Solder joint reliability of cavity-down plastic ball grid array assemblies

S.-W. Ricky Lee

Department of Mechanical Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong

John H. Lau

Express Packaging Systems, Inc., Palo Alto, California, USA

A computational model was established in this study to simulate cavity-down plastic ball grid array (PBGA) assemblies. Stress analysis was performed to investigate the solder joint reliability of a PBGA-PCB (printed circuit board) assembly. The packages under investigation had two different body sizes and two kinds of ball population. The diagonal cross-section of the assembly was modeled by plane-strain elements and was subjected to a uniform thermal loading. The solder joints were stressed due to the mismatch of the assembly's coefficient of thermal expansion (CTE). The accumulated effective plastic strain was evaluated as an index for the reliability of solder joints. Effects on solder joint reliability such as package size and ball population were identified. Furthermore, it was found that, unlike conventional PBGA assemblies, the outermost solder ball has the highest plastic strain for all cases in the present study. This peculiar phenomenon was further discussed with the consideration of package deformation.

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Introduction

The general trends for microelectronics are smaller size, faster speed, larger number of interconnects, and higher power consumption. In order to fulfill the more and more challenging requirements, many advanced electronics packaging technologies have been developed in the past decade. One typical example is the ball grid array (BGA) packages. There are many forms of area array packages for various applications. In particular, due to the cost effectiveness and the ease of implementation, the plastic ball grid array (PBGA) package has gained increasing attention from the electronics industry. It is expected that the PBGA package will overwhelm the market for electronic modules with pin counts from more than 208 to 420 in the coming decade[1].

PBGA packages are compatible with surface mount technology (SMT) which is a main stream in the manufacturing industry of electronics. For surface mounted components (SMC), the solder joints are not only the passage of electrical signal, power, and ground, but also the mechanical support to hold the module in position on the PCB. It is well known that most solder materials are susceptible to low cycle fatigue[2]. Since the dimensions of solder joints are relatively small and the electronic modules will experience thermal cycles during service, the solder joint reliability of SMCs is a major concern. It has been identified that the stress and strain in solder joints are mainly induced by the mismatch of coefficient of thermal expansion (CTE) between SMC and PCB[3]. The loading and deformation may highly depend on material properties, package configurations, and assembly geometries[4]. For conventional leaded SMCs such as quad flat packages (QFP), the structural compliance is relatively large due to the existence of long leads. As a result, the solder joints are usually less stressed. On the other hand, for BGA type of packages, the stand-off distance between the component and the PCB is rather short (the compliance is small). Therefore, the solder joint reliability becomes much more critical[5].

The investigation of solder joint reliability for PBGA assemblies has been a popular research topic in the past few years[6-8]. In the literature, the focus was overwhelmingly placed on the analysis of face-up type of packages. In fact, the PBGA family has a twin with cavity-down configurations. A representative example of this category is the Super-BGA of Amkor/Anam[5]. The cavity-down PBGA have many advantages such as shorter wire-bonding, better thermal management, and thinner package profile. However, the study of solder joint reliability on such type of package assembly is very limited[9]. In the present study, a computational model was established to simulate the cavity-down PBGA-PCB assemblies with various configurations. The diagonal cross-section of the assembly was modeled by plane-strain elements and subjected to a uniform thermal loading. The accumulated effective plastic strain was evaluated as an index for the

reliability of solder joints. The objective is to identify the effect of package size and ball population on the solder joint reliability. The results of this study may provide packaging engineers with certain guidelines for new package design.

Finite element model for computational analysis

The package under investigation in this paper was a cavity-down PBGA with perimeter solder ball array. The major dimensions of the package are shown in Figure 1. The material properties of package constituents are given in Table I. Two design parameters, namely, solder ball population and package/die size, were considered in the present study. The configurations of various cases are presented in Table II. Since the thermal loading response is most critical in the largest planar dimension, the diagonal cross-section was considered in the modeling. A schematic diagram for the PBGA-PCB assembly is shown in Figure 2.

A commercial finite element code, ANSYS, was employed in this study for stress analysis. The diagonal cross-section of the PBGA assembly was modeled by eight-node quadrilateral plane strain elements. Owing to symmetry, only half of the cross-section was simulated. All materials were assumed to be linear-elastic except that the solder balls were elasto-plastic. A uniform temperature change of 85°C was applied to the whole assembly. Within the scope of the present study, all material properties were assumed to be temperature independent.

