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Application of the Axiomatic Design Methodology to the Design of PBGA Package with Polyimide Coating Layer

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The purposes of the paper are to apply the axiomatic design methodology to the design of PBGA package with polyimide coating under hygrothermal loading in the IR soldering process and to suggest more reliable design conditions by stress analysis. The analysis model is a 256-pin perimeter Plastic Ball Grid Array (PBGA) package with the polyimide coating surrounding chip and above surface of BT-substrate. The polyimide coating is suggested to depress the maximum stresses occurred on the stress concentration positions. The axiomatic design methodology is proved to be useful to find the more reliable design conditions for PBGA package. Finally, the optimal values of design variables to depress the stress in the PBGA package are obtained.

Key Words : BGA Package, IR Soldering, Axiomatic Design, Polyimide Coating, Stress

1. Introduction

BGA package is used very much in the electronic devices due to many advantages, such as higher pin count, smaller size, lower switching noise, larger pitch and higher assembly yield etc.. But, potential package reliability problems can still occur such as the delamination between each part, cracking in the each layer, moisture absorption, excessive solder joint deformation due to substrate warpage, large variation in solder ball size and solder ball failure (Moore and Jarvis, 2001 ; Jung et al., 1997).

BGA packages usually have those reliability problems in IR soldering process and various cyclic thermal shock testing (Hwang, 1994 ; Hong and Su, 1998). Therefore, the structural analysis has been needed to prevent the failure of IC package and many works are accumulated.

Jung et al. (1997) applied a detailed nonlinear finite element analysis to study the thermal cyclic response of solder joints in two BGA packages as a full-matrix and a perimeter with considering time-independent plasticity and time-dependent effect, and presented the locations of critical solder joint to be most susceptible to fatigue failure. Mawer et al. (1993) obtained thermal fatigue life of the plastic BGA package by thermal shock tests and three-dimensional linear elastic as well as one-dimensional nonlinear finite element simulations, and found that solder joint diameter, height and chip size are the important factors to fatigue life of solder joints. Ahn and Kwon (1995) investigated the popcorn phenomena in a PBGA package under the preconditioning test conditions and IR soldering process through finite element method and experimental tests using scanning acoustic tomography and optical microscopy, and finally proved that

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new types of substrates with open thermal via-holes can prevent popcorn cracking. McCluskey et al. (1996) examined the popcorn cracking phenomenon and presented the results that the crack occurred from the die-attach region is propagated into the dielectric region. Egan et al. (1999) obtained the warpage in chip-scale (CSP) and plastic ball grid array (PBGA) packages by measuring two curvatures and compared the results with those from 3D numerical simulations. Aihara et al. (2001) tried to improve anti-solder crack performance on Fine Pitch BGA (FPBGA) and warpage on Mold Array Package-BGA (MAP- BGA), and presented the optimum combination of materials of molding compound and die attach paste.

Moore and Jarvis (2001) examined one of the common modes of structural failure in multi-chip BGA package, related the locations of failure to the stresses generated in the reliability tests, and determined the method to avoid this failure mechanism by using finite element simulations.

In general, the design of machines consists of conceptual and detailed design (Suh, 1990). The conceptual design has been carried out mainly with the designer's experiences, and a lot of time and expense are used. To save them, the axiomatic design methodology is proposed. By using the axiomatic design methodology in the conceptual design process, the machines can be designed logically and the detailed design can be carried out independently and successively. Gunasekera and Ali (1995) applied the axiomatic design methodology to the conceptual design of metal forming process and present the results to reduce the time and effort necessary to achieve a workable solution. But, it can be applied to the detailed design, too. Shin et al. (2001) designed a motor-driven tilt/telescopic steering column by using the axiomatic design methodology, which is applied from the conceptual design to the detailed design to improve safety and vibration performance. But, the application of the axiomatic design methodology to the IC package has not been done yet.

