Thermal Fatigue Life of Underfilled μBGA Solder Joint

H. H. Kim, S. W. Han, H. I. Kim, M. Choi, and Y. E. Shin

Abstract

In this paper, the effect of underfill packages was investigated by numerical approach and experimental test. Reliability improvement was the main issue in the package technology. BGA , CSP and small-sized packages, have problems due to concentration of the stress in solder joints. One of the latest technologies to overcome is underfill encapsulant. Mainly, it is noticed the effect of the underfill in the packages. The predicted thermal fatigue lifes are performed by Coffin-Manson's equation with ANSYS (v.5.62). Also, thermal cycle test during from 218K to 423K was included. Finally we could find that underfill greatly reduce the concentration stress in solder joint, thus the fatigue life was improved than without underfill.

Key Words : BGA, Solder joints, Underfill, FEA, Fatigue life, Encapsulant.

1. Introduction

The cut-edge technologies in industry fields, for example, portable electronics products such as camcorder, PDAs, cellular phones, etc. require the higher performance, more I/O (Input and Output) counts, and smaller size. The trends of package are actually varied to highly concentrated and reliable products, such as μBGA(Ball Grid Array), CSP(Chip Scale Package) and Flip Chip. To satisfy these requirements, various researches for those packages have been accomplished with many different approaches. The reliability of solder joints is one of the most important issues for the life of electronic devices. Consequently, many scientists have tried to verify the thermal fatigue characteristics of solder joints in the packages and their effects on working life.$^{1)}$

For the application of μBGA or CSP packages, a board level reliability is very important matter. Mechanical stimulations such as impact, vibration, or bending can induce plastic deformation of the solder joints. Also, regular temperature changes usually cause mismatches of the components due to the different CTE (Coefficient of Thermal Expansion), and those dimensional mismatches result in thermal deformation and crack of the packages.

Therefore, within the last decade, vigorous researches have been concentrated to improve the board level reliability. With those great efforts, we could obtain the improvement in the reliability. However, μBGA and CSP, small-sized packages, have other mechanical problems induced by concentration of the stress in solder joints.$^{2)}$

The gap between the board and package, which called Standoff, has a bad effect on the board level reliability of μBGA package. The shorter Standoff height is, the more sensitive thermal and physical stresses in solder joints. Finally, it shortens the life of the package.

One of the efficient ways to solve these problems is underfill process. Underfill can relief the stress, which comes from the mismatches of CTE and mechanical shock.$^{3)}$

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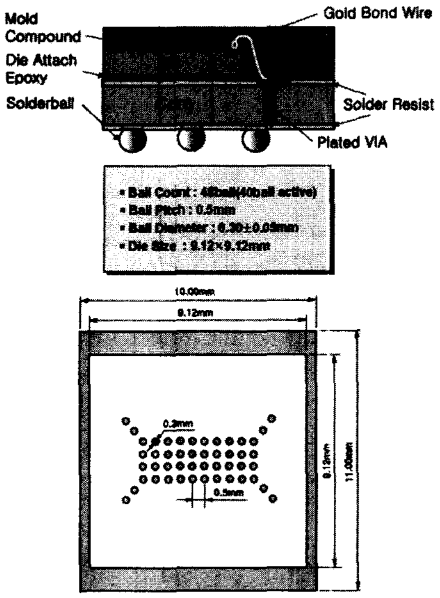


Fig. 1 Cross sectional view of μBGA package and package outline

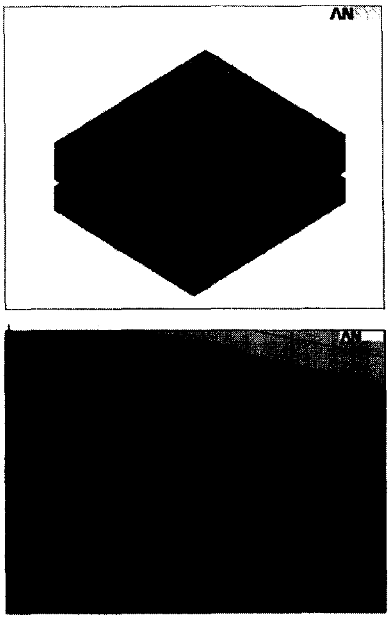


Fig. 2 A finite element model of the underfilled μBGA package

A recent study cites that the underfilled μBGA solder joint has longer thermal fatigue life than that of them without underfill.[4)]

In this paper, the thermal fatigue lifes of μBGA package according to the existence of underfill were calculated. As a theoretical approach, FEA (Finite Element Analysis) was conducted to investigate the stress concentration and distribution of strain rate around the solder joints. Then, we could obtain theoretically predicted fatigue life with the plastic strain amplitude and Coffin-Manson's equation. Finally, to validate the theoretical fatigue life, we conducted thermal fatigue experiment and compared the result with predicted one. The cross sections of the samples were investigated by SEM (Scanning Electron Microscope) and EDX (Energy Dispersive X-Ray).

