Effects of solder balls and arrays on the failure behavior in Package-on-Package structure

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A B S T R A C T

In this article, the failure behaviors of different solder balls and arrays used in a commercial product were investigated experimentally and computationally. The results indicated that the effect of different solder balls and arrays on the failure behavior of Package-on-Package (PoP) structure cannot be ignored. For example, the failure mechanism of a structure with 2 × 15 solder balls could be characterized as a deformation-cracking-delamination model under axially tensile loading, while as a deformation-instability model under three-point bending loading. The allowable deformation of the former is ten times larger than that of the latter. In addition, the failure behavior for a structure with different solder balls and arrays varies. It is strongly dependent on the stiffness of PoP structure, which is dominated by the number and array of the solder balls. The relationship between the stiffness and the number appears nonlinear. More specifically, there is the maximum value for a structure.

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1. Introduction

With the development of science and technology, a wide range of electronic devices and products are prevalently used in micro-manufacturing, aerospace and automobile industries. The most novel designs with high performance including the intelligent functional electronic components are becoming more and more important and necessary. The electronic packaging is a key process in the electronic devices manufacturing, such as the micro-electromechanical systems (MEMSs) and ultra-large-scale integrated circuits (ULSIs) structure. As the development of ULSI and the sharp increase of packaging density, the structural features and multi-elements/multi-scale matching and service in complex/variable environments are essential challenges. In order to assure the failure-free performance in the electronic applications, we not only need to understand the physical failure mechanism of an electronic product, but also need to enable one to predict and quantify a threshold service condition by using effective qualification test and failure analysis [1,2]. Package-on-Package (PoP) is a novel 3-dimension (3D) high-density packaging method, which integrates the chip scale package (CSP) in the top part with the fine-pitch ball grid array package (FBGA) in the bottom part by using solder balls and printed circuit board (PCB) [3–7]. Thus, to date, it has become the first choice in several industries [3–5].

The packaging process raises a unique challenge since there is not any gap among the lower die bond wires. There are different types of solutions for stacking the dies including: dummy silicon-as-spacer; die attach paste-as-spacer and thick die attach film-as-spacer. The die attach competing technology is also different in the ability and reliability of the package process. Upon the structure, the die attach elements were sandwiched between two dies which need to maintain sufficient adhesion strength [7,8]. Moreover, there is a limit for these cohesive strengths in the PoP structure during service and there are some other important issues such as the capacity of carrying either loading or deformation for the package structure and reliability degradation at high temperature or cyclic thermal-stress effects without structural fracture.

In our previous works [2,8,9–13], the fracture/fatigue behaviors of different packages and film/substrate have been introduced based on a wild spectrum of experiment and finite element (FE) analysis. These results affirmed that the micro-crack initiation and propagation behaviors and failure models are dependent on the synergistic effects of the interface strength, the matching both copper film and different substrate materials, the effect of copper film thickness on the failure model for the film/substrate through the scanning electron microscope (SEM) in situ observation and scratch testing method. For instance, when the thickness of the copper film is far less than that of the substrate, the elastic instability of the copper film could easily occur at the free surface, subsequently the multi-crack takes place in the film layer [10,11,14]. However, when the thickness of the copper film is thick
enough, the interface crack would first initiate and then induce the copper film fracture. Therefore, the failure problems with the free surface and interface involved are complex, especially for the failure characterizations in the meso-scale. The aims in the present article are to characterize the failure behavior with effective factors then to obtain deeply insight into the physical failure mechanism of PoP structure under various mechanical loadings in order to improve packaging process.

