Angled High Strain Rate Shear Testing for SnAgCu Solder Balls

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Abstract

A high speed shear test of solder ball at different shear angles has been developed and investigated for SnAgCu solder balls. The objective of the test is to introduce vertical loading component in the high speed shear test and to study intermetallic response of different solder balls. The shear test is performed at three angles of attack e.g. 3, 5 and 10 degree. The basic shear tester allow high speed shear tool movement of up to 4000 mm per second, and capture the load displacement curve experienced by the shear tool. Using this setup, high-speed shear characterization has been carried out on microBGA sample with Sn3Ag0.5Cu and Sn1Ag0.5Cu solder on Ni/Au pad finish.

In this paper, the effect of angle shear at high speed on these SnAgCu BGA balls is presented, with the details of load-displacement response and failure mode for these solder balls. Generally all the samples show changes in ductile-to-brittle failure as shear speed increases. The angled shear test lead to down shift of ductile-brittle transition to occur at lower shear speed with larger shear angle. It is found to improve sensitivity in revealing brittle failure for solder ball characterization.

Introduction

Due to the susceptibility of drop impact damage on solder interconnection, the popularity of portable products has led to a greater concern on solder joint performance under high strain rate loading conditions. At the present, high strain rate behavior of solder joint has been evaluated using high speed shear test on component level or board level drop impact testing. While the board testing is time consuming and laborious, the correlation of component level high speed shear testing on BGA solder ball is still under investigation by different researchers [1, 2]. One of the main issues faced by this approach is the limitation of test: that it requires component mounted on board for testing, and little info about the peeling or tensile loading to the component under test can be obtained from the test. Such a test is difficult to be implemented in the component manufacturing environment where component level ball integrity test are preferred. Today most of manufacturers are still performing the classical ball shear test and some have equipped with ball pull test. However both these technique have their limitations. In reality, solder ball interconnection is subjected to combined shear, tensile and peeling stresses. Hence a realistic assessment of solder ball integrity should incorporate such loading component simultaneously in the same test.

Nevertheless, shear test is still considered to be a preferred method for its convenience and ease of implementation [3-6]. For these purposes, we have developed a novel high speed shear test method that allow high strain rate testing of solder ball at different shear angles. The objective is to introduce simultaneously vertical and horizontal loading to the ball under test in a single ball shear test. Such a mixed mode loading is useful for solder ball integrity assessment as many realistic applications are under mixed mode condition.

For demonstration and proof of this concept, we have implemented the test method with three angles e.g. 3, 5 and 10 degree. A commercial available basic shear tester allows high speed shear tool movement of up to 4000 mm per second, and to capture the load-displacement response of the shear tool. The test method is made to ensure the point of contact between shear tool and solder ball for all the three shear angle will be consistent on the solder ball is achieved.

Using this setup, high speed shear characterization has been performed on 2 types of solders, namely Sn3Ag0.5Cu and Sn1Ag0.5Cu on microBGA package with Ni/Au pad finish.

Test specimen and test procedure

The microBGA sample is shown in Figure 1 (a), where the total I/O numbers is 54 with solder ball size and pitch at 0.4 mm and 0.8 mm respectively. The solder ball is consisted of Sn3Ag0.5Cu and Sn1Ag0.5Cu. Solder pad material is Cu with sold-mask-defined (SMD) configuration, and coated with electrolytic NiAu finishing.

During shear experiments, the load-displacement responses of the shear tool are captured for different shear speed and shear angle. After the testing, the sheared samples are subjected to microscope and SEM inspection for failure mode identification. To determine a meaningful shear speed range for the experiment, some initial shear tests have been performed to ensure the ductile-brittle transition will be covered in the shear speed experiment. In this case, the tool speeds range from 50 mm/s to 2500 mm/sec has been selected.
Shear angle and shear speed on load-displacement curve

Figure 2 shows the shear force (g)-displacement (µm) curves from experiment at various shear speeds for Sn3Ag0.5Cu samples. The curves plotted in Figure 2(a) (b) (c) and (d) present the shear test under 0, 3, 5 and 10 degree respectively.

