Experimental Techniques for Fatigue Reliability of BGA Solder Bumps in Electronic Packaging*

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Reliability of the solder bump has been studied by accelerated testing with several experimental techniques. A new thermal fatigue test apparatus using thermal conduction was constructed, which could produce temperature gradient effects without any additional design of test specimen and control the temperature of specimen easily. For the simulation of temperature change due to the heat generation of chip, a specimen (chip) was put on a heating plate through which heat flux was conducted. A small-sized electromagnetic type fatigue tester and a micro-mechanical testing machine were developed. High cycle fatigue test was performed by a small-sized electromagnetic type fatigue-tester. The time to failure was determined by measuring the changes in resistance. Using micro-mechanical tester, isothermal fatigue test was performed to investigate the optimum shape of solder bumps. The isothermal low cycle fatigue test of solder bumps was performed with four different shapes and the equivalent plastic strain distributions of four different cases were calculated using finite element method.

Key Words: BGA, Solder Bump, Thermal Fatigue, Reliability, Electronic Packaging

1. Introduction

The ball grid array (BGA) package is a second level package, which is attached to a printed circuit board (PCB) through solder bumps to form a final second level assembly. There is an increased thermal fatigue problem with this type of attachment because the module is soldered directly to the PCB. Without lead to take up the thermal strain developed by the mismatch in the coefficient of thermal expansion (CTE) between the module and the PCB, the BGA packages are prone to thermal fatigue failure. To verify the solder joint reliability, power cycling method and chamber cycling method have been generally adopted⁽¹⁾⁻⁽⁴⁾. The power cycling tests, using the heat generation of chip itself, can produce the temperature gradients, which can lead to the cyclic warpage and transient condition. But the power cycling test method has a disadvantage that it uses specially

designed power chip for this special purpose. Therefore a new thermal fatigue test apparatus using thermal conduction was constructed, which can produce temperature gradient effects without any additional power chip and control the temperature of specimen easily. For the simulation of temperature change, a specimen (chip) was put on a heating plate through which heat flux was conducted.

In addition to thermally induced stresses, electronic systems often are subject to vibration environments. These vibrations occur during shipping, handling, and operation. To assure high product reliability, it is necessary to provide estimating tools of vibration fatigue life. For this purpose, an automated fatigue-testing system was developed to evaluate the integrity of the electronic packaging subjected to mechanical vibration. With the fatigue testing system, the mechanical integrity of the solder joints in surface mounted components has been studied by a mechanical flexural fatigue test. The high cycle fatigue tests of solder joints are performed under constant amplitude loading. The fatigue life is determined by the changes in the electrical resistance in the solder joints.

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To determine the optimal shape for reliability enhancement of solder bump, isothermal low cycle fatigue testing of solder bumps having the different shapes was performed with the machine that provides cyclic shear strain in the solder bumps.

2. Thermal Fatigue Test

Reliability evaluation of solder joints has been carried out mostly by temperature cycling in environmental chambers rather than by power cycling (power on/off with or without ambient temperature cycling) simulating actual operating cycles. This has led to an emphasis on matching the coefficient of linear thermal expansion, α of the substrate to the coefficient of the module. These temperature extremes which can cause unusual behavior of the constituent materials different from that of normal operating conditions, might be meaningful for military applications. However, they might lead to wrong conclusions for applications where cycling stresses are not imposed by such temperature extremes but by power cycling and/or smaller ambient temperature variations⁽²⁾. Furthermore temperature cycling can produce neither the temperature gradients, which can lead to cyclic warpage, nor the transient conditions resulting from power cycling and which can lead to increased cyclic strains on the solder joints.

2.1 Test apparatus construction

A new thermal fatigue test apparatus using thermal conduction was constructed, which can produce temperature gradient effects without any additional power chip. For the simulation of temperature change due to the heat generation of chip, a specimen (chip) was put on the heating plate, and heat flux was conducted through the plate as shown in Fig. 1.

