An Overview of Solder Bump Shape Prediction Algorithms with Validations

Kuo-Ning Chiang and Chang-An Yuan

Abstract—**The trend to reduce the size of electronic packages and develop increasingly sophisticated electronic devices with more, higher density inputs/outputs (I/Os), leads to the use of area array packages using chip scale packaging (CSP), flip chip (FC), and wafer level packaging (WLP) technologies. Greater attention has been paid to the reliability of solder joints and the assembly yield of the surface mounting process as use of advanced electronic packaging technologies has increased. The solder joint reliability has been observed to be highly dependent on solder joint geometry as well as solder material properties, such that predicting solder reflow shape became a critical issue for the electronic research community. In general, the truncated sphere method, the analytical solution and the energy-based algorithm are the three major methods for solder reflow geometry prediction. This research develops solder joint reliability design guidelines to accurately predict both the solder bump geometry and the standoff height for reflow soldered joints in area array packages. Three simulation methods such as truncated-sphere theory, force-balanced analytical solution and energy-based approach for prediction of the solder bump geometry are each examined in detail, and the thermal enhanced BGA (TBGA) and flip chip packages are selected as the benchmark models to compare the simulation and experimental results. The simulation results indicate that all three methods can accurately predict the solder reflow shape in an accurate range.**

Index Terms—**Chip scale packaging, flip chip, reflow, reliability, solder joint, thermal enhanced BGA, wafer level packaging.**

I. INTRODUCTION

WITH increasing development in packaging technology, critical issues of packaging design include the following: re-routing/wireability, and bridging possibility; the reliability characteristics of the solder I/Os; and the development cycle time. For a specified solder material, solder joint reliability has been found [1], [2] to be highly dependent on the solder joint geometry characterized by the standoff height, lower/upper contact angles of the joint, solder pad diameter and pad shape, etc. In recent years, the design on experiment (DOE) methodology has been extensively adopted in many advanced package designs. However, DOE methodology requires many design cycles and is very time consuming. Importantly, this methodology lacks sufficient physical information for further structural improvement and optimization of packages. Therefore, a fast and accurate algorithm must be developed to accurately predict the solder reflow shape. Moreover, the detailed geometrical information of the solder joint should be transferable to a finite element program such as MSC/NASTRAN, ANSYS, or ABAQUS to analyze the reliability of the package.

The truncated sphere method does not take any force or energy factors into consideration because it is a purely geometrically-based algorithm. The truncated sphere method can predict the standoff height and the maximum solder width of the solder ball within an accurate range for a lightweight package. The force-balanced analytical solution includes the surface tension effect and has shown promising results in predicting the PBGA solder reflow shape [5]. The analytical solution can deliver good predictions of solder shape if the surface arc of the solder joint remains a perfect circular curve; if the gravity density of the solder ball could be neglected, and if the sizes of the lower and upper pad are similar. In general, none of these methods may be used to calculate the contact angle, which is a critical factor in determining the reliability issue of the package.

Energy-based methods such as the surface evolver [8], include surface tension, gravitational effects, and internal/external pressures. Solder joint equilibrium is achieved when the forces due to surface tension, gravity and solder internal/external pressures are all balanced. Surface evolver allows fully 3-D problems to be examined by discretizing an initial surface into a set of inter-connected triangular facets and then iterating this initial surface toward 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 solder density. Surface evolver is quite robust in analyzing the single 3-D solder model, and it has been successfully applied for predicting the final shape of the BGA joint after reflow, for various pad sizes and shapes, solder volumes, specific solder heights, and surface tensions. However, surface evolver involves modeling inconvenience and intense CPU usage when applied to multiple solder joint models, especially when the pad dimensions, surface tension, and solder volumes for each joint in the area array are not uniform. This research mainly aims to develop the solder joint reliability design guidelines, and to select a feasible algorithm to predict both the solder bump geometry and the standoff height of an area array package.

