Dynamic behaviour of electronics package and impact reliability of BGA solder joints

Q Yu¹, H Kikuchi¹, S Ikeda¹, M Shiratori¹, M Kakino², N Fujiwara²
¹Department of Mechanical Engineering and Material Science, Yokohama National University, Japan.
²Production Engineering Laboratory, Corporate Production Engineering Division, Matsushita Electric Industrial Co., Ltd

Abstract

The purposes of this study are to clarify the dynamic behavior of BGA(Ball Grid Array) or CSP(Chip Scale Package) packaging subjected to an impact loading, and to establish a simple analytical method of impact reliability assessment for solder joints. A 3-D analytical model of PCB mounted with a BGA chip was used to simulate the impact behavior of BGA packaging, and explicit-based FEM code LS-DYNA was used to carry out the dynamic analysis. It was found that the impact reliability of solder joints is greatly affected by the falling posture. However, it was found that fine meshing of solder joints causes a rapid augmentation of calculation cost. In this study, the authors proposed a new method of transient response analysis by utilizing implicit-based FEM code NASTRAN to drop the calculation cost of impact study. It was shown that the present method can accurately simulate the dynamic behavior of BGA packaging including the time histories of the deformations and stresses, and it can drop the CPU time to about one tenth of that of LS-DYNA analysis. Furthermore, based upon the analytical and experimental results, it was found that the impact reliability of solder joints is dominantly affected by the first mode vibration of PCB, and the effect of the higher modes can be neglected. Finally, a basic concept for impact reliability assessment method was proposed for CSP solder joints based on the results of the present analytical method and set of free fall drop tests of PCB(Printed Circuit Board) mounted with a CSP chip.
1 Introduction

Recently, it is noticeable that electronic equipment tends to be minimized and portable, such as cellular phones, notebook PCs etc. Until now, the assessment of fatigue life reliability for solder joints in electronic devices was carried out by applying a thermal cyclic loading. Nevertheless, as a new problem, it appears that solder joints are broken by the drop-impact, which is a tendency of portable electronic equipment. However, the dynamic behavior of solder joints in a BGA or CSP Package is not quite clarified, so impact reliability assessment for solder joints has not been still established. The purposes of this study are to clarify the basic dynamic behavior of BGA packaging subjected to an impact loading. The detailed contents of this study can be stated as follows:

1) The effects of the collision condition between a cellular phone and the ground. (falling angle)
2) The effects of the dynamic deformation behavior (vibration behavior) of PCB.
3) Basic impact-induced failure mode of solder joints.

In this study, a free fall drop-impact test was used, and explicit-based FEM code LS-DYNA was used to study the basic behavior of the drop-impact test. The effects of falling angle were discussed by the analytical results of the LS-DYNA model. The effect of the dynamic deformation behavior of PCB was evaluated by using transient response analysis, and implicit-based FEM code NASTRAN was applied. At the same time, the dynamic material properties of solder joints and PCB were measured. Finally, the impact failure mode of solder joints was studied in line with concepts of fracture mechanics and the experimental results.

2 The relation between fatigue life and drop height for free fall drop test

The authors have carried out a free-fall drop test of the BGA package mounted on the PCB. As the test conditions, a test piece of PCB with a BGA package fixed to the jig is released from the hand as it became horizontal with the ground. The cycle to failure were defined as the cyclic number when the BGA solder joints at the package corner break. The falling height was changed from 30cm to 100cm at intervals of 10cm. Figure 1 shows the relation between the fall-height and the cycle to failure. It is indicated that almost all plots are on a linear curve. However, as the falling height is higher than 80cm, the variation of cycle to failure increases. It is thought that the PCB can keep its balance and drop to the ground with horizontal posture when the fall height is lower than 70~80cm.

On the other hand, if the falling height increases to above 80cm, the balance of PCB will be upset by the air resistance and its posture cannot really be kept horizontal before the collision. This is because the air resistance to the rear surface of the jig is proportional to the square of its speed, and as its speed increases over about 3.5m/s, the jig can easily be upset by the air resistance. As a result, the kinetic energy absorbed by the PCB decreases because of the slanted
posture, and the failure life of BGA solder joints increases in comparison with the case where a horizontal collision occurs.

