Abstract

Assembly of components with large pads, such as high-brightness LEDs or high-power dies, often is soldered with preforms because of lower voiding and lower flux fumes generated when compared to solder paste, and because of its better thermal and electrical conductivity compared to Ag epoxy. This is particularly true when the joints are to be formed within a cavity. Although lower than solder paste, the voiding in the solder joint is still a concern for high-reliability and high-performance devices. In this study, voiding at high-power die-attach reflow soldering using preforms was simulated with the use of Cu coupons to mimic both the die and substrate. Voiding behavior was studied by varying solder alloy types, quantity of flux coated on the preforms, extent of oxidation of the Cu coupons, reflow peak temperature, and the weight applied on top of the simulated die. For SAC305, with increasing weight, the bondline thickness (BLT) maintained constant initially due to solder surface tension, then reduced rapidly at weight higher than 50g. The voiding area % increased with decreasing BLT first, then levelled off at a lower BLT, although the voiding volume decreased with decreasing BLT due to constrained lamellar solder flow. Voiding was the highest for SAC305, followed by 57Bi/42Sn/1Ag, with 63Sn/37Pb being the lowest, and increased with increasing oxidation of Cu coupon. With increasing flux quantity, voiding increased for SAC305 and 63Sn/37Pb, but decreased for 57Bi/42Sn/1Ag, mainly due to the different temperature ranges at reflow. Voiding increased with increasing reflow temperature up to 170°C due to increasing vaporization, decreased with further increase in reflow temperature up to 210°C due to increasing flux activity, and increased again at temperature beyond 210°C due to rapid flux outgassing.

Introduction

Assembly of components with large pads such as high-brightness LEDs or high-power dies often is soldered with preform, mainly due to a lower voiding and lower flux fumes generated when compared to solder paste, and also because of its better thermal and electrical conductivity compared to Ag epoxy. This is particularly true when the joints are to be formed within a cavity. Although lower than solder paste, the voiding in the solder joint is still a concern for high-reliability and high-performance devices. In this study, voiding behavior of large pad high-power devices was simulated with Cu coupon to Cu coupon sandwiches. Its assembly using flux-coated preform was studied, with variation in solder alloy
type, quantity of solid flux coated on solder preforms, Cu coupon pre-oxidation extent, reflow temperature, and pressure exerted onto the sandwich during reflow. The results will be reported and discussed here.

Experimental

Solder Alloy Type
Preforms of three solder alloys were tested: 96.5Sn/3Ag/0.5Cu (SAC305), 63Sn/37Pb, and 57Bi/42Sn/1Ag. The preform diameter was 0.906-inch and 0.006-inch thick.

Flux Coating
The preform was pre-coated with a solid flux film using liquid flux at 0.5, 1.0, and 2% flux concentrations in isopropyl alcohol upon application.

Cu Coupon Oxidation Pretreatment
The copper coupon (0.906-inch diameter, 0.020-inch thick) was used to simulate both die and substrate, and was pre-cleaned by soaking in a diluted HBF₄ aqueous solution, followed by deionized water rinsing and air drying. These cleaned Cu coupons were then oxidized by placing them on a 230°C hot plate for 0, 30, and 60 seconds, and 5 minutes prior to the soldering process.

Die-Attach Sandwich Setup
The high-power die-attach setup was simulated with the use of two copper coupons, which were to be joined with a flux-coated solder preform. A 3-inch x 3-inch ceramic plate was used as a carrier. The simulated die-attach sandwich (Cu coupon on a solder preform, then placed on another Cu coupon) was placed on the carrier. At die-attach with solder preforms, many industry manufacturing processes use fixtures with some weight on the die to secure the sandwich. In this study, metal weights varying from 0 to 100 grams were placed on the top of the sandwich to simulate the fixture weight. Paper cardboard was placed on top of the die for heat insulation if a weight was used.

Reflow Peak Temperature
The sandwich on the carrier was placed on a 5-zone in-line contact reflow oven, and then sent through the reflow oven with various peak temperatures as shown below:
SAC305: 240°C, 250°C, and 260°C
63Sn/37Pb: 205°C, 215°C, and 225°C
57Bi/42Sn/1Ag: 160°C, 170°C, and 180°C

Reflow Under Various Pressures
For SAC305, various weights were placed on top of the sandwiches at reflow: 0, 10, 30, and 100 grams. For this set of assembly, freshly cleaned Cu coupons, 0.5% flux concentration, and a peak temperature of 240°C were used. Ten sandwiches were reflowed for each condition. For 63Sn/37Pb and 57Bi/42Sn/1Ag, 0, 10, 20, and 30 grams of weight were used for the pressure study.