II. METHODS FOR PREDICTING LIQUID SURFACE SHAPE

Generally the geometry-based truncated sphere method, the force-balanced analytical solution and the energy-based algorithm are the three main methods for predicting solder reflow geometry. Each method is described in the following section.

Manuscript received May 16, 2000; revised February 26, 2001. This work was supported by the National Science Council, R.O.C., under Contract NSC89-2212-E-007-014.

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Publisher Item Identifier S 1521-3323(01)04070-9.

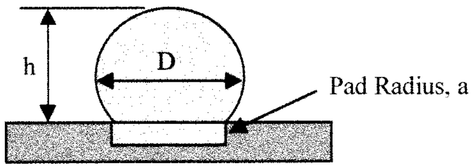

Fig. 1. Solder ball cross section view.

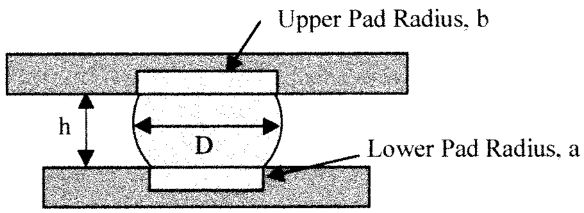

Fig. 2. Solder ball on the board.

A. Truncated Sphere Theory

For the geometry-based method, the solder bump after reflow is assumed to be a truncated sphere (Fig. 1). The truncated domain is defined by the pad, which is determined owing to that molten solder does not flow onto a nonwettable solder mask. The diameters of the solder bump and pad are expressed as D and a; the solder height is h. The dimensions $R(2R = D)$, a and h are related as in

$$\begin{aligned} h =& R + \sqrt{R^2 - a^2} \\ R =& \frac{h^2 + a^2}{2 \cdot h}. \end{aligned} \tag{1}$$

The volume of the solder ball with dimensions D, a and h can be estimated from the volume of a truncated sphere according to

$$\begin{aligned} V =& \frac{\pi}{3} \cdot \sqrt{R^2 - a^2} \cdot (2 \cdot R^2 + a^2) + \frac{2}{3} \cdot \pi \cdot R^3 \\ =& \frac{\pi \cdot h^2}{6} [3 \cdot D - 2 \cdot h] \end{aligned} \tag{2}$$

$$V = \pi \cdot \left(\frac{h^3}{6} + \frac{h \cdot a^2}{2} \right). \tag{3}$$

In practice, the bump height h and solder diameter D can be determined by changing the solder volume V. Furthermore, for an area array package mounted on a printed circuit board (PCB), the solder joint between the package substrate and PCB assumes the shape of a "double truncated sphere" (Fig. 2). As a result, once the solder volume is known, the standoff height and the diameter of the solder ball can be predicted by (4)–(6). In other words, the solder volume and D can also be calculated by the expected value of h

$$h = \sqrt{R^2 - a^2} + \sqrt{R^2 - b^2} \tag{4}$$

$$R = \frac{\sqrt{h^4 + 2 \cdot h^2 \cdot (a^2 + b^2) + (a + b)^2 (a - b)^2}}{2 \cdot h} \tag{5}$$

$$\begin{aligned} V =& \frac{\pi}{3} \cdot \left[\sqrt{R^2 - b^2} \cdot (2R^2 + b^2) + \sqrt{R^2 - a^2} \cdot (2R^2 + a^2) \right] \\ V =& \frac{\pi}{12 h^3} \cdot [A(A^2 + 6a^2 \cdot h^2) + B(B^2 + 6b^2 \cdot h)] \end{aligned} \tag{6}$$

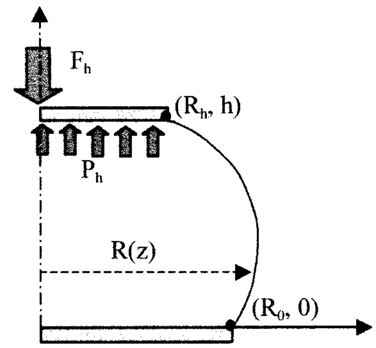

Fig. 3. Solder joint upper pad force balance diagram.