2. Experimental methods

2.1 Thermal cycling test

The test package was 48 μBGA assembled by eutetic eutetic Sn-37Pb solder and it also used in cellular phone now. It is the kind of the CSP which chip area is wider than package area. Test specimens consists of 40 active balls and 8 nonactive balls. Actually 40 active balls were observed under thermal cycle test. Cross sectional view of μBGA package and package outline was shown in Fig. 1.

Two groups of μBGA packages (with / without underfill) were located under air-to-air temperature cycling chamber.

Experimental temperature range was 208K ~ 423K and 5 minute's dwelling time at each extreme. It took 30 minutes to finish 1 cycle as shown in Fig.3.[6)] After thermal cycle test, the samples were cross-sectioned and observed with the SEM. Changing of the grains in solder joints and a progress of thermal fatigue was investigated.

2.2 Numerical approach

Darveaux suggested that the FEA methods about reliability on the BGA solder joints under thermal cycling condition.[7)] Through the simulation, visco-plastic strain on the solder joints can be investigated. In this research a nonlinear 3-D finite element models were implemented using ANSYS 5.62 and JCG solver. The modeled μBGA package consisted of 48 solder joints with ball height of 0.15 mm, and pitch of 0.5 mm. The model was simplified a quarter size because the module was symmetric. For the convenient analysis, the component was modeled as six parts incapsulation, silicon chip, Cu pad, solder joints, underfill. A finite element model of the quarter underfilled μBGA package was shown in Fig. 2.

All components were assumed that the materials were isotropic elastic materials except solder. The solder was considered as linear about yield condition depends on the temperature, because solder has high-flexibility and low yield-strength characteristics.

Table 1 Material properties of μBGA package

	ρ (kg/mm^3)	E (E,GPa)	CTE (ppm)	V
Encapsulant	1.870E-6	2.54	16.9	0.4
SI Chip	2.330E-6	131	2.7	0.3
Cu Pad	8.960E-6	120	17	0.35
Sn-Pb	8.400E-6	32	24.7	0.38
Underfill	1.810E-6	9	26	0.3
PCB	1.920E-6	22.5	36	0.3

Material properities of μBGA package was shown in Tabel 1.[5] Also, the bilinear kinematic hardening option for a cyclic behavior during thermal cycling was used. It is suitable for general small strain of materials that obey Von-Mises yield criterion.

For the thermal analysis, 8-node 3-D thermal elements (solid 70) were used to convert thermal cycling to uniform temperature loading. Symmetric boundary conditions are applied to the two planes of symmetry. One node along the axis of symmetry at the center of device was completely restrained to eliminate rigid body motion. Temperature profile of thermal cycling test was shown in Fig. 3. The temperature was varied from 208 to 423K with a ramp time of 10 minutes and a dwell time of 5 minutes at the temperature extremes.

