



Effect of the drop impact on BGA/CSP package reliability

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Abstract

In this study, ball grid arrays (BGAs) and chip size packages (CSPs) were evaluated with respect to their solder joint reliabilities under drop impacts. The correlation between solder joint stresses and motherboard strains was confirmed by numerical analysis, and the motherboard strains caused by the drop impacts were measured to evaluate the BGA/CSP reliability. The authors found that the stress at a solder joint differs depending on the package structure, even if the motherboard strain is the same, and that underfilling eases the motherboard strain and disperses the stress concentrated on a solder joint. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

For the past several years, the personal digital assistants (PDA) devices like mobile telephones have become smaller and more light weight at a remarkable speed. Fig. 1 shows the weight transition of mobile telephones in Japan. For weight reduction, the great contributing factor is the adoption of ball grid arrays (BGAs) and chip size packages (CSPs) having structures that effectively reduce mounting areas.

Regarding the reliability of the BGA/CSP joints, many studies primarily by temperature cycle tests have been reported, and package materials and structures for such joints have been proposed to ensure high reliability [1–3].

When mobile telephones and any other PDA devices are used, the BGA/CSP solder joints seem to sustain a significant amount of damage not by external temperature changes but by short-time stresses such as drop impacts [4–6].

The authors mounted many kinds of BGA/CSP packages on motherboards and then performed drop tests and temperature cycle tests. Almost all packages satisfied our objective reliability in the temperature cycle tests, but many packages did not do so in the drop tests. The location of damage was at different places on the package side and on motherboard side, depending on the sample conditions.

This paper reports the results of surveying the reliability against drop impacts with the parameters of package structure, board pattern (resist type) and pattern adhesive strength; and the effectiveness of underfilling is also reported.

2. Relationship between stress and strain

The stresses that a solder joint receives from a drop impact are difficult to measure. Therefore, this is a great subject to clarify for evaluating reliability. In this study, based on the assumption that package-mounted motherboards were dropped onto the floor with the package side down, numerical analyses were performed about the solder bump stress and the motherboard strain. Solder bump stress; at the corner bump in a BGA/CSP, the Z-axis package (perpendicular to the motherboard). Motherboard strain; generated at the position 0.5 mm

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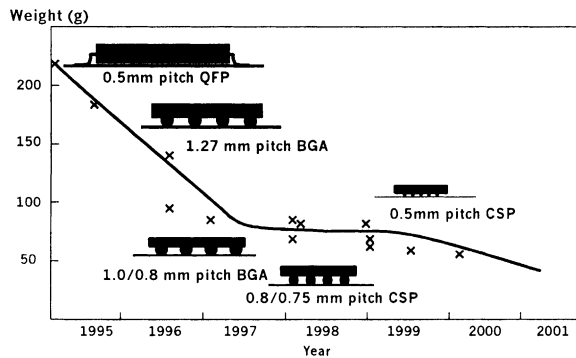


Fig. 1. Weights of mobile telephones in Japan.

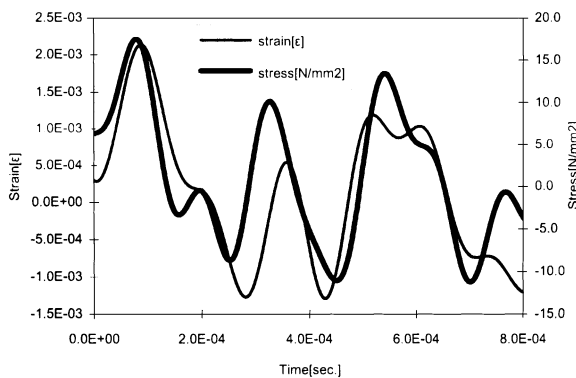


Fig. 2. Stress on solder ball and strain of motherboard obtained by numerical analysis.

away from the pattern where the corner bump is connected. For this numerical analysis, the non-linear dynamic analysis program LS-DYNA3D was used. Fig. 2 shows the analysis results. The solder bump stress and motherboard strain were found to show changes of an almost equal phase. In experiments where boards and packages were almost the same conditions, the joint damage was greater as the board strain was greater [7]. Based on those results, the authors performed drop tests on BGA/CSP-mounted boards while measuring the motherboard strains generated.

