The Effects Of The Bondpad and Solder Sphere Sizes on The Ball-Shear Strength of fpBGA Packages

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Abstract

Chip Scale Package (CSP) is an important configuration for applications where physical space is the main consideration. For the Ball Grid Array (BGA) configuration, CSP can take on the form of fine pitch Ball Grid Array (fpBGA) packages. The fpBGA packages are essentially smaller version of the Plastic Ball Grid Array (PBGA) packages in which ball pitches, bond-pads, and solder balls are reduced in size. Like all other electronic packages, the fpBGA must also undergo reliability testing and one of the critical parameters is the ball-shear strength. For the ordinary BGA packages, the industry typically requires the minimum ball-shear strength of 1.0 kg, but there is significantly less agreement on the corresponding value for the fpBGA packages. In the absence of consensus, the common practice has been to scale the ball-shear values according to the reduction in the bond-pad area. That is, if for an ordinary BGA package, the minimum ball-shear strength were 1.0 kg, then for a fpBGA, the minimum ball-shear strength would be decreased by the square of the radius ratio. The key question is whether the ball-shear strength varies proportionally to the bond-pad area. This is the motivation for the current study. The objective of this work is to investigate the factors that affect the ball shear strength of a fpBGA package in order to have a better understanding of how it varies for different configurations. Of specific interest is the dependence of the ball-shear strength on several geometrical parameters. The present results showed the previous assumption of the ball-shear dependence to be invalid.

Key words:
Bondpad, Solder Sphere Size, Ball Shear Strength, and Electronic Packaging.

1. Introduction

One of the trends in the development of electronic devices is "smaller is better", since in some applications, the physical size of the devices is one of the major considerations. An example of this is in applications such as videocameras and cellular phones.
Consequently, the die size has continued to decrease, which brings with it the demand for smaller Chip Scale Packages (CSPs). The Ball Grid Array (BGA) configuration is a common form of CSP that can maximize the number of input/output terminals (I/O) for a given package area. The fine pitch Ball Grid Array (fpBGA) package is one type of CSP package and is essentially a smaller version of the Plastic Ball Grid Array (PBGA) package but with finer ball pitches, smaller solder ball sizes and bond-pad opening sizes.

As in all BGA packages, the fpBGA packages must also undergo reliability testing. One of the critical parameters is the ball-shear strength, which is the measure of the reliability of the solder joint under the service condition. Not surprisingly, a lot of work has been done on the reliability of solder joints, especially on the effects and growth of intermetallic compounds1-8, earlier studies that tended to focus on the solder material itself. In the last 5-6 years, increasing focus has been placed on the BGA package and the integrity of its solder balls9-12. By comparison, fpBGA package is a newer member of the BGA family, and as such, quite a few unknown still remains. In particular, questions arise on how the smaller solder balls will behave. To address this issue, an increasing number of studies has focused on this technical topic. For example, studies have recently been done on how the solder ball interact with the Printed Circuit Boards13, and how the package reliability is affected by lead-free solder balls14.

Despite the increasing number of studies in the community, there still remain questions on how the ball-shear strength of a fpBGA should vary. On an ordinary BGA, the industry has typically established a minimum mean ball-shear strength of 1.0 kg. However, it is not clear, what should be the corresponding value for a fpBGA. In the absence of data, OEMs assume the ball-shear strength to decrease according to the bond-pad area. Using this assumption, the OEM imposes upon the subcontractor a minimum ball-shear strength that must be met. The question is whether this is a realistic target value. The implication of an unrealistic value is significant not only for the subcontractor but also for the OEM, as precious time may be spent pursuing an unrealistic goal. This is the motivation for the current study. The objective is to present more data, which along with others from the community, can lead to a better understanding of the ball-shear characteristic of a fpBGA package, and eventually lead to a more accurate minimum ball-shear criterion.

In this study, a series of ball-shear measurements were performed to measure the variation of the ball-shear strength for various design parameters. The parameters include the following, the solder ball sizes, the size of the bond-pad opening, the solder-mask opening pattern, and the gold thickness on the bond pads. The results showed the ball-strength to possibly be related to the ratio of the bond-pad radii, as opposed to the previously assumed parabolic function. In addition, the results were correlated and the corresponding equations are presented for future references.