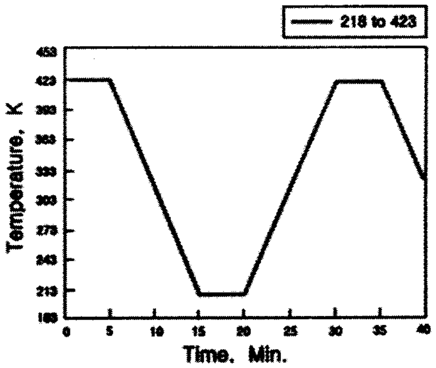


Fig. 3 Temperature profile of thermal cycling test

3. Results and discusion

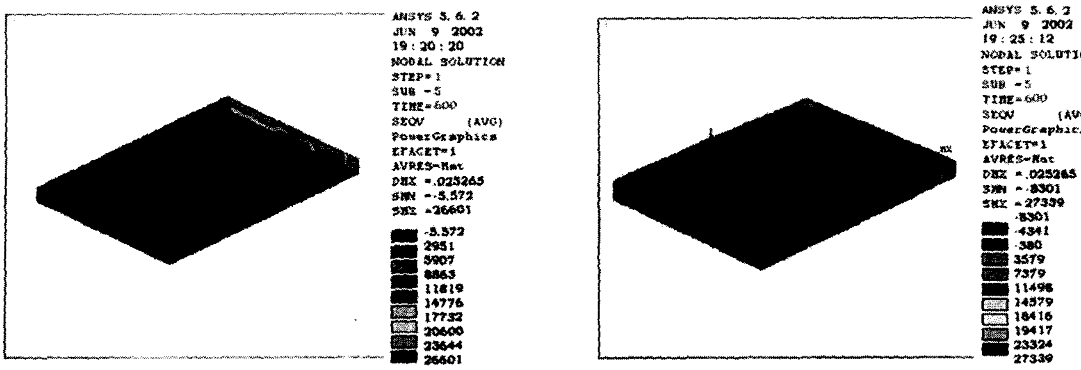
3.1 Numerical results

Fig. 4 shows the distribution of Von-Mises equivalent stress in the package assembly components from FEA results. Fig. 4 (a) shows in silicon chip, Fig. 4 (b) shows in underfill, Fig. 4 (c) shows in FR-4 PCB and Fig. 4 (d) shows solder joints. The results shows that the most stress concentrated area is between upper substrate and solder surface in solder joints. Also, the area contacted with solder in the PCB is one of the most stress concentrated areas. From Fig. 4 (b), the stress was distributed by underfill. Both stress and strain due to CTE mismatch between the chip and PCB were considerably decreased by the presence of underfill, which had relatively low Young' s modulus and CTE. From these results, it was concluded that the strain concentration near the interface was significantly reduced by the presence of the underfill material. For the prediction of thermal fatigue life N_f of solder joints, a Coffin-Manson equation was used.

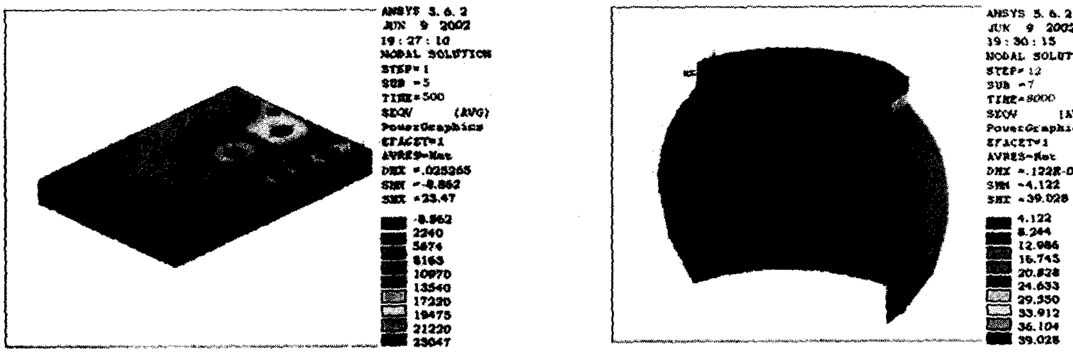
The equation is given by

$$\triangle \varepsilon_p \cdot N_f^{\alpha} = C \qquad (1)$$

Where N_f is fatigue life, α and C are fatigue coefficient, and ε_p is plastic strain amplitude.



(a) Si chip b) Underfill



(c) PCB (d) Solder joints

Fig. 4 Stress distribution in package assembly

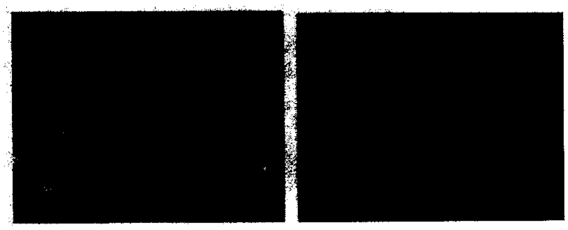
Fatigue coefficient was α = 0.49, C = 0.24 which was announced former Sn-37Pb solder fatigue coefficient.$^{8)}$ The result of fatigue life confirms that underfilled package have 14 times longer than without underfill. The main reason of this is, underfill can take in part of the relief the concentrated stress, so it lessens the plastic deformation in solder joints. Table 2 has detailed plastic strain amplitude and fatigue life of solder joints from FEA. It shoud be noted that the actual thermal fatigue life depend on the various processing factors as well as the service conditions.