3. Strain measurement and drop test

Fig. 3 shows a schematic of the drop test. A motherboard mounted with a BGA was directly dropped with the package side down from a height of 1 m onto a floor, and its strain waveform was measured. The test sample was a motherboard with strain gages affixed exactly to the surface on the opposite side of a BGA package corner bump.

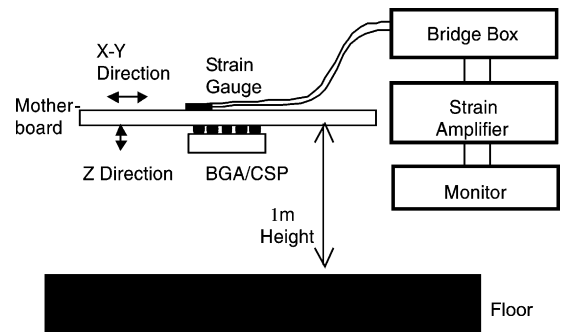


Fig. 3. Drop test.

motherboard : $30 \times 120 \text{ mm}^2$, 0.7 mm thick,

BGA : $20 \times 20 \text{ mm}^2$, 0.8 mm pitch,

strain gage : gage length 0.2 mm.

Fig. 4 shows a measured strain waveform for the drop test sample. The motherboard received elongation and compression strains repeatedly within periods as short as 40 ms. When a collision between the BGA and floor generated a compression stress at the bump, an elongation strain was generated on the other side of the motherboard. When the board bounced, we assumed an elongation stress was generated at the bump and the board surface received a compression strain. Since a solder bump cannot withstand the elongation and compression stresses generated within this short time, a rupture was expected to occur at a solder joint.

The strain changed depending on the drop height and motherboard weight. Simultaneously the joint damage was greater as the board strain was greater.

Fig. 5 shows a strain waveform of a motherboard inside mobile telephone dropped from a height of 1.5 m.

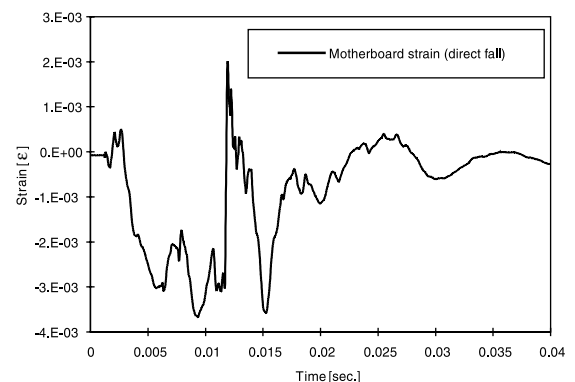


Fig. 4. Strain of motherboard.

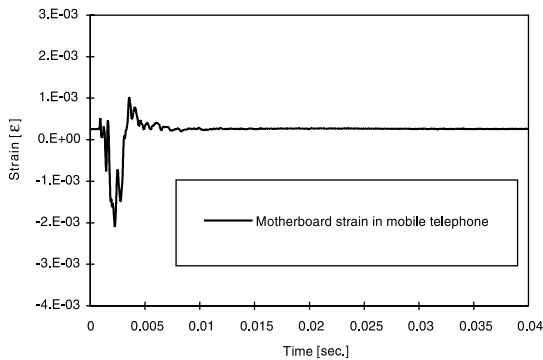


Fig. 5. Strain of motherboard in mobile telephone.

The measurement location was on the opposite side of a motherboard where a BGA of $20 \times 20 \text{ mm}^2$ is mounted. In this measurement, the strain of a motherboard also differed depending on the product shape, screw location, and package layout. However, almost all strain values were lower compared to those for a motherboard dropped directly onto a floor.

