Analysis of Reflow Geometry for The Hybrid-Pad-Shapes System of Ball Grid Array Packages

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ABSTRACT

In this work, a methodology of solder reflow geometry prediction for hybrid-pad-shapes (HPS) system is developed. In the reflow process, many parameters will influence the final joint shapes and there is no closed-form solution for non-axisymmetric type solder pad prediction such as elliptical and rectangular pads. However, conventional approach like energy-based simulation model for predicting geometries in multiple/hybrid joint arrays is very difficult and time consuming. This work presents an approach combining the analytical and the energy-based methods and is capable of solving any kind of HPS system, such as round, elliptical, and rectangular pads. Furthermore, a detailed geometry information of the solder joints can be transferred to any conventional pre-processor/solver such as MSC/PATRAN, MSC/NASTRAN, LS-DYNA3D, ABAQUS and ANSYS. for reliability analyses. The objection of this work for predicting multiple/hybrid solder reflow geometries in ball grid array type interconnects is to achieve optimal joint geometries from the standpoint of improved yield and better reliability cycles under thermal loading. Furthermore, results presented in this study can be used as a reference for area array interconnects design.

Keywords: Solder Reflow, Hybrid-Pad-Shapes, Ball Grid Array Package.

INTRODUCTION

As the advanced electronic packaging technology is moving to the CSP, wafer level packaging, fine pitch BGA (ball grid array) and high density interconnects, the wireability of the PCB/substrate and soldering technology are as important as reliability issues. For optimal solder interconnects design of advanced electronic packages, designer should take both the reliability and wireability into consideration to fully utilize the foot print area of packaging. In this work, a hybrid method for predicting the geometries of solder joints under multiple and HPS configuration is developed. This new hybrid method in conjunction with analytical (for round pad) and energy-based approach (for irregular pad shapes) can solve the final accurate geometry shapes of multiple/hybrid pads system within a short time.

Many solder joints prediction models have been

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developed based on analytical method (Chiang 1998; Heinrich et al., 1993) and energy-based method (Chiang, 1998, 1999; Patra et al., 1995; Brakke, 1994). However, not much work has been carried out on the hybrid (analytical/energy-based) method for prediction of the geometries of the solder joints of multiple/hybrid pads area array packages.

The main objective of this research is to develop a hybrid model for predicting geometry shapes of solder joints under elliptical/round/rectangular pad boundary conditions. This approach can be coupled with finite element system for analysis of the solder joints reliability characteristics. In this research, a three-dimensional solder liquid formation model is developed for predicting the general geometry, the restoring force, and the wireability of solder joints in the area array type interconnects (e.g., BGA, flip chip and wafer level packages) under elliptical and non-round pad configurations. In general, the reliability of the solder joints is highly dependent on the thermal-mechanical behaviors of the solder, the geometry configuration of the solder ball such as standoff height/contact angle, and the geometry layout/material properties of the package. Therefore, an optimized solder pad design should not only lead to a good wireability but also achieve a good reliability life of the solder joint. Furthermore, for the hybrid analysis approach, the general-pad-shapes solder reflow simulation in this paper is based on an energy minimization engine called Surface Evolver, and the round-pad-shape solder reflow is calculated by analytical solution.

For the energy-based method, the surface tension of a liquid is a measure of the energy required to enlarge the liquid surface area. This energy may also be interpreted as the force per unit length, tangential to the edge of the surface, trying to minimize the surface area. The solder joint equilibrium is achieved where the forces due to surface tensions, gravity and solder internal/external pressures are all in balance. The Surface Evolver could simulate the surface whose geometry is determined by surface tension and other energies, such as gravity. Evolver allows the investigation of fully 3-D problems by discretizing an initial surface into a set of inter-connected triangular facets followed by iterating this initial surface towards a minimal energy configuration by conjugate gradient methods. A range of different boundary conditions and energy integrals may be applied to the model such as fixed constraints, surface tension forces, solder volume, and density . The Surface Evolver is quite robust for analysis of the single 3-D solder model, and it has been successfully applied for predicting the final shape of the BGA joint after reflow according to various pad sizes and shapes, solder volume, specific solder height, and surface tension. However, the Surface Evolver encounters modeling inconvenience and computational time consuming while applying to HPS/MBM (multiple-ball model) solder joint model, especially when the pad dimensions, surface tension, and solder volumes for each joint in the array are not uniform. Therefore, a hybrid method is critically needed for the analysis of the geometries of HPS/MBM solder joint model.