Table 2 Plastic strain amplitude and fatigue life of solder joints

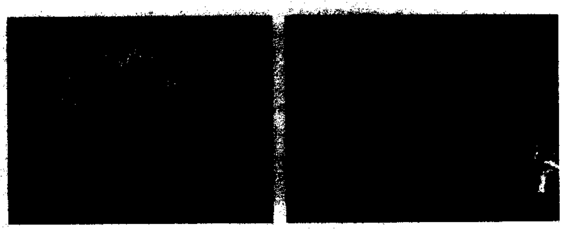
	Without Underfill	With Underfill
$\Delta\varepsilon_p$	0.008045	0.002188
N_f	1022.3	14574.7

3.2. Thermal cycling test results

In the product, Sn-37Pb assembled product can occur plastic deformation under operation temperature, because low melting point of the solder. It is easy to weaken the solder joints by the grain size also tend to be larger, produce the void in solder. Fig. 5 (a) gives a beginning of the crack, after 500 cycles in 48 μBGA without underfill. After 600 cycles, the crack developed by 30% (Fig. 5 (b)). Almost 50% of the fatigue crack propagation was shown after 700 cycles in Fig. 5 (c). Finally, solder joints was completely failed after 800 cycles shown in Fig. 5 (d). However, under the same condition, we couldn't find any propagation at the underfilled μBGA package. From Fig. 6 (b), the fatigue crack propagation can find and from Fig. 6 (c), 50% propagation was developed. About after 6000 cycles, solder joints was failed shown

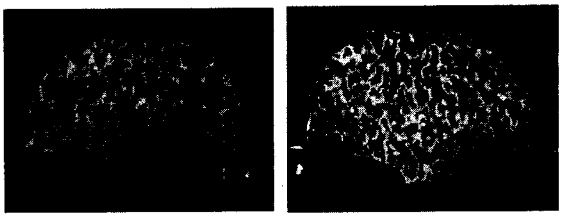


(a) After 500 cycles (b) After 600 cycles

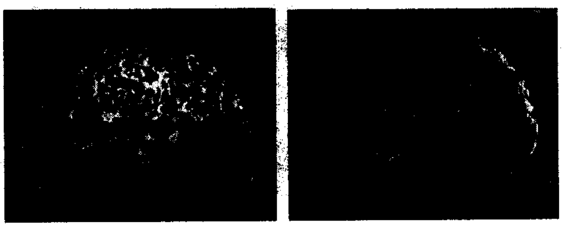


(c) After 700 cycles (d) After 800 cycles

Fig. 5 Cross sectional view of solder joints without underfill (thermal cycling between 208K and 423K)



(a) After 4500 cycles (b) After 5000 cycles



(c) After 5500 cycles (d) After 6000 cycles

Fig. 6 Cross sectional view of solder joints with underfill (thermal cycling between 208K and 423K)

in Fig. 6 (d).

The result from the recently studies, underfilled assembly has almost 15 ~ 20 times loner fatigue life than without underfill assembly in 258 ~ 398K temperature range.[3] In our research, we confirmed about 8 to 15 times longer fatigue life from the experimental and numerical results. Difference between former studies and this study came from the difference of the solder joint shape. Normally BGA has symmetric shape, but the sample which is used in this research is 4×10 lined type. Thus, the package has considerable stress concentration at the outer solder joints. Also, the temperature condition (218 ~ 423K) is more extreme than that of the former studies (258 ~ 398K). These differences could synthetically affect the fatigue life. As a result, the board level reliability was improved in underfilled μBGA package. The component of the underfill is epoxy and it has low CTE, so it may help to reduce the CTE mismatch between silicon chip and substrate.

In the metallurgical point of view, the grain coarsening of solder was not clearly observed at the package without underfill. Moreover, in underfilled μ BGA, the grain size is larger by increasing number of the cycle, and the shape of the solder bump was also unstable. It might be resulted from the thermal effect in the solder because underfill interrupted the circulation of the heat. Also, the grain coarsening of solder can give a fatal disadvantage to the applied package in the metallurgical point of view. Therefore, a careful consideration and further investigation for the thermo-mechanical behavior and metallurgical characteristic of the solder joints are indispensible.

4. Conclusion

1. Underfilled μBGA package has about 8 times longer thermal fatigue life than the package without underfill. Also, the undefill effectively reduce thermal deformation and stress concentration on the solder joints.

2. FEA results show that underfill material can improve the fatigue life about 15 times more than without underfill material. According to the plastic strain amplitude was decreased by underfill, the thermal fatigue life was dramatically increased.

3. The underfill material played an important role in reducing stress and strain due to the thermal cycling. Thus, the board level reliability dramatically improved

in underfilled μBGA package.

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