2. Samples and experimental procedures

Samples used in the mechanical tests are cut from the actual structures (a commercial produce) including three main components of the top stacked die chip scale package (CSP), the bottom fine-pitch balls grid array (FBGA) package and the printed circuit board (PCB) as shown in Fig. 1(a). The package was cut using cutting machine with blade. The cutting speed of sample is 20 mm/s, and the revolution speed of the blade is 500 r/min. The cutting surfaces of the specimen were polished by an abrasive paper and carefully cleaned by the ethyl alcohol to reduce the influence of the coarse surface. To accomplish the aforementioned, the FBGA and PCB structures with different solder balls were cut into a series of samples with the different geometrical sizes, with different numbers and arrays of the solder balls. The samples were used for the SEM in situ observations either in the bending or in the axially tensile tests. The sample is subjected to the tensile loading through two pins combined with the loading system so that the solder ball is mainly carrying the shear loading as shown in a typical Fig. 1(b). In the three-point bending test, the span is 10 mm and the diameter of indenter is 2.5 mm. All samples for the SEM in situ observation are placed in the vacuum chamber (at a pressure of $10^{-4}$ Pa), and they are controlled by displacement at a rate of about $4 \times 10^{-4}$ mm/s. The displacement range of the system is ±25 mm. The signal of SEM was directly transferred to a computer via a direct memory access type A/D converter, referred to the previous literature [8,11,15–20]. The main parameters of the top package, bottom package in the FBGA structure and the printed circuit board (PCB) are listed in Table 1.

3. Experimental results based on SEM in situ observation

Fig. 2(a)–(f) presents the typical failure behavior of the samples with $2 \times 15$ solder balls and arrays in the axially tensile tests. When the applied tensile loading ($P$) and displacement ($\delta$) approach to about $P = 10$ N and $\delta = 0.024$ mm respectively, no significant deformation and interface crack between balls and substrate occur at all solder balls as shown in Fig. 2(a) and (b) which is the magnified version of the intact solder ball structure (marked with the symbol A) with a scale bar of 50 μm. However, with the increase of applied tensile loading ($P = 35$ N) and displacement ($\delta = 0.104$ mm) respectively as shown in Fig. 2(c), a slight plastic deformation appears in some solder balls, especially the asymmetry plastic deformation can be seen at corner of solder balls, such as in one marked with A as shown in Fig. 2(c). At this point, the applied tensile loading is not able to grow all the way down, but the displacement manages still to increase. It means that the structural damage of the structure with $2 \times 15$ solder balls and arrays occurs at either some interfaces or some corners of solder balls as shown in Fig. 2(d) and (e). When the displacement of the structure with $2 \times 15$ solder balls and arrays increases to 0.467 mm, the loading was fleetly dropped and the solder balls break successively away from either the top or bottom substrate as shown in Fig. 2(f). In Fig. 2(f), it is clearly seen that the separation distance between two solder balls shortens from over than 500 μm as shown in Fig. 2(a) to less than 20 μm as shown in Fig. 2(b) because either larger plastic deformation or delamination occurs in the solder balls. And the crack initiates first at the corners with the higher stress concentration. Therefore, the failure behavior of a structure with $2 \times 15$ solder balls and arrays can be concluded as the deformation-cracking-delamination model under the tensile loading.

In the SEM in situ tensile tests, the failure characterization was found that the failure location of a sample with solder balls was to occur periodically in some stress concentration points of solder balls from applied loading seat to the middle solder ball. The failure location of a sample with solder balls did not occur in all stress concentration points of solder balls even if each solder ball has the same stress concentration condition. One of effective reasons is that the periodicity damage behavior of the sample with solder balls should be dominated by the mechanical vibration of PoP structure which induces by loading amplitude destabilization even if we have a high control precision. The mechanical vibration of PoP structure should be the probability of large events when the control model was used the displacement at a rate of about $4 \times 10^{-4}$ mm/s, especially the damage loading amplitude of this structure is not over about 40 N. In present article, the relative softer element is solder balls and the relative harder element is the top or bottom substrate so that the perturbed point occurs easily at the solder balls. Therefore, to find the perturbed effect of the solder balls on the failure resistance, the fifteen cases with the different numbers were studied as shown in Fig. 3. And the relationship curves between the axially tensile loading and displacement for the representative eight cases among the fifteen cases are plotted in Fig. 4. Fig. 4 shows that the transformation tendency of all 8 force–displacement curves have some similarities. All the 8 curves can be divided into 3 phases: initial stage of the first 2 or 3 points, which caused by the simulation methods that can be ignored; linear stage of the linear period of the curves, where the force and displacement both increased linearly; failure stage, where the force increases slowly and the displacement increases rapidly. In order to discuss the differences of the experiments, the tensile
Table 1
Main parameters of the top, bottom package and printed circuit board.