However, the package model with polyimide coating has been shown to reduce the stress and the possibility of failure in IC package (Yang et al., 2004 ; Lee and Yang., 1999 ; Romer and Pape, 1989 ; Takeuchi et al., 1990 ; Omi et al., 1991). Romer et al. (1989) showed that the compressive stress increases as the thickness of polyimide coating increases. Takuechi et al. (1990) presented the experimental results that the coating of various polyimides on the upper surface of IC chip has a good adhesion property and can suppress the occurrence of package cracks. Omi et al. (1991) reported that the polyimide coating on the backside of the diepad can depress the crack at the corner of diepad.

Until now, no researches have been done to apply the axiomatic design methodology to the IC package with polyimide coating. Therefore, in this paper, we apply the axiomatic design methodology for the detailed design of plastic ball grid array (PBGA) package under IR soldering process, and show the effect of polyimide coating on the stress in the package. Finally, we present the values of design parameters to decrease the stress in the package with polyimide coating through the axiomatic design, and show its availability by discussing the result.

2. Temperature and Thermal Stress Analysis

The package is 256-pin perimeter PBGA package as shown in Fig. 1. The silicon chip is mounted on BT (Bismaleimide-triazine) resin and encapsulated with EMC (epoxy molding compound). Then BT resin is soldered to FR 4 PCB. The software used for the finite element analysis is ABAQUS (ABAQUS User's Manual). The element used to obtain the temperature distribution is a two-dimensional quadrilateral isoparametric and stress analysis is done under a two-dimensional plain strain condition. These are due to the reports (Moore and Jarvis, 2001 ; Kelly, 1999) that the result of stress analysis with a 2-D plain strain model for PBGA package is approximate to that with a 3-D model.

The 2-D FE model is composed of half the package because it is symmetric. The quadratic shape function is used. The numbers of elements

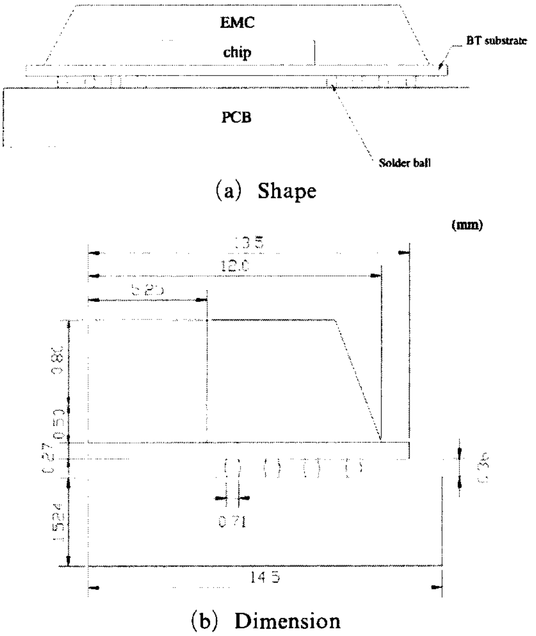


Fig. 1 Schematics of 256-pin PBGA-P package

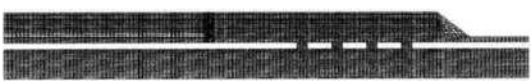


Fig. 2 FE model of PBGA-P package

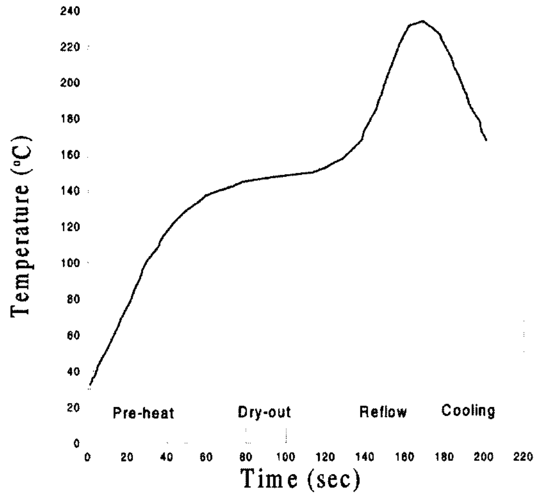


Fig. 3 Temperature profiles at boundary surfaces of PBGA package during reflow soldering process

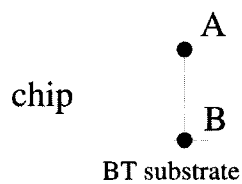


Fig. 4 Stress concentration positions

and nodes are 4594 and 14374, respectively, which are shown to be enough for the numerical accuracy. The FE meshes are identical for the calculations of the temperature and stress distributions as shown in Fig. 2.