![Graph](image)

Fig. 1 Results of free fall drop test

### 3 The repetitive drop test

Based upon the experimental and analytical results, a new drop test equipment was used as shown in Fig. 2, and new CSP specimens were used. Generally, besides the CSP package, there are many other devices on the same PCB, and the dynamic behavior of PCB is affected by their weight, and so forth.

![Diagram](image)

Fig. 2 Repetitive drop test equipment

Here, a weight was attached at the center of PCB of TYPE A, as shown in Fig. 3. Furthermore, another kind of specimen TYPE B, was also prepared to study the effect of the vibration modes of PCB on the impact reliability. In TYPE A, the CSP package was mounted at the center of jig, and in TYPE B, the package was shifted 10mm from center of jig. The specimens were dropped repetitively along the guide rails that horizontally control the attitude. After every 5 cycles, whether or not the crack appeared in the solder joints was
observed with a microscope. The relation between the falling height and the cycle to fatigue crack appearance is shown in Fig.4. Because the package in TYPE A was set up at the center of PCB, the failure probability of the solder joints at four corners was almost equal. The results for TYPE B as those of TYPE A, under testing in the same conditions, it is not only clear that the fatigue life is longer than that of TYPE A, but also that the cycles to failure at the left corner of the package are different from those at the right corner.

![Image of Specimens](image)

**Fig.3 Types of the Specimens**

![Graph of Results](image)

**Fig.4 Results of Repetitive drop test**

4 **The effects of high frequency flexural vibration and damping for solder joints**

It has not been clear how the high order vibration modes affect the impact reliability. To establish a reliability assessment method for the impact problem, it is very important to judge whether the high order modes should be included or not. This is because there seems to be hope of a simple assessment approach, if it becomes clear that the first normal mode dominantly affects the impact
reliability. Here, FEA was used to confirm the above problem. The test results of TYPE A and TYPE B are listed in Table 1.

<table>
<thead>
<tr>
<th>Drop Height (cm)</th>
<th>Cycle to Crack generating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TYPE A</td>
</tr>
<tr>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>70</td>
<td>11</td>
</tr>
<tr>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>Average</td>
<td>12</td>
</tr>
</tbody>
</table>

It can be inferred that the solder joints in TYPE A are affected by the 1st mode deformation of PCB more than in TYPE B. Nevertheless, it has to be studied using detailed FEA to confirm which corner (right or left corner) in TYPE B is more affected by the 1st mode deformation. The transient response analyses were carried out to examine the correlation between the test results and the analysis results, where the FEM code NASTRAN was used. As analytical conditions, an initial velocity of 3.7 m/s was given to all nodes in y-direction supposing the case with a falling height of 70 cm, and only the base surface of the supporter was fixed in the y-direction. And the relative displacement in the Y direction between the upper surface and the under surface of solder joints at the end of the package was chosen as the evaluation parameter. The results of the left solder joints and the right joints in TYPE A and in TYPE B are shown in Figures 5-1, 5-2, and 6-1, 6-2, respectively.

Fig. 5-1 Relative displacement of left corner solder
In each fatigue, two kinds of analytical results are plotted, one is the transient response analysis with damping neglected, the other is the analysis with damping included, where the damping ratios were measured by the experimental results. From the results of TYPE A, it is found that at the both ends of a package, the relative displacement histories are almost equal. Based upon the results with damping included, it is found that the period of the early vibration cycles is very short, and its frequency (3110Hz) is equivalent to the characteristic frequency of the second mode of PCB, and there is no difference between the peak values at the right and left ends of the package.

Fig. 5-2 Relative displacement of right corner solder

Fig. 6-1 Relative displacement of left corner solder
Fig. 6-2 Relative displacement of right corner solder

Fig. 7 TYPE A MODE 1 (768Hz)

Fig. 8 TYPE B MODE 2 (1810Hz)
However this high frequency vibration is quickly damped, and after several cycles, the first mode vibration (768Hz) becomes the dominant response, where its deformation mode is shown in Fig.7, and the peak values at both ends are equal. As a result, no difference of the failure probability between both ends could be confirmed by the experimental results. Therefore, which mode (first mode, the higher modes) is the dominant factor for the impact reliability could not be clarified. However, the facts were examined by the results of TYPE B model. The analytical results of TYPE B model are shown in Figures.6 and 8. It is found that the peak values and the frequency of the early cycles are very similar to those of TYPE A, and no difference between the right and left ends can be confirmed. As mentioned above with the experimental results shown in Table 1, the average cycle to failure of the solder joints at the right end in TYPE B is longer than that in TYPE A, and the cycles differ between the right joints and left joints in the same TYPE B. Therefore, the results of the high mode vibration (the peak values) do not match the tendency of the experimental results.