To evaluate the reliability against drop impacts, we decided to drop motherboards with the package side down onto a floor from a height of 1 m in subsequent experiments. A daisy chain between a board and a package was designed, and each experiment was performed while the daisy chain resistance was measured. When the loop resistance fluctuated by 10% or more from its initial measurement, we judged the corresponding sample as a failure.

4. Effect of package design

4.1. Test samples

Fig. 6 shows the structure of three types of packages evaluated on motherboards in this study. Package A consists of a chip die-bonded onto a buildup multilayer board of 0.7 mm thick and encapsulated in an epoxy resin (size: $20 \times 20 \text{ mm}^2$). Package B consists of a chip die-bonded onto a polyimide substrate of 0.07 mm thick and encapsulated in an epoxy resin (size: $6 \times 8 \text{ mm}^2$). Package C consists of a chip and a polyimide substrate of 0.05 mm thick with a 0.15 mm thick elastomer between them (size: $6 \times 8 \text{ mm}^2$).

Eutectic solder (Sn/Pb) was used for both the package ball and soldering paste.

4.2. Test results

Table 1 lists the drop test results. The numerators of the fractions in the table indicate the total numbers of

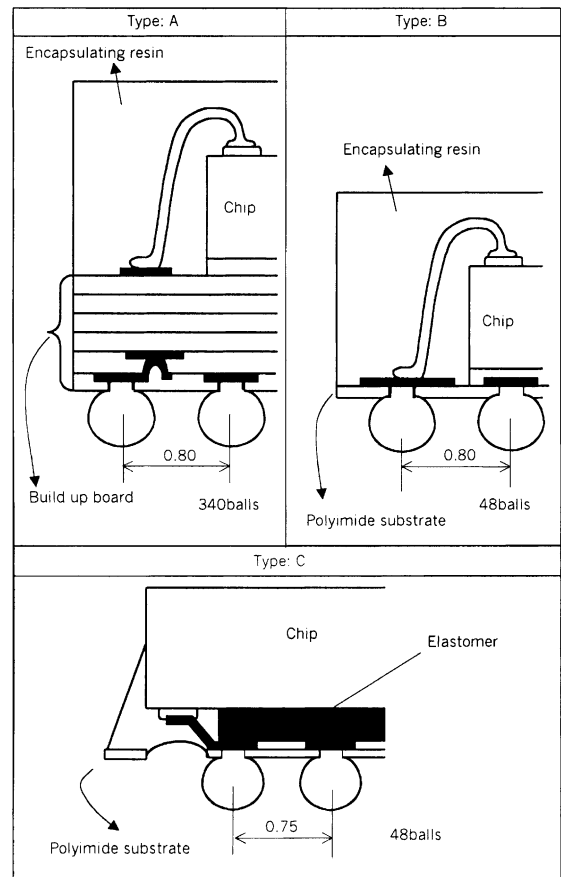


Fig. 6. Test samples: package (mm).

Table 1

Results of drop tests (numbers of failed samples/test samples)

Package	1 m × 5	1 m × 10	1 m × 20	Strain
A	1/10	1/10	2/10	5E-03 ε
B	0/16	3/16	10/16	2E-03 ε
C	0/13	0/13	0/13	2E-03 ε

Board: Non-solder mask defined (NSMD) pad, buildup board.

samples judged as failures after the samples were dropped 5, 10, and 20 times from a height of 1 m. The denominators indicate the numbers of samples tested. Each strain value indicates the maximum strain along a motherboard surface on the opposite side of a package corner bump. The strain tended to increase with larger packages.

According to the test results, joint reliability cannot be properly evaluated with only board strains if different types of packages are mounted. In other words, joint reliability was obviously different between packages B and C, whose motherboard strains in the drop tests were almost equal.

