The performance and fracture mechanism of solder joints under mechanical reliability test

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\textbf{Abstract} 

The drop resistance and fracture behavior of Sn–37Pb, Sn–3.0Ag–0.5Cu (SAC305), Sn–1.0Ag–0.5Cu (SAC105), and Sn–8.5Zn–0.5Ag–0.01Al–0.1 Ga (SnZn-5e) solder ball joints under the board-level drop test (BLDT) and the ball impact test (BIT) were studied. The results show that the drop reliabilities in terms of the characteristic life ratio from the Weibull plot are SnZn-5e : Sn–37Pb : SAC105 : SAC305 = 3.1 : 2.9 : 2.1 : 1. It was observed that failure of Sn–37Pb occurred at the eutectic tin–lead phase whereas it took place at the brittle interface between the (Cu,Ni)\textsubscript{5}Sn\textsubscript{5} inter-metallic compound and Ni layer in SAC305. The failure of SAC105 was found to be located within the solder matrix as well as at the interface of the inter-metallic compound. The failure of SnZn-5e depends on the morphology of the interfacial inter-metallic compound. The failure modes of Sn–37Pb and SAC305 after the BIT were similar to those after the BLDT. The maximum impact force (\(F_{\text{max}}\)) and the initial fracture energy (\(E\)) from the BIT can be used to evaluate the drop reliability of solder joints.

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1. Introduction

Due to environmental concerns, lead-free solders have been become widely used in the electronic packaging industry. Compared to eutectic Sn–Pb solder, lead-free solder is usually brittle and stiff, making it prone to damage after an impact force [1]. With the increasing number of portable electronic products, the reliability of lead-free solder joints in resisting mechanical force has become a major issue in the electronic packaging industry.

The board-level drop test (BLDT) [2,3] can be used to measure the reliability of solder ball joints. In the BLDT, the sample falls at a fixed angle, allowing the fracture mechanism of the solder ball joint in an accelerated environment to be evaluated. According to previous studies [4–7], a positive correlation exists between the characteristics of impact force profile and the reliability obtained from the drop test. The ball impact test (BIT) using an impact force exerted to a single solder joint. The development of the test apparatus, numerical studies have been performed by Yeh et al. [8,9] to investigate transient structural responses and failure modes of the solder joint caused by the impact process. The relationship between the BIT and BLDT for the Sn–Ag–Cu system has been studied [6]. The type and shape of the inter-metallic compound formed in the solder are complex due to the numerous types of lead-free solder alloy and pad. Few studies have compared the fracture mechanism of solder ball joints after the BIT and BLDT.

In the present study, the stability and fracture behavior of Sn–37Pb, Sn–3.0Ag–0.5Cu (SAC305), Sn–1.0Ag–0.5Cu (SAC105), and Sn–8.5Zn–0.5Ag–0.01Al–0.1 Ga (SnZn-5e) solder joints under the BLDT and BIT were studied. The characteristic life, maximum impact force (\(F_{\text{max}}\)) and the initial fracture energy (\(E\)) from the BIT can be used as a reference when designing electronic products.