Voiding Assessment
After reflow, the sandwiches were examined under X-ray to determine the voiding area percentage.

Bondline Thickness (BLT)
For SAC305, three sandwiches for each weight condition were cross-sectioned to determine the bondline thickness under various weights.

Results

Effect of Weight on SAC305 System Using X-ray Images
Figure 1 shows the X-ray images of SAC305 sandwiches under various weights. Here, the flux concentration was 0.5%, the peak temperature was 240°C, and the coupons were etch-cleaned prior to use. Although 10 samples were prepared for each combination of conditions, three sandwiches were removed due to large opens in the solder joints because the image analysis software was unable to determine the voiding % properly. Most of the samples showed full wetting to the perimeter of coupons, and only a few showed a small fraction of non-wetting near the edge of the joints.
Most of the voids showed plain vacancy, except for a few samples where some spotty light-colored solder was seen within the voids, such as in the third image of the 10-gram series and the first image of the 30-gram series. The spotty solder islands were attributed to the once-formed liquid joints, but were wiped out partially by expanding voids.

In most images, concentric ring textures can be seen clearly, indicating the Cu coupons may be warped. Also, the joint appeared to be thicker toward the center, and the solidification may have been developed stepwise from the edge toward the center.

**Bondline Thickness (BLT)**

The 100-gram weight samples showed a much lighter shade of color than the other three weight samples, suggesting much thinner solder BLT data for SAC305 joints under various weights. The sandwich samples were cross-sectioned, as exemplified in Figure 2, with the BLT measured at both the edges and the center. The average value was calculated to represent the BLT of a given weight condition, as shown in Table 1.

**Voiding versus Weight Analysis**

The actual voiding data of SAC305 under various weights are presented in Figure 3 and Figure 4. Other than the 100-gram condition showing a wider voiding distribution, no clear trend can be concluded.
<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>Sample</th>
<th>BLT-left (mm)</th>
<th>BLT-center (mm)</th>
<th>BLT-right (mm)</th>
<th>Average (mm)</th>
<th>Overall Average (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>B</td>
<td>0.060</td>
<td>0.120</td>
<td>0.095</td>
<td>0.092</td>
<td>0.163</td>
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<tr>
<td>0</td>
<td>F</td>
<td>0.221</td>
<td>0.214</td>
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<td>0.217</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>G</td>
<td>0.177</td>
<td>0.226</td>
<td>0.138</td>
<td>0.180</td>
<td></td>
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<tr>
<td>10</td>
<td>K</td>
<td>0.208</td>
<td>0.223</td>
<td>0.140</td>
<td>0.190</td>
<td>0.179</td>
</tr>
<tr>
<td>10</td>
<td>N</td>
<td>0.162</td>
<td>0.101</td>
<td>0.138</td>
<td>0.134</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>L</td>
<td>0.237</td>
<td>0.126</td>
<td>0.280</td>
<td>0.214</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>R</td>
<td>0.225</td>
<td>0.099</td>
<td>0.318</td>
<td>0.214</td>
<td>0.191</td>
</tr>
<tr>
<td>30</td>
<td>E</td>
<td>0.124</td>
<td>0.152</td>
<td>0.240</td>
<td>0.172</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>N</td>
<td>0.225</td>
<td>0.196</td>
<td>0.136</td>
<td>0.186</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Y</td>
<td>0.022</td>
<td>0.033</td>
<td>0.055</td>
<td>0.037</td>
<td>0.037</td>
</tr>
</tbody>
</table>

Table 1. BLT of SAC305 sandwiches under various weights.

Figure 2. Edge view of cross-sectioned samples under 30 grams of weight.

Figure 3. Actual voiding data of SAC305 under various weights.

Figure 4. Voiding data of SAC305 under various weights.

Figure 5. Relationship between weight and BLT for SAC305.
The lack of an obvious trend could be attributed to data scattering. It might also be possible that weight may not be a direct governing parameter. Similar to all other liquids, liquid solder is expected to follow fluid dynamics, with a greater difficulty to have lamellar flow under a small clearance. Since voiding involves void coalescence and escaping, and both will be facilitated by a higher BLT, it makes sense to investigate voiding behavior around the bondline thickness. Figure 5 shows that with increasing weight, the BLT maintained constant around 0.18mm at first, then decreased at a weight higher than 50 grams, and then reached 0.04mm at 100 grams of weight.