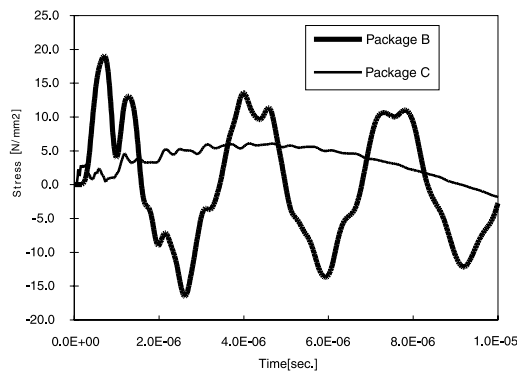


Fig. 7. Numerical analysis of solder ball.

For B, 10 of 16 samples failed after 20 drops from a height of 1 m. For C, however, 13 samples did not fail even after 20 drops from a height of 1 m. In dye penetrant tests, the samples of B judged as failures showed solder cracks near the package patterns. We believe this reliability difference is attributable to the package structure. The elastomer (Young's modulus: about 6 N/mm²) between the Si chip and polyimide substrate in the samples of C seemed to have absorbed the elongation and compression stresses at the solder between the package and motherboard.

A numerical analysis was performed on the samples of B and C. Fig. 7 shows the time transition of a stress generated on a solder joint interface (on the Z-axis; perpendicular to a interface) when a board was dropped from a height of 1 m. Consequently, the stress was found to be small in the samples of C.

5. Effect of motherboard design

5.1. Test samples

Fig. 8 shows the structures of the motherboard used in this study. Resist does not overlap the pattern in the non-solder mask defined (NSMD) pad, but it does overlap by 50 μ m around the edge of the pattern in the solder mask defined (SMD) pad. The motherboard thickness is 0.70 mm. From the point of view of pattern adhesive strength, the motherboard samples can be further classified as buildup boards of 16.7 N/mm and Aramid-epoxy boards of 6.9 N/mm.

5.2. Test results

Table 2 lists the drop test results for the buildup boards.

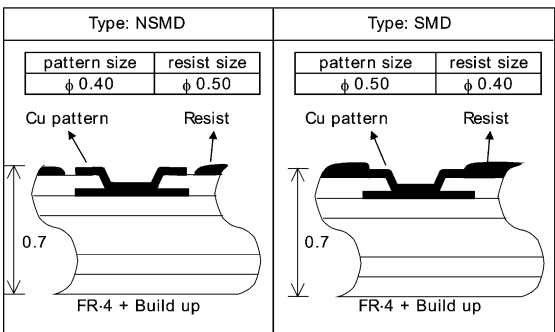


Fig. 8. Test samples: Buildup board for 0.8 mm pitch CSP (mm).

Table 2
Results of drop tests

Buildup board	1 m $\times$ 5	1 m $\times$ 10	1 m $\times$ 20
NSMD	1/10	1/10	2/10
SMD	5/10	8/10	8/10

Package: Type A.
Board: solder mask defined (SMD) pad.

Table 3
Results of drop tests

Aramid-epoxy board	1 m $\times$ 5	1 m $\times$ 10	1 m $\times$ 20
NSMD	10/10	–	–
SMD	8/10	10/10	–

Package: Type A.

By comparing the effects of motherboard resist among the packages of A, more failed samples were found in the SMD type. When Ni/Au-plated electrodes were used on the motherboards, many interfacial cracks were observed between the Ni and Ni–Sn alloy layers. The SMD type tends to have the problem of stress concentrations at this electrode interface. The NSMD type, however, demonstrated high reliability, seemingly because of the advantages of the three-dimensional form encapsulating the motherboard pattern with solder.

Table 3 lists the results when Aramid-epoxy boards of low electrode adhesive strength were used. Electrode delaminations from the motherboards occurred at high frequencies in the NSMD type and lowered the reliability.

These results indicate that motherboards should be designed by considering the pattern surface treatment conditions and pattern adhesive strength.

6. Underfill process

It is currently impossible to change all of the BGA/CSP structures to C in order to improve the reliability

against drop impacts. In addition, the reliability is difficult to improve because fine-pitch patterning limits pattern designs. Therefore, packages and motherboards vulnerable to drops require other methods to enhance the reliability. To ensure high reliability against drop impacts under all circumstances from manufacturing to use, we studied the application of underfilling to BGA/CSP packages.

