AN FEA AND DOE ANALYSIS TO PREDICT DEFORMATION AND WARPAGE OF OPTOELECTRONICS PACKAGE LIDS

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ABSTRACT

A design of experiment (DOE) analysis is reported on data from warpage simulations using finite element analysis (FEA) of a lidded electronics package. Warpage in a lid of an optical electronics package can detrimentally affect the reliability of the package as well as its optical performance. The present study focuses on the variety of materials and designs of lids relevant to recent technologies in electronics packaging. The FEA formulation in this study accurately predicts deformation and warpage in the elastic region with optimal computational time achieved through a choice of boundary conditions and mesh sensitivity studies.

This study mainly focuses on how warpage is affecting the lid deformation and techniques to characterize it. FEA is used to create a prototype which is similar to the actual product. The experiment is designed considering different variables such as both the design and the material of the lid. DOE and subsequent statistical analyses are applied to understand the correlation between these parameters. The most significant parameter in terms of the warpage deformation is addressed. Based on this study, the appropriate design and material are suggested for the development of the lid over the package. This becomes helpful when there is an optoelectronic package undergoing thermomechanical loading; warpage may not only adversely affect solder joints but other parts of the package as well. So, in this work, characterization of the lid of the package affected by warpage is the focus area. The analysis indicates that there is no significant interaction between the two parameters expected to affect the warpage in the lid. Material properties of the lid are found to have a greater effect on the warpage of the lid as compared to variabilities introduced in lid designs in this study. This study will be helpful for the development of technologically advanced packages associated with optoelectronics.

Key words: Optoelectronics, lidded package, warpage, DOE, FEA

INTRODUCTION

The focus of this study is to analyze warpage or deformation in optoelectronics (OE) lidded electronics packages. Although experimental methods provide more realistic measurements of the deformation/warpage for actual packages, they may have constraints in terms of expensive hardware, limitation over skills to operate, calibration accuracy, possibility to introduce human error, and not to mention the expense of using actual prototypes or packages to conduct these studies.

On the other hand, the finite element analysis (FEA) method has the advantage of creating a simulated prototype of the OE package, and to study it under different loading conditions in a quick time frame. However, validation of the method is necessary and the software skills necessary to develop the FEA models, not to mention access to the software, are hurdles to overcome.

Analytical/quantitative methods (such as CLPT and Suhir's theory) have limitations for providing a suitable solution for all types and designs of the package. Quantitative methods also focus more on estimating warpage on the mid plane of the package whereas in simulation modeling, the focus of the study can be associated with different components of the package.

In this work, the results from FEA are compared to analytical calculations made using the classical laminate plate theory (CLPT) as well as the modified Suhir's approach. It is observed that FEA results are more accurate as they account for the performance of die attach/underfill materials regardless of the small thickness of the layer. The FEA data are finally used to conduct a design of experiments (DOE) analysis to investigate the influence of three distinct designs and six material choices on warpage of a lid. The FEA simulations performed consider only material behavior within the elastic limit and in some situations, plastic deformation may occur which is more permanent and as such requires a more comprehensive analysis in the plastic region to enhance the data set for DOE studies.

BACKGROUND

As alluded above, there can be three general techniques to measure warpage: 1) using actual products/prototypes; 2) using analytical/quantitative techniques based upon package dimensions and composition; 3) measuring the warpage of simulated packages under stress/strain situations via FEA.

Warpage Measurements of Actual Packages

Warpage measurement of actual packages is typically conducted by two categories of experimental techniques – contact and non-contact. Contact methods include the gauge-indicator shim method and contact profilometry. Non-contact methods include non-contact profilometry, optical interferometry (different techniques), digital image correlation, and moiré techniques (shadow, projection, and digital fringe projection).

In 2013, Kang and Ume [1] did an extensive comparison of the aforementioned techniques. Their analyses suggested that shadow moiré is a better approach than the others.

Analytical Methods to Estimate Warpage

Two useful, analytical techniques to estimate warpage based on package properties are CLPT and an approach based on a modification of Suhir's theory initially proposed in 1980.

