Fatigue Reliability Evaluation for Sn–Zn–Bi and Sn–Zn Lead-Free Solder Joints

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The use of Sn–Zn–Bi and Sn–Zn solders is increasing because of their low cost and low melting point. Therefore, it is important to ensure the fatigue strength of Sn–Zn–Bi and Sn–Zn solder joints. In this study, the mechanical fatigue strength of Sn–Zn–Bi and Sn–Zn solder joints was evaluated by using chip scale package (CSP) specimens. The influence of surface treatment on the fatigue strength was investigated by using specimens with Ni/Au or pre-flux on a Cu-pad. These specimens were aged at 85, 125 and 150 °C for 500 and 1000 h to investigate the influence of the appearance of intermetallic compounds at the joint interface. Through a series of isothermal mechanical shear fatigue tests and finite element method (FEM) analyses, it was found that the fatigue lives of Sn–Zn–Bi and Sn–Zn solder joints were greatly affected by the aging temperature. In particular, when Sn–Zn–Bi and Sn–Zn solder joints with Ni/Au plating of the Cu-pad were aged at a temperature above 125 °C, the fatigue strength decreased remarkably in comparison with the specimens without Ni/Au plating.

1. Introduction

The recent development of electric and electronic devices has been remarkable. Electric and electronic devices have spread into society in various forms such as audio-video equipment, household electric appliances, and information processing products such as the mobile phone and personal computer. With the proliferation of electric and electronic devices, the use of Pb as solder material has been increasing.

At the same time, there have been serious debates about the environmental impact of Pb and whether Pb should be removed from solder joints. The debates are now developing into a remarkable movement to establish regulations for the removal of Pb, especially in European countries and Japan. Therefore, many studies have been aggressively promoted to develop technologies for replacing Sn–Pb eutectic solder with lead-free solders.

Generally, thermal fatigue failure of solder joints in electronic devices occurs due to mismatched thermal expansion between the package and the printed circuit board. The authors have previously studied and established an evaluation method of thermal fatigue strength for the ball grid array (BGA) structure using Sn–Pb eutectic solder.1)

As interest in lead-free solder materials continues to grow, so does the appreciation of the merits of conventional Sn–Pb eutectic solder, such as its low melting point, good wettability and high electric and mechanical reliability; it is very difficult to find a lead-free material that has superior or comparative characteristics compared with Sn–Pb eutectic solder.

Now, among the many candidates, the most favorable lead-free solder materials for reflow soldering are Sn–Ag–Cu–(Bi) and Sn–Zn–(Bi). Sn–Ag–Cu solder has excellent electrical and mechanical reliability. But, it is difficult to use in all types of packages because its melting point (217 °C) is much higher than that of Sn–Pb eutectic solder (183 °C). Also, Sn–Ag–Cu solder could have a harmful effect on the chip or other components during the reflow process. Thus, a solder material with a low melting point is in demand. The Sn–Zn system solder is a candidate for a low melting point material, and it has the additional advantage of low cost.

This paper describes the series of mechanical shear fatigue tests carried out using Sn–9 mass%Zn, Sn–8 mass%Zn–3 mass%Bi, Sn–3 mass%Ag–0.5 mass%Cu and Sn–37 mass%Pb CSP specimens, and compares the fatigue strength of these solder joints.

2. Material Properties and Fatigue Strength of Sn–9 mass%Zn and Sn–9 mass%Zn–3 mass%Bi Solders

The melting point of Sn–9 mass%Zn solder is close to that of Sn–Pb eutectic solder. Moreover, Sn–9 mass%Zn solder has excellent ductility, which makes processing easy.2) Therefore, Sn–9 mass%Zn solder is a promising lead-free solder material. On the other hand, the wettability of Sn–9 mass%Zn solder is not good during the reflow process because Zn is more rapidly oxidized than Pb.3)

In order to improve the wettability and lower the melting point, Bi is added to Sn–Zn solder at about 3 mass%. The mechanical properties of Sn–8 mass%Zn–3 mass%Bi solder are greatly influenced by the addition of Bi. Bi lowers the melting point of the solder while increasing the hardness of the solder matrix. Figure 1 shows the relationship of the flow stress and strain in Sn–37 mass%Pb and Sn–3.5 mass%Ag–0.75 mass%Cu, Sn–2.9 mass%Ag–0.5 mass%Cu–3 mass%Bi and Sn–8 mass%Zn–3 mass%Bi lead-free solders at the strain rate 0.001/s at room temperature. The shear specimen of lap joint type was used for this test.4) Solder joint dimensions were 10 mm long × 5 mm wide × 1 mm thick. From the results, it turns out that the Sn–8 mass%Zn–3 mass%Bi solder material shows higher yield strength in comparison with the other solder materials. Since Sn–8 mass%Zn–3 mass%Bi solder has high yield strength, the resistance of deformation causes high stress concentration at the corner of the interface between the solder joint and the Cu-pad. Furthermore, at the interface of the Sn–Zn–(Bi) solder joints, Cu5Zn8/...
3. Mechanical Fatigue Test of CSP Specimens

To investigate the mechanical fatigue life of the solder joint, mechanical shear fatigue tests of chip scale package (CSP) specimens were carried out. The specimens were provided by a task group of the Japan Institute of Electronics Packaging (JIEP).

