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Reliability study of package-on-package stacking assembly under vibration loading

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ABSTRACT

The vibration reliability of lead-free solder joints of Package-on-Package (PoP) is investigated by experimental tests and finite element method (FEM) simulations in this paper. A 14 × 14 mm two-tier PoP module was selected for this study. The natural frequencies and modes were determined by FEM and verified by experimental tests. The printed circuit board (PCB) assemblies are tested under harmonic vibration. Vibration test results show that the vibration reliability of top package is better than the bottom package, and the outermost corner solder joints of the bottom package are the critical solder joints for the PoP under vibration loading. The stress characteristics of solder joints obtained by FEM are well correlated with the experimental results. Failure mechanism analysis indicates that the bottom solder joints become the most vulnerable part of the PoP under vibration due to the bigger relative displacements between the PCB and the bottom package. The micro-structural analysis indicates that cracks usually originate in the bottleneck position of the solder balls, extend within bulk solder and then propagate along the interface between the IMC layer and the bulk solder. The influence of bottom solder joints standoff for vibration reliability was analyzed by FEM as well. Results show that the higher the bottom solder joints' standoff, the more difficult the failure for the PoP assembly.

1. Introduction

In recent years, packaging technology has changed from two-dimensional (2-D) package to three-dimensional (3-D) high density package. 3-D packages make use of space in the out-of-plane direction to decrease package size while still increasing number of I/Os. Among the 3-D package family, one of the more common package types is the package-on-package (PoP) architecture because of its practicality and flexibility on assembling manufacture. Typical PoP structure consists of a top package and a bottom package. The electrical and mechanical connection is implemented by the solder joints between the two packages, as shown in Fig. 1. The PoP has wide applications in mobile phones, tablet personal computers, smart watches and other portable electronic products. In spite of a great success of the PoP in the market, some reliability issues have been highlighted. One of them is the board level reliability under vibration loading. Vibration related failures account for about 20% of all failures in electronic products, according to a report by U.S. Air Force. Therefore, it is important to understand the dynamic response characteristics of PoP assemblies, as well as the failure mechanism of solder joints under vibration.

So far, most of vibration reliability studies focused on the traditional package types such as QFN [1,2], BGA [3–6] and CCGA [7,8], and relatively limited work considered the PoP. T.H. Li et al. [9] analyzed the random vibration reliability of PoP solder joints using the FEM. They pointed out that the maximum stress on the bottom package solder joints is much larger than the maximum stress on top package under vibration loading, and the maximum stress of the PoP occurred on the solder joints located at the corner of bottom package body. Liu et al. [10] discussed the board level dynamic characteristics of the PoP, they found that the natural frequency of the entire assembly device has been significantly affected by the position of PoP structure. When the PoP structure is located at the center of the PCB, the frequency is the minimum. In general, there are few researches focusing on the vibration fatigue of the PoP, and most of researches are based on the theory and simulation at present.

In order to study the failure mechanism of the PoP under vibration loading, the vibration reliability of lead-free solder joints of Package-on-Package (PoP) is investigated by experiment tests and FEM simulations in this work. A finite element model of the PoP assembly was developed, and the natural frequencies and mode shapes were analyzed by FEM and verified by experimental tests. The dye-pry and cross-section tests were performed to study the cracked solder joints in experiments, and the failure mechanism of the PoP is discussed by comparison with the FEM simulation results. The influence of bottom solder

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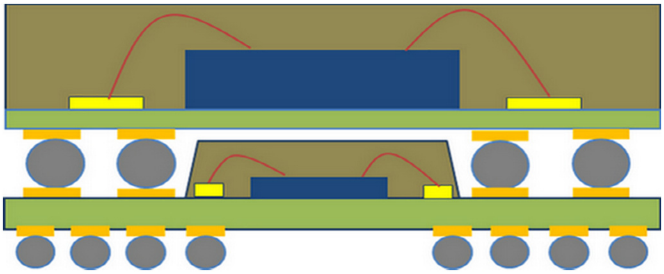

Fig. 1. Schematic of the PoP stacking assembly.

joints standoff on vibration reliability was discussed within a reasonable design range of the actual product as well.