ALGORITHMS

The hybrid method is a combination of energy-based and analytical methods. The fundamental algorithm for these two methods are as follows:

Energy-Based Method

The solder joint provides structure support, heat path, and the electrical signal/power transmission between the different levels of packaging. To evaluate the general solder reflow geometry shape, and standoff height of the molten solder, it is desired to find out the force-balanced height along the gravity direction. Recently, Surface Evolver has been intensively used to estimate the restoring force and shape of elliptical/round/rectangular pads (Chiang, 1999). For this particular application, it is assumed that the eutectic solder ((63%Sn/37%Pb) is perfectly wettable to the copper pad. Furthermore, in the static equilibrium condition, the total energy of a liquid body consists of three major energy portions: the surface tension energy, the gravitational energy, and the external energy. Based on these energies, the variational free energy and restoring force along the gravitational direction of the solder ball can be expressed as:

$$\delta E = T\iint_S (div\vec{h} - \vec{n}\cdot D\vec{g}\cdot\vec{n})dA + \rho g\iint_S ((div\frac{z^2}{2}\vec{k})\vec{h}) - curl(\vec{h}\times\frac{z^2}{2}\vec{k})\cdot d\vec{A} - P\iint_S \vec{h}\cdot d\vec{A} \quad (1)$$

$$F_r = \frac{\partial E}{\partial H} = (\partial E_{surface\_tension} + \partial E_{gravity} + \partial E_{external\_force})/\partial H \quad (2)$$

Where E is the total energy associated with the solder standoff height and each part of the energy in Eq. (2) can be written as

$$\frac{\partial E_{surface\_tension}}{\partial H} = T\iint_s (\nabla\cdot\vec{h} - \vec{n}\cdot D\vec{h}\cdot\vec{n})dA \quad (3)$$

$$\frac{\partial E_{gravity}}{\partial H} = \rho g\iint_s [\nabla\cdot(\frac{z^2}{2}\vec{k})\vec{h} - \nabla\times(\vec{h}\times\frac{z^2}{2}\vec{k})]dA \quad (4)$$

$$\frac{\partial E_{external\_force}}{\partial H} = -P\frac{\partial V}{\partial H} = -P\iint_s \vec{h}\cdot d\vec{A} \quad (5)$$

In the above equations, $\vec{h} = [(z_{top} - z)/(z_{top} - z_{base} - H)]\vec{k}$ is a variational vector field which is a perturbation function. T is the surface tension, ρ is the density, and g is the acceleration due to gravity.

A most common way to determine the restoring force of the molten ball along the gravitational direction is to give a downward or upward shift (perturbation) on the lower or upper solder pads. Different shifts on the solder pad will correspond to different molten ball geometry shapes and different gravitational restoring force while maintaining the same solder volume and pad size. In a conventional reflow process, the solder geometry shape such as contact angle versus standoff height should be an unique pair. Usually, from the reliability point of view, one would prefer that the solder joint could have a higher standoff height with blunter contact angles. To reach this optimum goal, the reflow process, pad layout/size and solder volume should be carefully examined.