From these graphs, some trends can be found. As shearing speed increases, the displacement is decreasing steadily, while maximum shear force increased. This is inline with the general expectation of strain hardening effect of solder material.

For low shear speed below 100 mm/s, the changes of displacement are insignificant in both displacement and peak load. As the shear speed increased, there is an increase in the ramp rate of shear force with drastic changes in displacement part. The sharp decreasing of shear displacement is an indication that the solder ball is going through from ductile failure to brittle failure. In between the two failure mode, where some irregular displacement has occurred, the transition of ductile shear to brittle shear is considered to have occurred.

Based on the above observation of the load-displacement curves, the shear speed for which different failure mode have occurred is summarized in Table 1, including the shear speed in which ductile-brittle transition is considered to have occurred. This result provides a clear picture of the changes taking place for different shear angle. Generally brittle failure tends to initiate at lower shear speed as shear angle increases. This include down shift of ductile-brittle transition to lower shear speed. Despite small increase in shear angle, the result indicates an improvement in the sensitivity of angled shear test in revealing brittle failure than horizontal shear test.

Figure 2: Typical loading curves for different shear speed and different shear angles for Sn3Ag0.5Cu solder balls
Characterization of failure mode

The sheared samples were inspected under optical microscope and SEM for its failure mode after shear testing. For convenient purpose, the failure modes are classified under a few categories namely bulk failure, bulk-IMC partial failure, IMC failure, IMC + partial pad peel failure, and pad peeling. Typical image of these failure modes are shown in Figure 4.

Table 1: Ductile-brittle transition as function of shear angle and shear speed

<table>
<thead>
<tr>
<th>Shear speed (mm/sec)</th>
<th>Ductile failure</th>
<th>Transition</th>
<th>Brittle failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero degree</td>
<td>10,50,70,100,</td>
<td>300,500,700</td>
<td>2500,3500</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 degree</td>
<td>10,50,70,100,</td>
<td>300,500</td>
<td>2500,3500</td>
</tr>
<tr>
<td></td>
<td>700, 1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 degree</td>
<td>10,50,70,100,</td>
<td>300</td>
<td>1500,2500,</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td></td>
<td>3500</td>
</tr>
<tr>
<td>10 degree</td>
<td>10,50,70,100,</td>
<td>300</td>
<td>700,1500,</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td>2500,3500</td>
</tr>
</tbody>
</table>

Figure 3 shows a direct comparison of load-displacement curve extracted for different shear angle for shear speed around the ductile-brittle failure transition region. The effect of shear angle on the load-displacement response described earlier can be clearly observed here.

Figure 3: Comparison of loading curve as function of shear angle

Figure 5 shows the compilation of failure mode as function of shear speed and shear angle for the Sn3Ag0.5Cu solder on Ni/Au finish. The results match well the load-displacement curve and once again the ductile-brittle transition is showing a down shift in shear speed as shear angle increased. The result from higher shear angle is clearly showing improved sensitivity in revealing IMC brittle failure. However, it is also observed that at higher shear angle, e.g 10 degree, the occurrence of IMC+partial pad peeling has increased as compared to the lower shear angle samples. We believe that the pad peeling is an indication of weaker pad to core substrate interface integrity. The increase in angle shear is able to reveal such weakness in the sample, subjected to the shear speed. At the same time, it is competing with the bulk-IMC mixed failure depends on which is weaker. As the strain rate further increased to the higher shear speed region, the brittle IMC failure become more apparent.
Comparison of SAC305 and SAC105

For comparison to Sn3Ag0.5Cu, the similar angled high speed shear test was also performed on Sn1Ag0.5Cu solder prepared on the similar package and pad finish. Figure 6 shows the compilation of failure mode for the 2 solder types. The results show SAC305 has lower resistance to occurrence of brittle IMC failure compared to SAC105. The result is consistent for all the 3 type of angle shear test. It is interesting to note that large shear angle, e.g. 10 degree, is showing better sensitivity in revealing the transition to brittle failure for the SAC305 as compared to SAC105. We suspect that the higher angle shear test may be able to bring out more subtle aspect of the solder ball integrity compare to normal horizontal shear test.