In heat conduction, Biot number plays a fundamental role in conduction problems that involve surface convection effects. If Biot number, $B_i \ll 1$, the resistance to conduction within the solid is much less than the resistance to convection across the fluid boundary layer. Hence the assumption of a uniform temperature distribution is reasonable. Biot number, B_i can be calculated as follows;

$$B_i = \frac{hL_c}{k} \quad (1)$$

where h is the convection coefficient, k is the conduction coefficient of the material, and L_c is the

Fig. 1 Power cycling simulation

characteristic length of the specimen. In real applications, h has the value of 5–10 (W/m²K) in case of natural convection, k has the value of some hundreds (W/mK), and L has the size of sub-millimeters, which produces the Biot number around 10^{-5} – 10^{-4} . From the value of Biot number, we can assert that there is only negligible difference between the temperature distribution of real chip operation and that of simulation by heating plate. Heat conduction provides easier and more reliable temperature control of specimen than power cycling or chamber cycling does. The design of the heating plate was required to conduct heat to specimen as uniformly and fast as possible.

The excessive size of heating plate could induce the thermal radiation problem from the heating plate to the substrate and increase the unnecessary volume which make temperature change difficult on heat transfer process. So the size of the area contacted with specimen was determined as the same size of the largest commercial chip and the other area was located as far as possible from the substrate. It was designed to accommodate four specimens on the heating plate at the same time. If the number of specimens increases, the size of the heating plate also increases, and then the temperature change of the coolant between the entrance and the exit of heating plate becomes so severe. To decrease the temperature difference, the pipe of the coolant was located alternately. The temperature gradient near the coolant pipes is very large since the temperature of the Nitrogen gas is beneath -100°C . To make the temperature of the specimen uniform, the coolant pipes are located as far as possible from the specimens.

A closed loop system was constructed to control the temperature of specimen with simultaneous heating and cooling. The schematic view of the apparatus is illustrated in Fig. 2

2.2 Specimen

The specimens are two pieces of FR-4 PCBs connected by four solder joints. The thickness of PCB is 1.2 mm. The diameter of solder pad is 1 mm. The solder paste used in this study was composed of 90% by weight of 63% Sn/37% Pb eutectic alloy balanced with rosin and solvent. For a constant-volume control, solder pastes were printed onto pre-cleaned specimens and reflowed in a normal IR reflow machine. For convenience, the PCB whose temperature is controlled by the heating plate is named as Plate A and the other PCB as Plate B as shown in Fig. 3. The size of Plate A is 30 mm × 30 mm × 1.2 mm and the size of Plate B is 40 mm × 40 mm × 1.2 mm. To control the temperature of specimens, K-type thermocouple was used. As shown in Fig. 2, four specimens were subjected to same temperature cycling and one of them was

Fig. 2 Schematic view of the apparatus

Fig. 3 Thermocouple and strain gages (1), (2), (3)

used for temperature control. In order for the specimen to have the same temperature as others, a small hole is drilled in the middle of Plate B and through the hole, a thermocouple was bonded to Plate A on the heating plate. With the thermocouple signal, a closed loop system was constructed. The temperature of Plate B was also simultaneously measured.

2.3 Experiment

Thermal fatigue tests were performed. The temperature profile used in fatigue test is depicted in Fig. 4. The temperature range was 20–130°C. The cycle of temperature profile consists of a heat-up transient from 20°C to 130°C in 10 min, a steady-state dwelling of 30 min, a cool-down transient to 20°C taking 10 min, and another steady-state dwelling of 10 min. Since stress relaxation of low-melting materials is a major factor of fatigue damage accumulation^{(5),(6)}, this duration has significant effect on fatigue life. But the dwelling time in low temperature is heat transient time that allows a cycle to finish rather than stress

Fig. 4 Temperature profile for fatigue test

Fig. 5 Strains of specimen

Fig. 6 FEM mesh and thermal analysis

relaxation of the solder. With the temperature of the PCB of specimen, the strains of both sides of Plate B were measured by strain gage. To get the pure thermal strain, the strain signal of a single unassembled PCB plate on the heating plate was acquired simultaneously. The temperature limit of the strain gage is 180°C and a high temperature adhesive is used. The results of these strain measurements are shown in Fig. 5. The highest strain occurs at Plate A because the temperature of plate A is about 25°C higher than Plate B. The temperature gradient of Plate B in vertical direction is assumed to be negligible. Therefore the strain difference between both sides of Plate B is due to the moment force loaded by solder joint.