The objective of this study is to investigate the effect of aforementioned design parameters on the reliability of solder joints. The accumulated effective plastic strain in solder balls was evaluated as an index of reliability. The typical stress and strain distribution in a solder joint is presented in Figure 3 for reference. It can be seen that the failure should be initiated from the corner of solder ball due to the rather high concentration of inelastic strain. The results of parametric study are discussed in detail in the following section.

Results of inelastic strain distribution

Figure 4 shows the distribution of the maximum accumulated effective plastic strain in each solder ball for four-row and five-row perimeter PBGAs with the package size of 35mm. It is observed that the distribution shows a concave pattern. In both cases, the highest inelastic strain (even though the value is very small) appears in the outermost solder joint. It seems that there is no effect from the solder ball population on this ultimate strain value. The second highest strain occurs in the innermost solder joint. Although this condition applies to both four-row and five-row configuration, the strain level of the former is obviously

Figure 1
Configurations and dimensions of cavity-down PBGA package

Table I
Material properties for computational modeling

Property	Si (die)	Molding compound	Solder ball (63Sn/37Pb)	Heat spreader	BT substrate	FR-4 PCB
Young's modulus (GPa)	131	16	10	110	26 (x,y) 11 (z)	22 (x,y) 10 (z)
Poisson's ratio	0.3	0.25	0.4	0.33	0.39 (xz,yz) 0.11 (xy)	0.28 (xz,yz) 11 (xy)
CTE ($\mu\text{e}/^\circ\text{C}$)	2.8	15	21	17	15 (x,y) 52 (z)	186 (x,y) 70 (z)

Table II
Configuration of cases for parametric study

Configuration	Package size A = 35 mm	Package size A = 35 mm
Four-row perimeter BGA	Die size a = 10mm	Die size a = 12mm
Five-row perimeter BGA	Die size a = 10mm	Die size a = 12mm

Figure 2
Schematic diagram of the cross-section of a PBGA-PCB assembly

lower than that of the latter. The reason will be discussed in the next section.

The results of a larger package with the package size of 40mm are given in Figure 5. The same trends as those identified in Figure 4 are observed. By comparing the numerical values of all four cases presented in Figures 4 and 5, the major features of results from the current computational analysis can be summarized as follows:

- 1 The distribution of maximum accumulated effective plastic strain in each solder ball always shows a concave shape which indicates there may be various mechanisms causing the deformation.
- 2 The highest inelastic strain always appears in the outermost solder joint. The value of this ultimate strain

is independent of the ball population and the package size.

- 3 The second highest inelastic strain always occurs in the innermost solder joint. The value of this strain strongly depends upon the ball population (four-row < five-row) and slightly varies with the package size ($A = 35\text{mm} > A = 40\text{mm}$).

For the intermediate solder joints, since their strain level is extremely low, there is no need to discuss them. Although the above characteristics are identified, it should be noted that the accumulated effective plastic strains in the solder joints of the cavity-down PBGA are smaller than those in the conventional face-up PBGA [6,7] and the solder-bumped

Figure 3
Typical stress and strain distribution in solder joint

flip-chip PBGA[8]. In fact, the strains obtained in this study are really very small (<0.1 per cent).

In the literature, the most critical solder joint for conventional face-up PBGAs is either underneath (for full-grid PBGA) or closest to (for perimeter PBGA) the silicon die[6,7]. The results of present study for the cavity-down PBGA seems to differ from the previous observation. In order to understand this peculiar phenomenon, further analysis on the deformation of the assembly was performed and discussed in the next section.

Discussion on deformation of the assembly

It is well known that the stress in the solder joints of SMCs is mainly induced from two types of thermal mismatch. One is caused by the difference in thermal expansion between the SMC and the PCB (global mismatch) and the other is called local mismatch. There are two kinds of local mismatch. The first kind is due to the difference in CTE between the solder ball and the adjacent materials. However, since all solder balls under consideration have similar adjacent materials, this local mismatch for these joints should be the same. The second kind of local mismatch is due to the difference in CTE of materials close to the solder ball. For instance, the deformation caused by the thermal mismatch between the silicon die and the copper heat spreader can affect the innermost solder ball. Therefore, an analysis in deformation is necessary.

Figure 6 shows the deformation of all cases under investigation. The applied thermal loading is a uniform temperature change. In order to inspect the deformation clearly, the displacement is magnified by 30 times. In this figure, an obvious local bending of the cavity-down PBGA package can be observed. This flexural behavior is due to the mismatch of CTE between the silicon die and the heat spreader (see Figure 1 and Table I). Since the former expands much less than the latter when the temperature is raised, the center portion of the package warps. From the shape of deformation, it is obvious that the innermost solder joint suffers the most from the said warpage. Therefore, the strain level in this solder ball should be higher than the others.

