A Component Level Test Method for Evaluating the Resistance of Pb-free BGA Solder Joints to Brittle Fracture under Shock Impact

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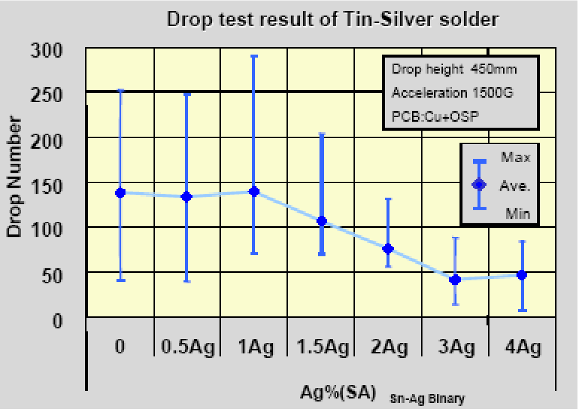
Abstract

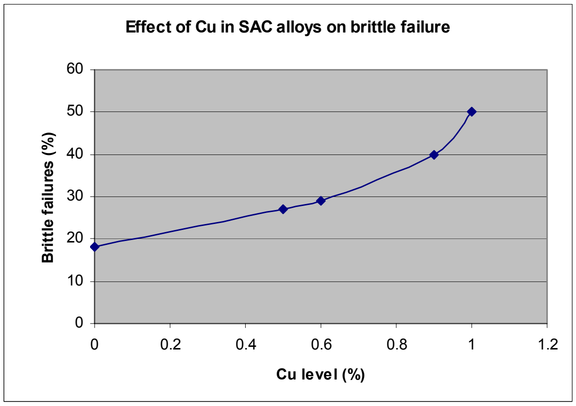
A high-speed shear tester has been used to evaluate the interface strength of Pb-free solder balls with varying Ag and Cu content to a BGA laminate interposer with different finishes. The shear rate used is 0.45m/s. Components with SAC405 and SnPb solder balls have been used as a reference. Results are compared with SAC305, SAC305 with NiGe addition, Castin 258 (2.5Ag-0.8Cu-0.5Sb), SAC105 (1.0Ag-0.5Ag), SAC101 (1.0Ag-0.1Cu-0.02Ni-xIn), SACX (0.3Ag-0.7Cu-0.1Bi), LF35 (1.2Ag-0.5Cu) and Sn3.5Ag. Electroplated NiAu finishes on the BGA laminate interposer studied come from different suppliers. Three failure modes are observed in the high speed shear test: brittle fracture in the intermetallic layer at the ball/interposer interface, ductile fracture in the solder bump and peel off of the solder pad from the interposer. Analysis of the fracture interface shows that almost all Pb-free solder alloys fail either in the intermetallic layer or by pad peel off. Only SAC101 and Sn3.5Ag show ductile fracture in the bump or pad peel off, but no fracture in the intermetallic layer. This is comparable with results for eutectic SnPb under these test conditions. A JEDEC board level drop test on same packaging with SAC101, SAC305 and SnPbAg shows that the number of drops to failure for packages with SAC101 is also higher than those with SAC 405 and even slightly higher than with eutectic SnPb solder balls. Failure analysis is done to understand the difference in shock resistance with different solder bumps. From the observations in both of the tests, it is evidenced that the high speed shear test, when combined with proper analysis of the failure mode, is a simple but very powerful tool to evaluate the resistance of Pb-free BGA solder joints to brittle fracture under shock impact.

Introduction

The mechanical robustness of IC packages under shock impact is becoming a hot topic in Electronics industry due to the relatively brittle nature of Pb free solder interconnections. Recently, BGA components with SAC 405 and SAC305 solder balls and with NiAu finished interposer show some problems in the field with missing balls from handling/transportation, and the failures have typically a brittle nature. It is shown from literature that compared with SAC405 and SAC305, decreasing the Ag- and especially the Cu-concentration may improve the packaging performance to resist shock impact, see figure 1 [1,2]. Data from different sources, however, are not consistent. Several possible test methods are described in literature; most are time consuming and expensive (e.g. JEDEC JESD22-B111 board level drop test) or do not address the correct failure mode (e.g. conventional shear test) [1 to 5]. This makes proper comparison difficult.