**Radius of Curvature**

The relationship observed between BLT and weight can be understood by reviewing the radius of curvature effect. For a curved surface, any point on the surface can be specified by two principal radii of curvature, as shown in Figure 6. $R_1$ is the radius of curvature in the plane of the paper and $R_2$ is the radius of curvature perpendicular to the plane of the paper.

$$\Delta P = \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right)$$  \hspace{1cm} (1)

Equation (1) describes the pressure difference across a curved interface ($\Delta P$) in terms of the surface tension of the interface ($\gamma$) and the two principal radii of curvature at a point on the surface [1].

The surface tension of SAC305 has been reported to be 0.568 N/m [2]. In the sandwich structure discussed here, $R_2$ was the Cu coupon radius, 0.906 inch (0.0115m). By setting an $R_1$ value being half of the BLT, or 0.003 inch (0.000076m), the pressure difference across the liquid solder surface is 765,000g-f/m². For the Cu coupon area used in this study, it should be able to maintain a constant BLT with a weight placed on top of the sandwich up to 318g-f.

The relationship observed between BLT and voiding can be calculated by multiplying BLT with voiding area %, and was expressed as an arbitrary unit.

<table>
<thead>
<tr>
<th>BLT (mm)</th>
<th>Voiding (area %)</th>
<th>Voiding (volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>28.9</td>
<td>4.71</td>
</tr>
<tr>
<td>0.18</td>
<td>30.3</td>
<td>5.44</td>
</tr>
<tr>
<td>0.19</td>
<td>24.1</td>
<td>4.59</td>
</tr>
<tr>
<td>0.04</td>
<td>32.0</td>
<td>1.17</td>
</tr>
</tbody>
</table>

*Table 2. Relationship between BLT and voiding, where the volume was calculated by multiplying BLT with voiding area %, and was expressed as an arbitrary unit.*
In this study, liquid solder was squeezed out at 100g, lower than the calculated 318g-f. This was probably attributed to the uneven BLT caused by warpage of the Cu coupon, as shown in Table 1.

**Lamellar Flow Effect**
Voiding is a function of BLT thickness, as shown in Figure 7, where the voiding maintained at about 32 area % at the thin bondline, then decreased gradually when the BLT was greater than 0.15mm. However, if the voiding was expressed as volume by multiplying the voiding area % with BLT, the relationship between voiding and BLT can be shown in Table 2 and Figure 8. Here, all void shapes were approximated as pancake, and the volume was expressed as an arbitrary unit.

Figure 8 results indicate the actual volume of voiding decreased with decreasing BLT. Under the 100-gram weight condition, not only did the liquid solder squeeze out, but the voids formed were not able to expand due to the constrained lamellar flow of liquid solder. Furthermore, the voids formed could not move around, and coalescence of voids became negligible. The X-ray images of the 100-gram column in Figure 1 show that no large void image can be observed.

In summary, the weight on the sandwich dictated BLT, which in turn governed the void content. The BLT maintained constant with increasing weight at first, then decreased with a further increase in weight. At a very low BLT, the actual void volume was low, although the void area % was not low. With increasing BLT, the void volume increased, but the voiding area % decreased slightly.

Since a very thin BLT is not desired based on reliability considerations, the study will be confined to weight no higher than 30 grams from this point on for comparison of SAC305, 63Sn/37Pb, and 57Bi/42Sn/1Ag. Also, with a small sample size prepared for each condition, data scattering was fairly significant. In order to get a meaningful trend, the effect of any given parameter was examined by taking the average value of all data involving other parameters. For instance, when examining the effect of oxidation on voiding, all data points were derived from the average of all flux quantities reflow peak temperatures, and weights.

**Effect of Oxidation and Alloy on Voiding**
Figure 9 shows the voiding performances of SAC305, 63Sn/37Pb, and 57Bi/42Sn/1Ag on Cu coupons preconditioned with various extents of oxidation. The data for each point was the average of all conditions, including flux quantity, reflow peak temperature, and weights.
and weight. Overall, with the increasing extent of oxidation, voiding maintained constant initially, then increased with further increase in the extent of oxidation. Voiding of SAC305 was higher than 57Bi/42Sn/1Ag, which in turn was higher than 63Sn/37Pb.

The initial insensitivity of voiding toward oxidation indicated that the oxide formed was easily removable at first. At 60 seconds of oxidation time, the voiding increased noticeably, reflecting that the oxide amount just reached the limit of fluxing capability. At 5 minutes oxidation time, most of the samples showed significant non-wetting. Since the image analyzer could not process those images properly for voiding, those data were not presented in the graph.