During the reflow soldering process, the changes of the temperature at the boundary of the package are shown in Fig. 3 (Pecht, 1999). By using the temperature profiles at the boundary surfaces of the package, the temperature distribution in the whole package is obtained by the FE analysis. In the calculation for the temperature distribution, it is assumed to be an adiabatic condition on the symmetric surface.

Material properties for temperature and stress analyses are shown in Table 1, where α_1 and α_2 are the coefficients of thermal expansion (CTE) below and above glass transition temperature, Tg, respectively. The temperature distribution of each node at the instant becomes the input data for calculating the thermal stress in the package. The stress free temperature is assumed 170℃, which is the molding temperature of the IC package. The boundary conditions for stress analysis are that the symmetric surface is fixed in the x-direction and the bottom surface of PCB is fixed in the y-directions.

After obtaining the thermal stresses on the whole locations in the package, the locations at which von-Mises stress is very high are shown in Fig. 4 and the values are presented in Table 2. The number of elements is selected relevantly with observing the convergence of stress values by doing the analysis with the variation of the number of elements. Table 2 shows that the stress is very higher than strength.

To know the effect of the polyimide coating on the stress in the package, we set up two model cases as shown in Fig. 5. The thickness of polyimide coating layer is 0.08 mm. With comparing the von-Mises stress, it is found that the stress

Table 1 Material properties of IC package

	EMC	Chip (Si)	Adhesive (Ag-epoxy)	BT substrate	Solder Ball (63Sn/37Pb)	PCB (FR-4)	polyimide (PMDA-ODA)
Specific heat (J/kg ℃)	1050	699	0.234	920.9	1050	1369	1100
Conductivity coefficient (W/m ℃)	0.735	148	374	0.17	0.245	0.35	0.2
Density (kg/m^3)	1.9×10^3	2.33×10^3	1.05×10^4	1.9×10^3	1.9×10^3	1.666×10^3	1.42×10^3
Thermal expansion coefficient (/℃)	α_1 : 1.0×10^{-5} α_2 : 4.5×10^{-5}	0.26×10^{-5}	α_1 : 4.9×10^{-5} α_2 : 2.4×10^{-4}	1.5×10^{-5}	2.1×10^{-5}	1.8×10^{-5}	2.0×10^{-5}
Young's modulus (N/m^2)	2.45×10^{10} (25℃) 2.0×10^{10} (70℃) 1.0×10^{10} (150℃) 1.0×10^{9} (215℃)	1.88×10^{11}	1.2×10^9 (23℃)	2.6×10^{10}	2.0×10^{10}	2.2×10^{10}	3.5×10^9
Poisson's ratio	0.23	0.28	0.3	0.11	0.3	0.11	0.3
Glass transition temperature (℃)	133-145	•	36	Very high	•	•	385

Table 2 Comparison of von-Mises equivalent stress and strength

Location	Ultimate strength (MPa) [22]	von-Mises stress (MPa)	stress/ strength
A	128	673.0	5.26
B	128	1439.2	11.24

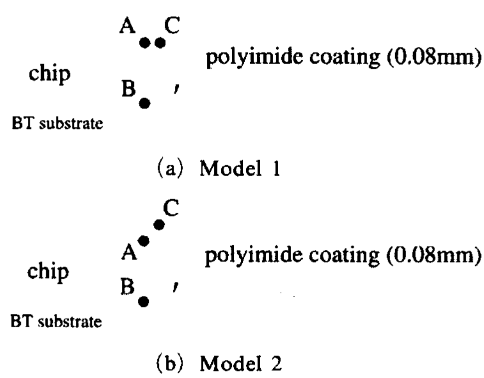


Fig. 5 Polyimide coating model

concentration positions are A, B, and C positions shown in Fig. 5 and the values are shown in Table 3 with those of the case without polyimide coating.

