Optimization of Stacked Die Design on Stacked Die QFN Package by Simulation Approach

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Abstract **In semiconductor industry, the technology of stacking dies into a package become popular without much consideration of potential reliability issues. However, Finite Element Method has been introduced to semiconductor industry to minimize the experimental cost and times. In this paper, Finite Element Method and statistical analyses are used to optimize the design parameter of stacked die. Birth and death element options are used to determine the die shear stress for manufacturing process. The die shear stress results after the fully processes are used for statistical analysis. Six factors are used in this study to identify the optimal design. It is suggested that, numerical simulation combining with Taguchi Method statistical analyses can be useful tool for optimization of stacked die design parameter.**

I. Introduction

Semiconductor industry is driving towards miniaturization, multifunctional and high density packages especially for portable electronic devices. The historical development of IC packaging also showed this obvious trend and the strength of the competition is indicated by their focus toward miniaturization [1-4].

The demand of miniaturized IC packages by customers also forced this trend and it is shown in reduced weight and small package size. Fig. 1 shows the trend of IC packaging over time. The trend clearly shows that the size and weight reduction is the main important features.

Conventional QFN which is from CSP family [5] comprises of silicon die, lead frame, mold compound and die attach paste [6]. For designing stage, reliability issue is very important due to the demand of manufacturing industry that very emphasizes the quality of the product. Other requirements from industry are good electrical performance, small size and have a low cost product [7].

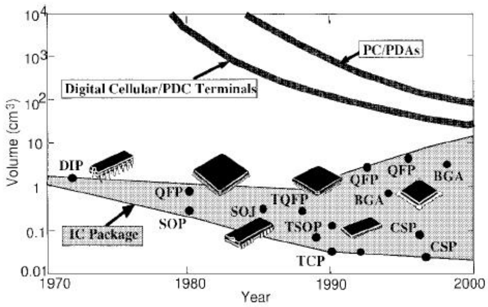

Fig. 1 Trend of miniaturization of IC package

Package development cycle usually includes design, build test and redesign steps if the design fail to full fill the specification. The test step includes electrical and reliability test. The latter is very costly due to the need of expensive test equipment and highly skilled manpower for data analysis and also damage the sample. The final design cycle usually takes about 3-4 month [8]. This design works becomes even more complicated and risky with the stacked die design.

One option that shows high potential to reduced development cycle is by using FEA method. Finite element modelling is widely used in semiconductor field as an analysis tool for reliability study [9-11]. It is also established as an effective tool for thermo mechanical reliability assessment of electronic assemblies. Finite element also was used to determine the time dependent fatigue response of a chip scale package under accelerated temperature cycling condition. Simulation technique was chosen for the analysis because the process of thermal cycling test is time consuming and costly and that finite element analysis help to reduce cost of experiments, development and experimental time [13].

In many industries, optimization is used to get the best solution for manufacturing process, condition, designing, material selection and many more to maximize the yield. One of the optimization choices is by using Taguchi Method by Dr. Genichi Taguchi [14-16]. This method has greatly improves the engineering productivity by consciously considering the noise factor. It focuses on improving the fundamental function of the product or process, thus facilitating flexible designs and concurrent engineering. This method also called as a Robust Design and if we recognized how variation in the environment and internal deterioration degrade reliability, it offers a new exciting way to "build reliability in" rather than depend on maintenance to assure reliability [17]

II. Materials And Methods

In this paper, different stacked die design for QFN packages are modelled by using FEA. Taguchi Method statistical analysis was used in this paper to analyze the data. This method is to seek the best factors or levels combination with lowest societal cost solution to achieve customer satisfaction. However, the Taguchi Method alone can only be used to optimize the single-response problem; it cannot be used to optimize the multi response problem. For this paper, Taguchi Method combining with Desirability Function was proposed to effectively optimize the multi responses problem.

III. Finite Element Analysis Of Stacked Die QFN Package

Quarter model for three-dimensional stacked die QFN package were build. The unit package sizes were set at 7x7x0.85mm3 with 48 leads at the bottom of the package. Top and bottom die dimensions were selected as a factor to vary for two levels. The models were developed contains four main components which are lead frame, mold compound, die and epoxy.

During the pre-processing phase in FEA, material properties for each materials involved in this package were defined. Table 1-4 shows the material properties for each material. Finite element analysis thermo-mechanical stresses were carried out with a reference temperature or zero stress temperature set at 175ºC (the curing temperature).