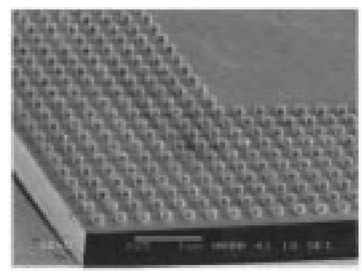

Fig. 4. Flip chip with 800 I/Os.

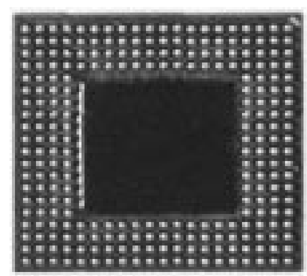

Fig. 5. TBGA with 256 I/Os.

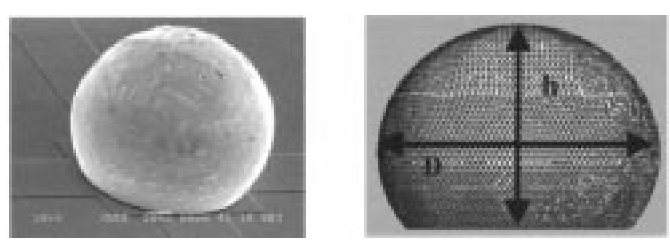

Fig. 6. Flip chip bump SEM and simulation pictures.

where

$$\begin{aligned} A =& \sqrt{h^4 + (a^2 - b^2)^2 + 2 \cdot (b^2 - a^2) \cdot h^2} \\ B =& \sqrt{h^4 + (a^2 - b^2)^2 + 2 \cdot (a^2 - b^2) \cdot h^2}. \end{aligned}$$

In the case of $a = b$, the solder volume equation can be simplified as

$$V = \frac{\pi \cdot h}{6} \cdot [h^2 + 3 \cdot (a^2 + b^2)]. \tag{7}$$

B. Force-Balanced Analytical Solution

Heinrich *et al.* [4], [5] and Chiang and Chen [1]–[3] have addressed the closed form solution of the force-balanced algo-

TABLE I
GEOMETRICAL CONFIGURATION OF FLIP CHIP SOLDER BUMP

Models	Pad Diameter (μm)	Solder Vol. (μm^3)	Bump Thickness (μm)
Case I	100	700,000	8
Case II	200	5,000,000	8

TABLE II
FLIP CHIP BUMP SHAPE SIMULATION AND EXPERIMENTAL RESULTS (UNIT: μm)

Models	Exp. Ave. Result with 10 Samples		Surface Evolver Simulation		Truncated Sphere Theory	
	h	D	h	D	h	D
Case I	91	117	92	119	88	116
Case II	163	238	169	230	166	226

rithm for solder formation. The geometrical prediction of the area array package on the board model is based on the following assumptions:

1) the solder joint attains static equilibrium when solidification occurs;
2) the solder pad on the substrate is circular and is perfectly aligned during solidification;
3) the free surface of the solder joint is axisymmetric;
4) the meridian defining the free surface of the solder joint is approximated by a circular arc;
5) the solder pad is completely covered by solder and the solder does not spread beyond the pad;
6) the solder pad is perfectly wettable, and the surrounding material is perfectly nonwettable.

A Laplace equation is used to calculate the contours of the solder surface. The equation governing the exact equilibrium configuration of the solder surface may be expressed as

$$P_0 = P_a + \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) + \rho g(h - z) \tag{8}$$

where

R_1 and R_2 principal radii of curvature of the solder surface at height h;
P_a, P_0, γ ambient pressure, internal pressure and surface tension, respectively;
variables P, R, R_1, and R_2 functions of z such that, $P = P(z)$, $R = R(z)$, $R_1 = R_1(z)$, $R_2 = R_2(z)$.