Table 3 shows that the stress values for the case with polyimide coating are smaller than those without polyimide coating except A positions in the polyimide coating model 1. In the research studied the properties of various polyimide coating and the effect of the coating on the crack occurrence and interface adhesion, Takeuchi et al.(1990) reported that high heat

Table 3 The ratio of von-Mises equivalent stress to strength in the polyimide coating model

Location	Ultimate strength (MPa) [22]	stress/strength		
		Without polyimide coating	Polyimide coating model 1	Polyimide coating model 2
A	128	5.26	6.08	2.09
B	128	11.24	4.66	4.59
C	102	•	2.30	3.24

resistance, high mechanical strength and stress relaxation property such as low elastic modulus are needed on the view point of stress relaxation and polyimide is most suitable. Therefore, our results that polyimide coating decreases the stress values seem to be reasonable. Table 3 also shows that model 2 is best.

3. The Application of the Axiomatic Design

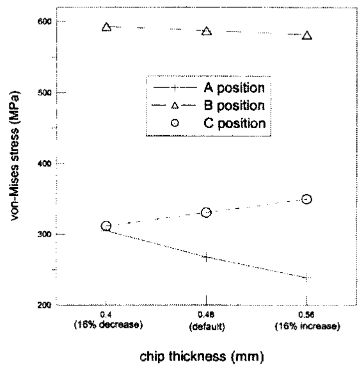
The axiomatic design approach consists of two axioms (Suh, 1990). Axiom 1 states that the FRs (functional requirements) in the functional domain go to the DPs (design parameters) in the physical domain during the design process. The mapping shows how a specific DP affects several FRs. Axiom 2 states that the one design with minimum information content is the best among all the designs satisfying axiom 1.

The relationships between DPs and FRs are expressed as

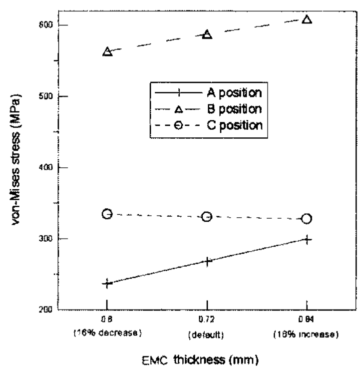
$$\{FRs\}=[A]\{DPs\} \quad (1)$$

where $\{FRs\}$ is the functional requirement vector, $\{DPs\}$ is the design parameter vector, and $[A]$ is the design matrix. For using the axiomatic design, the design matrix must be a diagonal or triangular one to satisfy the independence axiom.

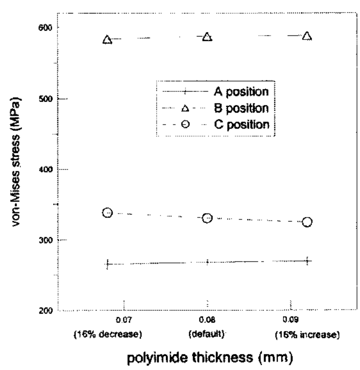
To get the design parameters affecting the stress values at the stress concentration positions in the BGA package with the polyimide coating, we examined the stress analysis for the package with the variation of dimensions such as chip thickness, EMC thickness and polyimide coating thickness. The results are shown in Fig. 6.



(a) von-Mises stress vs. chip thickness



(b) von-Mises stress vs. EMC thickness



(c) von-Mises stress vs. polyimide thickness

Fig. 6 Changes of von-Mises stress with the dimensions of several design parameters

From the above results, the design equation can be represented as follows :

$$\begin{Bmatrix} Stress\_A \\ Stress\_B \\ Stress\_C \end{Bmatrix} = \begin{bmatrix} X & X & O \\ O & X & O \\ X & O & X \end{bmatrix} \begin{Bmatrix} chip\ thickness \\ EMC\ thickness \\ polyimide\ thickness \end{Bmatrix} \quad (2)$$

