Prediction of Solder Joint Profile in J-Lead Connection*

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Abstract

Numerous research efforts have evidenced that the solder joint profile in SMT affects reliability of the joint. In this work, the three-dimensional solder joint profile of the J-lead is predicted by minimizing the energy due to surface tension and gravity. Geometric complexity stemming from the curved shape of the J-lead is resolved by employing a transformed coordinate and corresponding element types with the geometric continuity condition in the finite element formulation. Based on the simulation results, the solder volume and pad length are found to have significant effects on the solder joint profile. The predicted solder joint profiles show reasonably good agreements with experimental data when the solder volume is adjusted by the amount of the volume loss due to wicking.

Key words: Solder joint profile, J-lead, Finite element modeling, Pad size, Solder volume

INTRODUCTION

The surface mount technology (SMT) is widely used to connect the leads of the chip on the pad through a reflow process, and has replaced the traditional through-hole technology (THT). Since the joint strength of SMT is generally lower than that of THT, the majority of research efforts for solder joints in SMT has been focused on the reliability which is affected by the solder joint profile. Prediction of the solder joint profile is also important to provide the design criteria on the process parameters such as the supplied solder volume and pad dimensions.

For several lead types such as the gullwing, I- and J-leads, attempts have been made to predict the solder joint profiles [1-5]. Although the J-leads have been widely used in SMT, numerical modeling and prediction for the case of J-lead connection are relatively scarce. The reason is that the solder joint profile of the J-lead is complex and thus previous simplified modeling techniques cannot be applied [1-3]. Joint profiles under the equilibrium state have been predicted by minimizing the surface tension and gravity energies exerted on the joint using the finite element method (FEM). Although the joint profiles of gullwing leads were computed [2, 3], the results were restricted to the cases when the lead was either perpendicular or inclined to pad surface. The

curved shape of J-lead and the three-dimensional joint geometry inhibit the previous formulation to the J-lead connection. As to the fillet profile for the J-lead, Surface Evolver which is a general purpose free-surface modeling software with the same principle of energy minimization, was used to estimate the three dimensional solder joint geometry of J-leads [4, 5].

In this work, the three-dimensional solder joint profile of the J-lead is predicted by extending the previous methodology [2, 3] of minimizing the energy generated by surface tension and gravity. Geometric complexity stemming from the curved shape of the lead is resolved by employing a transformed coordinate, corresponding element types and geometric continuity condition for the FEM. Therefore, this paper provides an efficient and accurate way of predicting the solder joint profiles dedicated to J-lead cases. Effects of the solder volume and pad length on the solder joint profile are investigated, and the predicted solder joint profiles are compared with experimental data.

NUMERICAL MODELING

Formulation

A solder joint profile under the equilibrium state can be determined by minimizing the potential energy and is subjected to the volumetric constraint condition [1-3],

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(a) Configuration of solder joint

(b) Fillet on vertical side of J-lead connection

(c) Fillets in toe and heel portions

Fig. 1 Solder joint profile of J-lead connection.

$$E = f_s \gamma dA + f_v \rho g z dV + \lambda (V_0 - f_v dV) \quad (1)$$

where S , V , γ , ρ , λ represent the surface and volume of solder joint, and the surface tension coefficient, the mass density of solder and Lagrangian multiplier, respectively. Several assumptions are made to simplify the formulation and numerical procedure: (i) the curved part of a J-lead is semicircular with constant radius as shown in Fig. 1, (ii) the solder fillet does not rise beyond the top of the curved section of the J-lead, (iii) there exists no gap between the bottom of the J-lead and pad surface, and (iv) the material properties used for computation are constant.

The entire surface of the solder joint associated with the J-lead connection is divided into two distinct portions. One portion is the fillet surface formed between the pad and the vertical side of the lead (surface I in Fig.

Fig. 2 Cylindrical coordinate system for surface II.

1b). The other portion is the fillet surface formed between the pad and the curved portions of the lead in the toe (front) and heel (rear) areas (surface II in Fig. 1c). Modeling of the solder joint geometry is performed independently for surface I and II, and both portions are combined using geometric continuity condition.

