A COMPARATIVE STUDY ON THERMAL AND MECHANICAL FATIGUE BEHAVIOR OF LEAD FREE SOLDER JOINTS

Ilho Kim and Soon-Bok Lee
Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology
373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Korea(ROK)

ABSTRACT

A mechanical cycling test was compared with a thermal cycling test. Deformation shape and the energy dissipation ratio of creep and plasticity were analyzed and compared for mechanical and thermal loading. Through those analyses, change of fatigue life during mechanical and thermal cycling tests was investigated. And a comparative study of lead-free and lead-contained solder was also made.

A pseudo-power cycling method was adopted to provide more realistic thermal cycling condition. Two types of specimens were tested using the pseudo-power cycling machine. First specimen was designed for fast testing and wide ranges of applied loading. The other was selected as a popular package commonly used in electronic industry. But the second type specimen takes a long time to perform a reliability testing. And bending cycling test was also performed with the second type specimen. A nonlinear finite element model was used to simulate the thermally and mechanical induced visco-plastic deformation of solder joint in packages. The fatigue life of bending cycling test was compared with that of thermal cycling.

Introduction

Recently, thermal cycling test is required for package reliability evaluation. So many testing specifications, such as MIL-STD, JEDEC and IPC specifications, describe thermal cycling test and the methodology to analyze the testing results in detail. Many researchers analyze the thermal cycling test results and make life prediction models. However, many failures in electronic packages have been reported due to the mechanical loads in the mobile devices. The researches and reliability testing specifications about mechanical loads are not enough. In this paper, the mechanical loading test was compared with thermal cycling test to enhance the understanding of the mechanical loading test.

Experiment – Pseudo-Power Cycling Test

Thermal fatigue tests were conducted using a pseudo power cycling machine which was newly developed for a realistic testing condition and testing efficiency. Generally the power cycling tests are required power (heating) chip and a high level controlling technique. To make power chip also required considerable cost and time. For the sake of convenience, many researches adopt a chamber cycling test method. But this method has some shortage; the package is put in the isothermal condition and heat transferred through convection which requires longer time.

The pseudo-power cycling method makes up for the weak points in power cycling and chamber cycling method. The schematic view of pseudo-power cycling machine is shown as Figures 1 and 2. During the pseudo-power cycling test, there exists thermal gradient between package and PWB, as real operation condition. And the heat supplied and removed by conduction, that makes the package was heated and cooled fast. Detail description on the pseudo-power cycling test method, are listed elsewhere. [1,2]

Two types of specimen were used, one was designed for fast testing (type #1), and the other is a conventional package (type #2). Type #1 specimen was shwon as Figure 3 where two identical FR-4 PCBs of 2.0mm thickness were bonded by 36 solder joints, 9 solder joints in each corner. Type #2 specimen was shown as Figure 4, that is 256 PBGA package made by Top Line Co. It takes a long time to complete the thermal testing of type #2 specimen, about two or three month. To complete series of test within a given time, the type #1 specimen was designed, with reduced solder ball numbers. Two type specimens have same solder ball size (760 ㎛) and solder composition (63Sn37Pb and 95.5Sn4.0Ag0.5Cu).