2. Experimental methods

In this study, the solder balls were attached to 10 mm × 10 mm thin fine-pitch ball-grid array (TFBGA) packages, which consisted of 181 solder balls. The TFBGA was bonded to a printed circuit board (PCB) using the reflow process. The diameter of the solder ball was 300 \(\mu\)m and the pitch between solder pad centers was 500 \(\mu\)m. The solders used in this study include Sn–37Pb, SAC305, SAC105, and SnZn-5e (Sn–8.5Zn–0.5Ag–0.01Al–0.1 Ga). The substrate metallization for Sn–37Pb, SAC305, and SnZn-5e solder balls were electroplated Ni immersed in Au and that for the SAC105 solder ball was organic solderability preservative Cu (OSP Cu). The solder balls for the BLDT (board-level drop test, Fig. 1a) were bonded to the printed circuit board, 132 mm × 177 mm × 1 mm, on which the metal pad for solder attachment is electroplated Cu. The diameter of the solder pad was 240 \(\mu\)m. Solder pastes were applied for joining the BGA package with PCB. The solder pastes applied were Sn37Pb for Sn37Pb solder ball, Sn9ZnAl(7 ppm Al) for SnZn5e, and SAC305 for all SAC solder balls. Reflow process was conducted following the JEDEC recommendations (J-STD-020D)
The packages for the BLDT test were reflowed twice, one for ball attachment and the other for board assembly. The specimens for the BIT test were reflowed once only. The Sn–37Pb and SnZn-5e solders, the peak temperature and dwell time at the peak were, respectively, 220 ± 5 °C and 80 s, while were 260 ± 5 °C and 70 s for SAC305 and SAC105. The BLDT was carried out according to the JEDEC) recommendations [2,3]. Four PCB test vehicles were adopted for the drop test for each solder. There are five BGA specimens arranged on each test vehicle. Hence a total of 20 BGA packages were applied for each solder for the drop test. The drop was conducted at an acceleration of 1500 G. The resistance of the testing specimen was measured every 0.1 s during the BLDT test using a resistance multi-event detector system. The specimen was regarded as failed when 60% of the consecutively measured resistance values are higher than 1000 Ω. The BIT (ball impact test) test was conducted with a self designed facility (Fig. 1b) of which a drop velocity of the impact head was set at 1.0–1.25 m/s to provide peak impact force of up to 20 N. The BIT test was to investigate the fracture behavior of the solder ball under high impact. Thus the solder balls were attached to the substrate on one side only.

3. Result and discussion

3.1. Microstructure of solder ball joints

The microstructures of the as prepared Sn–37Pb, SAC305, and SAC105 solder ball joints are presented in Fig. 2. The related intermetallic compounds were identified using energy dispersive spectrometer (EDS) analysis. Fig. 2a shows the backscattered electron (BSE) image of the Sn–37Pb solder joint. The white phase is an α-lead-rich phase and the gray phase is the β-tin matrix. The intermetallic compound that formed near the interface includes a Ni5Sn3 layer and some (Au, Ni)Sn4 clusters. Fig. 2b shows the BSE image of the SAC305 solder joint. Some granular Ag3Sn was found in the solder matrix and a layered (Cu, Ni)6Sn5 was found near the interface. Fig. 2c shows the BSE image of the SAC105 solder joint. A scallop shape of Cu6Sn5 layer was found near the interface. Some granular Cu6Sn5 were also found in the solder matrix.

The microstructure of the SnZn-5e solder joint was greatly changed by the second reflow. Fig. 2d shows the BSE image of the SnZn-5e solder joint before the second reflow. Some granular AgZn3 were found in the solder matrix and a double-layered inter-metallic compound was found near the interface; the compositions of its outer layer and inner layer were identified as AgZn3 and AuZn3, respectively. Many micro-cracks were found near the double-layered inter-metallic compound. According to the magnified image, parts of AuZn3 and AgZn3 break away from the Ni substrate.

The microstructure of the SnZn-5e solder joint became more complex after the second reflow. The double-layered inter-metallic compound broke away from the Ni substrate to various degrees. The layered inter-metallic compound broke away from the substrate as high as the 1/4 height of the solder ball, as shown in Fig. 2e. Some micro-cracks were also found near the double-layered inter-metallic compound.

3.2. Characteristic life, maximum impact force, and initial fracture energy of the solder joints

The number of drops to failure of Sn–37Pb, SAC305, SAC105, and SnZn-5e solder joints was measured as 99–622, 29–216, 35–702, and 65–859, respectively. The results for the BLDT were analyzed through Weibull plot. The characteristic life defined as the number at 63.2% of failures. Fig. 3 shows the Weibull plot of the solder ball joints. The characteristic life of the Sn–37Pb, SAC305, SAC105, and SnZn-5e solder joints was measured as 336, 118, 253, and 368, respectively. These figures, if taken as the life comparison, count for the life ratio of SnZn-5e:Sn–37Pb:SAC105:SAC305 = 3.1:2.9:2.1:1. Further considering the 10% failure, the drop life is 32, 62, 113, and 129, respectively, for SAC305, SAC105, SnZn-5e, and Sn–37Pb, which counts for the 10% life ratio of SnZn-5e:Sn–37Pb:SAC105:SAC305 = 3.5:4.0:1.9:1. This result may indicate that the SnZn-5e could exhibit higher risk of early failure than the Sn37Pb, but both are superior to the SACs in the early failure concern.