The surface I in Fig. 1b can be described by the height function, $y = \zeta(x, z)$, where x - z plane corresponds to the pad plane. The energy functional of this region was previously derived [2],

$$E_1 = \int_{A_1} \left(\gamma \sqrt{1 + \zeta_x^2 + \zeta_z^2} + \frac{\rho g}{2} \zeta^2 - \lambda \zeta \right) dx dz - \int_{s_1} \gamma \zeta \cos \theta_c ds \quad (2)$$

where θ_c denotes the contact angle, A_1 the area of fillet surface projected to the pad and s_1 the interface line between solder and lead. For the surface II in Fig. 1c, a cylindrical coordinate system is introduced as illustrated in Fig. 2. The surface II can be described by defining an angle function, $\theta = \theta(r, z)$, which denotes angle between the r - z plane and the point on the fillet surface (Fig. 2). The energy functional for surface II can be expressed by an area integral in the r - z plane, in a similar form to equation (2),

$$E_2 = \int_{A_2} \left\{ \gamma \sqrt{1 + (r\theta_r)^2 + (r\theta_z)^2} + \rho g (R\theta - r \sin \theta) r - \lambda (r\theta - r\theta_p) \right\} dr dz - \int_{s_2} \gamma R \theta \cos \theta_c ds \quad (3)$$

where the subscripts r and z denote the partial differentials, R the outer radius of the lead and s_2 the intersection line (Fig. 1a). The function, $\theta_p(r-z)$, is the angle between the r - z plane and the corresponding point on the pad plane.

The energy functional of the entire solder fillet can be expressed as:

$$E = E_1 + E_2 + \lambda V_0 \quad (4)$$

An efficient finite element solution procedure is possible because the volume integral of equation (1) is converted to the area integral form in equation (2) and (3). The boundary conditions are given along the perimeter of the pad (s_3 and s_4 in Fig. 1a) as:

$$\zeta = 0 \text{ along } s_3 \text{ and } \theta = \cos^{-1}(R/r) \text{ along } s_4 \quad (5)$$

Finite Element Method and Geometric Continuity

The numerical procedure to minimize the energy functional is devised by using the finite element method in two dimensions. The integration domains on x - z and r - z planes in equation (4) are discretized by C^0 type elements. The height function $\zeta(x, z)$ and angular function $\theta(r, z)$ are interpolated in terms of the unknown nodal values and shape functions as:

$$\begin{aligned} \zeta(x, z) &= \Theta_i N_i(x, z) \text{ in } A_1 \text{ and} \\ \theta(r, z) &= \Theta_i N_i(r, z) \text{ in } A_2 \end{aligned} \quad (6)$$

We note here that the unknown nodal values, Θ_i , designate the nodal solder joint heights in A_1 and the nodal angle in A_2 .

The extremum conditions of the energy functional are defined as:

$$\frac{\partial E}{\partial \Theta_i} = 0 \text{ and } \frac{\partial E}{\partial \lambda} = 0 \quad (7)$$

Equation (7) is converted to the algebraic form as:

$$K_{ij} \Theta_j + \lambda \Psi_i + E_i = 0 \text{ and } \Psi_i \Theta_i + V_o = 0 \quad (8)$$

where

$$\begin{aligned} K_{ij} &= \gamma \int \frac{r^2}{\sqrt{1 + (r\theta_r)^2 + (r\theta_z)^2}} \left(\frac{\partial N_i}{\partial r} \frac{\partial N_j}{\partial r} + \frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} \right) dr dz \\ &+ \gamma \int \frac{1}{\sqrt{1 + \zeta_x^2 + \zeta_z^2}} \left(\frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} \right) dx dz \\ E_i &= - \int_{s_1} \gamma R N_i \cos \theta_c ds - \int_{s_2} \gamma N_i \cos \theta_c ds \\ &+ \rho g \int \{ r R N_i - r^2 N_i \cos(\theta^p N_i) \} dr dz \\ \Psi_i &= - \int r N_i dr dz - \int N_i dx dz \end{aligned}$$

As equation (8) is nonlinear, the numerical solutions of λ and Θ_i are obtained using the appropriate iteration scheme after imposing the boundary conditions in equation (5). Details of the solution techniques can be found in Reference [2].

While the entire fillet surface composed of surfaces I and II is continuous, the nodes on the interface lines extended from the surfaces I and II, do not match one to

Fig. 3 Two interface curves for geometric continuity.

one, which is called non-conforming aspect. Therefore, the geometric continuity condition should be imposed along the interface of two portions. The discrepancy is resolved by employing a technique widely used in the contact problem [7] though there exist minor errors.

The technique to enforce the geometric continuity utilizes the constraint such that a node in one surface should reside on the line corresponding to the other surface during the solution iteration as in Fig. 3. The node m for surface II should be on the line interpolated by two nodes, i and $i+1$, in surface I. Since the node m has radial value, r_m , and the coordinates of point m' can be expressed by the nodal values in surface I, the continuity condition can be written as:

$$\theta_{m'} = \sin^{-1}(x_{m'}/r_m) \quad (9)$$

where m' is the artificial matching point on the line interpolated by nodes i and $i+1$. The new set of angle function values can be computed for every node m on the interface using the values of x_i , x_{i+1} , and previous solutions of y_i , y_{i+1} . These new values are imposed as the essential boundary condition for the next iteration step. The iteration continues until a sufficient match between two surfaces is reached.