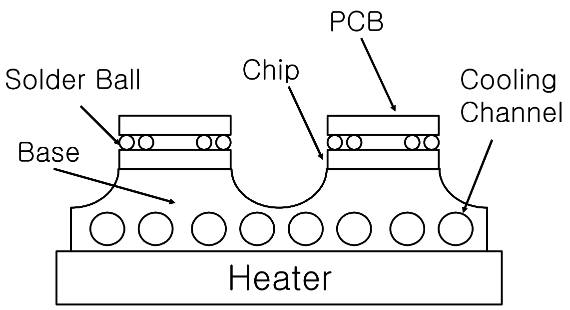


Figure 1. A schematic view of pseudo power cycling machine

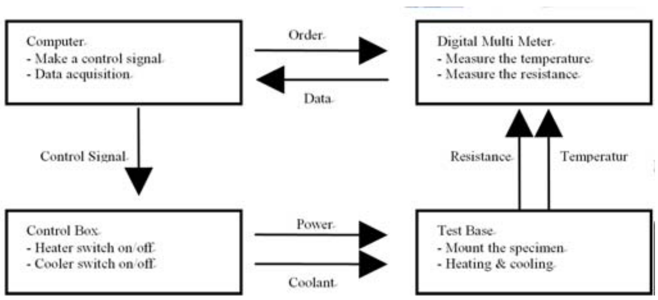


Figure 2. System flow chart of pseudo power cycling machine

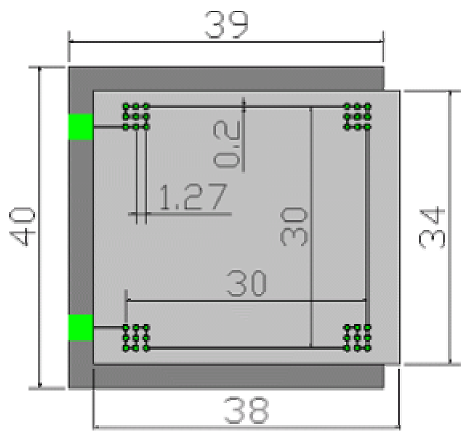


Figure 3. Dimensions of thermal specimen type #1 (mm).

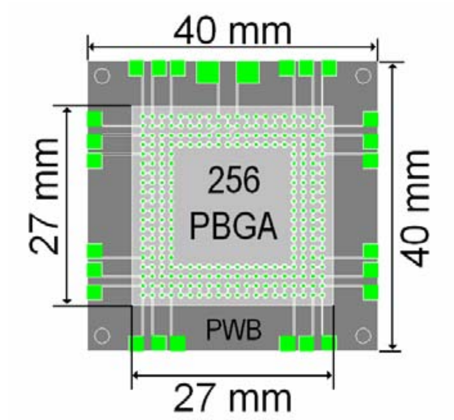


Figure 4. Dimensions of thermal specimen type #2 (mm).

Experiment – Mechanical Bending Test

In this research, a small size bending tester was used as shown in Figure 5. [3] In this testing system, the electromagnetic actuator with a computer aided controller applies the cyclic force to the specimen. And high resolution loadcell and LVDT measure the applied force and the moving distance of the whole specimen. The strain measurement system was constructed, which can measure 8-channel strains simultaneously. To verify the performance of bending tester and grip alignment, strain gages are attached at the symmetric points with respect to x-y axis. The strain-signals from the symmetric points were found to be almost same, which guarantees the tester to be accurately aligned.

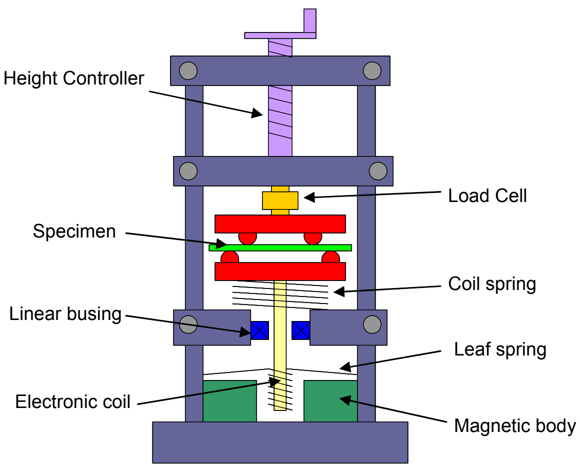


Figure 5. Mechanical bending test system using a electro-magnetic coil.

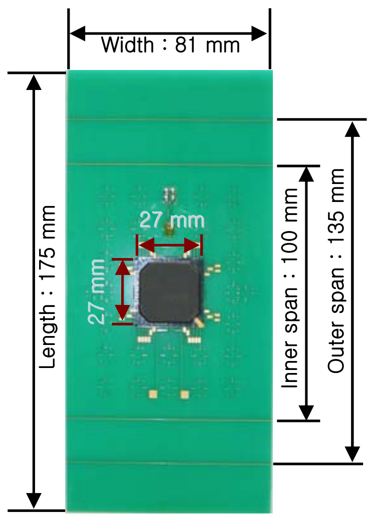


Figure 6. Four point bending test specimen, 256PBGA package was attached to the PWB board

In this research, the single-side board with one unit was tested under four-point bending loads to analyze the test results easily and accurately. The test specimen used for mechanical bending test was a 256 PBGA, it is same package with type #2 thermal specimen. To get the uniform stress field near the package, simple finite element analysis was performed and PWB size was determined as Figure 6.