<table>
<thead>
<tr>
<th>Geometrical parameters</th>
<th>Top package</th>
<th>Bottom package</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die size/mm</td>
<td>8 x 8 = 0.08 (die A, B)</td>
<td>7.6 x 7.6 x 0.08</td>
</tr>
<tr>
<td></td>
<td>7.8 x 7.8 x 0.05 (die C)</td>
<td></td>
</tr>
<tr>
<td>Number of die</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Substrate size/mm</td>
<td>14 x 14 x 0.128</td>
<td>14 x 14 x 0.100</td>
</tr>
<tr>
<td>Ball diameter/mm</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Ball material</td>
<td>SnAgCu</td>
<td>SnAgCu</td>
</tr>
<tr>
<td>Number of balls</td>
<td>152</td>
<td>491</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical parameters</th>
<th>Top package</th>
<th>Bottom package</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder ball</td>
<td>31.98</td>
<td>0.4</td>
</tr>
<tr>
<td>Die</td>
<td>162.72</td>
<td>0.28</td>
</tr>
<tr>
<td>Die adhesive</td>
<td>0.87</td>
<td>–</td>
</tr>
<tr>
<td>Molding compound</td>
<td>25.14</td>
<td>0.25</td>
</tr>
<tr>
<td>Copper piece</td>
<td>128.93</td>
<td>0.35</td>
</tr>
<tr>
<td>BT substrate (anisotropy)</td>
<td>$E_1 = E_2 = 15.03, E_3 = 6.90$</td>
<td>$\mu_{12} = 0.16, \mu_{13} = 0.24, \mu_{23} = 0.49$</td>
</tr>
<tr>
<td>FR4-PCB (anisotropy)</td>
<td>$E_1 = E_2 = 17.82, E_3 = 7.84$</td>
<td>$\mu_{12} = 0.11, \mu_{13} = 0.13, \mu_{23} = 0.39$</td>
</tr>
</tbody>
</table>

Fig. 2. SEM in situ observed images for solder balls ($\varnothing$300 μm) under axially tensile loading.

Fig. 3. Typical solder ball arrays models for experiments and simulations.
strength and stiffness were defined. The tensile strength indicates the maximum tensile force during the loading process and the stiffness indicates the slope of the linear stage. The results indicate that the axially tensile strength \( P \) and stiffness \( N/mm \) depend strongly on the number of the solder balls. The larger number of the solder balls number is, the higher of strength of the structure with the different solder balls is. In addition, the curves demonstrate a good elastic–plastic relationship of the solder balls. In elasticity regime, the slope of the curve is defined as the stiffness of the structure. It is important that the effect of a structure with solder balls on the stiffness is apparently non-linear. All stiffness values of these structures are plotted as shown in Fig. 5. It can be found the stiffness increases first with the number \( n \) of the solder balls with a maximum value when \( n = 9 \), and then decreases steadily with number of the solder balls. That is, when the number of solder balls is less than 18 \( (2 \times 9) \) solder balls, the stiffness of solder balls monotonously increases while it exceeds 18 \( (2 \times 9) \) solder balls, the stiffness relaxed decreases. The relationship between the stiffness and the number of the solder balls can be expressed as following:

\[
K = 82n - 146; \quad n < 9 \\
K = 34 + 729e^{-0.05n}; \quad n > 9
\]  

\( (1) \)

In addition, the effect of the stiffness on the failure behavior of the structure with solder balls and arrays should be considered in the reliability evaluations for particular products and applications. The effect mainly reflects that the failure location of solder balls and arrays is determined by the loading destabilization due to driving mode (a displacement control) controlled by several parameters, i.e. the rate of about \( 4 \times 10^{-3} \) mm/s and stiffness of PoP structure. Therefore, the failure behavior of a structure with either \( 2 \times 15 \) solder balls or \( 2 \times 9 \) solder balls experiences the same failure process of deformation-cracking-delamination under tensile loading except that the crack initiation location of solder balls differs from each other.