EXPERIMENTS

The experiments are performed for PLCC chips and rectangular pads to compare with the calculated solder joint profiles. The outer radius and width of the lead are 0.8 and 0.43 mm, and pad length and width are 2.5 and 0.635 mm, respectively. After the paste is supplied using a metal mask with 150 μ m thickness and the chip is placed, soldering is carried out through a standard reflow process [6]. The 63Sn/37Pb solder is approximately 55% volumetric fraction of the supplied RMA

Fig. 4 Typical cross-section of solder joint.

paste. The joint cross-sections are polished and the typical image captured by a camera is illustrated in Fig. 4.

During the reflow process, it is observed that significant amount of the supplied solder flows upwards and covers the lead surface, which is called wicking. Although this phenomenon of wicking is known to occur by non-uniform heating during reflow [8], its effect on solder joint geometry has not been quantitatively estimated. In practice, appropriate solder volume is determined by the estimation based on the experience and experiment considering the amount of volume loss due to wicking.

RESULTS AND DISCUSSIONS

The solder joint profiles are calculated using 400 elements representing a half of the symmetric pad. The contact angle is 0 degree, mass density and surface tension coefficient of the solder are 8340 kg/m³ and 0.49 N/m, respectively [9]. The calculated solder joints are illustrated in Fig. 5, with solder volumes of 0.035 and 0.045 mm³. As expected, the fillet height increases with larger solder volume. The plots also illustrate continuity of the surface profile of the solder joint across the interface of two surfaces.

Effects of the solder volume on joint profile are shown in Fig. 6 with the lead radius of 0.5 mm, pad length and width of 1.5 and 0.35 mm, respectively. The solder volumes of 0.016, 0.02, 0.04 mm³ are used for calculation, and the J-lead is placed at the center of the pad. The solder joint profiles in the toe and heel are identical due to symmetry. With the solder volume of 0.016 mm³, the solder profile is highly concave and the solder does not spread to the end of the pad. The surface tension dominates fillet formation with small solder volume. As the solder volume increases, the fillet height increases and the profile becomes less concave.

(a) V_o = 0.035mm³

(b) V_o = 0.045mm³

Fig. 5 Calculated solder joint profiles.

Fig. 6 Effect of solder volume on solder joint profile.

With the fixed lead position and solder volume, effects of the pad length on the joint profile are illustrated in Fig. 7. When the lead is located 0.75 mm from the pad front and the solder volume is 0.025 mm³, the joint profiles are calculated with pad length of 1.25, 1.5 and 1.

Fig. 7 Effect of pad length on solder joint profile.

7 mm. For the short pad (Fig. 7a), the heel fillet profile is almost linear, and the toe fillet is concave. When the pad length increases to 1.5 mm which is a symmetric configuration (Fig. 7b), the front and rear fillet profiles become identically concave. When the pad length increases further to 1.7 mm (Fig. 7c), the solder in the heel does not spread over 1.5 mm and yields profiles similar to those in Fig. 7b. This result implies that the solder joint profile is strongly affected by the pad length when the pad is shorter than a certain value (in this case, 1.5 mm). When the pad becomes longer than this threshold value, the joint profile is hardly affected by the pad length.

The computed cross-sections are compared with the experimental data as in Fig. 8. With the solder volume of 0.064 mm^3 , the calculated joint profile shows large discrepancy with the experimental data in the toe and heel portions due to wicking. The amount of solder volume loss due to wicking is estimated from the thickness and length of the solder coating. When the adjusted solder volume of 0.0415 mm^3 is used, the calculated profiles show better agreements with the experimental data. Therefore, the volume adjustment according to

Fig. 8 Comparison of calculated and measured solder joint profiles.

the wicking effect is found to be a key factor for realistic prediction of the solder joint geometry.

CONCLUSIONS

This paper extends the previous numerical procedure based on energy minimization and finite element method to the modeling of J-lead connection. Three-dimensional solder joint geometry is predicted by employing different coordinate systems for two distinct portions and developing corresponding element type. The modeling of the solder joint profile performs independently for each surface portion and both portions are combined using the geometric continuity condition. The solder volume and pad size are found to have significant effects on the solder joint geometry. It is also witnessed that adjustment of the supplied solder volume produces reasonable agreements between the calculated and experimental joint profiles accompanying wicking

phenomena.

Potential applications of the present work are discussed in the context of determining the supplied solder volume and pad demensions in the SMT design. It is also expected that this approach can provide the joint geometry for reliability analysis. Since a significant amount of the solder volume is spent for coating the lead, the quantification of the wicking effect leaves a formidable task in future study to predict accurate solder joint profiles.

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