Finite Element Analysis

A three-dimensional finite element model was made using the modeling software Partran. Finite element analysis using ABAQUS was performed to extract the applied stress and strain in solder joints. Due to the symmetry, only one-eighth of the package was modeled for type #1 and #2 thermal cycling specimen and quarter was modeled for bending cycling specimen. For the calculation efficiency, important solders were meshed finely, and the others were meshed coarsely.

The FE model of type #1 thermal cycling specimen was consisted with 20,962 elements and 25,110 nodes, it is depicted Figure 7. Figure 8 shows the FE model of type #2, it has 31,945 elements and 39,091 nodes. In the FE model of bending test, there are 60,656 elements and 75,343 nodes (Figure 9). All of this FE models have same mesh size and same material properties. Generally the FEA results have some difference according to the mesh size. To reduce the mesh dependency the same mesh was adopted in all models. The material properties of the models are from Park [4], Hong [5] and Lau's work [6] where 95.5Sn3.9Ag0.6Cu is selected for 95.5Sn4.0Ag0.5Cu solder due to the lack of available material data. A constitutive model that includes both creep and plasticity was employed.

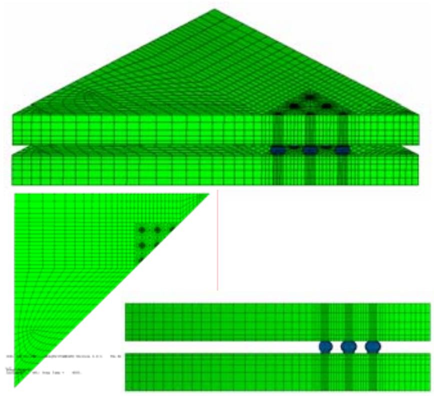


Figure 7. Finite element model for the type #1

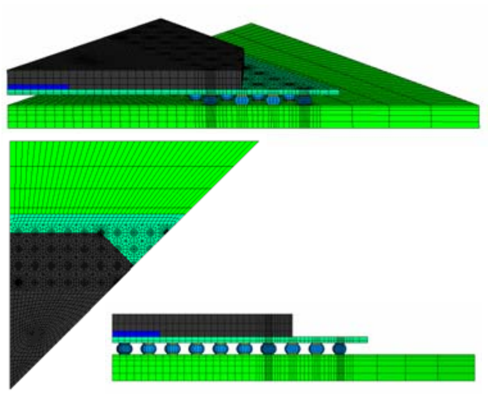


Figure 8. Finite element model for the type #2

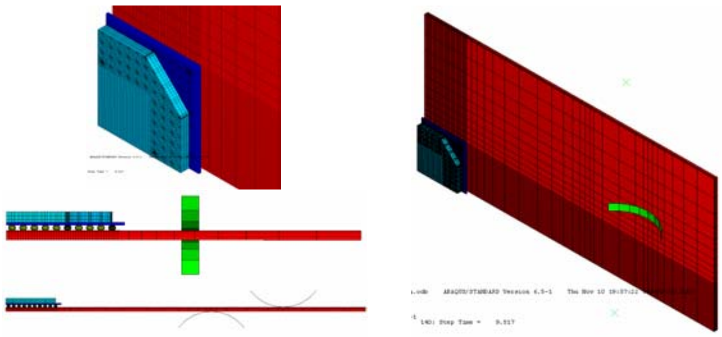


Figure 9. Finite element model for the bending cycling specimen

Experimental Result and Discussion

Table 1 and Figure 10 represent the experimental conditions and results of thermal cycling test for type #1 specimen. There exist cross points between the lead-contained solder and the lead-free solders. In large ΔT regions lead-contained solder (63Sn37Pb) had a good fatigue resistance, but in small ΔT regions lead-free solder (SnAgCu) had a longer fatigue life. According to the result in Figure 10, the solder which exhibit a good reliability can be reversed defending on the testing conditions.