On the other hand, the SEM in situ experimental results under three-point bending loading indicate that the effect of different loading types on the failure behavior of a structure with the solder balls is also different. For example, Fig. 6 shows the failure behavior of the structure with \( 2 \times 15 \) solder balls and arrays. That is, the deformation-instability of solder balls contributes on the crack of the top substrate. The substrate crack and the solder ball instability is a common failure behavior of a structure with \( 2 \times 15 \) solder balls and arrays under 3-point bending loading, which is different from that under tensile loading. The interface crack was not found at the corners of solder ball even though there is a larger deformation of the solder ball as shown in Fig. 6(c). The deformation discrepancy of mark B and mark C is also obvious. The deformation of mark C is larger than that of mark B, but the crack initiation on the top substrate occurred near the mark B. It indicates that the geometrical instability of the bottom solder ball caused sufficient brittleness crack initiation and propagation of both the substrate and the solder ball array in FBGA and in CSP [2,13]. This reveals the fact that the failure process of a sample with \( 2 \times 15 \) solder balls and arrays in 3-point bending tests happens in the following order: deformation, instability of the bottom solder balls subsequently cracking of either the substrate or the die layer. The crack initiation location in either the substrate or the die layer is dependent on the stiffness matching of the different elements of FBGA or CSP structure, especially on the mechanical property and thickness of adhesive layer. This is due to the fact that the adhesive layer can affect the transmission of applied bending loading [2]. Meanwhile, the top substrate has broken when the bending deflection displacement is 0.05 mm and the applied loading is about 40 N. The critical failure value \( (0.05 \text{ mm}) \) for the deformation of the FBGA structure under three-point bending loading is far less than that \( (0.5 \text{ mm}) \) under tensile loading. Therefore, the effect of the applied loading types on the failure behavior of FBGA structures is more notable. For the case with tensile loading, the deformation of the solder ball induced the interface crack, while for the case under three-point bending loading, the deformation-instability of the solder balls caused the cracking of either the substrate or the die layer [2,13]. Therefore, the critical failure deformation value varies as well.

4. Discussion

The commercial FE software ABAQUS was used to simulate the fracture process. According to the SEM images and sizes of samples, the effective adhesive, a copper land with a size of \( 0.4 \text{ mm} \times 0.4 \text{ mm} \), is inserted between the solder ball (SnAgCu) and the substrate (FR4) as shown in Fig. 7. The mechanical parameters of materials were listed in Table 1. In general, the available traction-separation model [21,22] assumes that the initial linear elastic behavior is followed by the initiation and evolution of the damage for FBGA structures. The elastic behavior is expressed in terms of an elastic constitutive matrix that relates the nominal stress to the nominal strain across the interface between the substrate/copper piece and the solder ball. The nominal stress is equal.
to the force component divided by the original area at each integration point, while the nominal strain is equal to the separation divided by the original thickness at each integration point.

As for the three-dimensional simulation problem of the FBGA structure, the nominal traction stress vector \( \boldsymbol{\sigma} \) consists of three stress components, i.e. \( \sigma_x \), \( \sigma_y \) and \( \sigma_z \), which represent the nominal stress in the copper piece. All displacement increments unit thickness are \( \Delta t = 1, 2, 3 \), respectively. Therefore, the nominal strains are expressed as follows:

\[
\varepsilon_i = \frac{\Delta t}{t_0}, \quad \varepsilon_2 = \frac{\Delta t_2}{t_0}, \quad \varepsilon_3 = \frac{\Delta t_3}{t_0}
\]