<table>
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<th>Table 1</th>
<th>$F_{\text{max}}$ and $E$ values of Sn–37Pb, SAC305, SAC105, and SnZn-5e solder ball joints.</th>
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<tr>
<td>Sn–37Pb</td>
<td>SAC305</td>
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<tr>
<td>$F_{\text{max}}$ (N)</td>
<td>6.42 ± 0.72</td>
</tr>
<tr>
<td>$E$ (µJ)</td>
<td>485.52 ± 82.31</td>
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Table 1 shows the mean and standard deviation of the maximum impact force, $F_{\text{max}}$, and the initial fracture energy, $E$, of the solder joints. As shown in Table 1, the order of $F_{\text{max}}$ and $E$ is as follows: Sn–37Pb > SnZn-5e > SAC105 > SAC305. Except for SnZn-5e, the order of $F_{\text{max}}$, $E$, and characteristic life are similar for the Sn–37Pb, SAC105 and SAC 305 solder ball joints. Accordingly, $F_{\text{max}}$ and $E$ can be used to roughly evaluate the drop reliability of solder joints. These values are believed to relate to the bulk properties of the solders and are to be discussed in the next section.

3.3. Fracture behavior of the solder ball joints

Fig. 4a shows the fracture behavior of Sn–37Pb solder ball joints after the BLDT. Cracks formed near the Ni substrate and a major crack is formed in the eutectic tin–lead phase. The uneven cracks through the solder joint indicate that the fracture behavior of Sn–37Pb solder ball joints belongs to that of bulk fracture. Fig. 4b shows the fracture behavior of Sn–37Pb solder ball joints after the BIT. The solder deformed along the impact direction and an elongated tail-like structure appeared near the end of the sample in the impact direction. The fracture behavior after the BIT also belongs to that of bulk fracture.

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The relatively low Young’s modulus of Sn37Pb solder, 25–34 GPa [11] comparing to 47 GPa for SAC105 and 54 GPa for SAC305 [11], may render the Sn37Pb solder behave more compliant than other solders under the BLDT and BIT tests. The lead-rich
phase in Sn–37Pb has a face-centered cubic (FCC) structure and the energy for the dislocation slip is small [12,13]. The lead-rich phase can absorb the stress in the crack tip while the body-centered-tetragonal (BCT) [12,14] structure tin-rich phase can obstruct the growth of cracks. Therefore, the $F_{\text{max}}$ and $E$ of Sn–37Pb solder ball joints are the highest obtained in this study and the characteristic life is higher than those of SAC305 and SAC105. The lower characteristic life of SAC305 than SAC 105 is also in parallel with the higher Young’s modulus of SAC305. Thus the $F_{\text{max}}$ and $E$ values of the SAC305 and SAC105 also reflect the relative reliability of the solder joints.

Fig. 5a shows the fracture behavior of SAC305 solder ball joints after the BLDT. A layered ($\text{Cu,Ni}_{6}\text{Sn}_{5}$) phase formed near the Ni substrate and a crack grew along the interface between ($\text{Cu,Ni}_{6}\text{Sn}_{5}$) and the Ni layer. The fracture behavior belongs to that of interfacial fracture. Fig. 5b shows the fracture behavior of SAC305 solder ball joints after the BIT. Some granular ($\text{Cu,Ni}_{6}\text{Sn}_{5}$) was found near the end of the sample in the impact direction. A fracture was also found between ($\text{Cu,Ni}_{6}\text{Sn}_{5}$) and the Ni layer. The fracture behavior also belongs to that of interfacial fracture.