Table 2 shows a testing condition and thermal cycling test results about type #2 specimen. Even if test condition makes ΔT large, lead-free solder has a longer fatigue life. This result is contrary to type #1 specimen's. The reason why this phenomenon

occurred is that the real applied stress at the type #2 specimen is lower than type #1 in same testing condition. Type #2 specimen has 256 solder balls, which is 7 times larger than type #1, that make it possible to distribute the thermal load. That means type #2 data fall into small ΔT region in type #1 test results.
The bending test conditions and results are shown in Figure 11. That result is similar to the thermal cycling test. Under high load conditions, lead-contained solders have longer fatigue life. On the contrary, lead-free solder sustain more cyclic loads under small load conditions. According to Figures 10 and 11, lead-free solder has good fatigue resistance in small load condition and lead-contained solder could sustain large loads.

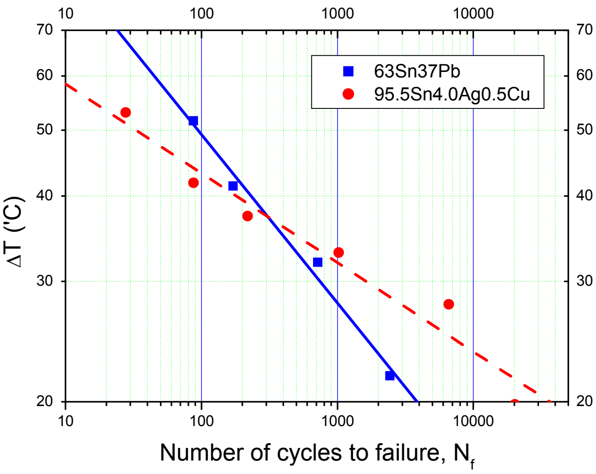


Figure 10. Maximum temperature difference between package and PWB vs. fatigue life curve

Sn37Pb	Sn4.0Ag0.5Cu
30~150℃	30~150℃
30~125℃	30~130℃
30~110℃	30~110℃
30~100℃	30~100℃
30~75℃	30~90℃
-	30~70℃

Table 1. Testing condition of thermal cycling test for type #1 specimen

	Sn37Pb	Sn4.0Ag0.5Cu
Test Condition	30~150℃	30~150℃
Fatigue Life	2616	4770

Table 2. Testing condition and the results of thermal cycling test for type #2 specimen

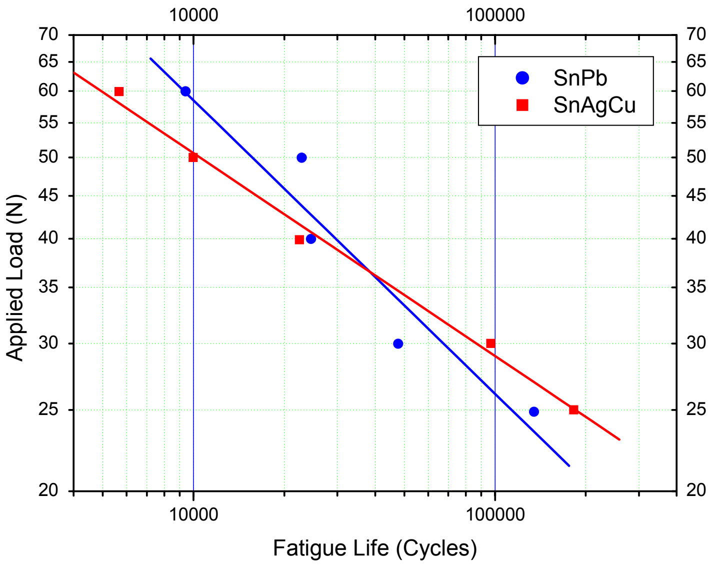


Figure 11. Maximum applied bending oad vs. fatigue life curve

Finite Element Analysis Result and Discussion

There is a large difference between the deformation shape of a bending specimen and a thermal cycling specimen. Figures 12 and 13 show the out-of-plane deformation of PWB under PBGA package. As shown in Figure 12, PWB under PBGA package is twisted. Along to bending load direction, PWB was deformed like Figure 14 that shows the maximum and minimum deformation during bending cycling test. In the Figure 14, minimum deformation is not zero, because the inelastic deformation was already occurred. At the area which located under solder joints, the deformation rate is higher than other locations. Bending load is extrinsic force, so outer solder joints endure almost loads and inner area of PWB is not subject to large force. Figure 15 shows the deformation on a transverse direction to bending-load. Due to PWB's Poisson ratio, the deformation is opposite and its magnitude is one-third of that of bending load direction.