(a) Effect of Cu in SAC alloys



(b) Effect of Ag in Sn-Ag alloys

Figure 1 Effect of metal element in SAC alloys on brittle failure of solder joins [1,2]

In this study, a high-speed shear test is explored to evaluate the shock behavior of BGA packages with a latest developed micro tester; the effect of different Pb-free solder bump compositions on the impact resistance of the interconnection in the package is assessed. Three groups of test and analysis have been done. Firstly, the effect of five Pb-free solder compositions is evaluated with NiAu finished substrates from two suppliers Sa and Sb, i.e. SAC101 (1.0Ag-0.1Cu-0.02Ni-xIn), SAC405, SAC305 + NiGe, CASTIN (2.5Ag-0.8Cu-0.5Sb), and SACX (0.3Ag-0.7Cu-0.1Bi).

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Secondly, four other compositions, SAC105 (1.0Ag-0.5Cu), SAC305, LF35 (1.2Ag-0.5Cu) and Sn3.5Ag have been evaluated on NiAu from supplier Sb and compared with SAC105 and LF35 on Cu-OSP finish. In a 3rd run, a drop test according to JESD22-B111 is done with SAC101, SAC305 and eutectic SnPb on NiAu finish and on Cu-OSP finish. For failure analysis, visual inspection of the fracture interface is done, cross-sections are made and analyzed with EDX, and the morphology of the intermetallics is evaluated after removing the bulk solder by etching.

High Speed Shear Test I

Traditionally, solder joint integrity was tested with a low shear speed, typically around 100µm/s. Most of the time, this results in cutting through the bulk of the solder [4]. Solder alloy properties, however, are highly strain rate dependant and hence, the fracture mode during impact is also strain rate dependant. To investigate brittle fracture, that is a typical failure under a high strain rate impact, a test with a high speed needs to be explored. In this study, a test speed of 0.45m/s and the offset of 50µm between the shear tool tip and the laminate interposer was applied after some trial runs and the brittle fracture of the interface between solder bump and the laminate interposer was well captured with these settings.

Samples in the high speed test are BGA 420 packages; the diameter of the solder balls is 0.6mm. The bond pad on the BGA interposer is solder mask defined and has an elecrolytic Ni/ Au finish. The Au thickness is around 0.1µm while the Ni thikness ranges between 2 and 5µm. The layout of the package is shown in figure 2. The solder balls were attached on the BGA interposer with a standard reflow process with a peak temperature of 240°C . After reflow, the samples have been stored at room temperature for about one month before execution of the high speed test. During the first goup of test, in addition to those packages with the Pb-free solder compositions SAC101, SAC405, SAC305 + NiGe, CASTIN, and SACX, packages with eutectic SnPb were also tested for reference. For each solder composition, 5 packages have been tested; on each package, 15 to 20 solder balls were sheared. A micro tester recently developed in Instron was used for this test (see figure3).

The fractures from the shear test are classified into 3 failure modes, i.e. fracture in bulk solder, fracture in the intermetallic compound layer (IMC) and fracture in substrate bonding pad, see figure 4. The fracture in bulk solder is a ductile failure, which is a predominant failure mode in solder joints in tranditional shear tests. The fracture in the IMC layer is a typical brittle failure, which is related to a high strain rate impact in solder interconnections. Another fracture in the bonding pad is mostly realted to the pad lift, which indicate a problem of adhesion between the solder pad and the base material and it is related to the PCB quality. Some mixed failure modes were also found which need to be subject of further study.

Figure 5 gives a failure mode distribution for tested packages with different solder compositions on both of interposer substrates. It can be seen that for SnPb solder composition, most failures are in bulk solder and no failure related to brittle fracture. This indicates that BGA components with SnPb solder balls is quite strong to resist a high strain rate impact. For packages with Pb-free solder composition SAC101, there is no brittle fracture found on both of substrate too, while a lot of brittle fracture found with other compositions. This indicates that SAC101 outperform other lead free solder alloys.

