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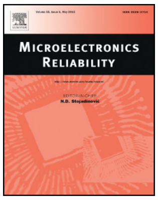

Force and collapsed shape of a liquid solder bump under load

N. van Veen, W. Luiten *

Philips Research Laboratories, 5656AE Eindhoven, The Netherlands

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ABSTRACT

It is shown that a collapsed solder bump carries load through a bump force that depends on the collapsed shape in a way that closely resembles the Young-Laplace (YLP) equation. The relation between force and shape allows deriving the force constant of the bump, which is important in solder bump reliability. For the commonly used ellipsoid shape model, the new force method gives similar results as the results derived conventionally from the increase in free surface energy but in a mathematically simpler way, omitting the difficult surface integral. The results confirm that the ellipsoid shape model is not a true solution for the collapsed shape. The new force based approach enables developing an improved shape model and it is shown that this satisfies both the YLP equation and minimum increase in surface energy better.

1. Introduction

Ball Grid Arrays (BGAs) and solder flip chips are carriers for the processors and memories in the microelectronics we use today. Originating from the end of the eighties, as successors of the fine pitch Quad Flat packs (QFP), they allow for high assembly yield and reliability. Especially they have driven the miniaturization of via technologies and fine line capabilities in printed circuit board to its current level. BGAs and solder flip chips can be seen as the true enabling technologies for the present and future mobile phones. A key feature of BGAs and solder flip chips is that they use arrays of small solder balls as interconnect to a motherboard. Due to the weight of the IC package, a liquid solder ball will flatten during soldering, and after solidification this determines the height and the shape of the solder interconnect, which is an important factor in its thermomechanical behavior. The ratio between the mechanical load and the resulting flattening, known as the force constant of the bump, is therefore a major parameter of interest in the reliability of solder ball interconnects. Flattening enlarges the free surface area of the bump. This requires work to be done against surface tension, which is stored as surface energy. The bump acts here as a (non-linear) spring [1]. The first published work on enlargement of the solder bump surface was published in the early nineties and was based on numerical modeling [2]. Brakke's Surface Evolver [3] attracted world-wide attention as it allows predicting the shape of a solder joint using minimization of the free surface as the driving force. Further work on bump shapes in relation to self-alignment was done in relation to opto-electrical components [4,5].

In this paper, we show a novel way of deriving the force constant of the bump, based upon the force opposing the load, which is derived from static equilibrium of forces in a free body diagram. For comparison, the force constant is also derived in the conventional way through minimizing the surface integral. The ellipsoid bump shape is used as a carrier. The force approach and the free surface approach show similar, but not identical, results for the force constant and the hydrostatic pressure over the height of the bump. We attribute this to the fact that the ellipsoid shape model as such is not optimal as it does not fulfill the YLP equation. Subsequently the new force method is used to derive a new alternative shape model, which is shown to be much closer to a true solution.

The work described in this paper builds on earlier results [6,7,8], which has led to new insights and allows for making more accurate but still analytical models for bumps in the liquid state. Part of it was presented at the Therminic 2016 conference [9].

The solder balls that we are investigating are 300 μm in diameter and typically have a height of 200 μm when reflowed. With the solder surface tension $O(10^{-1})$ J/m^2 and ball radii $O(10^{-4})$ m, the contribution

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Abbreviations: P, hydrostatic pressure [N/m^2]; R_1, R_2, principal radii of curvature [m]; γ, surface energy density [J/m^2], equals surface tension [N/m]; p, radius of contact pad [m]; j, p/K, the ratio of bond pad radius to undeformed bump height [-]; K, height of bump under zero mechanical load [m]; k, half the height of bump under zero mechanical load [m]; H, height of bump under mechanical load [m]; h, half the height of bump under mechanical load [m]; Δ, K-H, compression of the loaded bump [m]; V, volume [m^3]; V_a, volume of compressed ellipsoid bump [m^3]; V_s, volume of sphere segment [m^3]; r(z), contour of bump [m]; φ, diameter of a solder ball with equal volume to solder bump [m]; a, bump shape parameter [-]; β, second bump shape parameter [-]; E(H), surface energy as function of bump height [J]; S(H), surface of bump as function of bump height [m^2]; c, force constant for the liquid bump [N/m]; t_1, t_2, t_3, parameters used in volume [m^3]; t, τ, u, r_0, abbreviation parameters; W, work [J].

* Corresponding author.
E-mail address: 4wendyluiten@gmail.com (W. Luiten).

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of surface tension to the hydrostatic pressure inside such small solder balls is $O(10^3)$ Pa. With a specific mass $O(10^3)$, gravity $O(10)$, volume $O(10^{-12})$ m^3 and area $O(10^{-8})$ m^2, the contribution of the solder weight to the pressure is $O(1)$ Pa, 3 orders of magnitude smaller. The weight of the solder itself is subsequently neglected throughout this paper.

2. The liquid bump as a spring

The shape of a liquid bump is governed by surface tension through the Young Laplace equation. This equation can be either derived from minimization of the work to create free surface or through static equilibrium of surface tension and hydrostatic pressure. For a liquid, the surface energy density γ [J/m^2] is equal to the surface tension γ [N/m]. The Young –Laplace equation reads:

$$P(z) = \gamma\left(\frac{1}{R_1(z)} + \frac{1}{R_2(z)}\right) \qquad (1)$$

$P(z)$ [Pa] is the hydrostatic pressure inside the liquid,[1] and $R_1(z)$ cq $R_2(z)$ are the principal radii of curvature of the surface.