Classical laminate plate theory (CLPT) is a popular method that considers an "n" layer laminate of the sample where mechanics of the stresses and deformation is simplified in terms of a matrix that considers the elastic modulus, Poisson's ratio, thermal expansion coefficient, and thickness of each layer. While not going into the details of the mathematics of CLPT in this paper, a good example of its use in electronics packaging is found in a work by Park et al. [2]. They have used this method for prediction of warpage in chip scale packages (CSPs) and for a flip chip package on a large substrate with an overhang. By utilizing the CLPT mathematical equations, they have developed a predictive model for optimized design parameters in flip chip package and assemblies

Tsai et al. [3] utilized a modified approach of Suhir's technique to measure warpage in a simplified flip chip package as shown in Figure 1.

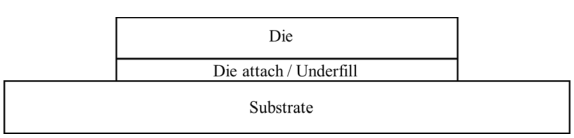

Figure 1. Simplified Flip Chip Package

They suggested that CLPT was not the best approach as CLPT assumes a constant radius of curvature, with respect to the Kirchoff-Love hypothesis. In their estimation, the die attach layer is more compliant than the CLPT approach allows. Similarly, we will not go into the mathematical details of the modified Suhir approach, but note that formulae to predict warpage incorporate elastic modulus, Poisson's ratio, and shear modulus of the material. As shown in their calculations, they conclude that low elastic moduli of the underfill can significantly reduce the maximum warpage and it was suggested to use either a low modulus of the underfill or low CTE for the substrate to reduce maximum warpage effect [3].

FEA Technique to Simulate Warpage

Different researchers have used FEA for solving thermo-mechanical analysis for different applications such as the study of crack propagation in solder joints, and thermal performance of power electronics. A good example of an FEA approach to study warpage behavior of an LGA electronics package considering different parameters was conducted by Sun et al. [4]. They simulated warpage of the package as based on two different thermal conditions: 1) ramp up from 175°C to 260°C and 2) ramp down from 175°C to 25°C. The stress-free state was assumed to be 175°C. Figure 2 shows a portion of their FEA quarter model and Table 1 provides details of the package and materials utilized in their study.

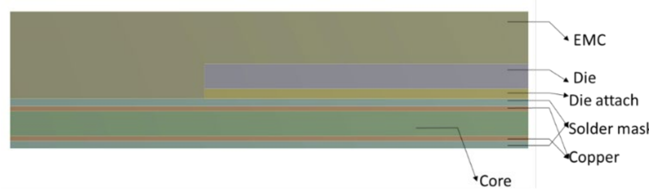

Figure 2. LGQ Quarter Model – Front View

Table 1. Package & Material Details in Sun et al. [4]

LGA layers	Length× Width	Thickness	Young's modulus at 25°C	Young's modulus at 260°C	CTE at 25°C	CTE at 260°C	T_g
Unit	(mm)		(MPa)		(ppm/°C)		(°C)
Die	5×9.7	0.1	131000		2.6		-
Die attach	5×9.7	0.04	230	5	41	172	41
EMC	8×10.5	0.35	24000	280	9	36	135
SM		0.03	2400	800	60	130	100
Core		0.1	28000	8600	*XY:14,Z:30	XY:7, Z:150	220
Cu		0.02	11700		17.3		-

In their work, FEA was effectively used to predict maximum out-of-plane deformation, whether concave or convex, as a function of ramp up or ramp down conditions as demonstrated in Figure 3. In this effort, as later described, our FEA approach is similar to that of Sun et al. [4] as we consider material properties, dimensions, and other geometrical parameters, along with estimating boundary and symmetry conditions of a quarter model for the packages studied, herein.