During a temperature cycle, the temperatures of the specimen are compared with the results of finite element analysis. Figure 6 shows the FEM modeling mesh and analysis result of thermal transient. Figure 7 shows the temperature change of Plate B, as the

Fig. 7 Thermal transient effect of Plate B

Fig. 8 Comparison of the strain drop with cycle number

temperature of Plate A changes along the temperature profile programmed previously. FEM result for the specimen was compared in Fig. 7. In Fig. 7, the temperature of Plate B of specimen shows hysteresis loop, which implies transient effect that could not be found in chamber cycling.

In this study, the fatigue crack started at the inner corner of the solder joint. Therefore it was hard to find the crack of solder bump by visual inspection. Moreover, the force loaded on the solder bump was shear force, so the crack couldn't show distinct resistance change. By these reasons, the moment of circuit board was measured by strain difference between two sides of Plate B. In Fig. 8, the drop of strains difference is shown clearly as the number of thermal fatigue cycle increases. The crack initiation fatigue life was defined by 25% drop.

3. High Cycle Fatigue Test

To verify the strength of interconnecting elements such as surface-mounted lead, attaching modules to board or card, mechanical tests for SMC assemblies are often used. Some researchers have tested SMC assemblies by twisting to verify the structural integrity or robustness of electronic packaging assemblies⁽⁷⁾⁻⁽⁹⁾. This is because during torsional flexing, the leads are substantially stressed, and their

Fig. 9 The loading fixture. (a) The loading configuration. (b) A photo of the loading fixture

solder joints are subjected to appreciable mechanical loading. High-cycle fatigue is also facilitated in this purely mechanical loading configuration. Ham and Lee⁽⁹⁾ performed fatigue tests on square boards with a central square module in this torsional loading configuration at the frequency of 40 Hz, so that they could obtain the high-cycle fatigue data within $10^4 - 10^7$ cycle range.

In the present work, the fatigue tests of BGA type solder bump were conducted in a similar loading configuration at the frequency of 40 Hz.

3.1 Experiment procedure

A PCB/solder bumps/PCB assembly was used in the torsional fatigue tests. The upper PCB and the lower PCB were bonded by 32 solder bump interconnections. The interconnections were daisy-chained so the solder joints could be monitored for electrical continuity during tests. The test board was made of single layer FR-4 epoxy/glass and the thickness is 1.2 mm. The surface composition of solder pads and signal lines were SMOBC/SSC (solder mask over bare copper/selective solder coating) and the diameter of pad is 1 mm. Solder bump heights were measured on several specimens; their average height was about 0.5 mm. The tests were performed using the automated fatigue-testing system, which consists of a small-sized fatigue-tester, a sensing part for electrical resistance change and a data acquisition part. The complete details of the testing system are given by Ref. (10), so only a brief summary of these details will be given here for convenience.

The loading fixture for the specimen was designed for torsional fatigue loading shown in Fig. 9.

The torsional loading fixture was made of aluminum and fabricated in the top and bottom part. Each fixture has two screws to tighten the diagonally opposite corners of the plate for applying reversible loading. The top fixture is connected to the load cell, and the bottom fixture is mounted on the actuator. The applied load measured by the load cell needs to be divided by 2 because the force is distributed between two loading points. The resistance change resulting from the applied cyclic stress in the testing is measured during the cyclic fatigue testing. The measurement is based on the principle of constant current potentiometer circuit⁽¹⁰⁾. The 32 solder bumps located peripherally at the upper PCB were daisy-chained and used as the resistance in the constant current potentiometer circuits. The resistance signal and load signal were monitored and recorded at the desired time interval by counting the cycle of loading accurately. For these fatigue tests, signals were recorded at the interval of 10 seconds, i.e., at every 400 cycles.