During the thermal cycling tests, the PBGA package specimen was loaded due to the CTE(coefficient of thermal expansion) mismatch between the package and PWB. That is intrinsic load. So the out-of-plane deformation of the thermal specimen is almost radially symmetric as shown in Figure 13 and the deformation magnitude is more continuous than bending case. The deformation is maximized at the high-temperature holding section and minimized at the lower-temperature holding section.

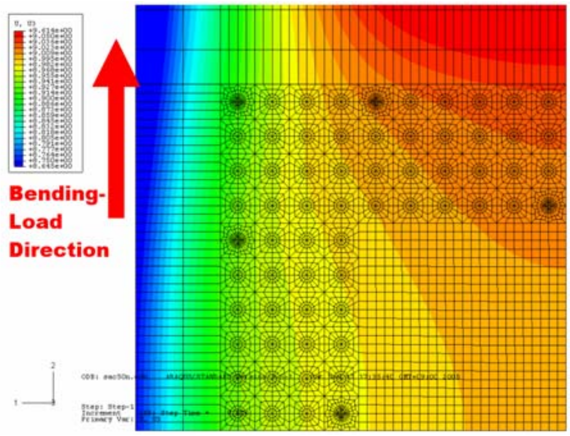


Figure 12. Out-of-plan deformation of PWB under PBGA package during thermal cycling tests.

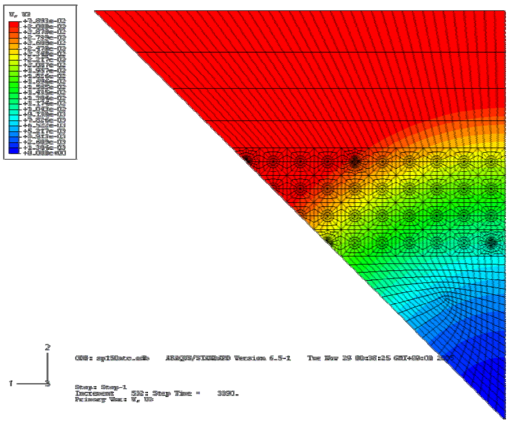


Figure 13. Out-of-plan deformation of PWB under PBGA package during bending cycling tests.

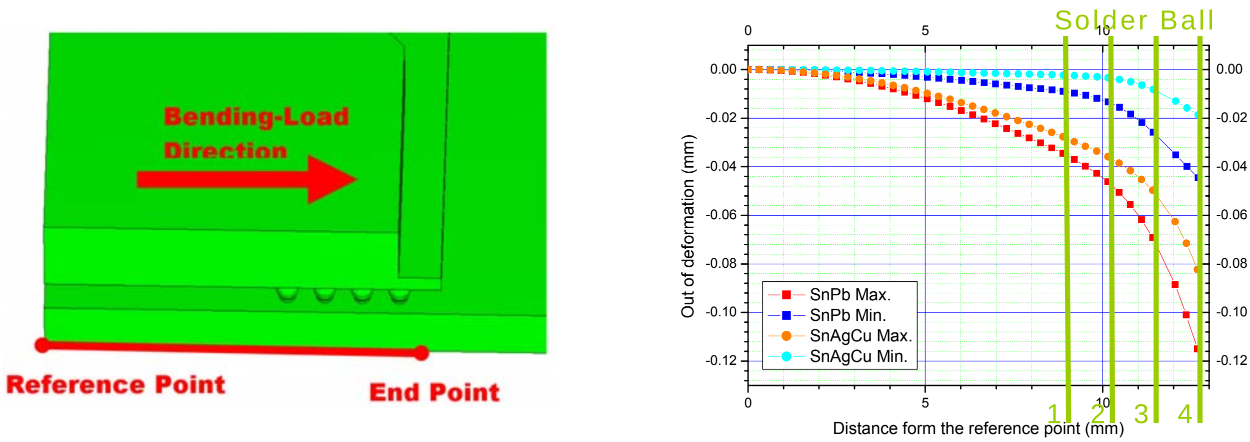


Figure 14. Out-of-plane deformation along to the bending-load direction.