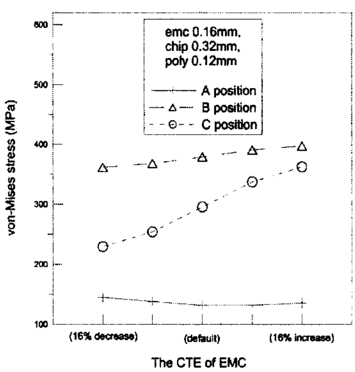
where X means that a DP has a relation with a FR and O means that there is no relation. However, Eq. (2) can be changed to the design equation with a triangular matrix, which makes us possible to apply the axiomatic design methodology, as follows :

$$\begin{Bmatrix} Stress\_C \\ Stress\_A \\ Stress\_B \end{Bmatrix} = \begin{bmatrix} X & X & O \\ O & X & X \\ O & O & X \end{bmatrix} \begin{Bmatrix} polyimide\ thickness \\ chip\ thickness \\ EMC\ thickness \end{Bmatrix} \quad (3)$$

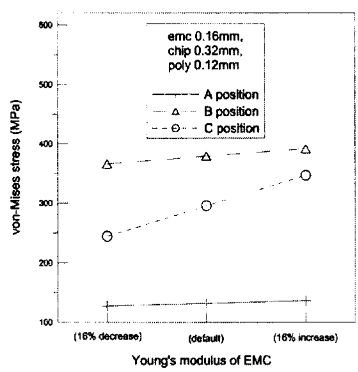
Without the axiomatic design methodology, 27 ($=3^3$) modelings and stress analyses are needed, but it is enough about 10 analyses in the axiomatic design. The final result is shown in Table 4. It shows that we can get the results to reduce the stresses on the stress concentration positions efficiently with a few analysis costs by using the axiomatic design.

Table 4 The ratio of von-Mises equivalent stress to strength by axiomatic design

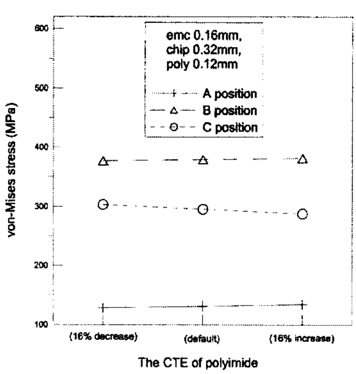
Location	Ultimate strength (MPa)	stress/strength		
		Without polyimide coating	Polyimide coating model 1	Using axiomatic design
A	128	5.26	2.09	1.03
B	128	11.24	4.59	2.96
C	102	•	3.24	2.90



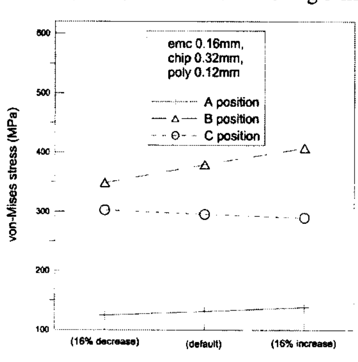
(a) von-Mises stress vs. EMC CTE



(b) von-Mises stress vs. EMC Young's modulus



(c) von-Mises stress vs. polyimide CTE



(d) von-Mises stress vs. polyimide Young's modulus

Fig. 7 Changes of von-Mises stress with the material properties of several parts

Table 5 The ratio of von-Mises equivalent stress to strength by axiomatic design for material properties

Location	Ultimate strength (Mpa)	stress/strength			
		Without polyimide coating	Polyimide coating model 2	Using axiomatic design for dimensions	Using axiomatic design for material properties as well as dimensions
A	128	5.26	2.09	1.03	1.11
B	128	11.24	4.59	2.96	2.39
C	102	•	3.24	2.90	0.95

In the usage of the axiomatic design, the number of FRs must be same with that of DPs. Therefore, it is impossible to use the design parameters more than three numbers in the case of three FRs. But, it is known that material properties as well as dimensions affect the stress values very much (Mertol, 1995; 1997). Therefore, we apply again the axiomatic design for material properties to the package model obtained through the axiomatic design for the dimensions. Since the EMC CTE and Young's modulus are known as the main factors to affect the stress values (Mertol, 1995) and the stress concentraion positions are the circumstance of polyimide coating, we examine the effect of EMC CTE, EMC Young's modulus, polyimide CTE and polyimide Young's modulus on the stress values. The results are shown in Fig. 7.

