Warpage Simulation and DOE Analysis with Application in Package-on-Package Development

Wei Sun, W.H. Zhu, C.K. Wang, Anthony Y.S. Sun and H.B. Tan
United Test & Assembly Center Ltd (UTAC)
Packaging Analysis & Design Center
5 Serangoon North Ave 5, Singapore, 554916
Email: Sun_Wei@sg.utacgroup.com, Tel: +65-65511345

Abstract

The current paper talks about warpage modeling and validation, DOE analysis and approximation model derivation, and solving of actual warpage problem. Warpage of actual PoP (Package-on-Package), both the top and bottom packages, was investigated extensively through modeling and experimental measurement. It was found that the current warpage modeling method using average CTE and linear elastic analysis yields acceptable accuracy. Full factorial DOE analysis using ANSYS, EXCEL and JMP was performed to analyze the impact of design and material impact on warpage of both bottom and top packages. Surprisingly it was observed from DOE analysis that die size has completely different impact on warpage for top and bottom package. An actual problem, where a PoP top package exhibited large crying mode warpage, was quickly solved with the established warpage analysis method.

1. Introduction

PoP is gaining more and more acceptance in the market for its flexibility and testability. However, the stacking of two packages vertically and mounting them onto PCB shed some concerns over SMT assembly yield, caused mainly by certain warpage patterns the two packages exhibit [1].

In the early stage of new package development, FEA (Finite Element Analysis) can help to reduce the matrix for physical trial run and speed up the turnaround time of design and material selection. It is therefore a valuable tool in product development. DOE (Design of Experiment) was initially developed to systematically conduct a series of physical tests to analyze the impact of input factors on output responses. Simulation-based DOE, where physical experiments are replaced by numerical experiments performed using computer simulation code, demonstrates its excellent capability in studying the effect of changes of input parameters on simulation outputs [2-15].

In the current paper, firstly the accuracy of current simulation method was examined. Warpage of a LGA and a wCSP was modeled for both room and elevated temperatures. Results were found to have good correlation with Shadow Moiré measurement data. Therefore, confidence was built up for further study in PoP package development. Secondly, the verified warpage prediction method was applied to upfront model the warpage of PoP bottom package, which is more critical for successful PoP stacking and SMT [1]. Engineering samples with different EMC (Epoxy Mold Compound) and die size/thickness were later built and subject to Shadow Moiré measurement. Again, good agreement was found between FEA results and measurement for all legs of test vehicles at both room and peak temperatures. Therefore, strong confidence was built up to use the current modeling method for warpage prediction of PoP bottom package in the future for design and material optimization. Thirdly, simulation-based DOE analysis was performed to quantitatively study the effect of design and material impact on PoP package. The DOE analysis capability was built based on current software resources including ANSYS, EXCEL and JMP. Both PoP top and bottom packages were investigated to analyze their warpage sensitivity to design and material change. Besides sensitivity analysis, a polynomial regression model can also be obtained by JMP to replace simulation for warpage calculation. This polynomial calculation equation is especially useful as in the early stage of package development, design and material inputs can just be plugged in to quickly calculate the warpage without actual simulation. Lastly, the established warpage modeling method was applied to solve an actual problem, where a new PoP top package exhibited excessive warpage and failed visual mechanical inspection. Simulation quickly helped find out the best solution and subsequent physical run confirmed this.

2. Validation of Warpage Modeling Accuracy

Warpage modeling method has to be validated in order to use it for further analysis. In this part, a LGA and a wCSP of which warpage measurement data were already available were modeled and their warpage was predicted with ANSYS. In this simulation, material property of polymers like EMC was considered linear elastic. Although EMC is visco-elastic in nature, such property data is not readily available from suppliers. Characterization of visco-elasticity in-house for each EMC consumes prohibitive cost and time and presents a non-economical solution. Average material property such as CTE over the temperature range under study gives reasonable and also economical estimates of the material behavior [16]. It is therefore used in the current simulation. It is also known that cure shrinkage of EMC plays some role in package warpage [16]. With cure shrinkage, the effective CTE of EMC is slightly higher for warpage simulation below 175C and lower for that above 175C. However, the cure shrinkage data of different EMCs used in the current study is not available from suppliers. Therefore, it is not included for the simulations in this paper.

Details of dimensions and material properties of the LGA and wCSP package are listed in Table 1 and 2. Geometry of the two packages exhibit quarterly symmetric, so 3D quarter models as shown in Figure 1 and 2 are used for current simulation analyses. Temperature cooling down from 175C to 25C and ramping up from 175 to 215C/260C with stress-free state assumed at 175C are simulated in ANSYS. The average CTE is calculated using Equation 1 when Tg falls in the simulated temperature range. Figure 3 illustrates how the warpage mode and value are defined in this paper.

Figure 4 shows the simulated warpage curve of the 8x10.5mm LGA at both room temperature and 260C. The curve shown is the warpage along package half diagonal. Figure 5 and 6 are the warpage curves along package whole diagonal measured from Shadow Moiré. It is seen that there is good agreement between simulation and measurement in terms of both warpage mode and value. Moreover, similar agreement between simulation and measurement was found in the 10x10.5mm wCSP package as shown in Figure 7-9. Therefore, some confidence is built up to perform warpage simulation analysis for PoP development using the current simulation method.