The cohesive elements are used to model the bonded interfaces. The stress–strain relationship in the local component directions for the coupled traction–separation behavior is denoted by the following equation:

\[
\begin{pmatrix}
\epsilon_1 \\
\epsilon_2 \\
\epsilon_3
\end{pmatrix} =
\begin{bmatrix}
K_{11} & K_{12} & K_{13} \\
K_{21} & K_{22} & K_{23} \\
K_{31} & K_{32} & K_{33}
\end{bmatrix}
\begin{pmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3
\end{pmatrix}
\]

However, in practical applications, the uncoupled behavior, in which each traction component depends only on its conjugate nominal strain, was often adopted. The damage evolution law describes the rate at which the stiffness of the elements is degraded once the initiation criterion is reached:

\[
\sigma_1 = \begin{cases} 
(1-D)\sigma_1 & \sigma_1 > 0 \\
\sigma_1 & \text{otherwise}
\end{cases}, \quad \sigma_2 = (1-D)\sigma_2, \quad \sigma_3 = (1-D)\sigma_3
\]

where \( D \) denotes the overall damage in the material and reflects the combined effects of all the active mechanisms. It is equal to 0 at the initial state. \( \sigma_1 \), \( \sigma_2 \) and \( \sigma_3 \) are the stress components predicted by the elastic traction–separation behavior based on the current strain without damage. If the damage evolution of structure is modeled, \( D \) monotonically increases from 0 to 1 upon future loading after the initiation of damage. The stress components in the traction-separation model are affected by the damage according to Eq. (4). In addition, to describe the damage evolution under both the nominal and shear deformations across the interface, it is useful to define an effective displacement \( \delta_{\text{eff}} \).

\[
\delta_{\text{eff}} = \sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2}
\]

By defining another two variables, i.e. \( \delta_{\text{eff}}^0, \delta_{\text{eff}}^{\text{max}} \) and \( \delta_{\text{eff}} \) (effective displacements at the initial state, at the maximum point in the traction–separation relation [23–26] and after complete failure, respectively), the damage evolution of the FBGA structure can be represented. Therefore, the value of linear damage \( D \) can be calculated via the following equation:

\[
D = \frac{\delta_{\text{eff}}^f (\delta_{\text{eff}}^{\text{max}} - \delta_{\text{eff}}^0)}{\delta_{\text{eff}}^{\text{max}} (\delta_{\text{eff}}^0 - \delta_{\text{eff}}^f)}
\]

According to the load–displacement curve under tensile and three-point bending loadings, the simulation on the damage of the solder balls and arrays becomes possible based on the Eq. (6).

The von Mises stress and equivalent plastic strain distribution under tensile loading were plotted for the structures with 2 × 15 solder balls and arrays (A1–A15 are observable solder balls) as shown in Fig. 8. It is clearly seen that there are different responses between the von Mises stress and the strain fields under the same applied tensile loading (\( P = 34 \) N) or displacement (\( \delta = 0.400 \) mm). Fig. 8(a)–(c) shows the von Mises stress field at the restrained end (A1), middle point (A7) and the applied loading point (A15), respectively. The maximum von Mises stress at these three points is 18.89 MPa, 18.10 MPa and 18.86 MPa, respectively. The stress responses have two hallmarks that are (1) the maximum von Mises stress occurred at the corner of the top and bottom substrates due to the stress concentration, and the maximum von Mises stress in every solder balls from the restrained end (A1) to applied loading end (A15) is approximately the same of about 18.00 MPa (its error is less than 5%); (2) but the maximum stress in the middle solder ball (A7) is the largest than that in other solder balls, in which its evolitional rate is the fast. This is because the mechanical vibration caused by the relative stress peak during the loading destabilization spreading process that may occur mainly in the middle solder ball (A7) but would not happen at the restrained end (A1) and the applied loading end (A15). It verifies the fact that the maximum stress occurred easily at the corners of the solder balls at the restrained end (A1) and the applied loading end (A15). Therefore, the failure location is easily found at these seats, subsequently either failure or instability will cast influence on the loading destabilization spreading when the control model was used by the displacement. Therefore, attention should be paid to the failure behavior of the restrained end (A1) and the applied loading end (A15) as well as the middle solder ball (A7) for the sample with 2 × 15 solder balls and array. However, the failure criterion of the solder balls is based on the Eq. (6) so that it is necessary to estimate the equivalent plastic strain fields for every solder ball. As the
solder ball has a good ductile, the failure behavior of the solder ball should be mainly dominated by the plastic deformation. Fig. 8(e) and (f) show the equivalent plastic strain fields of corresponding solder balls. The results imply that the maximum equivalent plastic strain field is still concentrated either at the top or bottom of the solder ball near the substrate as shown in Fig. 8(e) and (f). So the failure probability is the most at the solder balls A1 and A15 solder ball. Therefore, the effect of solder ball array on the failure behavior under the tensile loading for the FBGA structure cannot be ignored. At the same time, the FE analysis agrees well with the SEM in situ observable results.

