. Ansys© is used here to predict the package warpage at 25C and 260C. Temperature dependent properties are assumed for all the materials. The impact of the given property variation on package warpage is compared against the base case warpage and the trend is discussed.

The base case package is a 12x12 mm package with 0.21mm substrate and a two die stack up. The mold compound properties are: Glass Transition Temperature (T_g) = 175C; Elastic Modulus above and below T_g = 24000 MPa and 2000 MPa; CTE 1 = 11 ppm and CTE2 = 40 ppm; Cure Shrinkage (CS) = 0.2%. The substrate properties are CTE = 17 ppm below 216C and 9 ppm above 216C.

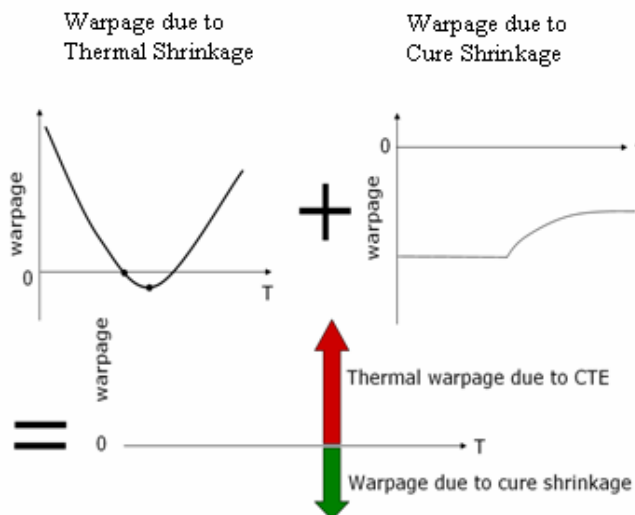


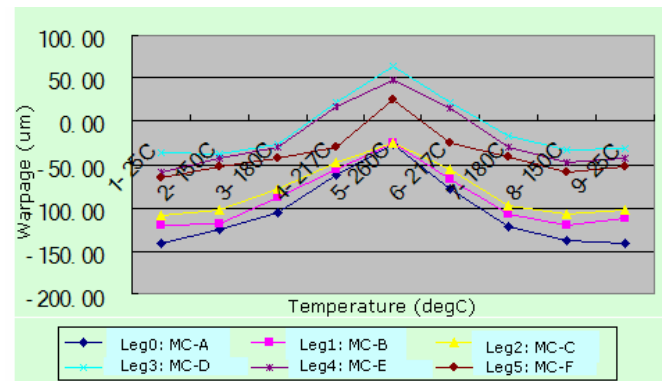
Fig. 4 Total package warpage

Results and Discussion

Effect of MC material properties on warpage

Fig. 5 shows the package warpage behaviors of 15mm x 15 mm sized PoP top packages with different molding compounds. The general trend of warpage behaviors for all legs is same as shown in Fig. 5. The RT warpages were smile (-) level and they started increasing toward zero warpage as the reflow temperature increased. The warpage levels with different legs were different at peak temperature of 260C.

The package test vehicles from leg 0 to leg 2 shows relatively (-) warpage at RT and also during liquidous temperatures from 217 to 260 C. Usually because the warpage requirement is within certain level of warpage, for example, +100 um and -100 um or less during solder ball reflow process for reliable and high yield PoP top and bottom packages interconnect, the warpage level should meet that requirement during liquidous temperature range. The package test vehicles from legs 3, 4, 5 showed relatively more crying warpage level when compared to legs 0, 1, 2. Those three legs showed similar warpage behaviors with slightly different warpage levels at room temperature and peak temperature at 260C. Leg 3 showed the higher warpage level at peak temperature compared to leg 4 and leg 5, and this can be explained by the molding compound material properties. According to the material properties for all molding compounds used in Leg 0 ~ 5, MC-D, E, F have smaller CTE below T_g and above T_g than MC-A, B, C.