If gravity is neglected, the governing equation may be simplified as

$$P = P_0 - P_a = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right). \tag{9}$$

For axisymmetric cases, the governing equation becomes

$$\gamma R R'' - \gamma (R')^2 + PR[1 + (R')^2]^{3/2} - \gamma = 0. \tag{10}$$

Fig. 3 indicates that the package weights at the upper pad F_h should be balanced by the solder joint internal pressure and the surface tension if the solder is in the minimum energy state. The solder volume is a function of $R(z)$, as in

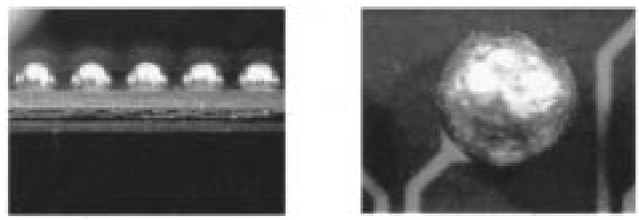

Fig. 7. Top and side views of TBGA solder bump.

$$V = \pi \int_0^h (R)^2 dz. \tag{11}$$

Heinrich *et al.* [5] proposed that if the meridian defining the joint's free surface, $R(z)$, is approximated by a circular-arc R_{arc}, then the volume and unbalanced force may be expressed as

$$V = \pi \int_0^h [R_{\text{arc}}(z)]^2 dz, \tag{12}$$

$$\delta F = F_h - \frac{\pi R_h}{2hR_{\text{arc}}} \times \left[\mp(R_0 + R_h) - \sqrt{\frac{4R_{\text{arc}}^2 h^2}{(R_0 + R_h)^2 + h^2} - h^2}\right]. \tag{13}$$

The meridian radius of the arc, R_{arc}, and the unbalanced force in (13) with an initial height h can be determined. The standoff height h must be adjusted for further iteration if $|\delta F|$ exceeds the converging tolerance. Once the force is balanced, the approximate shape and height of the solder ball can be determined.

C. Energy-Based Method

Determining the restoring force in the direction of gravity helps in evaluating the geometrical shape and standoff height of the solder ball. In general, the total energy of a liquid body consists of three major energy portions: the surface tension energy, the gravitational energy, and the external energy that is related to

TABLE III
TBGA SOLDER BUMP SHAPE RESULTS (UNIT: μm)

Exp. Ave. Result with 10 Samples		Surface Evolver Simulation		Truncated Sphere Theory	
h	D	h	D	h	D
590	817	600	820	644	798

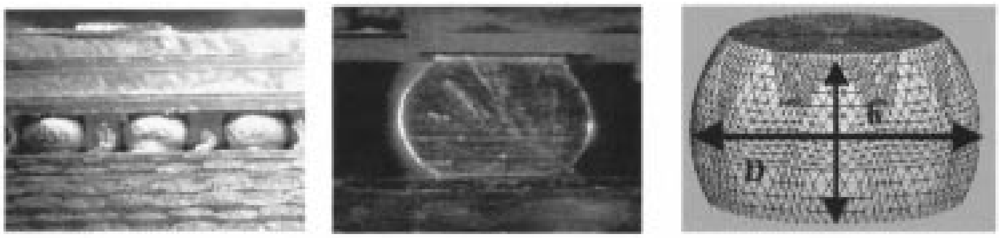

Fig. 8. TBGA solder ball experimental and simulation pictures.

the change in solder volume. Accordingly, the variational free energy and restoring force along the gravitational direction of the solder ball is given by

$$\begin{aligned}\delta E =& T\int\int_S (\operatorname{div}\vec{h} - \vec{n}\cdot D\,\vec{g}\cdot\vec{n})dA \\ &+ \rho g\int\int_S \left(\operatorname{div}\frac{z^2}{2}\vec{k}\right)\vec{h} \\ &- \operatorname{curl}\left(\vec{h}\times\frac{z^2}{2}\vec{k}\right)\cdot d\vec{A} - P\int\int_S \vec{h}\cdot d\vec{A}, \end{aligned} \tag{14}$$