2. Experimental and finite element modeling

2.1. Test vehicle and vibration testing

The test vehicle used in this study consists of two two-tier PoP stacking assembles with 14 mm × 14 mm body size that mounted on a PCB board. The PCB is made of FR4 and is 200 mm in length, 56 mm in width, and has a thickness of 1 mm. Two specially designed PoP assemblies with built-in daisy chain circuit were assembled on the central part of the PCB, as shown in Fig. 2. Lead-free solder 96.5Sn-3.0Ag-0.5Cu (SAC305) was used in assembly of those components. The bottom package body of the PoP is a Package Stackable very thin fine pitch BGA (PSvfBGA) with 152 solder joints, and the top package body is a Fine-Pitch Ball Grid Array (FBGA) with 353 solder joints. The bottom solder joints have 0.5 mm pitch and 0.3 mm diameter and the top solder joints have 0.65 mm pitch and 0.45 mm diameter, as shown in Fig. 3. The dimension parameters are listed in Table 1.

To perform the vibration tests, the PCB assembly was fixed on the shake by four corner screw holes. Two accelerometers were used to characterize the system. One accelerometer was placed on the shaker to measure the input acceleration G_{in}, and another accelerometer was placed on the central of the PCB to measure the output acceleration G_{out}, as shown in Fig. 4. A fatigue failure test was conducted by subjecting the PCB assembly to 7.5 G input acceleration ($G_{in} = 7.5$ G) at the first natural frequency until failure of each daisy chain occurred sequentially. Since the first natural frequency of the test vehicle is 87 Hz (obtained by modal analysis), the frequency range is selected from 83 Hz to 91 Hz, which is 5% around the first natural frequency. An event detector continuously monitors the resistance of the daisy chain circuits to record the failure time. Time-zero resistances of daisy chain circuits were measured to be around 1.9–3.6 Ω. A failure of the solder joint is assumed to occur when total resistance is greater than 1000 Ω for 0.21 μs [11]. Once the event detector has considered a daisy chain failed, failed times are recorded in the WinDatalog software.

2.2. Finite element modeling and modal analysis

The mechanical performance of the test vehicle is studied through finite element analysis (FEA). The FEA model of the PCB module as presented in Fig. 5 is constructed with the commercial computer software ANSYS. In order to simplify the calculation, non-essential factors were neglected. The simulation model of the PoP only contains solder ball, package substrate, Cu pad, and mold compound. Table 2 shows the material types and properties [12,13] for each component. The PCB was fixed on the shake by four corner screw holes so that the finite element model is assumed to have the same boundary condition with the experiment. The natural frequencies and mode shapes were determined by using ANSYS software.

In order to verify the simulated results, experiment modal testing was performed by Polytec Laser Doppler Vibrometer, as shown in Fig. 6. The PCB module was fixed on the experiment table by four corner screw holes to guarantee the same boundary conditions with the vibration tests. The whole modal testing system consists of three parts: excitation system, measuring system, and computer analysis system. Signal generator is used to excite the PoP module. The responses on the PoP

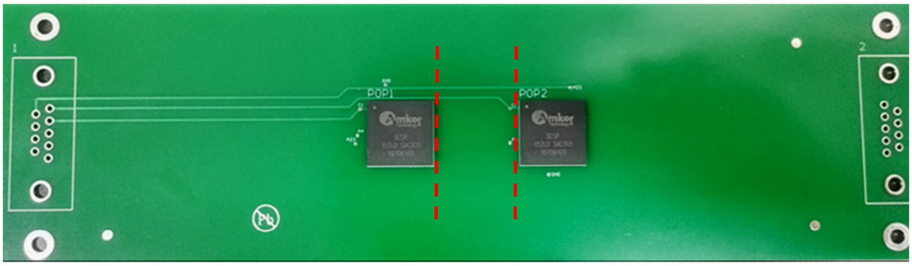

Fig. 2. Details of test vehicle.

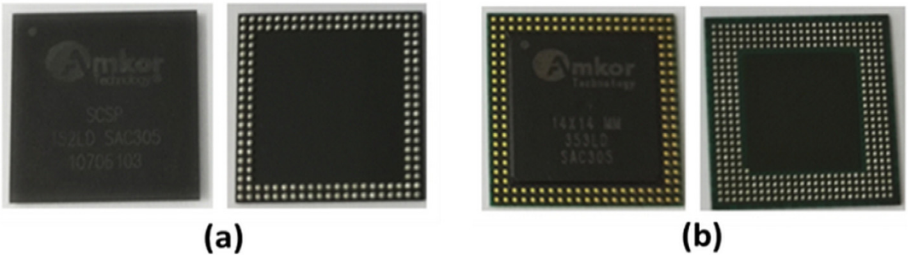

Fig. 3. (a) The top package; (b) the bottom package.