With reducing manufacturing load as the first priority, we selected and developed materials that are easy to apply, infiltrate between packages and motherboards, and cure completely at low temperatures in a short time (Table 4). For evaluation, epoxy resins E and F and silicon resin G were used. All of these resins cure at 150 °C within 10 min.

Table 5 lists the drop test results when these resins were used.

Epoxy resins of great Young's modulus were found to be more effective at improving the drop reliability than silicon resins of small Young's modulus. The reliability was different between E and F, although both are the epoxy type. The test samples using resin F exhibited the problem of electrode delaminations from motherboards.

The resin adhesion to motherboards differed between E and F; it was about 23.5 N/mm² for E and 16.7 N/mm² for F. Resin F may have peeled from boards because of a low adhesive strength, resulting in pattern delaminations. Considering these results, an appropriate underfill resin requires a great Young's modulus and high adhesion to motherboards and packages.

Fig. 9 compares the measured strain waveform between samples underfilled with resin E and samples without underfilled. Underfilling obviously reduced strain and accelerated attenuation.

However, underfilling was expected to lower the reliability in temperature cycle tests because the coefficient of thermal expansion differs between the underfill resin and the motherboard or package materials (coefficient

Table 4
Underfill resin

Resin	Young's modulus (N/mm ²)	Hardening conditions
E	3528	150 °C/10 min
F	2803	150 °C/10 min
G	5	150 °C/10 min

Table 5
Results of drop tests (underfilled samples)

Resin	1 m × 1	1 m × 5
E	0/10	0/10
F	2/10	3/10
G	10/10	–

Package: Type A.

Board: Aramid-epoxy board, NSMD pad.

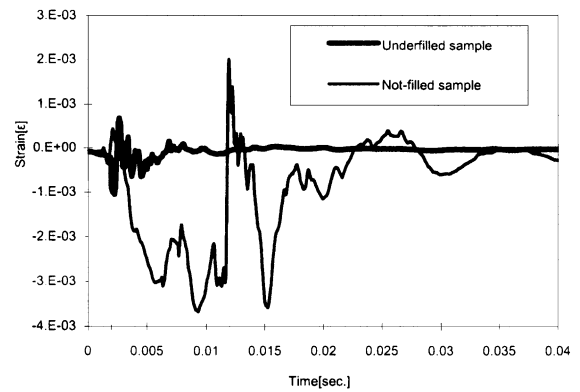


Fig. 9. Strains of motherboards with and without underfilling.

Table 6
Results of temperature cycle tests

Package	Resin	100 cycles	300 cycles
A	–	0/10	0/10
	E	0/10	0/10
C	–	0/14	0/14
	E	0/16	3/16

Conditions: –65 to +125 °C (30 min/30 min).

Board: Aramid-epoxy board, NSMD pad.

of thermal expansion for resin E: about 80 ppm/°C). Therefore, temperature cycle tests were performed on samples underfilled with resin E. Table 6 lists the test results.

The samples of A show sufficient reliability. The samples of C show deterioration of reliability after 300 cycles, but they satisfy our criterion of 100 cycles for mobile equipment. When the failed samples after 300 cycles were inspected, cracks were detected at the soldered sections of C-type packages.

A great variety of BGA/CSP packages are used in products, where the state of the package surface in contact with an underfill resin is not uniform and the coefficient of thermal expansion varies according to packages (the encapsulating resin). Therefore, a new underfill resin should be developed through further studies on the trends of development and materials of BGA/CSP packages and motherboards.

7. Evaluation of fine-pitch CSP reliability

The demand for CSP of the real chip size has resulted in the reduction of the solder ball pitch to 0.5 mm. Compared with a 0.8 mm pitch CSP, a 0.5 mm pitch CSP has an electrode area of about 1/2 and a bump volume of about 2/7. The bump height was also reduced to about 200 μm. The corresponding connection

Table 7
Results of drop tests

Package	Resin	1 m × 10	1 m × 20
B	–	10/10	–
(0.5 mm-p)	E	0/10	0/10

Package: Type B, 0.5 mm pitch, 240 balls.
Board: Aramid-epoxy board, SMD pad.