The next step is automatic mesh generation. After the models were completely built, an automatic mesh computer generated was applied to the model. This important step was done as a description for the input data. Fig. 2 shows a quarter model for QFN package without mold compound for better visualization that has been completely meshed.

Temperature (ºC)	Young's Modulus (GPa)	Poisson's Ratio
-73	188.4	0.2786
27	187.3	0.2783
127	186.0	0.2781
227	184.5	0.2778
345	184.5	0.2778

Table 3 Material properties for Silicon Die

Temperature (ºC)	Young's Modulus (GPa)	Poisson's Ratio
-65	7.5	0.35
25	7.5	0.35
250	0.34	0.35
260	0.34	0.35

Table 4 Material properties for Epoxy

Temperature (ºC)	Young's Modulus (GPa)	Poisson's Ratio
-65	28	0.3
25	28	0.3
240	0.8	0.3
260	0.8	0.3

Table 5 Material properties for Mold Compound

Temperature (ºC)	Young's Modulus (GPa)	Poisson's Ratio
25	128.9	0.34

Table 3 Material properties for Lead Frame

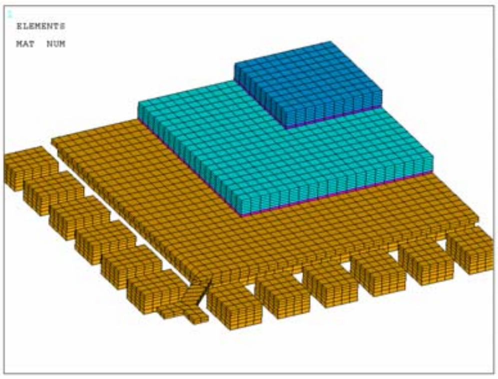

Fig. 2 Meshed Quarter Model for QFN Package

Another step consist in pre-processing phase is boundary condition and loading. The boundary condition defined for this model is shown in Fig. 3 and Fig. 4. Fig. 3 shows the symmetrical boundary condition was defined for XZ Plane and YZ Plane. Due to the symmetrical geometry model, both the XZ Plane = 0 and YZ Plane = 0 were set as symmetry boundary condition area. Fig. 4 shows the nodes at the bottom area of the lead frame were defined as 0 for Degrees of Freedom. The area was set as 0 for displacement for any axis means the lead frame is assumed fix.

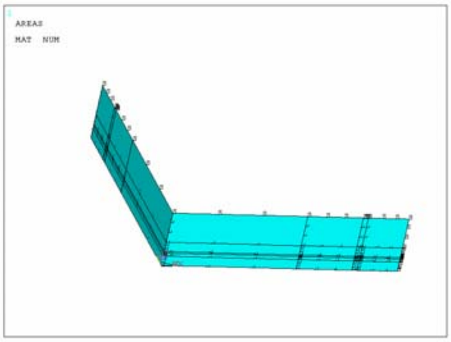

Fig. 3 : Symmetrical boundary condition

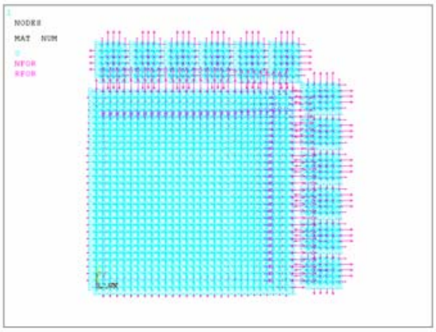

Fig. 4: Fix displacement boundary condition

Birth and death element option was used as input file to simulate the manufacturing process. In finite element analysis, the developments of stacked die QFN package processes were assumed have 6 main processes. The first process is Bottom Die Attach with curing temperature is 175ºC and followed by 25ºC for Cool to Room Temperature after bottom die attach process. The next process is Top Die attach with the same curing temperature and Cool Down Temperature for bottom die process. Then the processes were continued with Heating Die to The Glass Transition Temperature which is 175ºC. Post mold cure (PMC) process was then simulated at 175ºC when mold compound was added to the package. The final process was defined as complete package at room temperature, 25ºC. For this study, the final process was selected to be analyzed as the area of concern due to the complete package development.

After the solution phase was completely run, the post processing phase was selected to obtain important information. For this case study, we may be interested in values of plane shear stresses and 1st principal stresses. All the results obtained were then analyzed by Taguchi Method to get the optimized design for stacked die QFN package.