Table 1: Details of the LGA package under study

LGA	Dimension (mm)		Material Properties				
	Size	Tks	E@25 (MPa)	E@260 (MPa)	α1 E-6	α2 E-6	Tg (C)
Die	5x9.7	0.1	1310000	1310000	2.6	-	-
DA	5x9.7	0.04	230	5	41	172	41
EMC	8x10.5	0.35	24000	280	9	36	135
SM	8x10.5	0.03	2400	800	60	130	100
Core		0.1	28000	8600	XY: 14 Z: 30	XY: 7 Z: 150	220
Cu		0.02	117000	-	17.3	-	

Table 2: Details of wCSP package under study

wCSP	Dimension (mm)		Material Properties				
	Size	Tks	E@25 (MPa)	E@215 (MPa)	α1 E-6	α2 E-6	Tg (C)
Die	9.3x9.5	0.26	131000	131000	2.6	-	-
DA	-	0.055	658	1	70	350	40
EMC	10x10.5	0.53	21560	686	10	42	120
SM	10x10.5	0.03	2400	800	60	130	100
Core		0.2	28500	11400	XY: 13 Z: 25	XY: 9 Z: 150	220
Cu		0.012	117000	-	17.3	-	

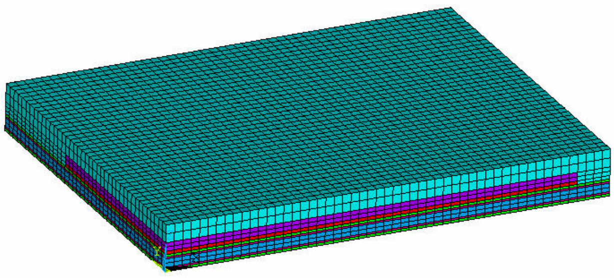


Figure 1: Quarter FE model of 8x10.5mm LGA

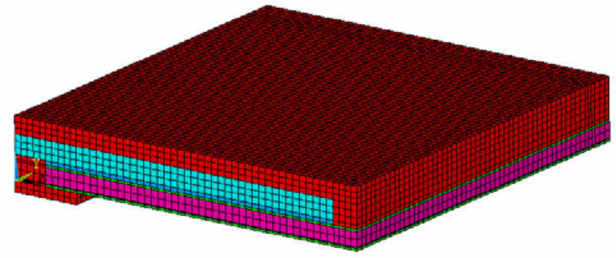


Figure 2: Quarter FE model of 10x10.5mm wCSP

$$CTE_{ave} = \frac{\alpha_1 (T_g - T_{final}) + \alpha_2 (T_{ref} - T_g)}{T_{ref} - T_{final}} \qquad \text{(Eq.1)}$$

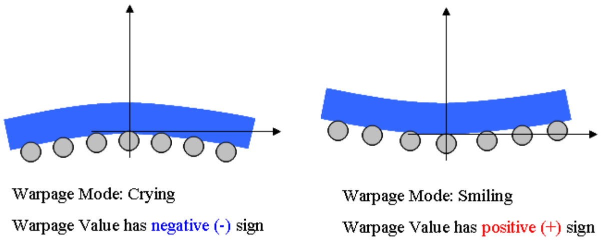


Figure 3: Warpage mode and value definition

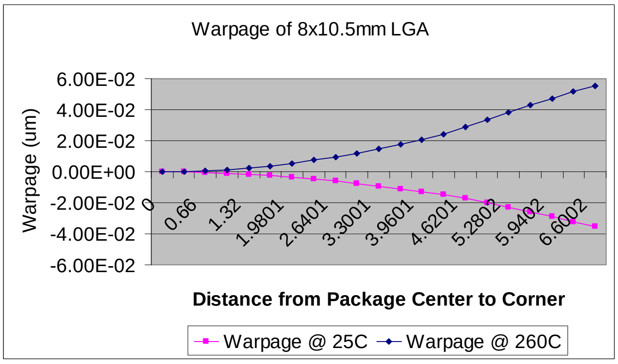


Figure 4: Simulated warpage curve along package half-diagonal (8x10.5mm LGA)

