Fatigue life estimations of solid-state drives with dummy solder balls under vibration

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Abstract

An investigation of the effect of dummy solder balls on the fatigue life of a solid-state drive (SSD) under vibration was studied. Finite element analysis and forced vibration experiments of an SSD were conducted to evaluate the fatigue life of an SSD. Global–local analysis techniques were adopted in the finite element analysis to calculate the stress of the solder balls in the SSD. In the vibration experiments, the SSD with dummy solder balls was excited via a sinusoidal sweep vibration around the first resonant frequency until the SSD failed. Using the stress results from global–local analysis and the cycle to failure results from the experiment, an S–N curve was derived for the SSD. This study showed that the solder joints at the corners of the controller package were the most vulnerable components, and that applying the dummy solder balls to those areas decreased the stress of the solder balls and increased the fatigue life of the SSD.

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1. Introduction

A solid-state drive (SSD) is an electronic product that uses flash memory to permanently store data, and is a next-generation information storage device that replaces hard disk drives (HDD). SSDs have no moving mechanical components, so they are characteristically light weight, low in noise, low in power consumption, and have fast data processing speeds as compared to HDDs. These advantages have increased the demand of SSDs. However, portable devices such as notebooks and tablet PCs are continuously exposed to vibrations and shock under various conditions, so an evaluation of the reliability and life of an SSD under vibration and shock has become important during the developmental process. Steinberg announced that 20% of electronic products are destroyed due to vibration [1], and the joint electron device engineering council (JEDEC), which is an independent semiconductor engineering trade organization and standardization body, set a standard for the vibration life test of electronic devices [2].

SSDs are an electronic product in which packages are connected to the printed circuit board (PCB) through the surface mounting of solder balls, and solder balls are the most critical components to determine fatigue-based failure in the SSD. Lead-containing solder material has been conventionally used for centuries, but applying lead-free solder materials for electronic devices has become obligatory due to environmental issues [3]. In particular, the Sn–Ag–Cu (SAC) series of lead-free solder is the most commonly used solder material because its mechanical properties are more robust than conventional solder materials [4–6]. SAC solder balls exhibit robust performance against static loads and thermal loads, but exhibit poor fatigue characteristics for dynamic loads such as drops and vibration [7].

Lee classified fourteen solder joint fatigue models into five categories: stress-based, plastic strain-based, creep strain-based, energy-based, and damage-based [8,9]. Vibration load conditions are one form of high cycle fatigue conditions, so the Basquin equation based on stress was a proper model to predict the fatigue life of solder joints [10]. Therefore, many researchers have conducted studies to predict the fatigue life of solder balls under vibration using the Basquin equation. Perkins and Wong proposed a vibration test method for solder balls of a ceramic column grid array and a plastic ball grid array, and showed that the Basquin equation was suitable for the vibration fatigue model [11,12]. Chen and Che predicted the fatigue life of flip chip solder balls under various load conditions using the cumulative damage index of Miner’s rule [13,14]. Cinar estimated the fatigue life change of Dynamic Random Access Memory (DRAM) modules according to the solder pad size change via vibration testing [15]. Methods to improve the fatigue life of solder balls have also been developed. Typical ways to improve the fatigue life of solder balls are the dummy solder ball method and the underfilling filling method. The underfill filling method is a method used to fill epoxy in the empty space.
between the PCB and package to decrease the thermal stress caused by the thermal expansion coefficient difference between the PCB and package material. Noh compared the fatigue life of electronic devices according to types of underfill, and found that applying the underfill filling method increased the fatigue life of devices by 250% [16]. Solder balls in the outermost corners are usually the most vulnerable to environmental conditions such as vibration, thermal cycling, shock, and bending. The dummy solder ball method involves replacing vulnerable function solder balls at the corners of a ball grid array with dummy solder balls which do not function electrically. Dummy solder balls do not affect the operation of the product, and stresses on the function balls near the outermost corners can be decreased by exchanging them with dummy solder balls. However, the effect of dummy solder balls on the fatigue life of electronic products such as SSDs has not been investigated and mechanical reliability improvements in the vibration fatigue life of SSDs has not been proposed.

In this report, the vibration fatigue life of a real SSD with dummy solder balls was estimated, and the effect of dummy solder balls on the fatigue life of SSDs was evaluated. Since the first natural frequency has a major influence on fatigue fractures caused by vibration, forced vibration analysis and experiments were conducted around the first natural frequency. Locations of vulnerable solder balls under vibration were determined via finite element analysis and experimentation. Local finite element analysis was performed to calculate accurate stress on the solder balls. The stress of solder joints was calculated via finite element analysis and the measured fatigue lifetimes of SSDs in vibration experiments were used to obtain the Basquin equation. Using the obtained Basquin equation, the number of cycles to failure was estimated for SSDs with and without dummy solder balls.