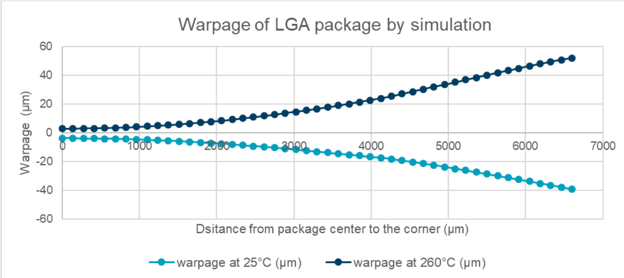

Figure 3. Simulated Warpage in Sun et al. [xx].

RESEARCH OBJECTIVE

The research objective of this work is to develop a DOE analytical method focusing on improving the performance of an electronic package lid under different proposed lid designs and material composition. A sub-objective of this work is to try to understand the effect of material and design shape on warpage of the lid by performing parametric analysis. This is important for technically advanced packages as shown in Figure 4, where the purpose of the lid is not only protection and separation of the system boundary from surrounding but also to create a cavity to hold the gas and provide an optical path. In such cases, even a small amount of warpage in the lid may cause failure to entire package.

In prior studies, solder joints are considered to be the most fragile parts of an electronics package. Furthermore, solder joint reliability is affected by package warpage.

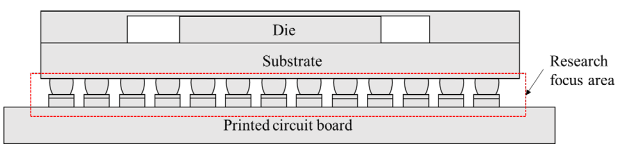

Figure 4. A Lidded Package Studied in this Work

There have been detailed studies conducted to understand the nature of the warpage. For some examples, Li [5], Singh [6], Chang and Chiou [7], and others have studied warpage of different packages in recent years. In these studies, different effects of the warpage mainly focused on the solder joints of BGA packages or the interconnects of the different layers of the package. As such, Figure 4 also highlights the area of focus in this research for electronics packages using schematic. Jang et al. [8] have studied the warpage behavior and reliability of the chip-on flex package for thermal loading using FEA and shadow moiré methods.

EXERIMENTAL DESIGN

In this work, a ball grid array (BGA) flip-chip package is selected having a size of 10mm × 10mm × 1.186mm where the die size is 3.89 × 4.43 × 0.30 mm. Figure 5 represents the schematic of the flip-chip BGA package without lid. The sample package is shown in Figure 6. Figure 6(a) shows the bottom view of sample flip-chip BGA package having 12 × 12 array of solder joints of diameter 0.45mm and pitch 0.8mm. Figure 6(b) shows the top view of the package without lid whereas Figure 6(c) shows top view of package with lid. These construction details are considered for package used for simulation.

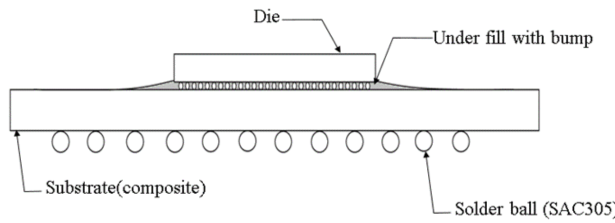

Figure 5. Schematic of package of without lid

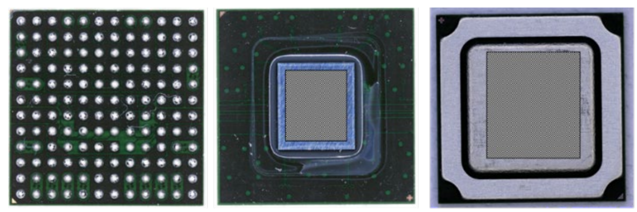

Figure 6. (a) Bottom view of the flip chip BGA package (b) Top view of the package without lid (c) Top view of the package with lid

As previously mentioned, a significant portion of this effort utilized the Sun et al. [4] approach in modeling. Similar to their effort, material properties as well as other dimensional details of the package utilized in this effort are as shown in Table 2.