(a)

Leg	MC	25C	150C	180C	217 C	260 C	217 C	180C	150C	25C
0	A	-141	-125.3	-104.7	-62.7	-26	-78	-122	-138	-141
1	B	-120	-118.2	-87.7	-56.3	-24.5	-67.2	-106.3	-120.3	-111.3
2	C	-108	-102.8	-78.2	-46.8	-25.5	-56.3	-97.3	-107	-101.8
3	D	-36.3	-38.2	-27.5	21	62.5	21.3	-17.5	-32.8	-32
4	E	-58.8	-43	-30.5	16.3	47.2	14.8	-29.5	-47.3	-43.5
5	F	-64.7	-53	-42.2	-30.7	24.7	-25.5	-41.8	-58.2	-53

(b)

Fig. 5 Warpage result with different MCs (a) graphical and (b) warpage data table vs. temperature (average value)

It is also thought that the reason for Leg 0 ~ 2 with large crying (-) warpages at low temperatures including RT is due to large mold shrinkage data together with higher CTE below T_g for MC-A, B, and C. The overall warpage behaviors and the molding compound material property effect can be explained by schematics as shown in Fig. 6. As mentioned before, the

CTE mismatch between various materials set in the package causes the warpages. Typically the plotted lines for different materials for silicon die, mold die, molding compound and substrate shows the dimensional changes as a function of temperatures. During molding process at 175°C, the molding compound and substrate are in equal length, which is a warpage free condition. Then the molding compound is almost fully cured and it shrinks due to the chemical cross-linking process, and the amount of this shrinkage is called “curing shrinkage”. Then the whole unit is cooled down to RT and all materials shrink according to their CTEs. Higher shrinkage of mold compound (due to thermal + cure shrinkage) relative to other components in a package results in crying warpage. This behavior was confirmed in Fig. 5(a) with all package units showing (-) warpages. Therefore, the Tg, CTE and the cure shrinkage property for molding compound determine the amount of crying warpage level with the same substrate material and package configuration at room temperature.

As the temperature goes up during the reflow process and eclipses Tg of molding compound, the molding compound expands more with large CTE above Tg than the substrate. This characteristic of thermal expansion for the substrate make the package unit having more crying warpage. That is the basis for leg3, 4, and 5 units to have (+) warpage at peak reflow temperature. But leg 0, 1, and 2 units have still (-) warpage even at peak reflow temperature because the unit started too negative warpage at RT due to higher cure shrinkage effect.

Therefore, the material property of the molding compound should be changed to control the overall warpage of the package unit as suggested in Fig. 6. The amount of the chemical cure shrinkage of the molding compound controls the smile warpage at RT together with the CTE mismatch between the molding compound and the substrate. Therefore, the amount of the chemical cure shrinkage and CTE mismatch of the molding compound to the substrate mainly determines

the amount of smile warpage at RT. It is also applicable to high temperature warpage control because the CTE mismatch between the molding compound and the substrate at peak temperature create crying warpage. Therefore the CTE2 above Tg of the molding compound contributes the amount of crying warpage at higher temperatures above liquidous temperature for reflow profile temperature. The glass transition temperature, Tg of the molding compound is also controlling the amount of the CTE mismatched warpage at low and high temperature. These material effects will be more discussed in warpage modeling results.

Effect of MC filler size on warpage behaviors

Fig. 7 shows the warpages behaviors of the individual units for each leg with different molding compounds as a function of reflow temperatures. The molding compounds from leg 0 to leg 2 have larger filler cut and average sizes for silica fillers. Those legs generally showed large deviation at each temperature, especially at lower temperatures. On the other hand, the warpage data for individual units of leg 2 to leg 5 shows relatively tight deviation mainly because they have smaller filler cut and average size for silica filler in molding compound formulation. Large warpage level deviation at each reflow temperature is not desirable. Due to the package unit for warpage measurement taken from different location on substrate strip before singulation, the explanation for large warpage deviation would be the filler concentration would be different due to filler migration phenomena. As the filler size is large, the more filler migration happens during mold flow process inside mold chasis. This results in filler concentration changes and final molding compound properties at different unit location, and eventually it affects the individual warpage level of each package unit. Therefore, it is important to have the filler size distribution control inside the molded package during the mold process for tight warpage control for individual package units.