Analytical Method

The geometry prediction of the closed-form solder ball model with round pad (figure 1) is based the following assumptions (Chiang 1998; Heinrich et al., 1993):

- the solder joint has attained static equilibrium when solidification occurs

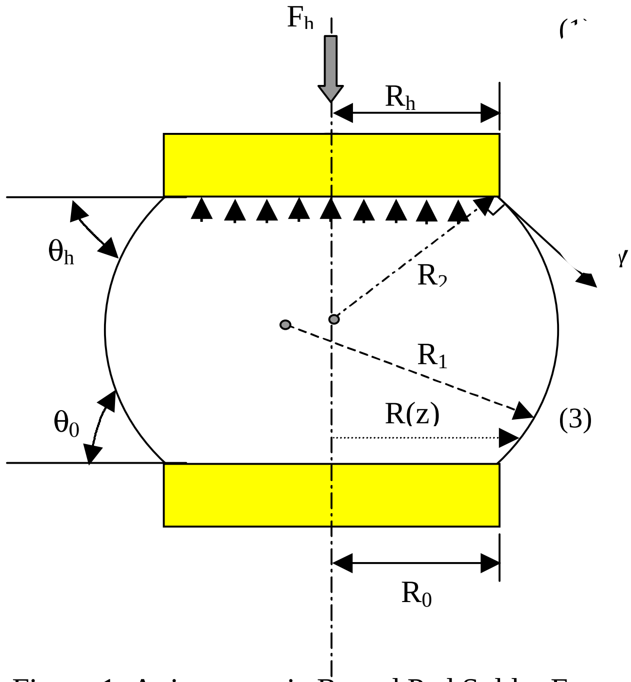

Figure 1. Axisymmetric Round Pad Solder Free Body Diagram

- the volume shrinkage due to solidification can be neglected
- the solder pad on the substrate is circular and is perfectly aligned at the time of solidification
- the free surface of the solder joint is axisymmetric
- the meridian defining the free surface of the solder joint is approximated by a circular arc
- the solder pad is completely covered by solder and the solder does not spread beyond the pad
- the solder pad metallization is assumed to be perfectly wettable, whereas the surrounding material is perfectly non-wettable

The calculation of contours of solder surface is made by Laplace equation. The governing equation (Chiang, 1998) to the exact equilibrium configuration of the solder surface may be expressed as

$$P_0 = P_a + \gamma(\frac{1}{R_1} + \frac{1}{R_2}) + \rho g(h - z) \quad (6)$$

In Eq. (6), R_1, R_2 are principal radii of curvature of the solder surface at height h. Where, P_a , P_0 , γ are the ambient pressure, internal pressure and surface tension, respectively. Variables P, R, R_1, and R_2 are function of z such that, $P = P(z)$, $R = R(z)$, $R_1 = R_1(z)$, $R_2 = R_2(z)$. If the gravitational force is neglected, the governing equation may be written as

$$P = P_0 - P_a = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad (7)$$

For axisymmetric cases, from the surface of revolution, the principal radii of curvature of the surface, R_1, R_2, may be derived, such that

$$P=\gamma\left\{-\frac{R''}{[1+(R')^2]^{3/2}}+\frac{1}{R\sqrt{1+(R')^2}}\right\} \qquad (8)$$

Also, from figure 1, F_h represented as package weight or applied force at each of the upper pad and it may be balanced by the solder joint internal pressure and surface tension such that

$$F_h + [\gamma\sin(\pi-\theta_h)]2\pi R_h - P_h\pi R_h{}^2 = 0 \qquad (9)$$

Furthermore, the volume constraint with an unknown height h is:

$$V = \pi\int_0^h (R)^2\,dz \qquad (10)$$

Finally, the unbalanced force for a single molten ball may be calculated as:

$$\partial F = F_h - \frac{\pi R_h}{2hR}\left[\pm(R_0+R_h) - \sqrt{\frac{4R^2h^2}{(R_0+R_h)^2+h^2} - h^2}\right] \qquad (11)$$

One may start to calculate the unbalanced force in Eq. (11) with an initial guess of standoff height h. However, increase or decrease in the standoff height h to repeat the solution procedure will be necessary, if the system is not in the balanced condition. Once the system forces are balanced, the final solder reflow shape and standoff height could be determined.