The package dimensions were 12 mm × 12 mm × 1.2 mm, and each package had 176 solder bumps. The pitch was 0.8 mm and the printed circuit board (PCB) had a thickness of 0.8 mm. Figure 2 shows the structure of the solder joint. FR-4 is the printed circuit board. As shown in Table 1, specimens were prepared with varying combinations of solder material, plating method, aging temperature and aging time. The preheat of each solder material was carried out at 150 °C for approximately 70 s. The temperature of the heating zone was 220 °C and the time of heating was 40 s. Table 2 shows the melting point of each solder material and the reflow peak temperatures.

Ni/Au plating processing is known as a surface treatment which can solve problems such as delamination fracture of some parts and poor wetting. In order to investigate the influence of the Ni/Au plating on the fatigue strength of the solder joint, electroless Ni/Au plating specimens were prepared. The average thickness of each sub layer was 5 μm/Ni and 0.05 μm/Au. To compare fatigue strength by difference of surface treatment method, organic solderability preservative (OSP) coated specimens were used for this study.

The authors have proposed that the isothermal mechanical shear fatigue test can be used to evaluate the thermal fatigue strength of Sn–37Pb solder joints instead of the thermal cyclic test. The consistency of these two kinds of test methods has sufficiently been taken for the Sn–37Pb solder joints case, where the failure mode was almost always the solder fatigue mode (i.e., cracks at the matrix of the solder material). However, the growth of the intermetallic compound in high-temperature dwell time must be considered, because an interface crack may occur when a lead-free solder material is used. In order to investigate the interface fatigue behavior using the isothermal fatigue test method, the specimens were heat-treated before the test to grow the intermetallic compound. In this test, the specimens were aged at 85, 125 and 150 °C for 500 and 1000 h and some specimens were exposed to a high-humidity/high-temperature environment (R.H. 85%/85 °C).

Figure 3 shows a schematic illustration of the isothermal mechanical fatigue test equipment used in this study. The upper and lower surfaces of the specimen were bonded to the jigs with quick-drying glue. The test was carried out approximately 2 h later after bonding. The prescribed shear displacement was applied repeatedly to the upper jig with the lower jig fixed. The displacement-controlled fatigue test was
carried out by applying triangular waves with a constant displacement rate that was controlled to give approximately a 0.001/s strain rate at the corner of the solder joint. Part of the solder joint was observed through a microscope of high magnifying power (maximum to 2500 magnifications on the display) all through the fatigue test. The relative displacement on the upper and the lower surfaces of the solder ball, $\Delta d$, was measured directly through optical micrographs. Although there can be other definitions for the number of cycles to failure, $N_f$, in this study it was defined as the number of cycles when the load measured by a piezo type load cell drops about 10% from the initial load. In order to investigate the stress and strain behavior in the solder joint under mechanical cyclic loading, elasto-plastic FEM analyses using ANSYS code were carried out.

The materials properties of solder used in the analysis are shown in Table 3. The analysis was carried out by fixing the lower surface of the PCB and applying several shear displacements to the upper surface of the CSP, as shown in the FEM model in Fig. 4. The equivalent inelastic strain range was given by the average value of the strain range at the nodes around the corner of the solder joint. Figure 5 shows the relationship between the relative displacement and equivalent inelastic strain range of each solder joint. The fatigue strength in the solder joint was evaluated from the results of the experiment and the analysis.

<table>
<thead>
<tr>
<th>Solder (mass%)</th>
<th>Elastic Modulus (GPa)</th>
<th>Poisson’s rate</th>
<th>Plastic property</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \varepsilon_{\text{in}}$</td>
<td>Strain</td>
<td>Stress (MPa)</td>
<td></td>
</tr>
<tr>
<td>Sn–8Zn–3Bi</td>
<td>36.2</td>
<td>0.3</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Sn–9Zn</td>
<td>39.2</td>
<td>0.3</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Sn–3Ag–0.5Cu</td>
<td>18.2</td>
<td>0.19</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Sn–37Pb</td>
<td>20.0</td>
<td>0.39</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
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<td>0.02</td>
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</tbody>
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Fig. 3 Isothermal mechanical fatigue test machine.