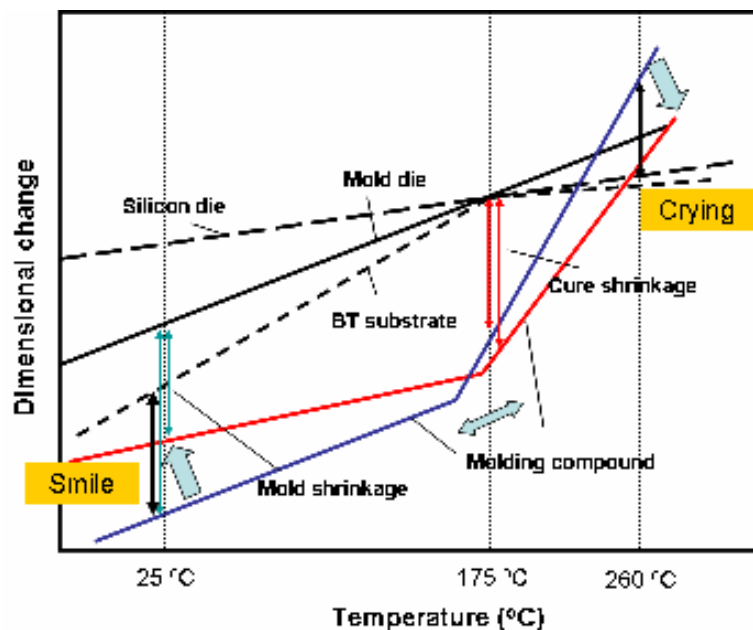


Fig. 6 Schematics of the dimensional change of materials inside PoP top package

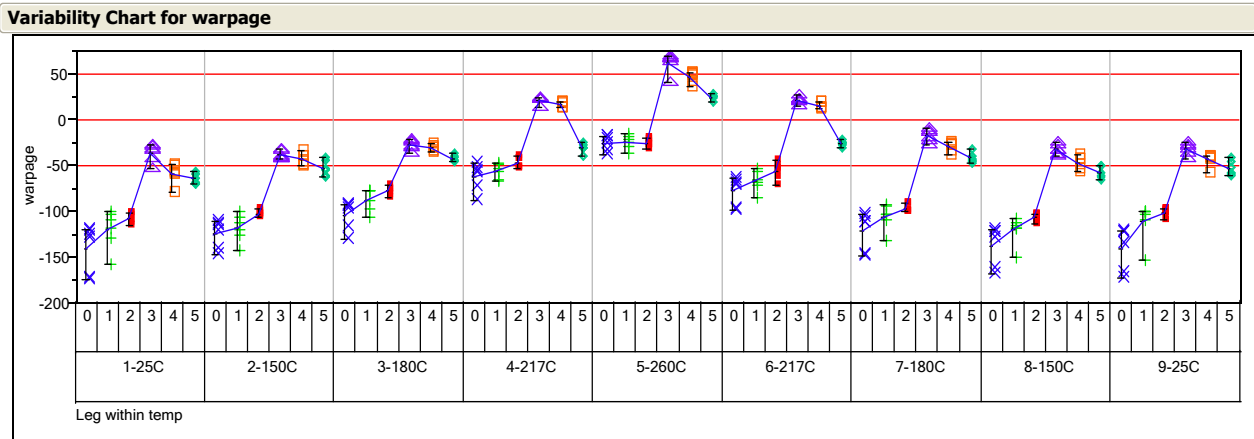


Fig. 7 Warpage deviation for 15PoP with different MCs throughout temperatures

Modeling results

Effect of Cure Shrinkage

% CS	Warpage (in um) Due to CS	
	25 C	260 C
0.10	-58	-37
0.15	-87	-56
0.20	-116	-75

Table.3 Package warpage calculation at RT and peak temperature with different cure shrinkage of MCs.