2. Global–local finite element analysis of SSDs

2.1. Development and verification of a finite element model for SSDs

We investigated an SSD with a mini serial advanced technology attachment (mSATA) model as shown in Fig. 1. NAND, DRAM, and controller packages were mounted on the PCB with SAC 305 solder balls whose yield strength is 36 MPa. Generating an appropriate finite element model of the solder balls was difficult because there were a large quantity of solder balls which were too small compared to the overall SSD. Therefore, a global–local finite element analysis method was used to effectively analyze the behavior of a solder ball [17,18]. Fig. 2 shows a global finite element model of the entire SSD with 48,052 solid elements with 8 nodes. The global finite element model was composed of three different parts: a PCB, solder ball, and package. Each solder ball was modeled with one solid element to minimize the number of element. The global finite element model was used to analyze the vibrational response of overall SSD and identify the position of the most vulnerable solder joint among all solder balls. Fig. 3 is a local finite element model of one solder joint which has 54,894 solid elements with 8 nodes. It is composed of a solder ball, upper and lower solder pads and solder masks, and parts of package and PCB. And the solder ball in the local finite element model was modeled with 10,224 solid elements. The displacement calculated from the global finite element model was substituted into all nodes on the cut boundary of the local finite element model to analyze the detailed behavior of the most vulnerable solder joint. In this research, all of the material behaviors were assumed to be linear elastic under vibration load, because all of the components were expected to be under yield strength. The material properties of the global and local finite element models are represented in Table 1.

In order to verify the developed finite element model of the SSD, modal analysis and modal testing were performed. Fixed boundary conditions were applied to the connector and two screw holes of the SSD in the analysis and experiment to describe real attached situations to the electronic device. The experimental setup to measure the natural frequency of the SSD is shown in Fig. 4. The SSD was excited by an impact hammer and the response of the SSD was measured with a laser Doppler vibrometer (LDV). Fig. 5 shows the frequency response function of the SSD mounted on a jig. The first natural frequency of the SSD was 1443 Hz, and the response of the SSD was dominant at the first natural frequency in the frequency range between 20 Hz and 2000 Hz as described in the JEDEC standard. In Fig. 6, the simulated natural mode at the first natural frequency was compared to the measured one. In the analysis and experiment, the maximum displacement occurred near the center of the SSD and the frequency difference was 0.649%.

2.2. Global finite element analysis

In global finite element analysis, the overall response of the SSD was analyzed. According to the JEDEC standard, a sweeping sine
signal with 20 G amplitude was used for forced vibration analysis. The frequency function for a 1 dec/min sweep rate could be represented as follows:

\[ f(t) = f_s 10^{\frac{t}{60}} \]

where \( f_s \) was the starting frequency. The sweeping sine function for the excitation force is shown below:

\[ p(t) = M_n a_0 g \sin \left( 60 \times 2\pi f_s \left( 10^{\frac{t}{60}} - 1 \right) \right) \]

where \( M_n, a_0, \) and \( g \) were the mass of the SSD, vibration amplitude, and gravitational acceleration, respectively.

The first natural frequency of the SSD was 1433.7 Hz, which was the only natural frequency in the frequency range between 20 Hz and 2000 Hz as described in the JEDEC standard. To determine the damping effect of the structure, the damping ratio of the first natural frequency was calculated from the frequency response function in Fig. 5 via the half power bandwidth method and applied in a forced vibration analysis [19]:

\[ \zeta = \frac{\Delta \omega}{2 \omega_n} = \frac{\omega_2 - \omega_1}{2 \omega_n} \]  

where \( \Delta \omega \) was the half power bandwidth between \( \omega_1 \) and \( \omega_2 \), and \( \omega_n \) was the natural frequency. The damping ratio \( \zeta \) was measured as 0.04.

Since the first natural frequency had a major influence on the vibration-induced fatigue fracture, global finite element analysis was conducted around the first natural frequency [20]. A mode superposition method using 40 natural modes was applied in the transient analysis of the global finite element model after confirming the convergence of the proposed global finite element model. The z-directional force as shown in Eq. (2) excited the SSD as a base excitation. An integration time step of 10 µs was set to accurately analyze the behavior of an SSD in its first natural frequency of 1433.7 Hz. Fig. 7 shows the time–displacement result at the center of the SSD during the forced vibration analysis. It showed that the maximum displacement occurred when the sweeping sine frequency passed through the first natural frequency [21,22].