**Effect of Flux Quantity and Alloy on Voiding**

The effect of flux quantity and alloy on voiding is shown in Figure 10. Two opposite trends of flux quantity were observed. For SAC305 and 63Sn/37Pb, the voiding decreased with increasing flux quantity. This can be attributed to a better wetting caused by more flux [2, 3, 4, 5].

For 57Bi/42Sn/1Ag, the flux quantity effect showed an opposite trend. The higher voiding caused by the higher flux quantity could be explained by the flux burn-off rate outweighing the wetting improvement rate. Since the flux used in this study was developed mainly for the SAC alloy system, it is reasonable to expect that the flux was much less effective at low soldering temperatures.

**Effect of Reflow Temperature and Alloy on Voiding**

The effect of reflow temperature on voiding is shown in Figure 11. A very complicated relationship was observed. Depending on the alloy type, a totally opposite trend could occur. For the low-temperature alloy 57Bi/42Sn/1Ag, with an increasing peak temperature, the voiding first increased, then decreased. The initial increase trend can be attributed to the low activity of flux, and the vaporization factor dominated the voiding behavior. At this temperature range, the flux activity was low and the more volatile constituents came out.

The subsequent decrease trend at 170°C to 180°C peak temperature can be attributed to the flux wetting factor, which increased considerably from 170°C to 180°C. This flux wetting dominating behavior was also observed on 63Sn/37Pb when the reflow temperature increased from 205°C to 215°C. However, when the reflow temperature further increased from 215°C to 225°C, the voiding increased again. This was attributed to the dominating flux outgassing phenomenon, presumably through combined vaporization and thermal decomposition.

The alternating dominant voiding mechanisms can be elucidated by examining the TGA data of the flux, as shown in Figure 12. At a temperature below 100°C (zone I), no volatiles came out. At 100-210°C (zone II), moderate weight loss occurred. Between 210°C and 300°C (zone III), rapid weight loss was observed. At temperatures higher than 300°C (zone IV), the weight loss rate slowed down again.

By cross-comparing Figures 11 and 12, the voiding increasing trend at temperatures above 210°C can be easily attributed to the
rapid weight loss rate with the increasing temperature. Below 210°C, the weight loss rate is moderate. The turning point on the voiding rate at 170°C can be explained by the flux being activated around 170°C. Below 170°C, the activity was very minute, and voiding increased by the flux vaporization rate was greater than voiding reduced by improved wetting. Once the flux was activated, the flux activity increased with increasing temperature [6], and the voiding decreased with increasing flux activity [7, 8]. The flux was activated above 170°C, thus the voiding reduced by improved wetting outweighed the voiding increased by increased outgassing.

Discussion

Solderability Factor
The voiding of SAC305 in the weight study was higher than that in other factors of the study. This was due to the difference in the solderability of different sources of Cu coupons used for those studies.

Solder Alloy Factor
The voiding difference between different alloys was mainly attributed to the difference in wettability, with 63Sn/37Pb being the best, followed by 57Bi/42Sn/1Ag, and SAC305 being the poorest, as reported in an earlier work [9].

Reflow Temperature Factor
The relationship between reflow temperature and voiding was a complicated one. This was caused by two changes induced by temperature. The first was the weight loss rate of flux, and the second was the flux activity.

Flux Quantity Factor
The flux quantity effect showed two opposite trends for different alloys. This was attributed to different reflow temperatures for different alloys.

Conclusion
Voiding at high-power die-attach reflow soldering using preforms was simulated with the use of Cu coupons to mimic both die and substrate. The voiding behavior was studied by varying solder alloy types, flux quantity coated on the preforms, extent of oxidation on the Cu coupons, reflow peak temperature, and weight applied on the top of simulated die. For SAC305, with increasing weight, the bondline thickness (BLT) maintained constant initially due to solder surface tension, then reduced rapidly at weights higher than 50 grams. The voiding area % increased with decreasing BLT at first, then levelled off at a lower BLT, although the voiding volume decreased with decreasing BLT due to constrained lamellar solder flow. Voiding was the highest for SAC305, followed by 57Bi/42Sn/1Ag, with 63Sn/37Pb being the lowest, and increased with the increasing oxidation of the Cu coupons. With increasing flux quantity, voiding increased for SAC305 and 63Sn/37Pb, but decreased for 57Bi/42Sn/1Ag, mainly due to the different temperature ranges at reflow. Voiding increased with increasing reflow temperature up to 170°C due to increasing vaporization, decreased with the further increase in the reflow temperature up to 210°C due to increasing flux activity, and increased again at a temperature beyond 210°C due to rapid flux outgassing.

Acknowledgement
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References