In SAC305 solder ball joints, cracks formed between the ($\text{Cu, Ni}_{6}\text{Sn}_{5}$) and the Ni layer in both the BLDT and BIT. The failure belongs to the interfacial fracture. Accordingly [15], the elastic modulus of SAC305 is about 51 GPa and the tin-rich phase has a BCT structure [14]. Most energy from the BLDT and BIT cannot be easily counteracted by the deformation of the bulk solder. The elastic modulus of $\text{Ag}_{3}\text{Sn}$, ($\text{Cu, Ni}_{6}\text{Sn}_{5}$), and the Ni layer are relatively high ($\text{Ag}_{3}\text{Sn}$: 68.72–84.2 GPa [16], ($\text{Cu, Ni}_{6}\text{Sn}_{5}$): 150–210 GPa [17], Ni: 217.74–234.30 GPa [18]). Therefore, the stress is not released by the deformation of the solder; it becomes concentrated near the interface. In this study, the interfaces near the neck of the substrate side are ($\text{Cu, Ni}_{6}\text{Sn}_{5}$/Solder and ($\text{Cu, Ni}_{6}\text{Sn}_{5}$/Ni layer. Because the elastic modulus of the solder is relative low, some stress between the ($\text{Cu, Ni}_{6}\text{Sn}_{5}$/Solder interface may be released more easily by the deformation of the solder or by a dislocation slip [15]. Then, cracks form at the interface of ($\text{Cu, Ni}_{6}\text{Sn}_{5}$) and the Ni layer. Due to the high elastic modulus of ($\text{Cu, Ni}_{6}\text{Sn}_{5}$) and Ni, the characteristic life, $F_{\text{max}}$ and $E$ of the SAC305 solder are the lowest among the four types solder ball joint.

Fig. 6a shows the fracture behavior of SAC105 solder ball joints after the BLDT. Fractures formed near the OSP Cu side. The fractures include both a bulk fracture on the left side and an interfacial fracture on the right side. Some samples exhibit only one kind of fracture mode, but most samples include both kinds after the BLDT. Fig. 6b shows the fracture behavior of SAC105 solder ball joints after the BIT. Some residual solder was found near the end of the sample in the impact direction and the inter-metallic compound was not stretched. As shown in Fig. 6b, a scallop $\text{Cu}_{6}\text{Sn}_{5}$ was found above the OSP Cu substrate. The fracture penetrated the scallop $\text{Cu}_{6}\text{Sn}_{5}$, and left some $\text{Cu}_{6}\text{Sn}_{5}$ on the Cu substrate. Accordingly, the fracture is an interfacial fracture.

In SAC105 solder ball joints, Fig. 7, the elemental analysis show that the Sn element exhibits two distinct regions. A green (stronger intensity) appearance in the color image signifies scallop $\text{Cu}_{6}\text{Sn}_{5}$, while the blue (weaker) region indicates the layer $\text{Cu}_{3}\text{Sn}$. In other words, the IMC formed include $\text{Cu}_{6}\text{Sn}_{5}$ and $\text{Cu}_{3}\text{Sn}$. Cracks formed in solder matrix, near $\text{Cu}_{6}\text{Sn}_{5}$ and $\text{Cu}_{3}\text{Sn}$ after the BLDT. The failure belongs to a mixed fracture mode. The scallop shape of $\text{Cu}_{6}\text{Sn}_{5}$ inhibits the crack propagation along the interface between the $\text{Cu}_{6}\text{Sn}_{5}$ and the solder. Cracks occur in the solder matrix and along
the interfaces of Cu$_3$Sn/Cu$_6$Sn$_5$ and Cu$_3$Sn/Cu. As described for Sn–37Pb, the solder matrix with a low elastic modulus can easily deform and counteract the impact energy. The elastic modulus of SAC105 is only 47 GPa\[15\] so the solder matrix has certain degree of drop resistance to cracks. In addition, cracks must pass through the Cu$_3$Sn and Cu$_6$Sn$_5$ inter-metallic compounds if they occur near the interfaces of Cu$_3$Sn/Cu$_6$Sn$_5$ and Cu$_3$Sn/Cu. A certain degree of drop resistance also exists near the inter-metallic compound. Since the drop resistances of the solder matrix and inter-metallic compound are similar, a mixed failure mode occurs. Therefore, the failure of SAC105 solder ball joints includes both interfacial fracture and bulk fracture.