While the SSD was deformed, von Mises stress was calculated at the solder balls under multiaxial stress and strain. Fig. 8 shows the maximum solder ball stress under NAND, DRAM, and controller packages according to frequency increase under 20 G vibration amplitude, and the positions of the maximum solder ball stress under NAND, DRAM, and controller packages are a, b and c in

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Table 1
Material properties of an SSD.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCB</td>
<td>FR4</td>
<td>2752</td>
<td>26,000</td>
<td>0.40</td>
</tr>
<tr>
<td>NAND, DRAM, controller</td>
<td></td>
<td>2114.2</td>
<td>13,000</td>
<td>0.40</td>
</tr>
<tr>
<td>Solder ball</td>
<td>SAC305</td>
<td>7094</td>
<td>44,113.2</td>
<td>0.36</td>
</tr>
<tr>
<td>Solder pad</td>
<td>Cu</td>
<td>8960</td>
<td>117,000</td>
<td>0.34</td>
</tr>
<tr>
<td>Solder mask</td>
<td>Epoxy</td>
<td>1150</td>
<td>5000</td>
<td>0.30</td>
</tr>
</tbody>
</table>

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Fig. 3. Local finite element model of a solder joint.

Fig. 4. Modal testing setup for an SSD.

Fig. 5. Frequency response function for an SSD mounted on a jig.

Fig. 6. First mode shape of a mounted SSD at the first natural frequency.
Fig. 9. The maximum stress was calculated at 1435 Hz, which was after the first natural frequency. The stress distribution of ball grid array on the top side of the SSD when the force excited at 1435 Hz, can be seen in Fig. 9. The solder ball under the controller package where the maximum displacement occurred also yielded the maximum stress. Large stress value was calculated at the solder ball near the corner of a package and it was calculated in order of the solder balls c, d, and e. The stress values of solder ball c and e were calculated as 16.89 MPa and 11.74 MPa under 20 G vibration amplitude. Thus, it was expected that solder balls would fail in the order of the solder balls c, d, and e. In the real SSD, solder balls c and d were dummy solder balls, and solder ball e was a function solder ball, so the SSD works until solder ball e fails. Even if the highest stress occurred at dummy solder ball c in the SSD, function solder ball e which was the most vulnerable among all function solder balls determined the fatigue life of the SSD.

2.3. Local finite element analysis

To identify the precise position and stress value for a vulnerable solder ball, a local finite element model of the SSD was analyzed under forced vibrations. For the local finite element analysis, a full matrix method was applied and the integration time step was set to 10 μs, which was identical to the value used for the global finite element analysis. Calculated time–displacement results around function solder ball e and dummy solder ball c from the global finite element model were applied to the cut boundary of the local finite element model as shown in Fig. 3(a).

Fig. 10 shows the stress distribution of dummy solder ball c of the controller package under forced vibration with an amplitude of 20 G. The results showed that the maximum stress occurred at the interconnections between the upper solder pad and solder ball and that the solder joint crack would occur at the interconnections between the upper solder pad and solder ball. Using the same method, a local finite element model was analyzed repeatedly for the function solder ball. Fig. 11 shows the maximum stress value at the interconnections of function solder ball e and dummy solder ball c according to vibration. Similar to the result of the global finite element analysis, the maximum stress of the solder ball in the local finite element analysis also occurred around the first natural frequency. For a vibration amplitude of 20 G, 6.26 MPa of stress occurred in dummy solder ball c, and 4.66 MPa of stress occurred in function solder ball e. Therefore, stress on a function solder ball within an SSD could be reduced by 26% by applying dummy solder balls.

3. Forced vibration experiments to estimate the fatigue life of SSDs

3.1. Forced vibration experiments of SSDs

Forced vibration experiments of SSDs were conducted to verify the position of the most stress concentration in global–local finite element analysis and to measure the number of cycles to failure for the SSD under various vibration amplitude. The SSD with dummy...
solder balls was excited by a LDS V450 magnet shaker with a sweeping sine signal. The sweep range was set between 1400 Hz and 1500 Hz to measure the response of the SSD around the first natural frequency. Vibration amplitudes of 20 G, 25 G, and 30 G were applied to determine the various fatigue lifetimes of the SSD according to the stress of the solder balls. The experimental setup is shown in Fig. 12. A signal analyzer and power amplifier were set to generate the sweeping sine signal and excite the SSD. The jig was used to mount an SSD on the shaker and to depict the real attached situation of the SSD to the electronic device. As shown in Fig. 12(b), the left side of the SSD was tightened on the base by two screws and the right side was closed by the cover and fastened by two screws to match the real joint condition of the SSD as well as the boundary condition of the global finite element analysis. The SSD was connected to a computer via a universal serial bus (USB) port, and detection of the SSD by the computer was simultaneously checked to measure the number of cycles to failure for the SSD. In the sweeping sine test, the total number of cycles to failure was calculated as follows:

$$ N = \frac{t_{\text{fatigue}}}{t_{\text{loop}}} \int_{0}^{t_{\text{loop}}} f \cdot 10^{2} \, dt $$

where $t_{\text{loop}}$ was the time required to increase the excitation frequency from 1400 Hz to 1500 Hz, and was the time difference calculated by substituting the starting and ending frequency to Eq. (1). $t_{\text{fatigue}}$ was the total time to failure for the SSD.