In practical applications, the simplified analytical model is quite suitable for parametric study of the round pad MBM solder reflow prediction. However, for HPS model the closed-form equation from Eq. (11) is not sufficient and it should be in conjunction with the energy-based method. The HPS force equation can be expressed as:

$$\sum_{i=1}^{n} \delta F_i + \sum_{1}^{m} \delta F_i = F \qquad (12)$$

where n is the number of axisymmetric solder joints that is calculated by analytical solution, and m is the number of general solder joints that is simulated by the energy-based approach. The SBM solution procedure of the analytical method has been fully discussed in the previous work (Chiang, 1998). Moreover, two single ball simulation models (analytical and energy-based methods) that described in the previous section may be easily incorporated into HPS module by iterating on the standoff height of the area array until the sum of all joint reaction forces on the system is balanced with the package weight W. The equation could be expressed as:

$$W - \sum_{i=1}^{n} \delta F_i + \sum_{1}^{m} \delta F_i = 0 \qquad (13)$$

Furthermore, the flow chart of this new hybrid method is shown in figure 2. (10)

DISCUSSION AND APPLICATIONS

This research proposes an approach combing the analytical and energy-based method to simulate the reflow shape of the BGA type interconnections.This new methodology could be very efficient to predict any kind of solder reflow geometry of MBM/HPS package system. For example, figure 3 demonstrates

system. four benchmark ball grid array packages with HPS/MBM configuration. These four benchmark cases are comprised of four different pad sizes, the configuration are R1, R2, E1, and E2. Furthermore, the solder material adopted in this work is 37Pb/63Sn where the surface tension force of the molten solder is 45 dynes/mm at 220 C^o. The radii of R1 and R2 are 0.3mm and 0.4mm , respectively , and the individual long/short axes of elliptical pads of E1 and E2 are 0.375mm/0.24mm and 0.5mm/0.32mm , respectively. Moreover , the reflow result of these models will compare with the conventional area array structure to realize the volume and pad size effects.