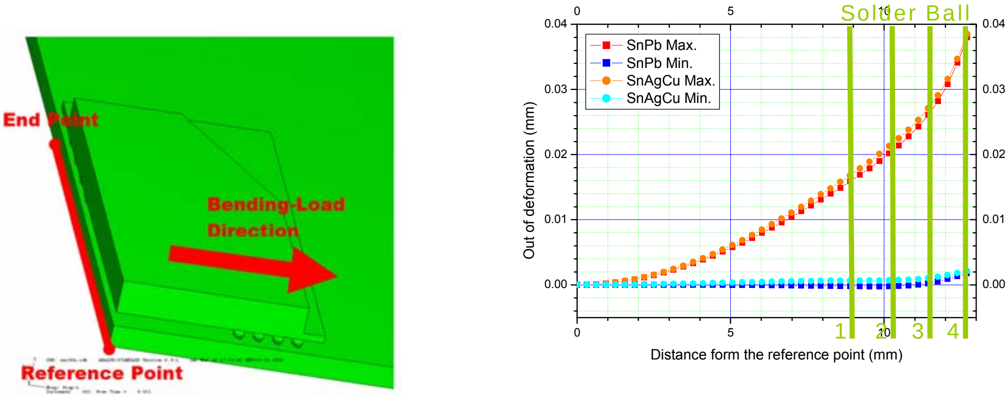


Figure 15. Out-of-plane deformation along to the transverse direction.

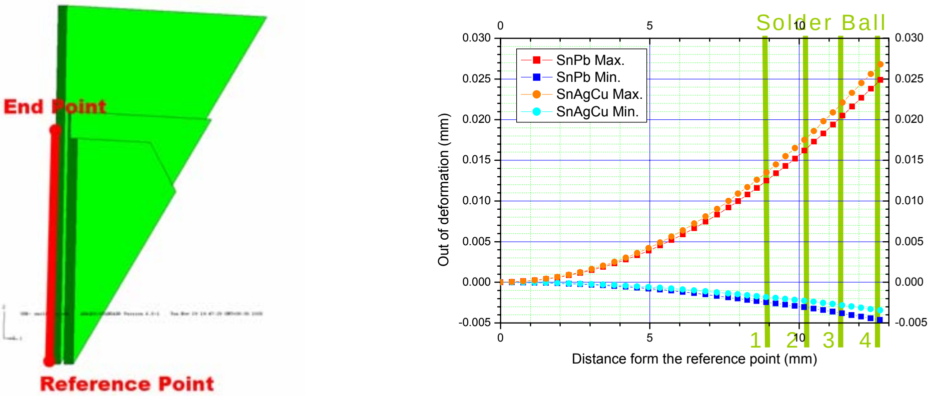
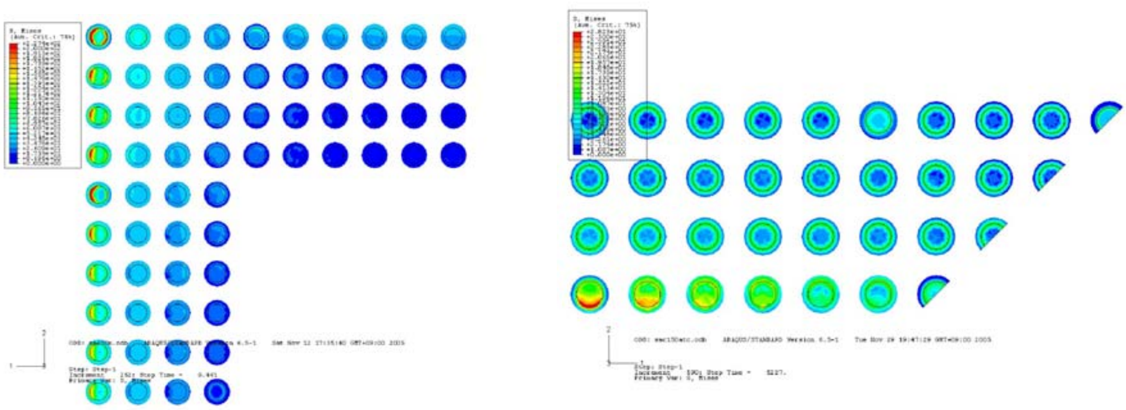


Figure 16. Out-of-plane deformation in thermal cycling case (type #2).