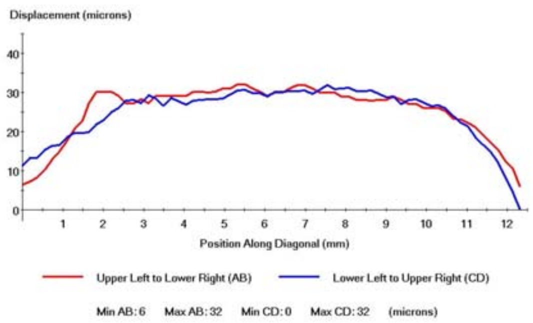


Figure 5: Shadow Moiré measurement @ 25 C for 8x10.5mm LGA

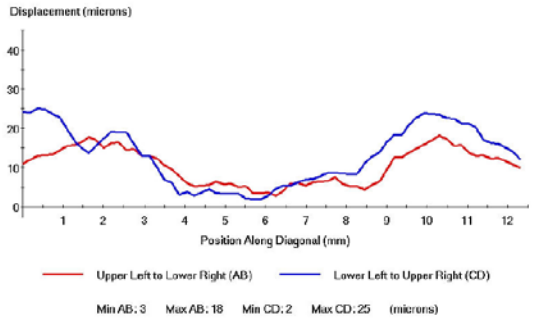


Figure 6: Shadow Moiré measurement @ 260C for 8x10.5mm LGA

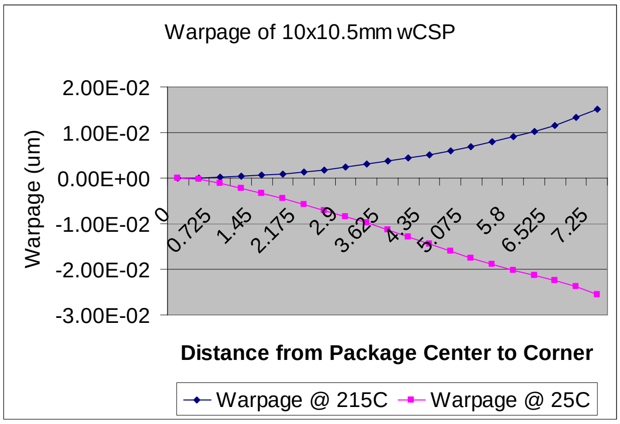


Figure 7: Simulated warpage curve along package half-diagonal (10x10.5mm wCSP)

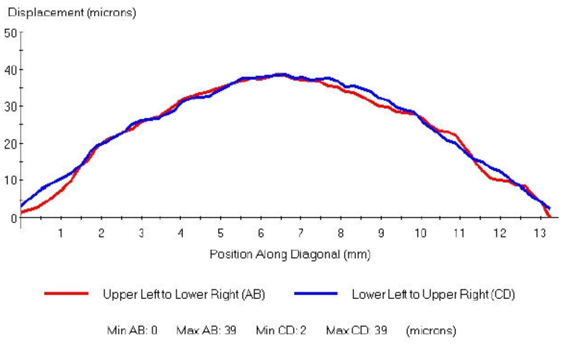


Figure 8: Shadow Moiré measurement @ 25 C for 10x10.5mm wCSP

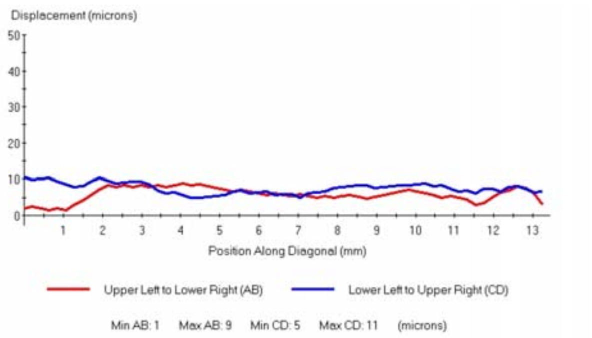


Figure 9: Shadow Moiré measurement @ 215 C for 10x10.5mm wCSP

3. Warpage Modeling of PoP Bottom Package

In this part, simulation is used extensively in a PoP bottom package development. The purpose is to study how material and die size/thickness impact warpage at both room and reflow temperature and to further experimentally verify the accuracy of current simulation method. Details of the PoP bottom package under study are listed in Table 3. Die size and thickness are varied. Six different EMCs as listed in Table 4 are used to study their impact on warpage. 3D quarter model as shown in Figure 10 is used for FEA simulation. Table 5 gives the summarized design and material DOE parameters used in this study. Naming convention is also given to facilitate understanding of subsequent analysis.

From Figure 11 and 12 we can see that at both room and reflow temperatures, simulation and measurement give good correlation for all the legs. Therefore, strong confidence is built up to use the current simulation method for future PoP package development especially for upfront simulation before physical run. From both simulation and experiment it is also noticed that reduction of silicon material as well as EMC with higher average CTE will shift the warpage curve upwards. However, such understanding of design and material impact on warpage is very qualitative. It is desirable to have a method to quantify such impact.

Table 3: Details of the 15x15mm PoP bottom package under study

PoP Btm Pkg	Dimension (mm)		Material Properties				
	Size	Tks	E@25 (MPa)	E@215 (MPa)	α1 E-6	α2 E-6	Tg (C)
Die	4.1^2 8.3^2	0.1 0.05	131000	131000	2.6	-	-
DA	4.1^2 8.3^2	0.04	230	5	41	172	41
EMC	11.55^2	0.3	Var	Var	Var	Var	Var
SM	15^2	0.03	2400	800	60	130	100
Core		0.2	28500	11400	XY:13 Z:25	XY:9 Z:150	220
Inner Cu		0.012	117000	-	17.3	-	
Outer Cu		0.022	117000	-	17.3	-	

Table 4: Six EMC materials for PoP bottom package

EMC	E@25 (MPa)	E@215 (MPa)	α1 E-6	α2 E-6	Tg (C)
A	21560	882	13	54	150
B	20580	392	10	41	110
C	23000	402	10	43	130
D	20000	304	14	55	135

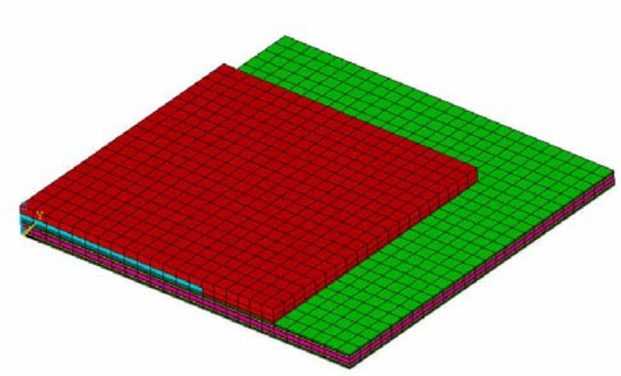


Figure 10: Quarter FE model of 15x15mm PoP bottom

Table 5: Parameters and naming convention used in simulation and experiment

Naming Convention		
Mold Cpd	Die Size	Die Thickness
A ~ D	B: 8.3x8.3mm S: 4.4x4.1mm	B: 100µm S: 50µm
E.g. C-B-S represents a leg using mold compound C, die size of 8.3x8.3mm and die thickness of 50µm		