On the other hand, after the high mode vibration is damped, the peak values of the basic mode show very good agreement with the experimental results. That is to say that the solder joints can be set in order of impact lives as (1) left solder joints in TYPE B, (2) right solder joints in TYPE B, and (3) left and right joints in TYPE A, and at the same time, the solder joints can be set in the same order of the peak values of relative displacement of the basic mode vibration. In conclusion, only the first mode (basic mode) should be included into the scenario for the reliability assessment of the impact problem, and the behavior of the second mode and the higher modes can be neglected. In this case the weight of chip is very light and the inertial load due to the weight is dispersed to every BGA bump, so it can be considered that the effect of inertial load of the chip on the corner BGA bumps is negligible.

5 The crack growth assessment in drop impact problem

From the results of the repetitive drop test, it was found that the dynamic fatigue crack concentrates at the interface between the copper pad and solder bulk, as shown in Fig.9, and the existence a large plastic deformation domain around the crack tip was not found.

![Fig.9 Picture of the dynamic fatigue crack](image-url)
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strength due to the sampling location (the upper and the lower samples on the produced ice matrix, see Figure 1) in the same case \((d \text{ and } d/a)\) was investigated. Figure 2 (right side) shows that the difference in the strength between the upper and the lower samples \((\sigma_u, \sigma_d)\) (see Figure 1) was less compared with level ice.

From the above discussion, it seems that the difference in ice strength according to the location and direction of ice is small in an ice ridge model compared with level ice. Although the results were based only on the average of sample data, we could also show the same results using ANOVA (analysis of variance). Generally, level ice shows anisotropy, in which the strength varies depending on the direction of the crystallographic axis and the size of the crystals. In other words, the strength of level ice is affected largely by the direction and location of ice, while ice ridge model does not show much difference wherever the ice is located or directed. Thus it can be supposed that the ridge model ice in the experiments has no specific alignment and no specific crystal size, since pre-crystallized ice blocks are randomly arranged and voids among ice blocks freeze up from the part close to the ice blocks.

3.2 Uniaxial compressive strength for ice ridge model with diameter \(d\) of core sample to representative length of ice block \(a\)

Figure 3 shows ridge strength versus \(d/a\) for each diameter \(d\) of core sample. Except the cases of small \(d/a\) (less than about 1) and very large \(d/a\), the strength seems to decrease slightly as \(d/a\) increases. But the analysis of variance shows little effect on strength of the change in \(d/a\). When \(d/a\) is close to 1 or less than 1, the strength tends to be low. In case that the diameter of core sample was small relative to ice block size, a flat and continuous block surface, including an interface between a block and a void, will be dominant or visible in the specimen since the ice blocks are almost cubical. Hence, the specimen will cause a failure easily due to such surface or interface, and the strength also depends on orientation of the interface. When \(d/a\) is less than about 1, the scattering in values
Furthermore, when the falling height is higher than 80cm, it is considered that an unstable fracture of the interface crack occurred. From the classified domain shown in Fig.11, the dynamic fracture toughness for the interface crack in solder joints can be calculated as $K_{IC} = 15\text{MPa√m}^{\frac{1}{2}}$.

6 Conclusions

1) Based upon the correlation of analytical and experimental results, it was shown that the 1st normal mode vibration is more dominant in the dynamic fracture of solder joints than higher modes.

2) Based upon the repetitive drop tests, it was found that the relation between the fatigue life and the falling height can be divided into two domains. If the falling height is higher than a critical value, an unstable fracture of interface crack will occur, and the dynamic fracture toughness for the interface crack in a solder joint can be roughly established at $K_{IC} = 15\text{MPa√m}^{\frac{1}{2}}$.

References