2. Experimental Work

As shown in Figure 1, the ASAT 36-fpBGA packages were used as the vehicle. These were 6mmx6mmx0.95mm 36-balls fpBGA units that used eutectic with 2% silver (62/36/2) solder balls. The experimental matrix involves different geometrical parameters, which are summarized in Table 1. Totally, 60 different configurations were studied, and these consisted of combinations from three solder ball sizes, five bond-pad sizes, two different gold-plating thickness, and two solder-mask patterns. As shown in Figure 2, the solder-mask patterns were either solder-mask-defined or nonsolder-mask-defined.

![Figure 1. Schematic of fpBGA package.](image)

**Table 1. Geometrical parameters used in the experiment.**

<table>
<thead>
<tr>
<th>Solder ball dia./mils</th>
<th>Gold plate</th>
<th>Pad dia./mm</th>
<th>Solder-mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 (0.3 mm)</td>
<td>Thin gold plating</td>
<td>0.20</td>
<td>Solder-mask defined pattern</td>
</tr>
<tr>
<td>16 (0.4 mm)</td>
<td>Thin gold plating</td>
<td>0.25</td>
<td>Non-solder-mask defined pattern</td>
</tr>
<tr>
<td>20 (0.5 mm)</td>
<td>Heavy gold plating</td>
<td>0.30</td>
<td>Non-solder-mask defined pattern</td>
</tr>
<tr>
<td>3 ball sizes</td>
<td>2 gold thicknesses</td>
<td>5 pad sizes</td>
<td>2 patterns</td>
</tr>
</tbody>
</table>

![Figure 2. (a) Solder mask defined pad opening pattern. (b) Non-solder mask defined pad opening pattern.](image)

These units were subjected to a total of of twelve sets of reliability conditions, as given in Table 2. These conditions are also summarized in Figure 3. Basically, the units can be separated into four groups: Virgin group (control units that have not been subjected to reliability conditions), MSL group (units subjected to MSL-3 and 3xIR reflow), HTSL group (units subjected to high-temperature storage), and TC group (units subjected to temperature cycling). Before and after different stages of reliability conditions, units were taken out for ball-shear measurements. Thus, this allows for the evaluation of the ball-shear value with respect
to the testing conditions as well as geometrical parameters.

Table 2. Number of measurements of three groups of units.

<table>
<thead>
<tr>
<th>Virgin units at time zero</th>
<th>High Temperature Storage Life (HTSL)</th>
<th>Temperature Cycle (TC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 set</td>
<td>6 hrs</td>
<td>Moisture sensitivity test: Level 3 + 3 x IR reflow</td>
</tr>
<tr>
<td>14 hrs</td>
<td>18 hrs</td>
<td>250 cycles</td>
</tr>
<tr>
<td>24 hrs</td>
<td>38 hrs</td>
<td>500 cycles</td>
</tr>
<tr>
<td>48 hrs</td>
<td></td>
<td>750 cycles</td>
</tr>
<tr>
<td>48 hrs</td>
<td></td>
<td>1000 cycles</td>
</tr>
<tr>
<td>1 set</td>
<td>6 sets</td>
<td>5 sets</td>
</tr>
</tbody>
</table>

The High temperature storage (HTSL) condition was performed at 150°C with 6 different durations using the Kwang Myung KM-703 high-temperature oven. The temperature cycling (TC) conditions was created using the TCT-100 Temperature Cycler; the temperature cycles consisted of a one-hour cycle period with the temperature varying from –60 to 150°C. The Moisture Sensitivity Level (MSL) condition was performed with the Kwang Myung KM-STD temperature and humidity chamber. An MSL Level-3 (MSL-3) condition (60% RH, 30°C, 192 hours storage) was used, and was immediately followed with a three-times IR reflow process. This reflow was performed in air using the JPL model RF-477 IR reflow oven. The reflow profile consisted of a 100-second ramp-up from 25°C to 183°C, a 100-second soak at 183°C, followed by a 30-second ramp to 235°C, where it remains for 15 seconds before ramping down to ambient at 5 °C/s.

Each unit was visually inspected for defects before being subjected to ball-shear measurements. As shown in Figure 4, the measurement was performed with a ball-shear tester, consisting of an horizontally-moving shearing tool. The tool was mechanically driven and a force-sensing device was attached to record the force exerted by the tool. Therefore, the tester could register the shear-strength of the ball that opposed this shearing action. However, if the sizes of the solder balls were inappropriately matched to the bond-pad areas, such as 16 mils ball with 0.5 mm pad or 12 mils ball with 0.45 mm pad, then the reflowed solder ball could only form a hemisphere or a hump on the pad. Since it was not possible for the shearing tool to exert a shearing force on such a hump, ball-shear tests were not performed with such combinations.