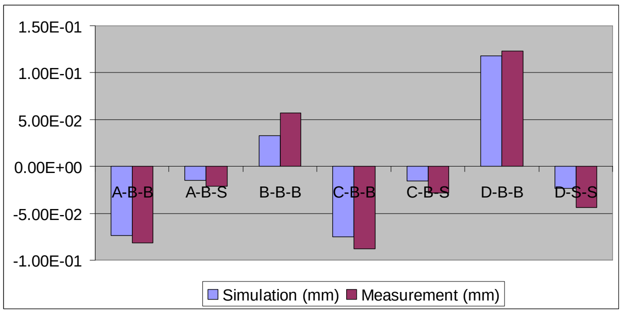


Figure 11: Warpage Correlation (Room Temperature Warpage)

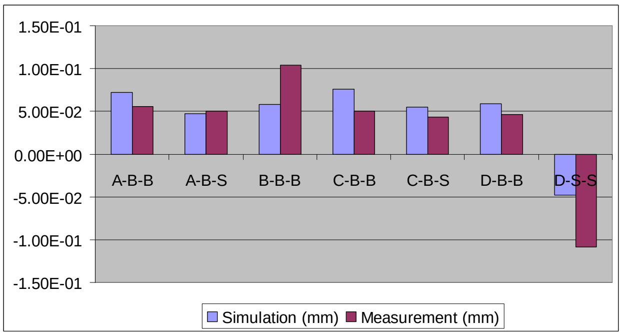


Figure 12: Warpage Correlation (Reflow Temperature Warpage)

4. DOE Analysis of PoP

Figure 13 is a schematic picture of the bi-material cantilever beam. Based on Timoshenko beam theory, the close-form mathematical solution to the warpage of this bi-material cantilever beam under temperature change is Equation 2. With this equation, one can easily calculate the impact of various material and dimensional changes on warpage. However, actual package is far more complex than a bi-material beam. Therefore, it is impossible to quantify the impact of design and material impact based on close-form theoretical equation.

DOE analysis, based on different sampling methods such as full factorial, Taguchi array, Box-Behnken, Central Composite Design and Latin Hypercube, provides a systematic way of data analysis using the results of a certain number of experimental legs. Coupled with computer simulation, DOE analysis can quickly help us to quantify the relationship between input parameters and output responses and identify how and how much the change in inputs affect the output. There is a number of commercial software available in the market for simulation-based DOE analysis such as Modelfrontier, Optimus and VisualDoC. But the current study employs existing software resources which include ANSYS/Mechanical, EXCEL and JMP software. ANSYS/Mechanical is the FEA simulation code, where a short APDL code is programmed to execute all the legs required by a DOE sampling method such as full factorial used in this paper. It should be noted that although ANSYS/Mechanical itself contains a full factorial DOE analysis function, such function is limited to 7 input parameters and 2 level analysis only. Therefore, it is impossible to put a medium-level setting of a parameter to see whether there is any non-linear effect and to study more than 7 DOE parameters. EXCEL is programmed using macro to import the result files generated systematically from ANSYS/Mechanical. The data imported by EXCEL is then easily copied and pasted into JMP software for full factorial DOE analysis. JMP itself is a powerful statistical analysis and DOE analysis tool used widely in manufacturing and quality management. With the combination of above three software, no additional cost is needed to purchase specialized software to perform DOE analysis. It should also be highlighted that the DOE analysis is not confined to full factorial sampling method only. Instead, every DOE sampling method supported by JMP can be easily programmed in ANSY APDL to perform the analysis.

Previously studied PoP is analyzed with this method. A full factorial analysis with 6 parameters as listed in Table 6 is performed. Good fit is achieved between simulation data and DOE predicted data as shown in Figure 14. Pareto plot that can tell us the quantitative effect of each DOE parameter is shown in Figure 15. It is seen that CTE of EMC have the most significant impact on warpage and increase in EMC CTE will shift the warpage curve upwards. The descending order of other parameters is die size, die thickness, EMC modulus and

CTE of substrate. From Figure 16, we can see that there is no significant interaction among the six DOE parameters. Apart from sensitivity analysis, another advantage of DOE analysis is that a polynomial regression model can also be obtained to replace simulation for warpage calculation. This polynomial is useful especially in the early stage of package development as design and material inputs can just be plugged in to quickly calculate the warpage without actual simulation. Seven EMCs whose material properties fall in the DOE analysis range and are listed in Table 7 are plugged into actual ANSYS simulation and also the approximation model. We can see from Figure 17 that the approximation model can generate almost the same results as actual simulations. With help of the approximation model, a plot showing the impact of EMC selection on warpage as shown in Figure 18 can be quickly drawn. This plot is helpful in EMC selection. Engineers can quickly tell from the plot which EMC can give better warpage performance.