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Compare the fracture mode of SAC105 solder ball joints after the BLDT and BIT, a mixture fracture was found after the BLDT and only interfacial fracture was found after the BIT. The result can be attributed to the difference between the two tests. In BLDT,
ball joints after the BIT. Cracks were found along the solder and at the interfaces of solder/AuZn3 and AgZn3/AuZn3. Fig. 9b shows the cross section image of a SnZn-5e solder ball joint after the BIT. Obvious dimples can be found on the fracture surface. According to the results in Fig. 9a and b, the failure of SnZn-5e after the BIT belongs to a mixture of fracture modes.

SnZn-5e solder ball joints have three fracture modes after the BLDT. In the first fracture mode, most AuZn3 and AgZn3 adhered to the interface between the substrate and the solder ball. The AuZn3 and AgZn3 act as the layered (Cu,Ni)6Sn5 in SAC305 solder ball joint and made an interfacial fracture between the intermetallic compound and the solder. Although the number of drops to failure is relatively low in this mode, the average number of drops to failure is relatively high among the four systems because the possibility of occurrence of this mode is low.

In the second mode, the AuZn3 and AgZn3 broke away from the interface. Due to the bent intermetallic compound, cracks did not easily grow along the interface between the intermetallic compound and the solder. The elastic moduli of AuZn3, AgZn3, the Zn-rich phase, and the Ni layer are higher than that of Sn-rich phase. Therefore, most cracks formed in the Sn-rich phase near the AuZn3 and AgZn3. The Sn-rich phase has a BCT structure which has a higher resistance to the growing cracks. Therefore, the number of drops to failure of the second mode is higher than that of the first mode.

In the third mode, the AuZn3 and AgZn3 broke far away from the interface and the distance between the intermetallic compound and the substrate was about 1/4 the solder ball diameter. Some Zn-rich phase was found between the intermetallic compound and the Ni substrate. Cracks were blocked not only by AuZn3 and AgZn3 but also by the Zn-rich phase, which further increased the drop resistance of SnZn-5e solder ball joints.

Due to the addition of Ga in the SnZn-5e, the toughness of the solder increased which benefit the buck fracture in the solder [19–21]. However, the structures of AgZn3 and AuZn3 are Hexagonal Closest Packed (HCP) [22] and cubic [23] structure, which cannot easily absorb energy by deformation. As the impact force transfer to the intermetallic compound, an interfacial fracture was formed. Then the SnZn-5e solder ball joints represent a mixture fracture mode after the BIT. Due to the relatively soft SnZn-5e solder and the stiff AgZn3 and AuZn3, the E value of SnZn-5e solder ball joints is higher than those of SAC105 and SAC305. Due to the intermetallic compound distribution in the solder changed to various degree after the second reflow and the fracture behaviors also have obvious different between the three modes, the drop reliability of SnZn-5e solder ball joint can not be evaluated from $F_{\text{max}}$ and $E$ easily as described in Section 3.3.

4. Conclusion

The results of the board-level drop test (BLDT) of TFBGA modules indicate that the 63.2% characteristic life of the solder balls tested exhibit the ratio of SnZn-5e:Sn37Pb:SAC105:SAC305 = 3.1:2.9:2.1:1, while the ratio at 10% drop life is 3.5:4.0:1.9:1. The distribution of intermetallic compound within the solder joint and the elastic modulus of the solders significantly determine the fracture mode of the solder joint upon the BLDT and ball impact test. The solder with relatively low elastic modulus and the formation of uneven distribution of intermetallic compound within the joint will give rise to higher characteristic life upon BLDT test. The fracture of the SAC solders mainly occurs at the interface between IMC and solder matrix or between IMC and substrate metallization. The SnZn-5e solder exhibits three fracture modes, with the fracture within the solder matrix predominated and thus gives rise to better characteristic life.
Acknowledgment

The authors acknowledge the National Science Council of Taiwan for the financial support for this research under grant NSC 98-2221-E-006-065-MY3.

References