3.2 Test results and discussion

The accelerated fatigue test was performed in a high-cycle force-controlled mode in which the specimen was subjected to a fully reversed sinusoidal twisting load at the constant frequency of 40 Hz. The applied force on the specimen was controlled to be constant until the failure occurred. To determine the life-time of the specimens, the change in resistance was recorded and monitored at the desired time interval. A typical resistance vs. cycles curve is shown in Fig. 10.

As the cycles increased, the magnitude of the resistance became larger. The increase in the resistance is caused by fatigue damage accumulation in the solder bumps. As seen in Fig. 10, there are two abrupt increases in the resistance. For two specimens, we interrupted the test after the first abrupt change and inspected the cross sections of the solder bumps located at the four corners of specimens using an optical microscope. The photocopy-(a) in Fig. 10 shows the cross section of a cracked solder bump after the first abrupt resistance change. It can be seen that the crack is near the interface between the solder bump and the copper pad on the lower PCB. The length of the cracks were about 100 μm - 200 μm . For other two specimens, we interrupted the test after the second abrupt change. The photocopy-(b) in Fig. 10 shows the cross section of the solder bump located at the corner of the specimens after the second abrupt resistance change. It can be seen that the crack is propagated through all the surface between the solder bump and the copper pad on the lower PCB. So the second abrupt change means the final fracture of a solder bump located at the corner of the specimen.

Fig. 10 A typical resistance versus cycles result

Fig. 11 Load amplitude versus number of cycles to failure

So, failure was defined in this high cycle fatigue by the first rapid increase in the resistance.

Figure 11 shows the fatigue test result indicating the load amplitude versus the number of cycles to failure. The applied loading is a fully reversed cyclic loading on the circuit card that varies from 12.6 N to

Fig. 12 Configuration of the specimen and loading fixture; (a) The specimen having the two BGA-type solder bumps; (b) Loading fixture of low cycle fatigue test

6.4 N, which creates a logarithmic distribution of the number of cycles from 90 600 to 466 800 as shown in Fig. 11. There was no failure up to 5×10^6 cycles in the case of 4.1 N. Each point on the curve represents a test specimen. The life means that the solder bump located at the corners of the specimen failed up to the crack length about 100 μm - 200 μm .

4. Shape Optimization of Solder Bump

An automated testing system was developed, which consists of testing machine part, a control and sensing part, and visual inspection part using a CCD camera. The testing machine applies a load to the specimen via a step motor attached a ball screw driven rail table. The displacement of the specimen can be controlled with the resolution of 0.5 μm by a personal computer and data acquisition system. The loading fixture for the specimen was designed to be suitable for pull, shear and bending test of SMC/PCB assembly. The capacity of load cell is 50 kgf and its signal can be acquired with the resolution of ± 2 mV in the range of 10 V. Using this system, it was possible to detect the failure of the interconnection very accurately by the load drop method, the resistance measurement and visual inspection. Various micro-mechanical tests are conducted with the developed machine.

The motivation of this study is that the effect of solder joint shape on the fatigue life is directly related to the quality of the soldering process. The specimens used in the experiments are three pieces of FR-4 PCBs connected by two solder joints as shown in Fig. 12(a). The thickness of the PCB is 1.6 mm. Four different types of solder bumps are studied. The diameter of solder pad is 2 mm. The solder paste used in the experiments was composed of 90% by weight of 63%Sn/37%Pb eutectic alloy balanced with rosin and solvent. To ensure good test specimens being assembled, the solder volume applied to each solder pad needs to be constant. For such a constant-volume

Fig. 13 Maximum equivalent plastic strain versus fatigue life defined by 10% and 25% load drop

control, solder pastes were printed to copper (Cu) pads by means of stencil printing.

In this approach, isothermal low cycle fatigue testing of solder bumps having the different shapes was performed with the machine that provides cyclic strain in the bumps at room temperature. The loading fixture for the specimen was designed to be suitable for fatigue loading shown in Fig. 12(b).