To validate the effect of the different solder balls and arrays on the failure behavior of actual FBGA structure, the actual numbers (152 the case when the diameter of the ball is $\phi = 500 \mu m$ and 491 for the case $\phi = 300 \mu m$) and actual array patterns of the solder balls are used in FE simulation. Fig. 9 shows the von Mises stress distribution of the solder balls under three-point bending loading when $\delta = 0.05 mm$. The von Mises stress fields reflect the complex distribution including that the stress level at the maximum deflection is less than that at other locations along the span direction ($X$-direction as shown in Fig. 9(a)). The stress distribution along the width direction of the sample ($Y$-direction as shown in Fig. 9(a)) indicated that the maximum von Mises stress occurred in the inner solder balls. It means that the failure is easier to happen in the inner solder balls. It is very difficult to detect these failures based on the general observational technology. In addition, due the diameter of solder ball on the top FBGA as shown in Fig. 9(b) is $\phi 500 mm$, the maximum von Mises stress field of the solder balls occurred near the maximum deflection. And the von Mises stress for the single solder ball concentrates at the corner or in the interface between the solder ball and substrate as shown in Fig. 9(b). Moreover, the amplitude of the von Mises stress field...
1. In the axially tensile test, the failure behavior of solder balls and two arrays obeys the evolutive process of deformation-crack-delamination of solder balls. The allowable deformation of a structure with $2 \times 15$ solder balls and arrays is 0.5 mm.

2. In the three-point bending test, the failure behavior of solder balls and two arrays could be characterized as the evolutive process of deformation-instability of solder ball, subsequently induced the crack-fracture of either substrate or die layer. The critical deflection deformation of a structure with $2 \times 15$ solder balls and arrays is 0.05 mm which ten times is less than that under tensile loading.

3. The failure probability of a structure with solder balls and arrays depends strongly on the stiffness of a structure with solder ball’s number and array. Moreover, the stiffness change trend is mainly determined by the solder ball numbers, the structure with $2 \times 9$ solder balls stands as a watershed value.

4. Considering the actual characterizations of PoP structure including two solder ball diameters of $\varnothing 300 \mu m$ and $\varnothing 500 \mu m$ as well as different numbers and arrays models on the substrate, the von Mises stress distribution fields under three-point bending indicated that the failure of solder balls would mostly likely occur at the near outer edge solder balls instead of the outer edge solder balls. It is of great challenge to detect the failure of solder balls based on an observable method.

5. Conclusions

Based on SEM in situ observations on the failure processes of different solder balls and arrays under different loading types and FE simulating analysis of actual FBGA structure, the effect of solder ball arrays on the failure behavior of FBGA structure under the tensile and three-point bending loadings are briefly concluded as following:

5.1 Concluding remarks

(a) von Mises stress distribution field for $\varnothing 300 \mu m$

![Image](https://example.com/s300.png)

(b) von Mises stress distribution field for $\varnothing 500 \mu m$

![Image](https://example.com/s500.png)

Fig. 9. Compared with the typical stress distribution fields for different sizes of solder balls under three-point bending loading $(\sigma \times 0.05 \text{ mm})$.

along the span direction (X-direction) is larger than that along the width direction (Y-direction).

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