In the experiment, it was confirmed that solder joint cracks occurred only in dummy solder balls c and d, and function solder ball e under the controller package. The experimental results showed that concentrated stress cracked dummy solder ball c first, propagating to dummy solder ball d, and finally to function solder ball e. The SSD malfunctioned after the stress cracks propagated to function solder ball e, and the cross-sectional images of cracked solder balls are shown in Fig. 13. The images showed that the crack occurred at the interconnection between the solder ball and upper solder pad. The position of the crack was same as with the concentrated stress in the local finite element analysis.

3.2. Derivation of the $S$–$N$ curve for SSDs

Fatigue failure occurred while a material was under repeated tensile and compression loading with damage accumulating. The number of cycles to failure for the material decreased as the external force and stress increased. The relationship between the amount of stress on the material and the number of cycles to failure could be represented by an $S$–$N$ curve [23]. In this study, the numbers of cycles to failure for the SSD under various vibration amplitudes were measured in forced vibration experiments, with the maximum stress at the most vulnerable solder balls being calculated via global–local finite element analysis. Two number of cycles to failure and one maximum stress for each vibrational amplitude were used to derive the SSD $S$–$N$ curve shown in Fig. 14. A stress-based $S$–$N$ curve for high cycle fatigue under vibration could be determined by the Basquin equation as follows:

$$ \sigma_{a} = \sigma_{f} (2N_{f})^{b} $$

where $\sigma_{a}$ was the stress amplitude and $2N_{f}$ was the number of failure reversals. The material constants $\sigma_{f}$ and $b$ were the fatigue strength coefficient and fatigue strength exponent, respectively. From Fig. 14, the material constants of the SSD with dummy solder balls were determined to be 112.7 MPa and 0.198, respectively. Fig. 14 shows that the fatigue lifetimes of an SSD under vibrational
amplitudes of 20 G, 25 G, and 30 G were estimated to be 9.09, 2.96, and 1.18 million cycles, respectively.

3.3. Fatigue life improvement due to dummy solder balls

The fatigue life improvement of an SSD due to dummy solder balls was estimated by assuming that dummy solder balls c and d were function solder balls. If dummy solder balls c and d were replaced with function solder balls and 20 G of vibration were applied to the SSD, 6.26 MPa stress would result, which was the stress on dummy solder ball c (the maximum stress value for all function solder balls). Using the derived S–N curve, the fatigue lifetime could be estimated for an SSD without dummy solder balls. In Fig. 15, the derived S–N curve showed that 6.26 MPa of stress resulted in 2.07 million cycles, which was 4.5 times lower than for a stress of 4.66 MPa, which was the stress on function solder ball e. Therefore, it could be concluded that applying dummy solder balls in the SSD decreased the concentrated stress in the function solder balls by 26% and increased the fatigue lifetime by 4.5 times for the given SSD.

4. Conclusion

In this study, the fatigue life of SSDs under vibration was evaluated with real modules, not daisy chains. The effect of dummy solder balls on the fatigue life of SSDs was also estimated via global–local finite element analysis and forced vibration experiments. Modal testing was conducted with an SSD attached to a jig, and finite element models were developed within 1% error of the SSD natural frequency. It was confirmed that the first natural frequency of an SSD had a dominant effect on fatigue failure. Therefore, a sweeping sine excitation around the first natural frequency was used to perform the analysis and experiment. The stress distribution for the global finite element analysis showed that the position of the most vulnerable solder ball was at the corner of the SSD controller package. Local finite element analysis was performed for each dummy solder ball and function solder ball. The results showed that the maximum stress of the function solder balls decreased by 26%, when dummy solder balls were applied at the corners of the packages. The number of cycles to failure were measured in forced vibration experiments and confirmed that the solder balls cracked at the same position of maximum stress as solder balls in the global–local finite element analysis. Based on the results of the forced vibration analysis and experiments, material constants of the Basquin equation were calculated, and the S–N curve was derived. Comparing the maximum stress of function solder balls in SSDs with and without dummy solder balls, the S–N curve showed that dummy solder balls increased the fatigue lifetime of SSDs by 4.5 times. This research will contribute to estimating and improving the fatigue life of SSDs.

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