The fatigue test was performed in a low-cycle displacement-controlled mode in which the joints were subjected to a fully reversed ramp cycle at the constant frequency of 1 Hz. The joints were deformed in shear with fixed displacement limits. The load cell and capacitance gauge provides the information about the load and displacement being applied to the specimen. To determine the life cycle of the solder bump, the load drop method, the resistance measurement and visual inspection were used. The final fracture of the bumps could be detected using the resistance measurement. Through a visual inspection using a CCD camera, propagation of a crack could be observed after the crack is visible. But it is difficult to detect the instant of crack initiation using the both methods. So the crack initiation fatigue life was defined by 10% and 25% load drop.

In view of crack initiation fatigue life defined by 10% and 25% load drop, it is observed the trend of increasing solder joint fatigue life with increasing height of the bump. The correlation of crack initiation cycles N_i versus maximum equivalent plastic strain is shown in Fig. 13. The fatigue life curve of solder bumps with various shapes becomes straight lines. The equivalent plastic strain was obtained from the finite element analysis. Three-dimensional finite

Fig. 14 The prediction of crack location from the finite element analysis: (a) Distributions of equivalent plastic strain; arrow indicates high strain location, (b) Photography of the fatigue failure on the solder bumps

element models are constructed to simulate the low cycle fatigue test of the specimens.

The resulting equivalent plastic strain contours for the bumps with different shapes, an hourglass and a barrel shape, are shown in Fig. 14(a). It can be seen that maximum equivalent plastic strain occurs near the interface between the pad and bump, while the hourglass-shaped bump has the maximum equivalent plastic strain at the center of the bumps. The results are consistent with the failure location as shown in Fig. 14(b). Considering above result, maximum equivalent plastic strain was favored to be the governing parameter in fatigue life of a lead/tin eutectic BGA solder joint and we concluded that the optimal shape of a lead/tin eutectic BGA solder joint is an hourglass shape.

5. Conclusion

A thermal fatigue tester was constructed by utilizing thermal conduction. This tester could simulate the effects of power cycling by controlling the temperature of a specimen, which allows various temperature histories according to the test needs. This test method is considered to be very useful not only for the thermal fatigue test of BGA solder joints but also for general reliability test. With this testing apparatus, thermal fatigue tests were executed.

The reliability of the PCB/32 solder bumps/PCB assembly has been studied by torsional high-cycle fatigue testing. The accelerated fatigue test was performed by a small-sized electromagnetic type fatigue-testing machine, and the time to failure was determined by measuring the changes in resistance. This experimental scheme could be used as an

Table 1 The specifications of each experimental technique

	Temperature Range	Cycle Frequency	Loading Type
Thermal Fatigue tester	20~150 °C	~ 2cycle/hour	Thermal Loading
Vibration tester	Isothermal	~ 50 Hz	Torsional Lading
Micro-mechanical tester	Isothermal	~ 0.5 Hz	Mechanical Loading

effective accelerated test method to estimate the high-cycle fatigue life of BGA solder bumps.

Using the micro-mechanical testing machine, BGA type solder/PCB joints have been tested isothermally. Low cycle fatigue test of solder bumps with four different shapes was performed and equivalent plastic strain distributions of four different cases were calculated using finite element method.

In vibration test, the time to failure was determined by the abrupt changes in resistance. However when the solder bump was deformed in shear mode, the crack couldn't show distinct resistance change. Therefore strain drop and load drop methods were useful.

Three experimental techniques were constructed for specific purposes as shown in Table 1. The thermal fatigue test apparatus using thermal conduction can simply simulate power cycling test. Therefore this experimental technique is very useful for reliability assessment of electronic systems under power on/off operation environments. The electronic systems are also subject to vibration environments during handling or operation, such as in vehicles and telecommunications. The small-sized electromagnetic fatigue tester is useful for reliability assessment under these vibration environments. In electronic packaging manufacturing process, there are many factors influencing the solder bump's thermal fatigue reliability, for example, shape, size, reflow process and pad materials. The micro-mechanical tester was constructed to evaluate these factors and was used to optimize the shape of solder bump.

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