Among 4 DPs, 3 DPs must be selected to make the triangular matrix in the design equation. Finally, the design equation is obtained as follows:

$$\begin{Bmatrix} Stress\_C \\ Stress\_B \\ Stress\_A \end{Bmatrix} = \begin{bmatrix} X & X & X \\ O & X & X \\ O & O & X \end{bmatrix} \begin{Bmatrix} \text{polyimide CTE} \\ \text{EMC Young's modulus} \\ \text{EMC CTE} \end{Bmatrix} \quad (4)$$

The final results to minimize the stress according to the material properties are shown in Table 5. It shows that the stresses at B and C positions decrease highly although the stress at A position increases a little than those with the axiomatic design only for dimensions.

For the application of the axiomatic design with 4 FRs and 4 DPs, we consider D position shown in Fig. 8. Table 6 shows that the stress value at D position is also higher than the strength.

Table 6 The ratio of von-Mises equivalent stress to strength in case of 4 FRs

Location	Ultimate strength (MPa)	stress/strength	
		Without polyimide coating	With polyimide coating
A	128	5.26	2.09
B	128	11.24	4.59
C	102	•	3.24
D	102	•	2.17

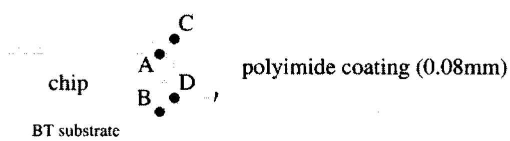
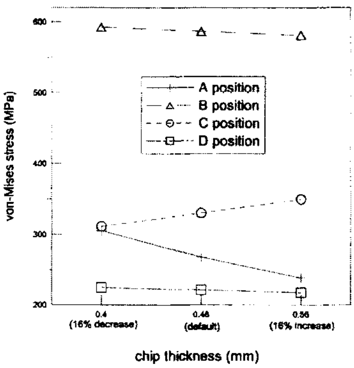


Fig. 8 Stress concentration positions in the polyimide coating model

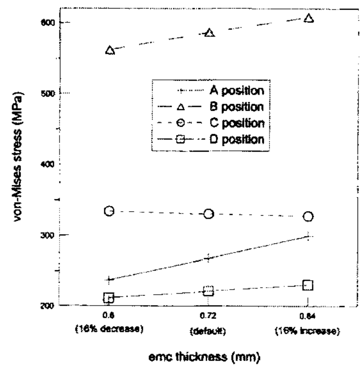
For the axiomatic design with 4 DPs, polyimide CTE is selected as 4^{th} DP with chip thickness, EMC thickness and polyimide thickness. The results of stress analyses are shown in Fig. 9. The triangular matrix is obtained in the design equation as shown in Eq. (5). The final results to minimize the stress are shown in Table 7.

$$\begin{Bmatrix} Stress\_C \\ Stress\_D \\ Stress\_A \\ Stress\_B \end{Bmatrix} = \begin{bmatrix} X & X & X & O \\ O & X & O & X \\ O & O & X & X \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} \text{polyimide CTE} \\ \text{polyimide thickness} \\ \text{chip thickness} \\ \text{EMC thickness} \end{Bmatrix} \quad (5)$$

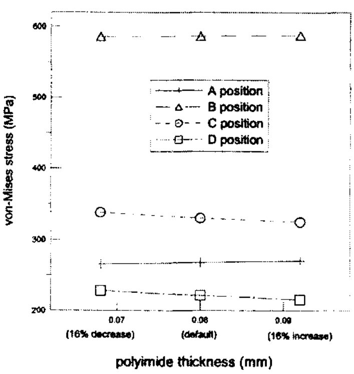
Without the axiomatic design methodology, 81 ($=3^4$) modelings and stress analyses are needed