The applied stress distribution on the solder balls are shown in Figure 17. In the bending cycling test, high stresses are loaded at the outmost solder balls on perpendicular to bending-load direction but in the thermal cycling test, high stress occurs at inner solder balls. Moreover in bending cycling test, maximum stress occurs at the interface between the solder and PWB, but in thermal cycling test, maximum occurs at the interface between the solder and package. When bending loads applied to an assembly of the package and PWB, PWB are extend by that force. Accordingly large force applied to interface between solder and PWB. But in the thermal cycling case, thermal load due to thermal expansion was uniformly distributed as compare with the bending test. So the solder interfaces that come in contact with bigger modulus material (the PBGA package) has higher stress level.



(a) (b)

Figure 17. The applied stress distribution on the solder balls at bending and thermal cycling tests. (a) bottom view of solder balls in SnAgCu 50N bending cycling case (b) view of solder ball in SnAgCu 30~150℃ thermal cycling case

Figure 18 and 19 shows the creep and plastic energy density during bending and thermal cycling tests. In bending cycling test, the outmost solders have large creep and plastic dissipation energy. But in thermal cycling test, large energy dissipation occurred at inner solders.

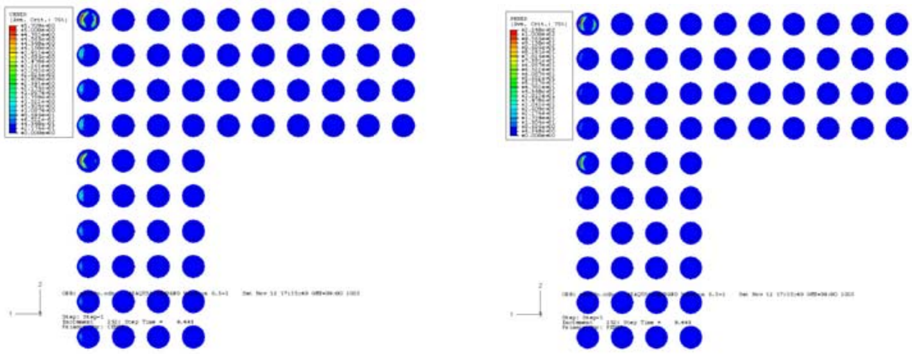


Figure 18. The creep and plastic energy density of solder joints' bottom area during a bending cycling test

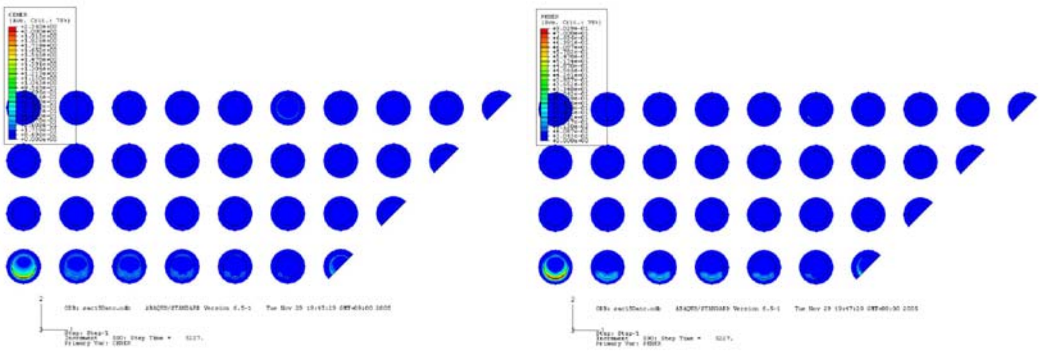


Figure 19. The creep and plastic energy density of solder joints' top area during a thermal cycling test

The energy-based method links the fatigue life to the inelastic strain energy dissipation of solder joints. The number of cycles before solder failure was calculated as Equation (1), where C1, C2 are material constants. ΔW_{avg} in Equation (2) is a volume-averaged energy at the critical interface.