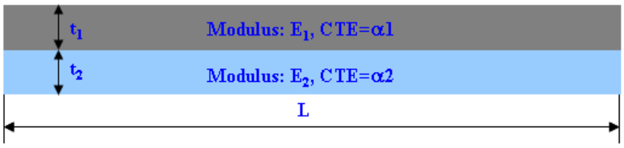


Figure 13: Bi-layer cantilever beam model

$$t = t_1 + t_2 \qquad q = \frac{E_1}{E_2} \qquad p = \frac{t_1}{t_2}$$

$$warpage = L^2 \frac{3(1+p)^2(\alpha_2 - \alpha_1)(T - T_0)}{4t\left[3(1+p)^2 + (1+pq)(p^2 + 1/pq)\right]} \qquad \text{(Eq.2)}$$

Table 6: DOE parameters for PoP bottom package

Ave CTE of Core (ppm/K)	RT Modulus of Core (MPa)	Die Tks (µm)	Die Size (mm)	Ave CTE of EMC ppm/K	Rom Temp E of EMC (MPa)
12ppm/K	20000	50	4.1^2	13	20000
14ppm/K	25000	100	8.3^2	24	26000
16ppm/K	30000			35	32000

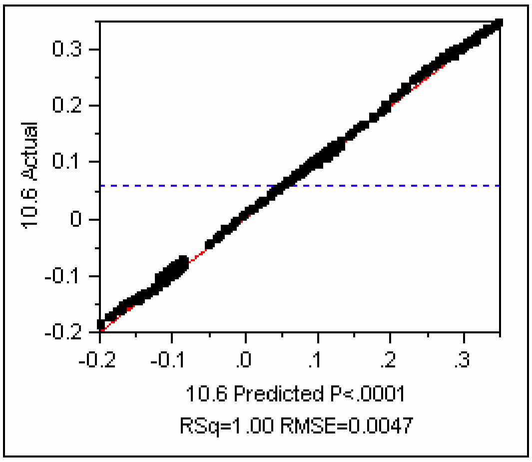
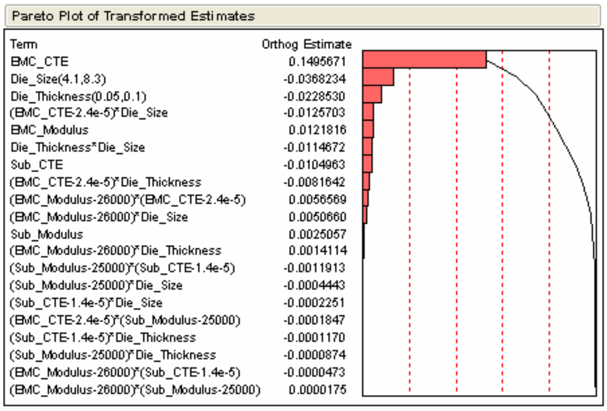


Figure 14: Simulation vs. Approximation model



Term	Orthog Estimate
EMC_CTE	0.1495671
Die_Size(4.1,8.3)	-0.0368234
Die_Thickness(0.05,0.1)	-0.0228530
(EMC_CTE-2.4e-5)*Die_Size	-0.0125703
EMC_Modulus	0.0121816
Die_Thickness*Die_Size	-0.0114672
Sub_CTE	-0.0104963
(EMC_CTE-2.4e-5)*Die_Thickness	-0.0081642
(EMC_Modulus-26000)*(EMC_CTE-2.4e-5)	0.0056569
(EMC_Modulus-26000)*Die_Size	0.0050660
Sub_Modulus	0.0025057
(EMC_Modulus-26000)*Die_Thickness	0.0014114
(Sub_Modulus-25000)*(Sub_CTE-1.4e-5)	-0.0011913
(Sub_Modulus-25000)*Die_Size	-0.0004443
(Sub_CTE-1.4e-5)*Die_Size	-0.0002251
(EMC_CTE-2.4e-5)*(Sub_Modulus-25000)	-0.0001847
(Sub_CTE-1.4e-5)*Die_Thickness	-0.0001170
(Sub_Modulus-25000)*Die_Thickness	-0.0000874
(EMC_Modulus-26000)*(Sub_CTE-1.4e-5)	-0.0000473
(EMC_Modulus-26000)*(Sub_Modulus-25000)	0.0000175

Figure 15: Pareto plot of different design and material parameters

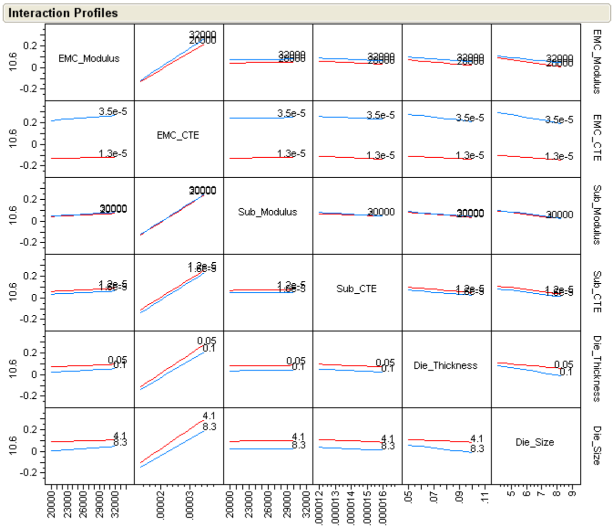


Figure 16: Interaction plot of different design and material parameters

Table 7: EMC properties of E~L

EMC	E@25 (MPa)	E@215 (MPa)	α1 E-6	α2 E-6	Tg (C)
H	20580	392	10	41	110
I	20000	304	14	55	135
J	23000	402	10	43	130
K	24000	280	9	36	135
L	23500	300	9	36	143
M	21560	882	13	54	150
N	30000	400	10	40	125