Fig. 4 Three-dimensional analysis model.

Fig. 5 Relationship between relative displacement and equivalent inelastic strain range.

4. Results of Mechanical Shear Fatigue Test

The fatigue life $N_f$ of a solder joint can be evaluated by Manson–Coffin’s law\(^{(13-15)}\) as

$$N_f = \frac{1}{2} \left( \frac{\Delta \varepsilon_{\text{im}}}{\varepsilon_0} \right)^n$$

where $\varepsilon_0$ and $n$ are material properties of the solder, $\Delta \varepsilon_{\text{im}}$ is the equivalent inelastic strain range that occurs in the solder joint. The inelastic equivalent strain range $\Delta \varepsilon_{\text{im}}$ was calculated by applying the shear displacement range $\Delta \delta_{\text{re}}$ between the upper and lower sides of each specimen. The data of $\Delta \varepsilon_{\text{im}}$ and $N_f$, which were obtained from the isothermal mechanical shear test, were plotted on log–log scale graphs, as shown in Figs. 6, 7, 8, 10, and 12. The axis of the abscissa...
shows the cycles to failure and the axis of the ordinate shows the equivalent inelastic strain range at the solder joints. The specimen is named by the solder material [9Zn, 3Bi, 0.5Cu, Pb]-reflow environment [air, N\textsubscript{2}]-surface treatment on the PCB side [Ni/Au, Cu]-surface treatment on the CSP side [Ni/Au, Cu]-aging temperature [85°C, 125°C, 150°C, 85°C (85%)]-aging time (500 h, 1000 h).

Figure 6 shows the relationship between the fatigue life \( N_f \) and equivalent inelastic strain range \( \Delta \varepsilon_{\text{in}} \) for Sn–9Zn, Sn–8Zn–3Bi, Sn–3Ag–0.5Cu and Sn–37Pb CSP solder joints without high-temperature aging. In Fig. 6, the dotted line represents the result of the mechanical shear fatigue test for the Sn–37Pb solder, and the solid line expresses the result of the Sn–3Ag–0.5Cu solder. From Fig. 6, it is found that Sn–9Zn and Sn–8Zn–3Bi solder without aging have superior fatigue strength to the Sn–37Pb solder. On the basis of these results, the authors investigated the effect of aging and Cu-pad plating on the fatigue strength for each specimen.

### 4.1 Fatigue strength of Sn–9Zn lead-free solders

Sn–9Zn solder reflowed in either an N\textsubscript{2} or air environment was prepared for this test. In this test, the authors investigated the differences in the fatigue strength of the Sn–9Zn solder after varying the reflow environment, heat treatment conditions and surface treatment method on the Cu-pad.

Figure 7 shows the fatigue strength of Sn–9Zn specimens reflowed in the N\textsubscript{2} environment. The specimens were reflowed in the condition of approximately 1000 ppm O\textsubscript{2} concentration level. The dotted line shows the average results of the mechanical shear fatigue test for the Sn–37Pb solder (using the data from Fig. 6). The solid line shows the average results of the Sn–9Zn specimen group with good fatigue strength. As shown in Fig. 7, most of the Sn–9Zn solder specimens, including the specimen without aging, have good fatigue strength in comparison to the Sn–37Pb solder. The fatigue life of some heat-treated specimens over 125°C decreases a little in comparison with the specimens of good fatigue strength. In the specimens exposed in the high-humidity/high-temperature environment, the fatigue strength decreases in proportion to the increased aging time.

Figure 8 shows the fatigue strength of the Sn–9Zn specimens reflowed in the air environment. As shown in Fig. 8, the results of the fatigue test are divided into two groups. The dotted line shows the average results of the mechanical shear fatigue test for the Sn–37Pb solder (using the data from Fig. 6). The solid line shows the average results of the Sn–9Zn specimens with good fatigue strength; the unaged specimens are located on this line. The solid line can be regarded as an approximate line of the fatigue strength for the Sn–9Zn solder, because its result agrees with the result of the torsion test of Komatsu’s research (slope \( \approx -1.74 \)).\textsuperscript{16} In the case of the pre-flux specimens, all of the aged specimens have fatigue strength similar to that of the initial state.
(unaged) specimens, even if heat treatment is carried out at 150°C for 1000 h. When the specimens with Ni/Au plating were aged at 85°C for 1000 h or much higher temperature conditions, the fatigue strength is lower. Although the fatigue strength decreases, they have almost identical fatigue strength with the Sn–37Pb solder (dotted line). However, when the specimens were exposed in the high-humidity/high-temperature environment, the fatigue strength greatly decreases.