$$F_r = \frac{\partial E}{\partial H} = \frac{\partial E_{\text{surface\_tension}} + \partial E_{\text{gravity}} + \partial E_{\text{external\_force}}}{\partial H} \tag{15}$$

where E is the total energy associated with the solder standoff height H, including the surface tension energy on the solder surface, the gravitational energy of the solder, and the energy due to the external forces. Each part of the energy in (14) can be written as

$$\frac{\partial E_{\text{surface\_tension}}}{\partial H} = T\int\int_S (\nabla\cdot\vec{h} - \vec{n}\cdot D\,\vec{h}\cdot\vec{n}))dA, \tag{16}$$

$$\begin{aligned}\frac{\partial E_{\text{gravity}}}{\partial H} =& \rho g\int\int_S \left[\nabla\cdot\left(\frac{z^2}{2}\vec{k}\right)\vec{h}\right. \\ &\left.- \nabla\times\left(\vec{h}\times\frac{z^2}{2}\vec{k}\right)\right]dA,\end{aligned} \tag{17}$$

$$\frac{\partial E_{\text{external\_force}}}{\partial H} = -P\frac{\partial V}{\partial H} = -P\int\int_S \vec{h}\cdot d\vec{A}. \tag{18}$$

In the above equations, $\vec{h}\left[(z_{\text{top}} - z)/(z_{\text{top}} - z_{\text{base}} - H)\right]\vec{k}$, is a variational vector field which is a perturbation function. T is the surface tension, ρ is the density, and g is the acceleration factor due to gravity. The restoring force of the solder ball along the gravitational direction can be determined by giving a downward or upward offset perturbatio on the solder pad. Different offsets on the solder pad correspond to different molten ball geometrical shapes and different gravitational restoring forces while maintaining the same solder volume and pad size.

TABLE IV
TBGA STANDOFF HEIGHT AND MAXIMUM WIDTH RESULTS (UNIT: μm)

Exp. Ave. Result with 10 Samples		Surface Evolver Simulation		Truncated Sphere Theory		Force-Balanced Method	
H	D	h	D	h	D	H	D
510	860	490	850	486	845	455	911

TABLE V
PBGA SOLDER SHAPE RESULTS (UNIT: MM)

Experiment (16 Samples)*, Std. Dev.=0.02		Force-Balanced Method		Truncated Sphere Theory		Energy-Based Method	
h	D	h	D	h	D	h	D
0.52	0.86	0.517	0.87	0.536	0.846	0.52	0.863

*[5]

III. SOLDER BUMP HEIGHT AND STANDOFF HEIGHT PREDICTIONS

This research considers two types of package as benchmark models. One is the light-weight flip chip package (Fig. 4) and the other is the thermally-enhanced BGA package with weighing 4.23 g (Fig. 5, 256 solder balls, 16.2 dyne/ball). Both solder materials are 37Pb/63Sn eutectic solder; the surface tension of the eutectic solder at 380°C is 463 dyne/cm (from the solder material menu of SenJu Metal Industry Co. LTD) and the density is 9.28 g/cm^3.

Table I shows the solder bump geometry configurations of the flip chip. Fig. 6 presents the SEM photograph and the surface evolver simulation graphic of the solder bump. Table II displays the simulation results according to truncated sphere theory and the energy-based surface evolver method with experimental validation. Results show that both simulation methods can accurately predict solder bump geometry shape.

The same methodology is applied to the TBGA (Fig. 7) bump prediction to investigate volume and gravity effects. In this case, the radius of the pad is 0.315 mm and the solder volume is $0.24\ \mathrm{mm}^3$. Table III shows the simulation and the experimental results.

Above results suggest that the energy-based method and the truncated sphere theory may accurately predict the micro-bump shape. However, Table III reveals that for a large ball size such as the TBGA package, the gravitational effect should account for the bump shape prediction. Theoretically, the truncated sphere theory over-estimates bump height and under-estimates the width of the solder ball.