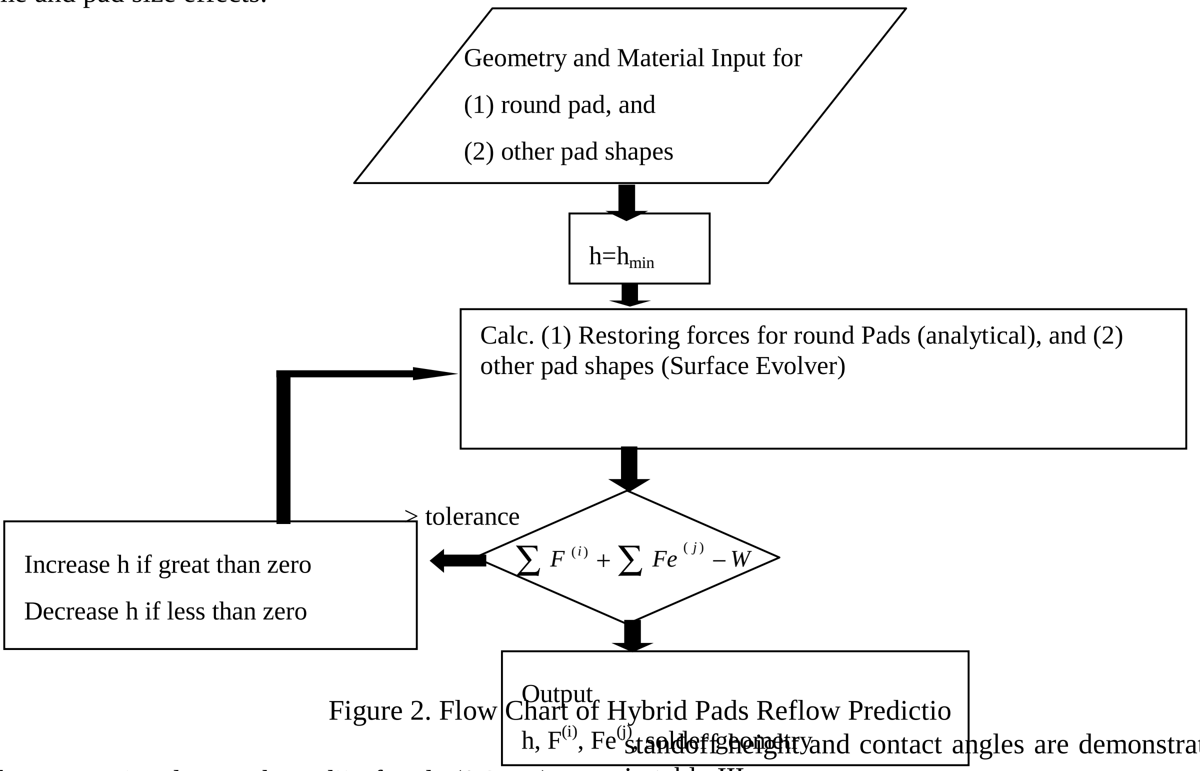

Figure 2. Flow Chart of Hybrid Pads Reflow Predictio

For the conventional case, the radii of pads (0.3mm) are uniformly distributed. The detailed information of the models is shown in tables I and II.

The restoring force vs. standoff height for E1 and E2 elliptical pads (single ball model) are shown in figures 4 and 5. Once this curve is obtained, one could either transfer this curve to a formulation of nonlinear spring of the form F(x)=K(x).x or write the curve data into database for standoff height vs. restoring force interpolation. The hybrid solution procedure of analytical and energy-based methods is clearly illustrated in figure 2.

In this study, geometry/shape results of four benchmark and conventional models are calculated. The hybrid method could predict the system standoff height and the geometry information of each solder ball in a short time, and this information is very helpful for finite element reliability analysis . Some typical data of the solder ball such as the system standoff height and contact angles are demonstrated in table III.

Table I: Model Configuration

Model	Pad Configuration	1/4 of Package Weight
Conventional BGA	R1	0.51g
Model I	R1,R2,E1,E2	0.51g
Model II	R1,E1,E2	0.51g
Model III	R1,R2	0.51g
Model IV	R1,R2	0.51g

Table II: Pads and Solder Volumes

Pad	Diameter (mm)	Long/short axes (mm)	Solder Volume (mm^3)

R1	0.3	-	0.2726
R2	0.4	-	0.4
E1	-	0.375/0.24	0.2726
E2	-	0.5/0.32	0.4

Model IV	0.552	142	135	-	-

Table IV: Volume effect of model IV

Volume of R2 (mm^3)	Standoff Height (mm)	Contact Angle (Degree)	
		R1	R2
0.4	0.552	142	135
0.45	0.576	137	142
0.5	0.6	133	147.4