Figure 9 shows optical micrographs of the Sn–9Zn solder. The unaged specimen of the Sn–9Zn solder shows the solder fatigue mode (i.e., cracks at the matrix of the solder material) [Fig. 9(a)]. In the specimens with Ni/Au plating aged above 125°C, cracks are mainly observed around the vicinity of the interface on the CSP side of the solder. The cracks initiated in the solder layer which is very close to the interface between the intermetallic compound layer and the solder in the aged Ni/Au plating specimens [Fig. 9(b)]. It is assumed that the interface on the PCB side was strengthened by plating with the Ni/Au. On the other hand, the interface on the CSP side was relatively weak and easy to break.

4.2 Fatigue strength of Sn–8Zn–3Bi lead-free solders

Figure 10 shows the results of the mechanical fatigue test for the Sn–8Zn–3Bi solder joints. The dotted line shows the average results of the mechanical shear fatigue test for the Sn–37Pb solder (using the data from Fig. 6), and the solid line expresses the approximate line of the fatigue strength for the Sn–8Zn–3Bi solder. The aged Sn–8Zn–3Bi specimens without Ni/Au plating treatment show similar fatigue strength to the initial state (unaged) specimen. When the specimens with Ni/Au plating treatment were heat-treated at 125°C for 500 h, their fatigue strength becomes lower than that of the Sn–37Pb solder. The growth of the intermetallic compound layer with increasing heat-exposure time generated concentration of high stress at joint corner. Interface fatigue crack caused by the high stress concentration is considered the reason for the fatigue strength reduction. In addition, another reason may be interpreted as the disappearance of Zn–Cu reaction layer and void formation as results the difference of diffusion velocity and reactivity of each component resulting in the change of layers from Zn–Cu to Sn–Cu. When the specimens were exposed in the high-humidity/high-temperature environment, the fatigue strength greatly decreases.

Figure 11 shows optical micrographs of the Sn–8Zn–3Bi solder joint. The Sn–8Zn–3Bi specimen without Ni/Au plating treatment shows fatigue cracks of the solder fatigue mode [i.e., the crack in the matrix of the solder material in Fig. 11(a)]; however, the Sn–8Zn–3Bi specimen with Ni/Au plating and aged above 125°C shows cracks generated only at the interface. The above results show that the change of fatigue fracture mode in solder joints from the solder fatigue mode to the interface fatigue mode decreases the fatigue strength.

4.3 Fatigue strength of Sn–37Pb eutectic solder

In order to compare the fatigue strength of Sn–37Pb eutectic solder with the fatigue strength of Sn–Zn–(Bi) solder, the authors carried out a mechanical fatigue test for Sn–37Pb. Figure 12 shows that the fatigue strength of heat-treated Sn–37Pb solder decreases a little in comparison with the specimen which was not heat-treated. The dotted line represents the result of the unaged Sn–Pb solder specimen. As a reference, the fatigue strength of unaged Sn–3Ag–0.5Cu is shown by the solid line. From this result, it is found that the plating component does not greatly influence the fatigue strength of Sn–37Pb solder joints. In the test, in the high-humidity/high-temperature environment, the fatigue strength of the Sn–37Pb solder does not decrease so much compared with that of its initial state, while the fatigue strength of the Sn–9Zn and the Sn–8Zn–3Bi solders decreases remarkably.
conclusions are as follows. Sn–9Zn and Sn–8Zn–3Bi solder joints were evaluated. The

5. Conclusion

In this study, the authors carried out mechanical shear fatigue tests with CSP specimens, and the fatigue strength of Sn–9Zn and Sn–8Zn–3Bi solder joints were evaluated. The conclusions are as follows.

(1) In the initial state (without heat-exposure) specimens, Sn–9Zn and Sn–8Zn–3Bi solder joints are as reliable as Sn–3Ag–0.5Cu solder joints, and they have higher fatigue strength than that of Sn–37Pb solder joints.

(2) In Sn–9Zn solder joints without Cu-pads plated with Ni/Au, the fatigue strength does not decrease. Although the fatigue strength decreases when the Cu-pads are plated with Ni/Au and aged at 125°C or less, they have superior fatigue strength to Sn–37Pb solder joints.

(3) When Ni/Au plating specimens are aged at more than 150°C, the fatigue strength at the solder joints decreases greatly. This is caused by the growth of the interface fatigue crack. When Sn–9Zn and the Sn–8Zn–3Bi solders are exposed in the high-humidity/high-temperature environment, their fatigue strength decreases greatly.

According to the above results, if these lead-free solder materials are used carefully with the correct environment and reflow conditions, practical applications of the Sn–Zn–(Bi) lead-free solder seem possible.

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