The warpage due to cure shrinkage is always –ve. Increasing the cure shrinkage will increase the warpage at both the 25C and 260C as shown in Table 3. Also it is noticed that the smile warpage at room temperature is higher than that of 260C because of higher modulus at room temperature. The effect of the cure shrinkage variation of the molding compound to the warpage level change is relatively huge from the modeling data, especially at RT.

Effect of CTE1

CTE1 (ppm)	Warpage (in um) due to thermal shrinkage at 25C
14	26
11	48
8	77

Table.4 Package warpage calculation at RT with different CTE1 of MCs.

As the mold compound CTE1 is reduced, the induced warpage due to thermal shrinkage will increase as shown in Table 4. This is due to the increasing CTE mismatch between the substrate and mold compound. The increased thermal warpage is needed to compensate the –ve warpage resulting from chemical shrinkage. The glass transition temperature of molding compound also plays the similar effect as CTE1 because it determines the effective CTE1. Lower Tg usually brings to high effective CTE1, which results in low thermal

shrinkage warpage at RT, and higher Tg results in high thermal shrinkage warpage at RT.

Effect of CTE2

CTE2(ppm)	Warpage (in um) due to thermal shrinkage at 260C
40	81
30	50
25	34

Table.5 Package warpage calculation at peak temperature with different CTE2 of MCs.

As the mold compound CTE2 is reduced, the induced warpage due to thermal shrinkage will decrease as shown in Table 5. This is due to the decreasing CTE mismatch between the substrate and mold compound.

The warpage due to cure shrinkage at high temperatures is lower; in order to compensate this lower thermal shrinkage is sufficient. The CTE2 of the molding compound is controlling the amount of the thermal warpage above Tg to compensate cure shrinkage.

Effect of Room Temperature Modulus

E1 (GPa)	Warpage (in um) due to thermal shrinkage at 25C
20	57
24	48
30	37

Table. 6 Package warpage calculations at RT with different RT modulus of MCs.

Increasing the mold compound modulus will decrease the warpage due to thermal shrinkage. This is due to the increased resistance of the mold compound to warpage. The increased thermal warpage is needed at room temperature in order to compensate the –ve warpage resulting from cure shrinkage.

Effect of Modulus above Tg

E2 (MPa)	Warpage (in μm) due to thermal shrinkage at 260C
2000	76
1500	69
1000	51

Table. 7 Package warpage calculations at peak temperature with different high temperature modulus of MCs

Increasing the mold compound modulus will increase the warpage due to thermal shrinkage. Lower thermal warpage is needed at reflow temperatures to compensate the lower α -warpage resulting from cure shrinkage at these temperatures.

In summary, the modeling results on the effects of the molding compound on the warpage control of the package during the temperature change were found to be almost matching to the experimental results.

Conclusions

The effects of material properties on PoP top package warpage during reflow process were investigated in this paper. Molding compound material significantly affected the overall warpage behaviors throughout from room temperature to reflow peak temperature. CTEs below T_g and above T_g , and cure shrinkage of the molding compound are important properties that affect the warpage level through the temperature variation during reflow process. There are other effects from the die attach material, package design, substrate materials and die stacking volume for warpage control, but material effect such as molding compounds is identified as one of key contributors. This study is useful for understanding the warpage behavior of any package configuration during board mount assembly through reflow process and for selecting the proper material options to control the warpage level to meet the assembly yield target.

Acknowledgments

The authors would like to thank the management for their support on this work. The author would also thank the warpage working group members including Ma Rong, Wenxin Chen, Zhenyu Huang at Intel FMG for their very useful discussion, and warpage data measurement and collection supports.

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