$$N = C_1 \Delta W_{avg}{}^{C_2} \qquad \text{Equation (1)}$$

$$\Delta W_{avg} = \frac{\sum_{i=1}^{n} dW_i V_i}{\sum_{i=1}^{n} V_i} \qquad \text{Equation (2)}$$

Figure 20 shows the inelastic energy dissipation per cycle at the stable cycle versus fatigue life curve. The curve of a bending fatigue life versus inelastic energy dissipation is almost linear, but power cycling results show non-linear behavior. At the same energy dissipation level, the bending fatigue life is longer than thermal cycling fatigue life. Generally the solder fatigue life are depended on a stain rate and temperature. In bending test, a cycle frequency is 1Hz and a testing temperature is room temperature. But in thermal cycling test, it takes 450~720 seconds per cycle and an average testing temperature was varied 50 to 80℃ according the testing condition.

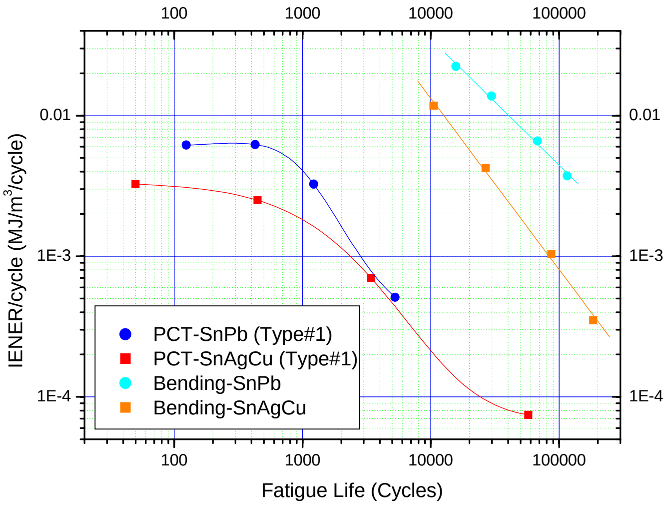


Figure 20. The inelastic dissipation energy versus fatigue life curve

Summary

In this paper, the mechanical cyclic bending test and thermal cycling test were performed. And non-linear finite element model which includes the creep and plastic constitutive equations was constructed and analyzed. Investigations of the deformation shape and the fatigue life behavior was conducted. The lead-free solder (95.5Sn4.0Ag0.5Cu) has stronger fatigue resistance than the lead-contained solder (63Sn37Pb) in lower loading level during the both cycling test. But if the applied load was increased, lead-contained solder has a longer life. Maximum stress points are different at each testing method. In the bending test, outmost solder at PWB side has maximum stress and maximum inelastic deformation. But in the thermal cycling test, inner solder joints have to endure large stress and inelastic deformation. From the inelastic energy dissipation per cycle versus fatigue life curve, it can be found that the bending fatigue life is longer than the thermal fatigue life and it is reconfirmed that cyclic frequency and testing temperature have an effects on the fatigue life.

Acknowledgments

This research was supported by Ministry of Science and Technology in Korea through “Development of Reliability Design Technique and Life Prediction Model for Electronic Components”.

References

1. Kim, I., Park, T. S., Yang, S. Y., Lee, S. B., “A Comparative Study of The Fatigue Behavior of SnAgCu and SnPb Slder Joints” Key Eng. Mat. 279-300, 831-836 (2005).
2. Kim, I., “A study on thermal fatigue behavior of BGA package”, Master’s thesis, MME 04018, KAIST (2004).
2. Kim, I., Lee, S. B., “Reliability Assessment of BGA Solder Joints under Cyclic Bending Loads”, EMAP2005, Japan (2005).
3. Park, T. S., “A study on mechanical fatigue behaviors of ball grid array solder joints for electronic packaging”, Doctoral thesis, DME 04041, KAIST (2004).
4. Hong, B.Z., “Thermal Fatigue Analysis of a CBGA Package with Lead-free Solder Fillets”, InterSociety Conference on Thermal Phenomena, 205-211 (1998).
5. Lau, J., Dauksher, W. and Vianco, P., “Acceleration Models, Constitutive Equations, and Reliability of Lead-Free Solders and Joints”, 2003 Electronic Components and Technology Conference, 229-236, (2003).