Table 2. Package & Material Details in this Research

Material layers	Length × Width	Thickness	Young's modulus	Poisson's ratio	CTE	T_g
Unit	(mm)		(GPa)	-	(ppm/°C)	(°C)
Die	3.89 × 4.43	0.3	131	0.3	2.6	-
PCB	15 × 15	0.5	242	0.11	19.60	
Solder joints	Φ 0.45	pitch 0.8	416	0.35	21.70	
Substrate	10 × 10	0.34	23	0.3	15	
Thermal interface material	3.89 × 4.43	0.12	0.163	0.3	1.92	
Under fill + bump	5.5 × 5.5	0.08	17.41 @ -55 °C, 14.68 @ 225°C	0.35	26.58 ($T<T_g$), 60.84 ($T>T_g$)	88

An underfill with micro bumps and a substrate with pre-preg layers are treated as composite materials and their material properties are included in Table 2. These are effective material properties calculated by using CLPT equations. Details of these can be found in Bajad [9] Figure 7 shows the cross section of the lidded package which exposes the composite layers such as substrate with pre–preg and underfill and microbumps under die. And Figure 8 provides a front view of a 3D, unlidded model of the package. This simulation is performed under thermal loading condition as per JESD22-A104D standards, with a ramp rate of 11.33°C/min, one thermal cycle from -40°C to 125°C /hour, and the stress-free temperature is 22°C.

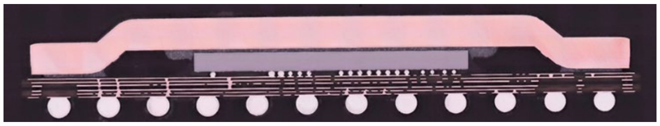

Figure 7. Cross section of the lidded package without PCB shows composite layer of underfill- micro bumps and substrate

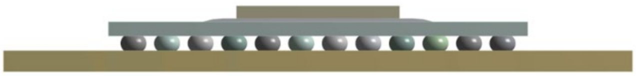

Figure 8. Front view of cross section of 3D model of package used in experiment

The meshed model is shown in Figure 9. Figure 10 shows the deformation measured in µm of the entire package at 125° C that considered for mesh sensitivity analysis. The mesh sensitivity plot in Figure 11 shows that as element size decreases, results do stabilize but computational time increases. After the mesh sensitivity analysis was conducted, the element size was fixed as 125µm for the remaining parametric analyses of the experiment.

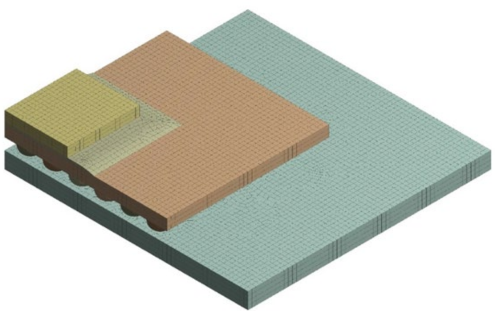

Figure 9. Meshed model of the package

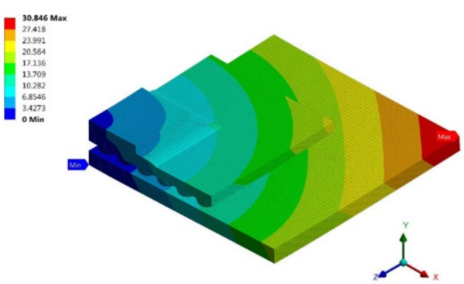

Figure 10. Deformation (µm) for mesh sensitivity study

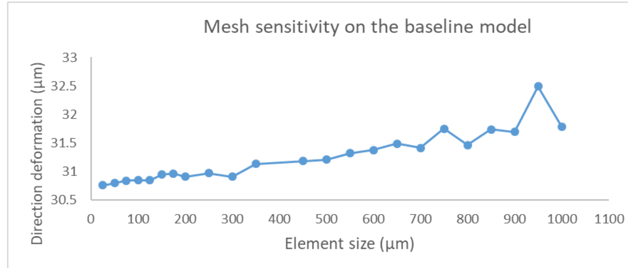

Figure 11. Meshed sensitivity on baseline model

In our DOE, we studied three different shapes for the lid design as shown in Figure 12.