IV. TAGUCHI METHOD AND DESIRABILITY FUNCTION

Table 5 below shows the control factor for stacked die design. These are bottom die area, bottom die thickness, bottom epoxy thickness, top die area, top die thickness and top epoxy thickness. The two level Taguchi L8 orthogonal arrays with these control factors is shown in Table 6.

In this case study, the responses or each run were obtained from the results of simulation. The result simulation that is significant with this case were top die shear stress, top die 1st principal stress, bottom die shear stress and bottom die 1st principal stress. Taguchi Method alone cannot solve the multi purpose response problem. Thus, in our case, combination of Taguchi Method and Desirability Function were used to get the solution.

The stress results of the simulations were obtained to be analyzed by Taguchi Method and Desirability function. As mentioned above, for responses for each run were used to get the optimized design.

	Control Factors	Level 1	Level 2
1	Bottom Die Thickness	0.15mm	0.25mm
2	Bottom Die Area	4x4 mm^2	5.08x5.08 mm^2
3	Bottom Epoxy Thickness	1 mil	1.2 mil
4	Top Die Thickness	0.15mm	0.25mm
5	Top Die Area	2x2 mm^2	3.3x3.3 mm^2
6	Top Epoxy Thickness	1 mil	1.2 mil

Table 5: Control factors for stacked die design

RUN	Control Factors					
	Bottom Die Thickness	Bottom Die Area	Bottom Epoxy Thickness	Top Die Thickness	Top Die Area	Top Epoxy Thickness
1	1	1	1	1	1	1
2	1	1	1	2	2	2
3	1	2	2	1	1	2
4	1	2	2	2	2	1
5	2	1	2	1	1	1
6	2	1	2	2	2	2
7	2	2	1	1	1	2
8	2	2	1	2	2	1

Table 6 : Taguchi L8 Orthogonal Array

RUN	Control Factors					
	BDT (mm)	BDA (mm^2)	BET mil	TDT (mm)	TDA (mm^2)	TET mil
1	0.15	4x4	1	0.15	2x2	1
2	0.15	4x4	1	0.25	3.3x 3.3	1.2
3	0.15	5.08x 5.08	1.2	0.15	2x2	1.2
4	0.15	5.08x 5.08	1.2	0.25	3.3x3.3	1
5	0.25	4x4	1.2	0.15	3.3x3.3	1
6	0.25	4x4	1.2	0.25	2x2	1.2
7	0.25	5.08x 5.08	1	0.15	3.3x3.3	1.2
8	0.25	5.08x 5.08	1	0.25	2x2	1

Table 7 : Taguchi L8 Orthogonal Array with control

The target value for each response of stresses is set to be the *smaller- the- better* which is defined as -10*log*[*MSD*]. In which *MSD* = 1/n y^2 is means square deviation, y is measured response and n is the number of measurements. Meanwhile, desirability function is an objective function that ranges from zero outside of the limits to one at the goal. The numerical optimization finds a point that maximizes the desirability function. The characteristic of a goal may be altered by adjusting the weight or importance. For several responses and factors, all goals get combined into one desirability function. The simultaneous function is a geometric mean of all transformed responses:

$$D = (d_1 x d_2 x....x d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}}$$

where n is the number of responses in the measure. If any of the responses or factors falls outside their desirability range, the overall function becomes zero. For simultaneous optimization each response must have a low and high value assigned to each goal. By computer aided statistical analysis software, the "Goal" field for responses must be one of five choices "none", "maximum", "minimum", "target", or in "range". Factors were included in the optimization.

V. Results And Discussions

Die shear stress and 1st principal stress for top and bottom die each run were analyzed by Taguchi method and desirability function. Results of simulation are shown by Table 8.

For bottom die shear stress response, the half normal plot is shown as Fig. 5. From Taguchi Method, four factors that are significant with the model are bottom die area top epoxy die area and interaction between bottom die thickness and top epoxy thickness. Value for Pred-R-Squared is 0.9934. Fig. 6 shows output of One Factor Plot for bottom die area. All the response's significant factors and pred R –Squared are summarized in Table 9.