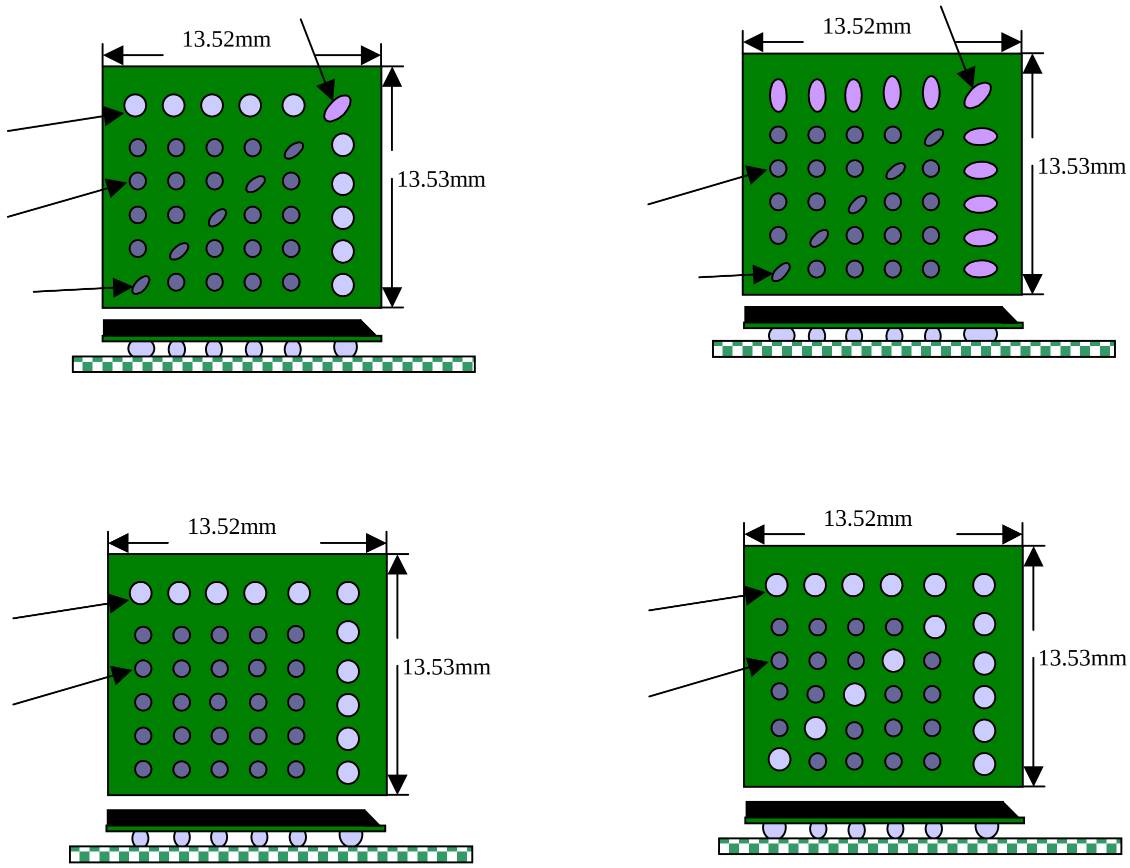

Figure 3. 1/4 of HPS area array package

Table III: Some typical geometry data of conventional and four HPS/MBM benchmark cases

Models	System Standoff Height (mm)	Contact Angles (Degree)			
		R1	R2	E1, long/Short Axes	E2, long/short axes
Conventional	0.542	144.7	-	-	-
Model I	0.548	143.2	136.2	118/155.6	112.8/150.4
Model II	0.544	144.3	-	120.8/158.1	114.3/151
Model III	0.55	143	136	-	-