Table 8
Results of temperature cycle tests

Package	Resin	100 cycles	300 cycles
B	–	0/10	0/10
(0.5 mm-p)	E	0/10	0/10

Condition: –65 to +125 °C (30 min/30 min).
Package: Type B, 0.5 mm pitch, 240 balls.
Board: Aramid-epoxy board, SMD pad.

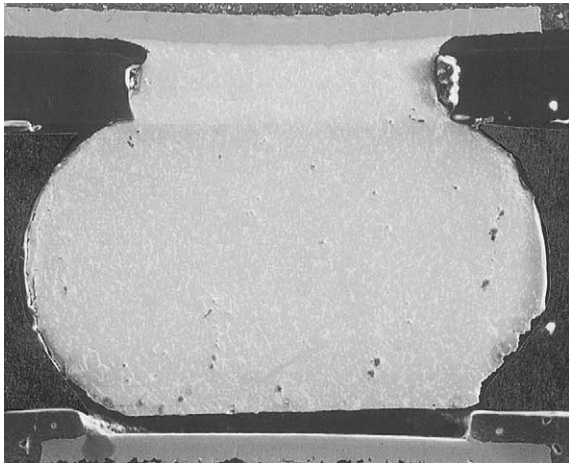


Fig. 10. Cross section of 0.5 mm pitch CSP solder joint (after drop test).

strength per bump was also lower, so even a slight shock was found to cause permanent damage to a solder joint.

Tables 7 and 8 list the reliability evaluation results for 0.5 mm pitch packages of type B (size: 10 × 10 mm², 240 balls). Fig. 10 is a SEM image showing the cross section of a sample after damaged by drop tests. Samples mounted on motherboards with Ni/Au-plated electrodes showed interfacial cracks between the Ni and Ni–Sn alloy layers. The underfilling material adopted for use in this study was found to permeate fully to even the lower part of the 0.5 mm pitch CSP and ensured high reli-

ability against drop impacts and temperature cycle stresses.

8. Conclusion

The authors have evaluated the reliability of BGA/CSP solder joints against drop impacts and clarified the following points:

(1) The characteristics of a stress generated by a drop can be estimated by measuring motherboard strain. However, the stress size depends on the package structure.

(2) Underfilling reduces the motherboard strain and the stress of solder ball.

(3) An underfill resin should be developed from resins with high Young's modulus and strong adhesion to motherboards and packages by checking the coefficients of thermal expansion against those of motherboards and packages.

9. Future work

(1) Surveying the effects of strain acceleration on solder joint reliability.

(2) Establishing an impact test method that can reproduce strain waveforms caused by drops.

(3) Surveying the effects on reliability by element distribution at the pattern-solder joint interface.

References

- [1] Hirayama N. Board assembly technology and reliability of D²BGA CSP. *J Jpn Inst Electron Packaging* 1998;1(5): 381–6.
- [2] Nishiyama Y. The reliability for μ BGA. *J Jpn Inst Electron Packaging* 1998;1(5):387–91.
- [3] Yu Q et al. Effects of BGA solder geometry on fatigue life and reliability assessment. *J Jpn Inst Electron Packaging* 1998;1(4):278–83.
- [4] Kimura T et al. CSP packaging and mounting technologies for mobile apparatus. *Proceedings of 1997 International Symposium on Microelectronics*, 1997. p. 256–61.
- [5] Goyal S et al. The role of case-rigidity in drop-tolerance of portable products. *The Int J Microcircuits and Electron Packaging* 1999;22(2):175–84.
- [6] Goyal S et al. Methods for realistic drop-testing. *The Int J Microcircuits and Electron Packaging* 2000;23(1):45–52.
- [7] Ishikawa S et al. Drop impact strength evaluation of solder joint in portable electric equipment. *Proceedings of the 11th Computational Mechanics Conference*, Suita, Japan, 1998; 18–20:523–4.