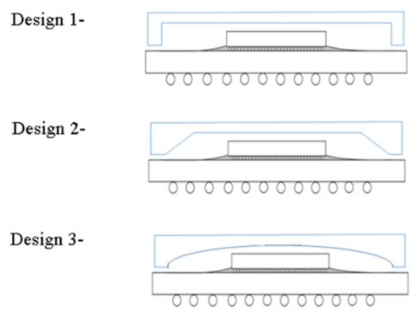

Figure 12. Three (3) different lid designs in the study

Furthermore, we studied six different sets of materials considered for the lid. The material properties are shown in Table 3.

Table 3. Six (6) material properties for lid construction

Material #	Young's modulus	Poisson's ratio	Coefficient of thermal expansion
Unit	(GPa)	-	(ppm/°C)
Material 1	129	0.34	17
Material 2	71	0.33	23
Material 3	45	0.35	26
Material 4	193	0.31	17
Material 5	13 in plane, 11 out plane	0.3	8 in plane, 42 out plane
Material 6	118	0.345	17.7

To be described in the following section, FEA simulations were carried out for all 18 (3*6) lid-design x lid-material configurations. The material properties that are known to vary across the 6 materials include Young's modulus, Poisson's ratio and coefficient of thermal expansion. Among the, the young's modulus varied the most from 11 GPa in the lowest case to 193 GPa in the highest. The CTE data varied within an order of magnitude between the best and worst cases. Assuming that the loading on the package lid leads to an induced warpage that is within the elastic region, these predictions are reliable. A mesh sensitivity study showed that computational time could be optimized and a mesh size / parameter of '125µm' was selected such that any further reduction in mesh size would lead to almost no change in the warpage prediction.

RESULTS

As mentioned in the Research Objective section, we are studying proposed designs. As such, we do not have the ability to measure warpage of actual packages. Thus, this study will compare warpage using analytical methods and the FEA results.

The analytical model of the CLPT three-layer package consists of the die, underfill and microbumps, and the substrate layer. FEA simulation is performed using these three layers and the value of warpage along the X-direction is obtained. Figure 13 shows the meshed quarter model and illustrates the three layers.

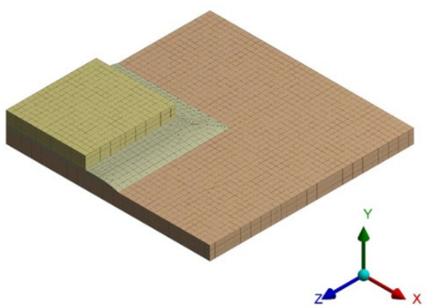

Figure 13. Isometric view of meshed quarter model of package considering three layers before solder and reflowing process

The details of the symmetry and boundary conditions are found in Bajad [9]. Figure 14 provides the correlated FEA results of the warpage in the X-direction. Since the package is approximately symmetric, the warpage in the Z-direction is expected to be similar.

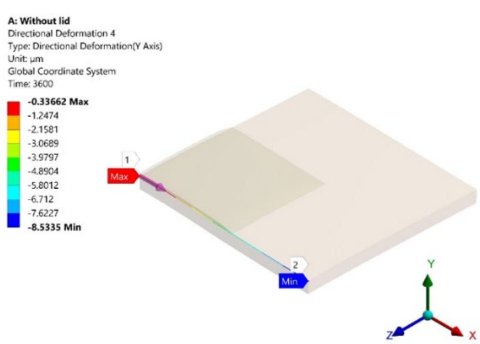

Figure 14. Warpage measured (µm) along the mid plane of the package in the X-direction

Figure 15 shows that analytical results (CLPT and modified Suhir approach) provide a fall-off shaped curve in which the effect of CTE of underfill material is considered insensitive to stresses and neglected due overall to small thickness of the underfill layer. Whereas, the FEA result provides an s-shaped curve which seems more accurate as it considers the effect of the underfill.