Figure 3. Flow chart of the experiment.

Figure 4. Schematic of ball-shear tester.

3. Results & Discussion

3.1. General Trends

Ball-shear measurements were performed, and the values were recorded. As a general observation, the fracture surface of the virgin unit (Figure 5a) showed a plastic deformation, while the fracture surface of the HTSL units (Figure 5b) showed a brittle failure. The fracture surface for the MSL and TC units were similar to those of the HTSL units.

Figure 5. Fracture surfaces after ball shear test a) for virgin units, b) for units after HTSL.

The ball-shear values were plotted against different bond-pad sizes and had been grouped into four different configurations, namely, “fine gold” with solder-mask-defined bond-pad opening (FSMD), “heavy gold” with solder-mask-defined bond-pad opening (HSMD), “fine gold” with non-solder-mask-defined bond-pad opening (FNSMD) and “heavy gold” with non-solder-mask-defined bond-pad opening (HNSMD). In Figures 6 to 9, the results of the ball-shear measurements from the virgin units are shown. The variations of the ball-shear strengths were different
from what was generally expected. First, it seems that for a given bond-pad size, a larger solder sphere will yield a higher ball-shear strength. This trend consistently repeats itself and was unexpected. The underlying mechanism would require further investigation, but the speculation is that the larger sphere may have the effect of decreasing the concentration of gold-tin intermetallics.

Another interesting observation can be drawn from Figures 6 and 7. That is, for any particular solder sphere size, its ball-shear strength decreases almost linearly with the bond-pad diameter, instead of parabolically. A linear fit was performed on these data and the corresponding equations are shown in these Figures. These equations can be useful for estimating the ball-shear strength of packages with different solder-ball and bond-pad sizes. Since the correlation coefficient between these data points and the straight-line was greater than 0.95, and since the standard deviation of the measurement was typically less than 0.04 kg, it is unlikely for this trend to be an artifact of experimental scatters. A linear trend is certainly unexpected and, if true, would indicate the existence of two counter-acting phenomena. That is, an increase in the ball-pad opening causes a second order increase in the ball-shear strength due to the increase in area, but perhaps also a first order decrease due to another mechanism. Thus, the balance yields only a first order dependence.

Yet another observation from Figures 6 and 7, is that the ball-shear strength of the FSMD group was about the same as that of the HSMD group. This is consistent with the expectation that at the virgin stage, variations in the gold plating thickness would have minimal effect on the strength of the solder joint. However, as shown in Figures 8 and 9, the corresponding comparison on the non-solder-mask-defined group (FNSMD versus HNSMD) did not yield similar results. This is likely due to the fact that ball-shears of this group tended to produce bond-pad detachment instead of cohesive failure due to shearing through the solder ball. Thus, the “ball-shear” value no longer reflects the integrity of the solder balls, but instead incorporates the adhesion strength of the bond-pad. As a result, the ball-shear strength of non-solder-mask-defined units is typically 35% lower than those with solder-mask-defined.

3.2. Effect of High-Temperature Storage

After six hours of storage at 150°C, the ball-shear strength of all the units had decreased, although, units from the solder-mask-defined (SMD) group still yielded higher ball-shear values than those in the NSMD group, Figure 10. In addition, as shown in Figure 11, units with a thinner gold plating (FSMD) yielded a higher ball-shear strength than those with a thicker gold plating (HSMD). This is expected as the thicker gold plat-
ing will give rise to more gold-tin intermetallic compounds, which are typically more brittle.

Further subjecting the units to another 8 hours of storage caused the ball-shear values from both the HSMD and NSMD groups to deteriorate faster and to eventually collapse into the same curve (Figure 12). The units from the FSMD group tended to be more robust and as shown in Figure 13, its ball-shear values did not collapse together until after a total of 48 hours of high-temperature storage. This latter behavior is consistent with the generally observed trend that significant deterioration in the ball-shear strength typically occurs after around 50 hours of high-temperature storage.