Finite element analysis of angled high speed shear

A further verification is also performed by using 3D Finite element modeling of ball shear test to investigate the effect of shear test at different angle. This approach can provide more detail information on the stress distribution in the solder ball and ball/Cu pad interface during the test. Solder and Cu pad materials are considered as elasto-plastic material, and solder mask and core are elastic. ANSYS/Mechanical and ANSYS/LS-Dyna are used for the static and dynamic simulation respectively. Only static analysis results are presented here.

When shear tool move at constant speed over solder ball, there is a reaction force activated from solder ball when both come into contact. Figure 7 shows the shear and normal force of the central contact node on the shearing ram. It is seen that the normal force from shear ram increases as shear angle
increases, while the effect shear angle on shear force has insignificant change.

Figure 7: Node shear and normal force in static shearing

Figure 8 shows the comparison of 3D distribution of normal stress and shear stress in the solder material just above Cu pad between zero and 5 degree shear angle, respectively. It can be seen that both stress patterns showed slight difference, while the normal stress magnitude for 5 degree increase significantly from zero degree.

Figure 8: Stress distribution in solder ball above Cu pad

Figure 9: Line stress distribution at solder/Cu pad interface extracted along point 1 and point 2.

Figure 9 shows the comparison of normal stress and shear stress distribution along the Cu pad/solder interface extracted from the middle cross-section plane of solder ball as function of different shear angle. Once again the result shows a clear trend of increasing normal stress as function of shear angle. This line plot provides a convenient way of looking at stress distribution at the Cu pad/solder interface although it is not necessarily a true reflection of the original 3D stress distribution. Nevertheless, it is suffix for illustration of the normal and shear stress component as the shear angle change.

Conclusions and recommendation

High speed shear characterization has been carried out on 2 types of SnAgCu solder on microBGA with shear angle of 3, 5, and 10 degree. In addition, 3D finite element modeling has been performed for stress distribution of ball shear test when subjected to change in shear angles. Some important results and recommendation are summarized in the following.

1) Ball shear test at higher shear angle improved the sensitivity of revealing brittle IMC failure of solder ball.
2) The improvement of the angle shear test has been shown in both load-displacement response of solder ball as well the failure mode of the samples.
3) The ductile-brittle transition of Sn3Ag0.5Cu and Sn1Ag0.5Cu solders on microBGA package with Ni/Au pad finish has been obtained for different shear speeds and different shear angles. It is found that
   a. Sn3Ag0.5Cu is more prone to brittle failure compare to Sn1Ag0.5Cu.
   b. For Sn3Ag0.5Cu, IMC failure was initiated at 700 mm/sec for 3 degree angle shear, and it was reduced to 100 mm/sec for 10 degree shear.
   c. For Sn1Ag0.5Cu, IME failure was initiated at 2500 mm/sec for 3 degree angle shear and it was reduced to 700 mm/sec for 10 degree shear.

4) Analysis of the angle shear test showed the peeling stress and normal stress increased in the solder when the shear angle is increased. The increased in peeling and normal stress in the solder ball is believed to be the reason for the improved sensitivity in revealing brittle failure in the angled shear test.

5) A shear test that provides simultaneous shear and pulling stress to the solder ball has been developed and it is recommended for use in solder ball integrity, reliability and IMC characterization purpose.

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References

4. X. J. Huang, S. W. Ricky Lee, C. C. Yan, 2002 Electronic Components and Technology Conference, p 968-973