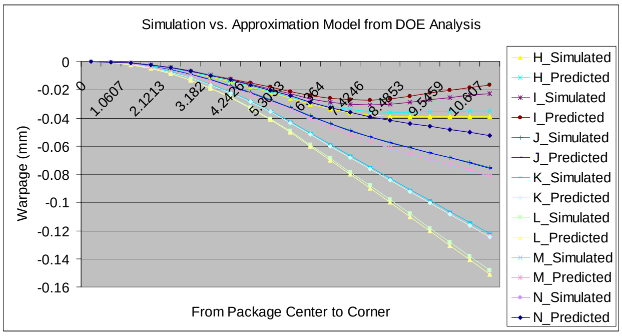


Figure 17: Comparison of simulation results and those calculated from derived approximation model

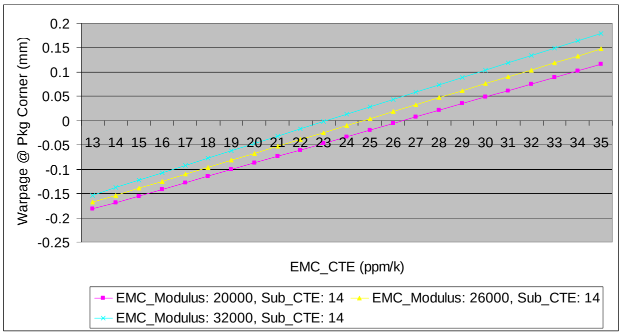


Figure 18: EMC properties on warpage

A similar DOE analysis is also conducted for PoP top package of which details are listed in Table 7. However, it is found that the obtained approximation model gives poor fit as shown in Figure 19. It is therefore very likely that some nonlinear effect exists as certain parameter changes from low level to medium level and to high level. Further scrutiny also confirmed that there are some strong interaction effects among mold cap thickness, die size/thickness and substrate core thickness as shown in Figure 20. With those nonlinear effects and strong interactions, special attention must be paid when doing data analysis. The approximation model derived from such case should not be used as the quick calculation tool any more as large deviation is obvious. Therefore, if approximation model is to be derived, it'd better to have different DOE analysis for each combination of mold cap thickness, die size/thickness, and core thickness or a different DOE sampling method should be tried.

Data analysis to scrutinize the die size effect is performed for the two nominal PoP top package designs highlighted in blue in Table 8. Warpage vs. Die Size plot is given in Figure 21 for die thickness of 50µm and 100µm. Contrary to previous finding on PoP bottom package where increase in die size will indirectly reduce EMC volume and shift the warpage curve downwards, it is found this time that increase in die size will further shift the warpage curve upwards instead of downwards. This is an important finding and is also later confirmed by physical measurement of engineering samples. One possible explanation is, as both mold cap and substrate core become so thin that die starts to play the dominant role in determination of warpage. Since silicon die is a very stiff material, increase in die size will make it more difficult to shift the warpage curve downwards.

As PoP top package is going for thinner mold cap and substrate core to redude the overall PoP height, attention must be paid when specifying the design guideline on warpage reduction. We cannot use the same design guidelines that related to die size/thickness in both PoP top and bottom package. A detailed DOE analysis should be conducted each time when developing a new PoP top package.

Table 8: Details of the 15x15mm PoP top package under study

PoP Top Package	Dimension (mm)		Material Properties				
	Size	Tks	E@25 (MPa)	E@215 (MPa)	α1 E-6	α2 E-6	Tg (C)
Die	4^2 8^2 12^2	0.1 0.075 0.05	131000	131000	2.6	-	-
DA	4^2 8^2 12^2	0.04	230	5	41	172	41
EMC	15^2	0.2 0.25 0.3 0.35 0.4	20000	304	14	55	135
SM	15^2	0.025	2400	800	60	130	100
Core		0.06 0.11 0.16 0.21	28500	11400	13 25	9 150	220
Copper		0.012	117000	-	17.3	-	