In general, units that were plated with thinner gold seemed to be more robust than those with thicker gold, as evident by the higher ball-shear strength and its lower rate of decrease. This is shown in Figure 14, where the ball-shear strength of FSMD units with 0.3mm opening exhibited a constant shear strength of around 0.6 kg even after 38 hours of storage, whereas the corresponding HSMD units produced a shear strength of only 0.3 kg after the same duration. This degradation of the ball-shear strength is an important factor, as end users often have specific requirements. For the present experiments, this degradation of the ball-shear strength was correlated as a function of the storage time and bond pad opening and for different solder ball sizes. These expressions are provided in Equations (1)-(3) and can be useful for future estimation purposes.

Figure 10. NSMD after six hours.

Figure 11. SMD after six hours HTSL.

Figure 12. Ball-shear value after 14 hours HTSL.

Figure 13. Ball-shear value after 48 hours HTSL.

Figure 14. Plot of the variation of the ball-shear value against time, 20 mils balls HTSL.

\[ S = (0.0357t + 3.6766) \phi_p + (0.0077t - 0.4152) \]

\[ S = (0.0055t + 2.24) \phi_p - (0.0053t + 0.0181) \]

\[ S = (0.0249t + 1.3197) \phi_p - (0.0106t - 0.1879) \]

where \( S \) is the shear strength in kg, \( \phi_p \) is the bond-pad opening in mm, and \( t \) is the storage duration in hours.
3.3. Effect of MSL and Temperature Cycling

For this section, the focus will be placed on solder-mask-defined (SMD) units, as the ball shear values from the non-solder-mask-defined units were often biased by the occurrence of bond-pad detachment. Figure 15 shows the variation of the ball-shear strength on the MSL condition, the subsequent temperature cycling and the size of the bond pad opening. Expectedly, the larger bond pad openings yielded a larger ball shear strength, because of the larger surface area between the solder sphere and the bondpad. Another observation was that the ball-shear values after the MSL condition were typically higher than the corresponding virgin units. This is likely due to the reflow process in the MSL conditions. This reflow causes the solder ball to repeat the melting and solidification process. This may somehow give rise to a stronger microstructure within the solder balls. In addition, the gold plating thickness seems to have little effect on the ball-shear strength of these units, which had been subjected to MSL and temperature cycling. Considering the fact that the brittle gold-tin intermetallic compound grows much slower at temperatures below 130°C, this tolerance for gold plating thickness is likely due to the fact that units undergoing temperature cycling typically reach or exceed 130°C for only a short period of time.

![Figure 15. Plot of the variation of the ball-shear value for units with 20 mils balls.](image)

Figures 16, 17 and 18 show the dependence of the ball-shear strength on the bond-pad size and on the testing conditions. Figure 16 shows the results using 20 mils balls, while Figures 17, and 18, respectively, show the results for 16, and 12 mils balls. As before, the ball-shear strength was found to decrease linearly with the bond-pad size, where the corresponding best-fit curves are also given in the Figures. Also, the larger solder balls tended to yield higher ball-shear strengths. Another interesting observation can be made among these three Figures by noting that as the size of the solder ball decreases, the ball-shear values seem to be more sensitive to the testing conditions. This is likely related to the smaller solder sphere volume and its lower ability to tolerate the same level of intermetallic compounds.

![Figure 16. Ball-shear strength of 20 mils balls with FSMD after MSL and TC.](image)

![Figure 17. Ball-shear strength of 16 mils balls with FSMD after MSL and TC.](image)

![Figure 18. Ball-shear strength of 12 mils balls with FSMD after MSL and TC.](image)

4. Conclusion

Due to the lack of information on the ball shear behaviors of fpBGA packages, the variations of ball strength with different design parameters are unknown. Experiments were performed to evaluate the effects of different geometrical parameters on the ball-shear strength of a fpBGA package. These parameters included bond-pad sizes, solder-ball sizes, gold-plating thickness, and solder-mask patterns. The units were subjected to high temperature storage as well as MSL conditions followed by the temperature cycling. Units were extracted at virgin stage as well as
at different testing stages, and the corresponding ball-shear strength was measured. The results showed an interesting trend that for a given bond-pad size, a larger solder sphere yielded a higher ball-shear strength. In addition, the results also showed the ball-shear strength and the bond-pad size to bear a strong linear dependence. While the exact mechanism for this behavior requires further investigation, this behavior seems to suggest that the effect of the area of the bond pad was competing with another mechanism that varied linearly with the diameter of the bond pads. Finally, the current results showed units with thinner gold plating thicknesses to be significantly more robust under high temperature storage conditions.

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