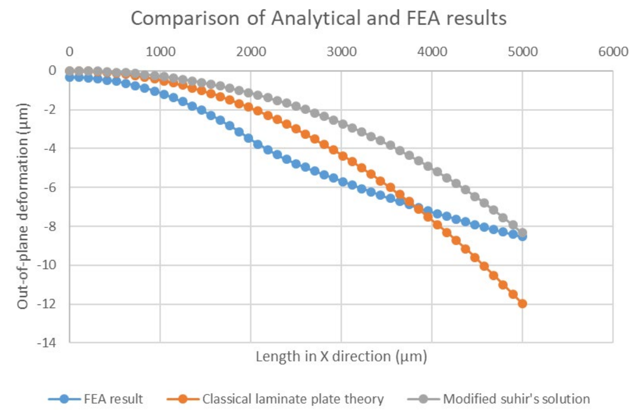

Figure 15. Warpage Comparison: CLPT, modified Suhir, and FEA

In this curve, it is also evident that in classical laminate plate theory that assumes radius of curvature is constant with respect to Kirchoff-Love hypothesis. This hypothesis is used to determine stress and deformation of thin layers when those are subjected to force and moment. The assumptions of this hypothesis that are the thickness of the layer is constant during deformation and straight lines normal to mid surface remains normal and straight after the deformation. This leads to more error in calculating response in terms of warpage. Due to this error, the classical laminate plate theory over-predicts the out-of-plane deformation by 40%. This highlights the substantially higher accuracy of FEA method that is presented in this work.

DOE Analysis

Maximum warpage values on the lid of the 18 configurations are presented in Table 4.

Table 4. Maximum lid warpage values (µm) at 125ºC

	Design 1	Design 2	Design 3
Material 1	10.610	10.362	5.357
Material 2	8.964	8.908	4.898
Material 3	9.295	9.437	-7.595
Material 4	10.128	9.881	4.894
Material 5	26.143	26.220	24.691
Material 6	9.851	9.579	4.629

A two-way analysis of variance (ANOVA) is performed to understand if there is any interaction between two independent parameters (material and design) on the dependent variable (warpage). For this analysis, the null hypothesis for a main effect is that the warpage means for all factor levels are equal and an interaction effect is that the warpage mean for the level of material factor does not depend on the value of the other levels of design factor. More details on the analysis of the DOE results, e.g., verifying normality of the residuals to support the ANOVA approach, are provide by Bajad [9].

The ANOVA results are shown in Figure 16. Since the p-value is less than the significance level (0.05), this indicates that the level of material and design factor, both, are significant main effects for lid warpage.

Factor Information

Factor	Type	Levels	Values
Material	Fixed	6	1, 2, 3, 4, 5, 6
Design	Fixed	3	1, 2, 3

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	5	896.81	179.362	18.39	0.000
Design	2	158.92	79.462	8.15	0.008
Error	10	97.53	9.753		
Total	17	1153.26			

Figure 16. ANOVA results

In addition to two-way ANOVA, the DOE is performed using a general full factorial analysis. This analysis considers the interaction between the material and design parameters and results in missing values of p and F. This is due to the use of a 2-level design with one replicate, including all the terms in the model. To remedy this situation, the model is re-fit neglecting the interaction term between the material and design factors. The Pareto chart in Figure 17 shows that the interaction between material and design parameter is not significant.

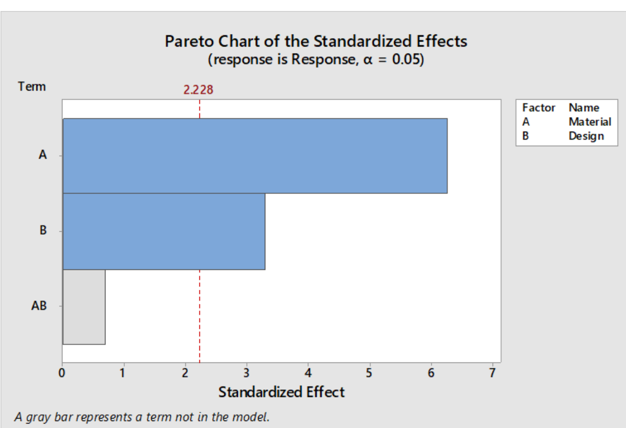

Figure 17. Pareto chart highlighting the significance of the material and design parameter

If the material parameter is compared with design then it indicates that the material parameter is more significant than the design parameter. The interaction plot between material and design parameter in Figure 18 shows near parallelism. This supports the assumption of an absence of interaction between two parameters.