In an axisymmetric coordinate system *(r(z),z)* the radii of curvature are

$$R_1 = \frac{\left(1 + r'^2\right)^{3/2}}{-r''} \qquad (2)$$

$$R_2 = r\left(1 + r'^2\right)^{1/2} \qquad (3)$$

With the notation $r' = \frac{dr}{dz}$ and $r'' = \frac{d^2r}{dz^2}$.

Substitution into the YLP equation yields the hydrostatic pressure P as:

$$P(z) = \gamma\left(\frac{-r''}{\left(1 + r'^2\right)^{3/2}} + \frac{1}{r\left(1 + r'^2\right)^{1/2}}\right) \qquad (4)$$

In the unloaded state, and in absence of its own weight, the principal radii of curvature are equal and the shape of the liquid bump is a sphere. When loaded, the sphere flattens, and upon removal of the load, surface tension causes the solder bump to revert to its initial shape. This behavior, deformation under load and full recovery of the initial state upon removal of the load, is by definition the behavior of a mechanical spring. The behavior of a spring is characterized by its force -displacement diagram, as illustrated in Fig. 1.

In flattening, free surface area is created in the bump. As the molecular bonds at the free surface are stronger by necessity, creating of free surface area costs energy, the amount of which per unit surface area is expressed as the surface energy density γ [J/m^2]. The stored surface energy can also be considered as the work done in flattening the bump, $W = \int F\, d\Delta$, shown in Fig. 1 as the area below the curve. For small displacements, the spring constant or the bump force constant is given by

$$c = \left.\frac{dF}{d\Delta}\right|_{\Delta=0} = \left.\frac{d^2W}{d\Delta^2}\right|_{\Delta=0} = \gamma\left.\frac{d^2S}{d\Delta^2}\right|_{\Delta=0} \qquad (5)$$

For large deformations, the linear approach cannot be used and non-linear effects have to be taken into account. Eq. (5) shows that for small displacements the bump constant can be derived either as the second derivative of the surface energy to the bump collapse displacement or as the first derivative of the bump force to the collapse displacement at $\Delta = 0$.

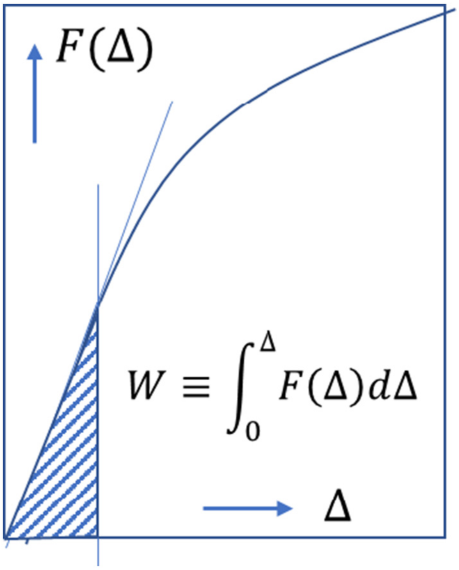

Fig. 1. Force-displacement diagram for the non-linear spring.

3. Surface energy approach for a ellipsoid bump shape

The shape of the solder bump is the shape where the minimum free surface is created. In consequence, the free solder shape is a sphere, as this has the smallest surface area for a given volume. In case of an unloaded liquid solder bump on a bond pad, the shape is the segment of a sphere, bounded on the top and on the bottom by the solder pads on the board and the IC, as shown in Fig. 2.

When the solder bump is loaded, the sphere segment will be flattened. It is convenient to model this flattened shape as an ellipsoid, truncated at the top and at the bottom by the solder pads. It should be noted that this ellipsoidal contour is not a true solution of the Young-Laplace equation, but an estimation of the true shape. The flattened solder bump is shown in Fig. 3.

The solder bump is axisymmetric around the z-axis and is confined between two pads with radius p. Fig. 2 and Fig. 3 show the uncompressed and the compressed bump and the relations between the compressed bump height H and half height h, uncompressed bump height K and half height k, and bump compression Δ:

$$\begin{aligned} h &= {}^1/_2 H \\ k &= {}^1/_2 K \\ \Delta = K - H &= 2(k - h) \end{aligned} \qquad (6)$$

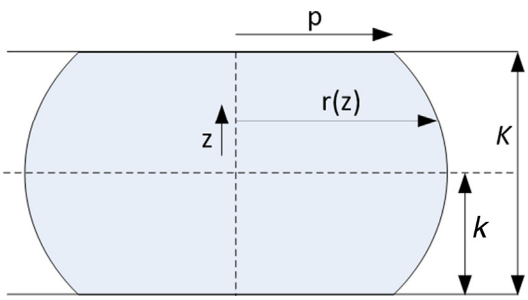

Fig. 2. The uncompressed bump represented as a sphere segment. The contour is indicated as r(z), the pad radius is indicated through p, K is the bump height and k is half the bump height.

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[1] Both P and p are in use as the symbol for pressure (N/m^2) or (Pa). In this work P is used to avoid confusion with the bond pad radius p (m).

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