The optimal design is shown in Table 10. The response can be predicted by this method. The optimal design suggested by the software was then used in FEA simulation and the results are compared. Table 11 shows the comparison between the predicted stresses result by Taguchi Method combined with Desirability Function and stresses results by FEA simulation. From the table, we can see that the percentage of error for bottom die shear stress, bottom die 1st principal stress, top die shear stress and top die 1st principal stress are 0.63 %, 1.9%, 7%, and 0.22% respectively. All the percentage errors are less than 10% and considered small. The desirability function for this model is 0.746

Run	Bot Die Shear Stress	Bot. Die 1st Prin. Stress	Top Die Shear Stress	Top Die Shear Stress	Top Die 1st Prin. Stress
1	25.2	108	49.2	102.0	25.2
2	26.1	111	35.1	136.0	26.1
3	32.8	111	47.9	98.9	32.8
4	25.8	116	32.3	127.0	25.8
5	31.6	113	31.6	130.0	31.6
6	23.7	111	27.6	120.0	23.7
7	30.4	110	45.2	110.0	30.4
8	22.3	109	44.2	97.9	22.3

Table 8. Die Stress Result for Each Run

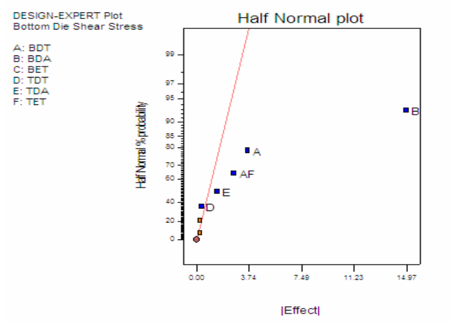

Fig. 5. Half Normal Plot Graph for Bottom Die Shear

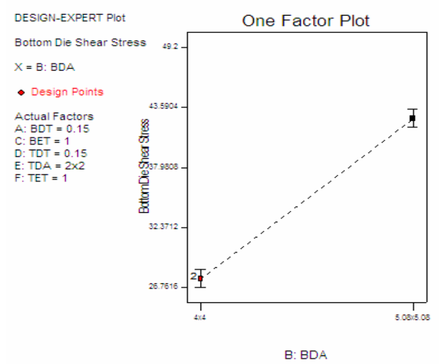

Fig. 6 One factor plot for Bottom Die Area

DIE STRESS	Significant factors	Prd-R^2
Bot. Die Shear Stress	BDA, TDA, Interaction BDT/TET	0.9934
Bot. Die 1st Prin. Stress	BDA, Interaction BDT/TET	0.9755
Top Die Shear Stress	BDT, TET	0.7879
Top Die 1st Prin. Stress	BDA, TET	0.6735

Table 9: Summary of die stress analysis

DIMENSION	VALUE
Bottom Die Thickness	0.15mm
Bottom Die Area	$4x4mm^2$
Bottom Epoxy Thickness	1mil
Top Die Thickness	0.25mm
Top Die Area	$2x2mm^2$
Top Epoxy Thickness	1mil

Table 10: Optimal design stacked die

DIE STRESS	TAGUCHI'S	FEA	ERR.
Bot. Die Shear Stress	27.975	27.8	0.63%
Bot. Die 1st Prin. Stress	111. 725	120	1.9%
Top Die Shear Stress	21.625	23.3	7%
Top Die 1st Prin. Stress	110.75	111	0.22%

Table 11: Taguchi's Method and FEA Comparison

From the analysis, it is shown that there are some interactions on the significant factors. Another FEA run is done by assuming the interaction is not significant with the model. A new optimal design stacked die by neglecting the interaction factors is summarized in table 12. The predicted responses and the real FEA result is shown in table 13. The percentages of error for the responses are 7.9%, 2.2%, 2.7%, and 4.5%. The desirability function for this model is 0.671

DIMENSION	VALUE
Bottom Die Thickness	0.15mm
Bottom Die Area	$5.08x5.08mm^2$
Bottom Epoxy Thickness	1mil
Top Die Thickness	0.25mm
Top Die Area	$2x2mm^2$
Top Epoxy Thickness	1mil

DIE STRESS	TAGUCHI'S	FEA	ERR.
Bot. Die Shear Stress	21.625	23.5	7.9%
Bot. Die 1st Prin. Stress	107.5	109.9	2.2%
Top Die Shear Stress	44.625	45.9	2.7%
Top Die 1st Prin. Stress	102.2	107	4.5%

Comparing between two results, the percentages of error for the latter model are larger than the first model. The desirability function for the first model is better than the second model. From this comparison, the first model gives more close prediction responses due to the significant interaction for the model. Thus, it is suggested the first model for the optimal design stacked die for Stacked Die QFN package.