A TBGA package on board is also investigated. In this case, the pad radius of 0.37 mm (lower/upper pad ratio is 1.18) is used on the board side. Fig. 8 shows the cross section of the solder ball and the corresponding simulation pictures. The results are shown in Table IV, indicating that both the energy-based and truncated sphere theories accurately predict shape. However, the force-balanced method provides less accurate results in this case.

Finally, experimental results from literature are adopted in this research to further verify each of the solder reflow shape prediction algorithms. A PBGA package was selected by Heinrich *et al.* [5]. This PBGA package contains 225 identical eutectic solder balls, of volume $0.26\ \mathrm{mm}^3$, specific gravitational density of $8.42\ \mathrm{g/cm}^3$ and surface tension of 48.1 dyne/mm. Radii of the upper and lower pads are 0.3 mm and 0.35 mm (lower/upper pad ratio is 1.17), respectively, and the total package weighs 1.8 gram (7.84 dyne/ball). Table V lists Heinrich's experimental results and this study's simulation results. In this case, all three methods gave good results in solder ball prediction.

Comparison of these two cases, the external loading of each solder ball of the TBGA (16.2 dyne/ball) is twice that of the PBGA package (7.84 dyne/ball). Moreover, the solder ball volume of the TBGA is smaller than the solder ball volume of the PBGA package and the pad size of the TBGA is bigger than the pad size of the PBGA package. The combination of these three factors may the cause of the inaccuracy of the force-balanced algorithm [7], [8].

IV. Conclusion

Methods for accurately predicting the bump and solder on board reflow shape have been investigated and experimentally verified. All three methods predict the solder reflow shape within an accurate range. Among these simulation methods, the energy-based theory best predicts the geometry of bump and solder on board. The truncated sphere theory is a purely geometrically-based method, and predicts to the same accuracy as does the energy-based theory. The force-balanced analytical solution gives good results for a light-weight package such as PBGA and flip chip. However, since this algorithm is very sensitive to package weight, this method is best not applied to a heave-weighted package such as TBGA type package.

References

[1] K. N. Chiang, H. C. Cheng, and C. M. Liu, "A comparison of thermal stress/strain behavior of ellipse/round solder pads, 1999 InterPACK," in *Advances in Electronic Packaging*. Maui, HI: ASME, 1999, vol. EEP-26–1, pp. 413–418.

[2] K. N. Chiang and H. C. Cheng, "On enhancing eutectic solder joint reliability using a 2nd-reflow-process approach," in *Proc. ASME Winter Annu. Meeting, Thermomech. Characterization Evolving Packag. Mater. Struct. Symp.*, vol. EEP-24, Anaheim, CA, Nov. 15–20, 1998, pp. 21–25.

[3] K. N. Chiang and W. L. Chen, "Electronic packaging reflow shapes prediction for the solder mask defined ball grid array," *ASME J. Electron. Packag.*, vol. 120, pp. 175–178, 1998.

[4] S. M. Heinrich, P. E. Liedtke, N. J. Nigro, A. F. Elkouh, and P. S. Lee, "Effect of chip and pad geometry on solder joint formation in SMT," *J. Electron. Packag.*, vol. 115, pp. 433–439, 1993.

[5] S. M. Heinrich, M. Schaefer, S. A. Schroeder, and P. S. Lee, "Prediction of solder joint geometries in array-type interconnects," *ASME J. Electron. Packag.*, vol. 118, pp. 114–121, 1996.

[6] S. K. Patra, S. S. Sritharan, and Y. C. Lee, "Quantitative characterization of a flip-chip solder joint," *J. Appl. Mech.*, vol. 62, pp. 390–397, 1995.

[7] P. E. Liedtke, "Prediction of solder joint geometry in surface mount technology—An analytical approach," Ph.D. thesis, Marquette Univ., Milwaukee, WI, 1993.

[8] K. A. Brakke, *Surface Evolver Manual, version 1.95*. Minneapolis, MN: The Geometry Center, 1994.

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