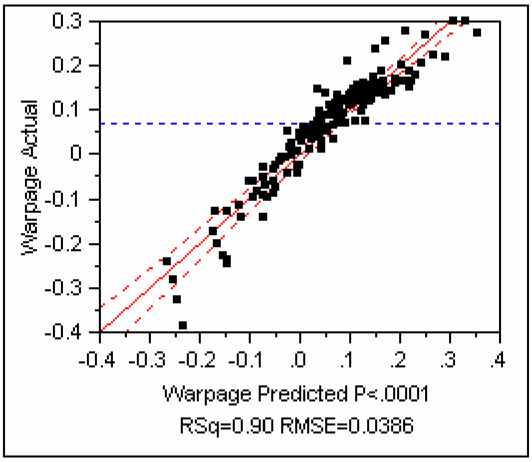


Figure 19: Simulation vs. Approximation model

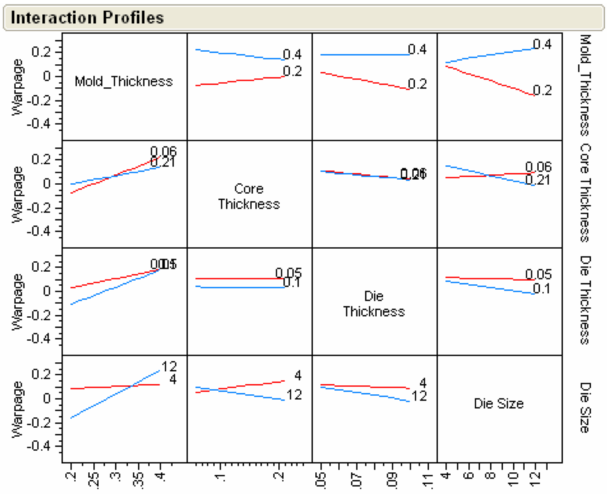
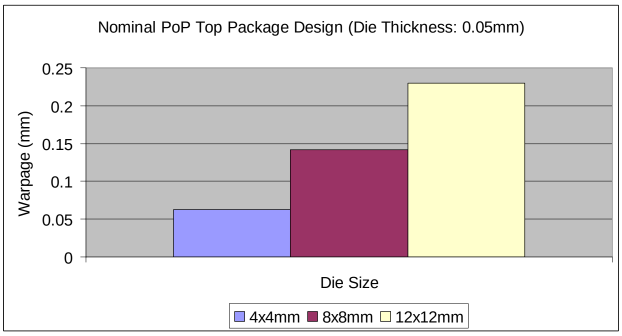
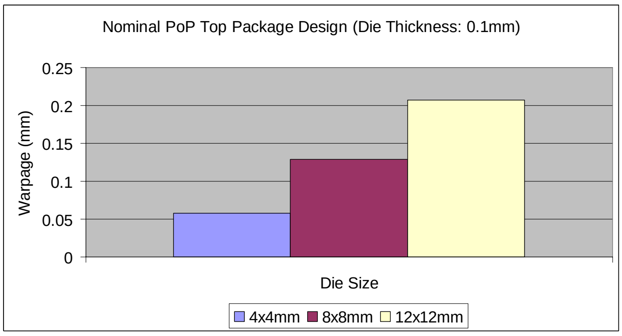


Figure 20: Interaction plot of different design and material parameters



(A)



(B)

Figure 21: Plot showing that die size increase results in warpage curve going further upwards

5. Case Study

In this case study, a new stack-die PoP top package as illustrated in Figure 22 failed end-of-line visual mechanical inspection with excessive crying mode warpage as shown in Figure 23. Several design/layout/material changes were proposed in an effort to reduce the warpage or in other words to shift the warpage curve upwards from excessive negative to less negative or slightly positive. However, the physical DOE matrix was too large and costly to run. Therefore, FEA simulation was requested to reduce the physical DOE matrix.

Due to half symmetry of the package structure, 3D half model as shown in Figure 24 was setup. By using the established modeling method and DOE analysis, it was quickly found that while design/layout changes do not affect the warpage too much, switching to certain mold compound material can significantly reduce the warpage. The five mold compound candidates are listed in Table 9. From Figure 25, we can see that the use of mold compound S, which has the largest average CTE, can significantly shift the warpage curve upwards or reduce the crying mode warpage. Subsequent physical DOE trial run with the simulation-selected mold compound confirmed the simulation finding. Therefore mold compound S is used as the standard BOM for PoP top package.

6. Summaries and Conclusion

Validated FEA simulation for warpage is a valuable tool in package development and failure analysis. With the use of DOE analysis, impact of a series of design and material parameters on warpage can be efficiently analyzed. The combination of ANSYS/Mechanical, EXCEL and JMP plus some programming provides powerful and low-cost tool for simulation-based DOE analysis. Design and material selection guidelines can be obtained from such simulation-based DOE analysis. Warpage calculator based on approximation model derived from simulation-based DOE analysis gives quick and reasonably accurate estimates of warpage.

7. Future Work

Material properties obtained from different suppliers were measured using different methods. It is therefore better to perform material characterization in-house using a unified method. Cure shrinkage is an important factor affecting warpage, future work will also perform characterization work on cure shrinkage of different EMC from different suppliers. With detailed in-house material testing data and cure shrinkage data, current warpage simulation should be progressing more towards a quantitative method.

Acknowledgements

The authors would like to thank UTAC management team for their support on this project. The engineering sample build work by Ravi, Kriangsak, Danny and Bimbo are greatly appreciated. The review work by UTAC paper review panel is also acknowledged.

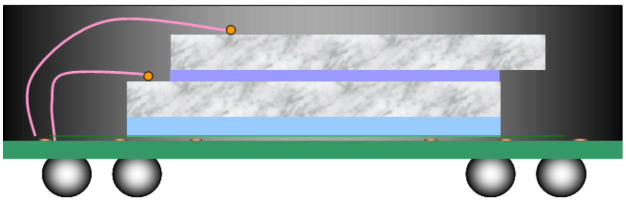


Figure 22: Schematic cross-section picture of current 14x14mm PoP top package

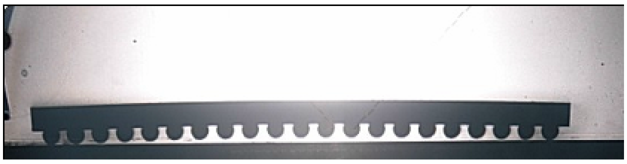


Figure 23: FA picture showing the large crying mode warpage

Table 9: Details of five EMC for warpage problem solving

EMC	E@ 25 (MPa)	E@215 (MPa)	α1	α2	Tg
O	27000	340	8	32	135
P	24000	280	9	36	135
Q	23500	300	9	36	143
R	21000	220	11	39	143
S	21560	882	13	54	150