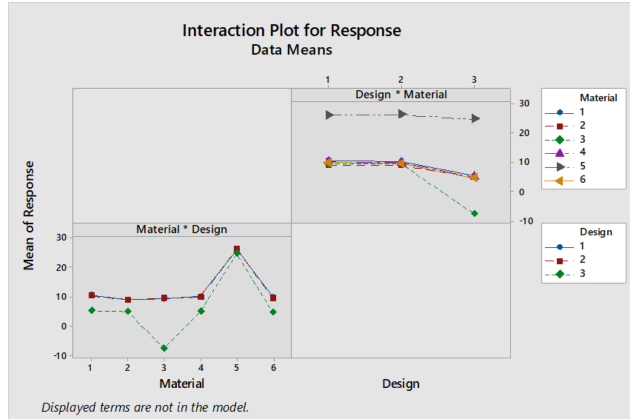

Figure 18. Interaction plot considering all the simulation cases for DOE

The main effects plot with warpage in Figure 19 shows that Material 5 has the highest response value where Design 3 has the lowest. This might be interpreted as the Design 3 shape causes the minimum warpage and Material 5 is more elastic in nature and gives maximum warpage. It is difficult to predict the plastic/permanent damage considering only elastic behavior of the material. It can be interpreted from the main effects plot that since the curvature of the lid is smoother, then the deformation is minimum.

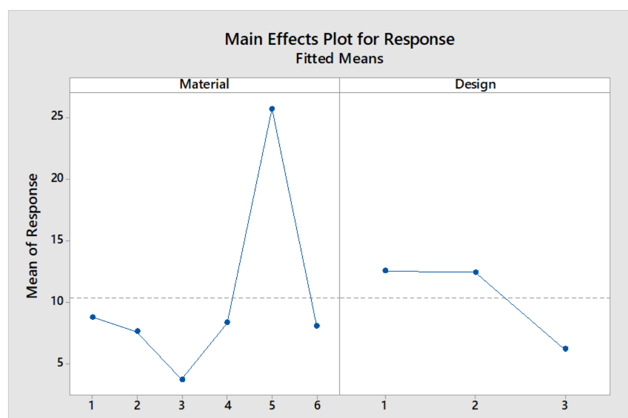

Figure 19. Main effects plot of the two parameters individually with respect to mean of response

CONCLUSIONS

After applying both analytical methods successfully on three layer assembly of the package and comparing it with FEA simulation, FEA results seems more accurate. Assumption made based on the literature survey are correct. The DOE analysis shows that there is no significant interaction between the two independent variables considered such as material of the lid and design of the lid. If results are analyzed considering only the lid design variable, then it might be said that, as the curvature of the lid becomes smooth, warpage deformation reduces.

It is also observed that type of material plays a more significant role in warpage deformation of the lid than the shape of the lid. In this simulation study, elastic material properties considered for the package such as Young's modulus, Poisson's ratio and CTE. Out of these three material properties, CTE should be more compliant to other layers in the package in order to reduce warpage. Experimental procedures to measure warpage may prove more accurate than analytical and numerical methods when actual prototypes are developed, since ultimate strength and plastic behavior of the material will be tested while thermal loading conditions are applied. However, as thermal loading will be accelerated, plastic deformations due to fatigue and creep will account more accurately for reliability in real life conditions. This is difficult to achieve by FEA tools or analytical tools. So experimental procedure of measuring this parametric study is important in future work to gain more accurate predictions.

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