VI. Conclusion

In this research, Taguchi matrix has been developed to determine the optimal stacked die design. Desirability function was used to solve the multi response problem in Taguchi Method. Comparison between model with considered interaction and model not considered the interaction gave different results. From the results, it is shown that the model without considering interaction gave higher error than the other model. It can be concluded that the interaction between bottom die thickness and top epoxy thickness are significant influence the stress of the package. As a result, an optimal design with minimum level for all factors selected except top die thickness was suggested by this method. In addition to that, the significant factors that influence the die stress were analyzed to get the optimal design. This study has demonstrated that Finite Element Analysis simulation combined with the Taguchi Method and Desirability Function can be a useful tool for the optimization of the stacked die design.

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References

[1] I. Anjoh, A. Nishimura, and S. Eguchi, "Advanced IC Packaging for the Future Applications," *IEEE Transactions on Electronic Devices*, vol. 45, no. 3, pp. 743-752 (1998)

[2] J.H. Lau, "Electronics Packaging Technology Update: BGA, CSP, DCA, and Flip Chip," *1997 IEMT/IMC Proceedings*, pp. 32-36 (1997)

[3] T.A.C.M Claasen, "System On a Chip: Changing IC Design Today and in The Future ,"*IEEE Computer Society*, pp. 20-26 (2003)

[4] G. Kuhnlein, "A Design and Manufacturing Solution for High Reliable non-leaded CSP's like QFN," *Electronic Components and Technology Conference.*

[5] T.Y.Tee, H.S. Ng, and J.L Diot, "Comprehensive Design Analysis of QFN and Power QFN Packages for Enhanced Board Level Solder Joint Reliability," *2002 Electronic Components and Technology Conference*, pp. 985-991 (2002)

[6] D.G. Yang, K.M.B Jansen, L.J Earnst, G.Q Zhang, W.D.V Driel, H.J.L. Bressers and J.H.J Janssen, "Numerical Modeling of Warpage Induced in QFN Array Molding Process,"

Microelectronics Reliabilit, vol. 47. pp. 310-318 (2007)

[7] K.B. Unchuwaniwala and M.F. Caggiano, "Electrical Analysis of IC Packaging with Emphasis on Different Ball Grid Array Packages," *2001 Electronic Components and Technology Conference* (2001)

[8] Tee, T.Y., Ng, H.S., Luan, J.E., Zhang, X., Goh, K.Y., Grech, A.M. & Duca, R. 2005, 4-Dimensional Design Analysis and Optimization of System-in-Package. 2005 Electronics Packaging Technology Conference.

[9] C.C. Ng and G. Govindasamy, "Thermal Simulation and Transient CFD Analysis of Stacked DIE QFN Package," *5th ASEAN ANSYS User Conference 2005,* pp. 179-186 (2005)

[10] X. Zhang and T.Y. Tee, "Advanced Warpage Prediction Methodology for Matrix Stacked Die BGA during Assembly Processes," *2004 Electronic Components and Technology Conference,* pp. 593-399 (2004)

[11] C.L. Yeh and Y.S Lai, "Transient Simulation of Solder Joint Fracturing Under Impact Test," *2004 Electronics Packaging Technology Conference,* pp. 689-694 (2004)

[12] S.G. Jagarkal, M.M Hossain and D. Agonafer, "Design Optimization and Reliability of PWB Level Electronic Package," *2004 Inter Society Conference on Thermal Phenomena*, pp. 368-376

[13] B.A. Zahn, " Impact of Ball Via Configurations on Solder Joint Reliability in Tape Based Chip Scale Package," *2002 Electronics Components and Technology,* pp. 1475-1483

[14] R.K. Roy, " Design of Experiments Using The Taguchi Approach" *John Wiley & Sons Inc* (2001)

[15] D.C. Montgomery, " Design and Analysis of Experiments," *John Wiley & Sons Inc* (2001)

[16] G.S Peace, "Taguchi Methods: A Hands On Approach," *Addison- Wesley Publishing Company*

[17] R.G. Batson and M.E. Elam, "Robust Design : An- Experiment- Based Approach to Design for Reliability," *Maintenance and Reliability Conference (MARCON)*,2002