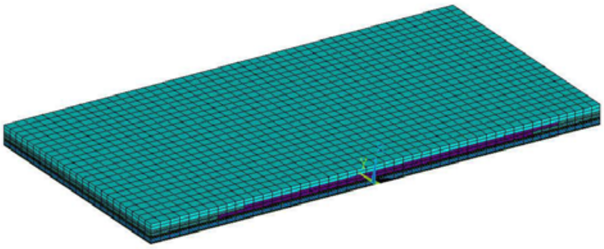


Figure 24: Quarter FE model of 14x14mm PoP top

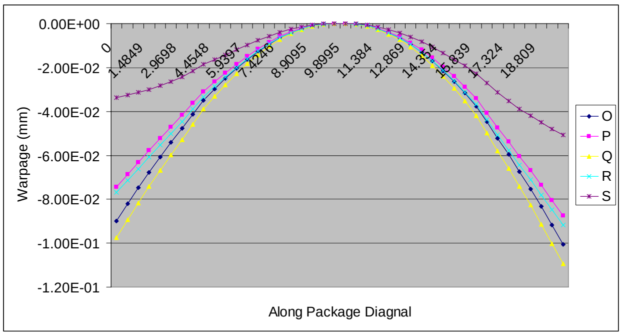


Figure 25: Plot showing the improvement of crying mode warpage with the use of mold compound S

References

1. Akito Yoshida et al, "A Study on Package Stacking Process for Package-on-Package (PoP)", Proceedings of ECTC2006, pp.825-830.
2. A. Mertol, "Application of the Taguchi Method on the Robust Design of Molded 225 Plastic Ball Grid Array Packages", IEEE Trans. Comp. Packag., Manufact. Technol. B, vol. 18, pp. 734-743, Nov. 1995
3. A. Mertol, "Optimization of High Pin Count Cavity-up Enhanced Plastic Ball Grid Array (EPBGA) Packages for Robust Design", IEEE Trans. Comp. Packag., Manufact. Technol. B, vol. 20, pp. 376-388, Nov. 1997
4. A. Mertol, **"**Application of the Taguchi Method to Chip Scale Package (CSP) Design**"**, IEEE Trans. Adv. Packag., vol. 23, 2000, pp. 266-276
5. A. Dasgupta, M. G. Pecht, B. Mathieu, **"**Design-of-experiment Methods for Computational Parametric Studies in Electronic Packaging, Finite Element in Analysis and Design**"**, 30 (1998), pp.125-146
6. G. Q. Zhang, J. H. J. Janssen, L. J. Ernst, J. Bisschop, Z. N. Liang, F. Kuper, and R. L. Schravendeel, **"**Virtual Thermo-Mechanical Prototyping of Electronic Packaging Using Philips' Optimization Strategy**"**, IMAPS2000, USA
7. S. Stoyanov, C. Bailey and M. Cross, **"**Optimization Modeling for Flip Chip Solder Joint Reliability, Soldering & Surface Mount Technology**"**, 14/1, 2002, pp. 49-58
8. B. Vandevelde, E. Beyne, G. Q. Zhang, Jo F. J. M. Caers, D. Vandepitte and M. Baelmans, "Solder Parameter Sensitivity for CSP Life-Time Prediction Using Simulation-Based Optimization Method", IEEE trans. on Electronics Packag. Manufact., vol. 25, 4, October 2002
9. B. Vandevelde, E. Beyne, G. Q. Zhang, Jo Caers, D. Vandepitte, M. Baelmans, **"**Parameterized Modeling of Thermo-mechanical Reliability for CSP Assemblies**"**, Journal of Electronic Packaging, vol. 125, December 2003
10. W. D. van Driel, G. Q. Zhang, J. H. J. Janssen, L. J. Ernst, **"**Reponse Surface Modeling for Nonlinear Packaging Stresses**"**, Journal of Electronic Packaging, vol. 125, December 2003
11. W. D. van Driel, G. Q. Zhang, J. W. C. de Vries, M. Jansen, L. J. Ernst, **"**Virtual Prototyping and Qualification of Board Level Assembly**"**, Proceedings of EPTC2003, December 2003
12. S. G. Jagarkal, M. M. Hossain, D. Agonafer, M. Lulu, S. Reh, "Design Optimization and Reliability of PWB Level Electronic Package", Proceedings of ITHERM'04, June, 2004 Las Vegas, USA
13. C. C. Lee, S. M. Chang, K. N. Chiang, **"**Design of Double Layer WLCSP Using DOE with Factorial Analysis Technology**"**, Proceedings of EPTC2004, December 2004
14. A. A. Giunta, **"**Use of Data Sampling, Surrogate Models, and Numerical Optimization in Engineering Design**"**, AIAA 2002-0538, American Institute of Aeronautics and Astronautics
15. Wei Sun et al, "Simulation-Based Design Optimization of Solder Joint Reliability of Wafer Level Copper Column Interconnectsz", Proceedings of ECTC2006, pp.444-450.
16. W. H. Zhu et al, "Cure shrinkage characterization and its implementation into correlation of warpage between simulation and measurement", Proceedings of EUROSime2007.