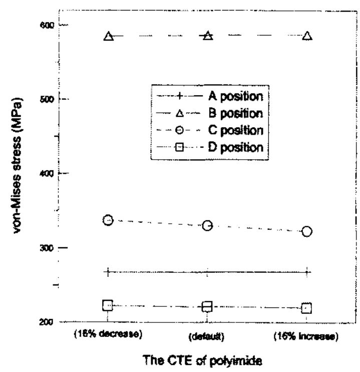
(a) von-Mises stress vs. chip thickness



(b) von-Mises stress vs. EMC thickngess



(c) von-Mises stress vs. polyimide thickness



(d) von-Mises stress vs. polyimide CTE

Fig. 9 Changes of von-Mises stress with the variation of 4 DPs

Table 7 The ratio of von-Mises equivalent stress to strength by axiomatic design in case of 4 DPs

Location	Ultimate strength (Mpa)	stress/strength			
		Without polyimide coating	Polyimide coating model	Using axiomatic design (3 DPs)	Using axiomatic design (4 DPs)
A	128	5.26	2.09	1.03	**0.96**
B	128	11.24	4.59	2.96	**2.91**
C	102	•	3.24	2.90	**3.13**
D	102	•	2.17	•	**1.65**

to know the effect of the 4 DPs on the stresses, but it is enough less than 20 analyses in the axiomatic design. From Table 7, we can observe that the stresses at A and B positions decrease a little and stress at C increases than those for 3 DPs.

Therefore, for the effective stress reduction, we examine the stress analyses with other design parameters and make the design equation to show the effect of them as shown in Eq. (6).

$$\begin{Bmatrix} Stress\_A \\ Stress\_B \\ Stress\_C \\ Stress\_D \end{Bmatrix} = \begin{bmatrix} \oplus & \oplus & O & O & O & \oplus \\ O & \oplus & O & O & \oplus & \oplus \\ \oplus & O & \Delta & \Delta & \Delta & O \\ O & \Delta & \Delta & O & O & X \end{bmatrix} \begin{Bmatrix} \text{chip thickness} \\ \text{EMC thickness} \\ \text{polyimide thickness} \\ \text{polyimide CTE} \\ \text{substrate thickness} \\ \text{chip width} \end{Bmatrix} \tag{6}$$

where $\oplus$ means there is a strong relation, X means there is a relation, Δ means there is a weak relation and O means there is no relation.

Table 8 The ratio of von-Mises equivalent stress to strength by axiomatic design in case of new 4 DPs

Location	Ultimate strength (Mpa)	stress/strength				
		Without polyimide coating	Polyimide coating model	Using axiomatic design (3 DPs)	Using axiomatic design (4 DPs)	Using axiomatic design (new 4 DPs)
A	128	5.26	2.09	1.03	0.96	0.94
B	128	11.24	4.59	2.96	2.91	2.70
C	102	•	3.24	2.90	3.13	2.85
D	102	•	2.17	•	1.65	1.65

From Eq. (6), by assuming that weak relation can be neglected, the new design equation with the DPs affecting largely on the stresses is obtained as follows:

$$\begin{Bmatrix} Stress\_B \\ Stress\_A \\ Stress\_C \\ Stress\_D \end{Bmatrix} = \begin{bmatrix} X & X & O & X \\ O & X & X & X \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} substrate\ thickness \\ EMC\ thickness \\ chip\ thickness \\ chip\ width \end{Bmatrix} \quad (7)$$

The final results to minimize the stress according to Eq. (7) are shown in Table 8. Table 8 shows that the axiomatic design with the new 4 DPs affecting on the stress strongly can bring the results to reduce effectively the stresses in the whole package.

4. Conclusions

In this paper, the application of the axiomatic design methodology for the detailed design of PBGA package to depress the stress is attempted. According to the thermal stress analyses in reflow soldering process, the stress concentration positions are found, and the polyimide coating is proposed to depress the stress and shows its usefulness.

To increase the reliability of the package, the axiomatic design methodology is applied to our model. It makes us know which factors decrease the stress value independently. The selection of the kind and the number of DPs appears to be very sensitive to the results. The material properties as well as the dimensions are factors to affect the stresses at the stress concentration positions.

In case of the few design parameters and functional requirements, the axiomatic design methodology can be a valuable tool to get the improved design specifications.

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