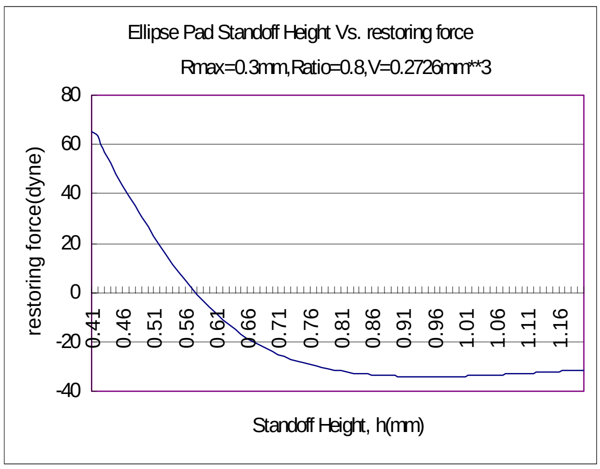

Figure 4. Restoring force vs. Standoff Height of E1 Ellipse Pad

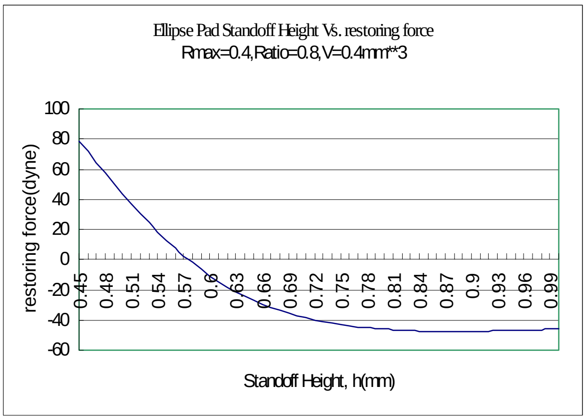

Figure 5. Restoring force vs. Standoff Height of E2 Ellipse Pad

Furthermore, table IV gives some idea about volume effect to the geometry change of the solder ball, in this study, the case IV is selected as a test model. The results indicated that the volume effect to the geometry change of the solder ball is significant. From the table, one could see that the standoff height and the contact angle of the large solder ball increased upon increasing the volume of large solder ball. In contrast, the contact angle of the small solder ball become blunter as the volume of large solder ball is increased.

From the long-term reliability of the solder ball aspect, both the standoff height and the contact angle are playing a very important role in the solder fatigue life. Generally, the higher standoff height with blunter contact angle will give a better reliability life of the solder ball. In many cases, it shows that the contact angle will be the major factor to drive the reliability characteristic, especially, when the contact angle become very sharp (e.g. more than 150^o). The hybrid methodology demonstrated a fast and feasible way to predict the solder reflow shapes of the area array package, furthermore, the geometry data could be transferred to finite element system for reliability analysis.

SUMMARY AND CONCLUSIONS

This research first proposed a fast and accurate approach that combined the analytical and the energy-based methods which is capable of solving any kinds of HPS/MBM system, such as round, elliptical, and rectangular pads, etc. Furthermore, a detailed geometry information of the solder joints can be transferred to any conventional pre-processor/solver such as MSC/PATRAN, MSC/NASTRAN, LS-DYNA3D (for drop test), ABAQUS and ANSYS for low cycle fatigue and reliability analyses. Moreover, the solder reflow prediction solver that developed in this research could be a very powerful design tool for flip chip, CSP, and wafer level packages for solder volume, pad type/size and layout design. The solver enable designer change the array layout, solder ball volume, pad size to achieve the optimal design at a short period, and could lead the package to meet the long-term reliability/wireability/form factor requirements.

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混合式墊片之球柵陣列回銲幾何預估研究

江國寧[1]，劉昌明[2]

本研究將發展一方法得以預估混合式墊片球柵陣列錫球迴銲之幾何外型。於迴銲過程中,許多參數對錫球外型具影響度。一般而言、圓形墊片因具軸對稱性其解析解過去已有多篇論文探討，然、對於非軸對稱形式錫球墊片的預測如、橢圓形或是長方形墊片則無法求得閉區間的收斂解。於液體成型理論中以能量法最為精準且泛用，然而,若以能量法來預測混合墊片球柵陣列錫球是很困難而且是非常耗時的。在本研究中提出一種結合解析法和能量法的方式，此混合法可以求解任意形式混合墊片系統,如正圓、橢圓和方形等墊片的外型組合系統。再者,液體成型後詳細的幾何資料亦可載入傳統的CAE前處理器/運算器中,像是 MSC/PATRAN, MSC/NASTRAN, LS-DYNA3D, 和 ABAQUS 等來進行加速熱循環負載可靠度分析。這個針對混合墊片球柵陣列 I/O 錫球迴銲外型預估所做的研究，其目的是為了要錫球外型能達到最佳化之目標，以期能使封裝結構體受到熱循環負載下之良率和可靠度壽命週期得以提昇。另、於本研究中所得到的結果也可以作為設計面積陣列形式電路接點的最佳參考。

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