On the other hand, it should be noted that the PCB would expand more than the PBGA in the x-axis (see Figure 2) due to the larger CTE in that direction (see Table I). According to the theory of thermoelasticity, the amount of mismatch in this in-plane deformation depends on the distance from a neutral point (DNP)[3]. Since the outermost solder ball has the largest DNP, its strain level should be higher than the others. Owing to the competition between the aforementioned two effects, namely, bending of the package and DNP of solder joints, the strain distribution in Figures 4 and 5 becomes a concave shape. Based on the results from computational analysis, it seems that the DNP effect prevails for the cavity-down PBGA-PCB assembly. Therefore, the outermost solder ball becomes the most critical joint in the assembly.

In another investigation on the solder joint reliability of cavity-down PBGA[9], it was reported that the innermost

Figure 4
Distribution of maximum effective plastic strain in solder balls (package size = 35mm)

solder ball has the highest inelastic strain. It should be noted that the chip size and the package size in that study were 8mm and 20mm, respectively. Comparing to the configurations in the present study (chip size/ package size: 10mm/35mm and 12mm/40mm), the innermost solder ball in[9] is much closer to the die. As a result, the aforementioned second kind of local mismatch outgates the

DNP-based global mismatch in[9]. Therefore, a result different from the present analysis was observed. Note that the PBGA assembly in this paper was modeled along the diagonal cross-section. However, if the center cross-section were modeled instead of the diagonal one, then a higher level of inelastic strain in the innermost solder ball could have been achieved.

Figure 5
Distribution of maximum effective plastic strain in solder balls (package size = 40mm)

Concluding remarks

In this study, a finite element model was established to simulate the cavity-down PBGA-PCB assembly. The accumulated effective plastic strain in the solder joints was evaluated as an index of reliability. It was found that the distribution of maximum strain in each solder ball shows a concave profile. The highest and the second highest inelastic strains always appear in the outermost and the innermost solder joints, respectively. In addition, the

effects of package size and ball population were presented. The analysis on the deformation of the assembly was performed as well. Efforts were made to explain the results of analysis to a certain extent. Further study is needed in order to fully understand the interaction between various mechanisms of thermal mismatch. However, since the accumulated effective plastic strain in cavity-down PBGA assembly is rather small, it can be concluded that the solder joints of this package should be very reliable in applications.

Figure 6

Comparison of deformation outline (displacement scale factor = 30)

(a) 4-row Perimeter BGA with Package Size = 35mm

(b) 5-row Perimeter BGA with Package Size = 35mm

(c) 4-row Perimeter BGA with Package Size = 40mm

(d) 5-row Perimeter BGA with Package Size = 40mm

References

- 1 Freyman, B., "The next ten years of ball grid array packaging", *Presentation in SMTA Annual Meeting*, San Jose, CA, September 1996.
- 2 Lau, J.H., *Solder Joint Reliability: Theory and Applications*, VNR, New York, NY, 1991.
- 3 Lau, J.H., *Thermal Stress and Strain in Microelectronics Packaging*, VNR, New York, NY, 1993.
- 4 Lau, J.H. and Pao, Y.H., *Solder Joint Reliability of BGA, CSP, Flip Chip, and Fine Pitch SMT Assemblies*, McGraw-Hill, New York, NY, 1997.
- 5 Lau, J.H., *Ball Grid Array Technology*, McGraw-Hill, New York, NY, 1995.
- 6 Lee, S.-W.R., and Lau, J.H., "Effect of chip dimension and substrate thickness on the solder joint reliability of plastic ball grid array packages", *Circuit World*, Vol. 23 No. 1, 1996, pp. 16-19.
- 7 Lee, S.-W.R. and Lau, J.H., "Design for plastic ball grid array solder joint reliability", *Circuit World*, Vol. 23 No. 2, 1997, pp. 11-14.
- 8 Lee, S.-W.R. and Lau, J.H., "Solder joint reliability of plastic ball grid array with solder bumped flip chip", ASME Paper No. 97WA/EEP-6, ASME Winter Annual Meeting, Dallas, TX, November 1997.
- 9 Pao, Y.-H., Jih, E., Adams, R. and Song, X., "Thermal fatigue analysis of BGA solder joints," *Proc. Surface Mount International Conference*, San Jose, CA, September 1997, pp. 159-71.