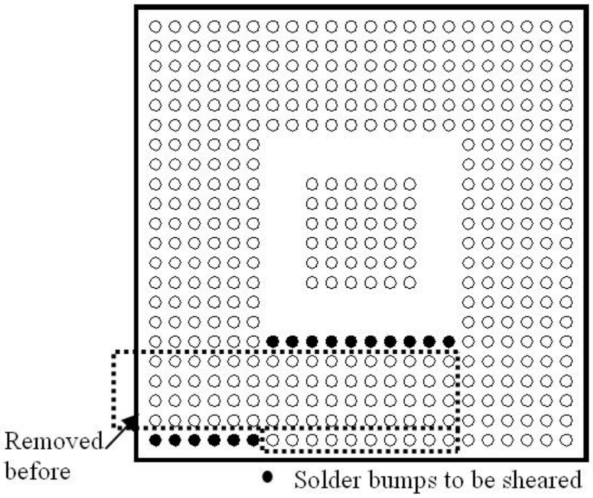


Figure 2 Solder bump arrays in BGA packages

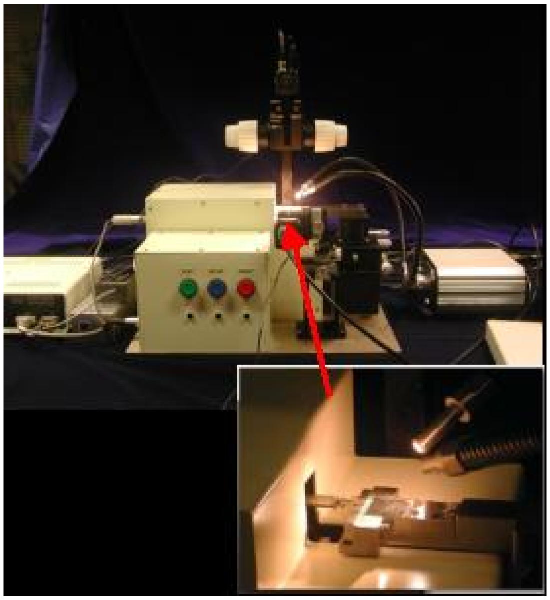
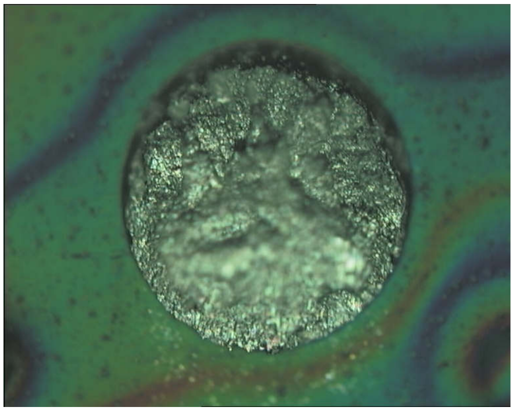
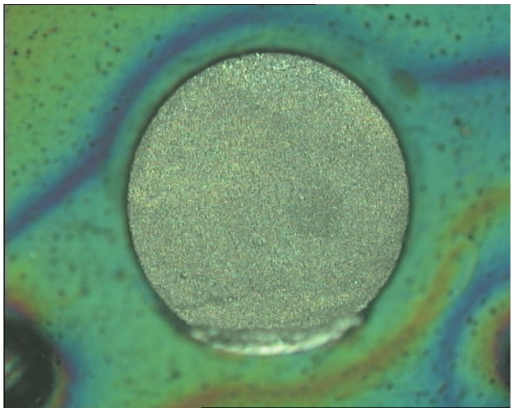


Figure 3 Micro shear tester

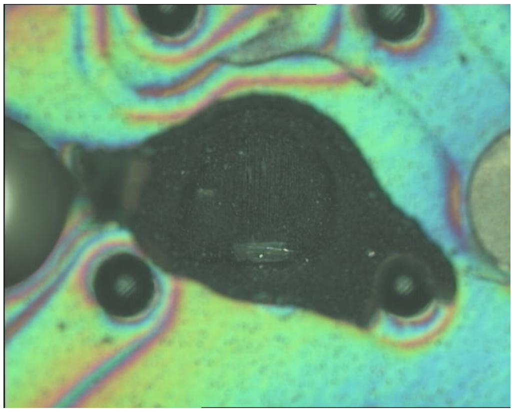
From the 3 failure modes, only the brittle failure at the ball/interposer is relevant for the robustness of the ball to interposer joint. Only SAC405, SAC305+NiGe, SACX and CASTIN have enough data for this failure mode to allow comparison of maximal impact strength and impact energy, because there is only pad peel found in SAC101 while only bulk fracture in SnPb. Figure 6 and 7 give the depicted cumulative impact strength and impact toughness (impact energy) distributions in solder joints on both of interposer substrates. The Kaplan-Meier method is used to separate the distributions for the 3 failure modes. From these, SACX exhibits the higher impact strength and impact toughness on both of substrates. CASTIN tends to perform worse in both of impact force and impact energy than other three alloys.



(a) Ductile fracture in bulk solder

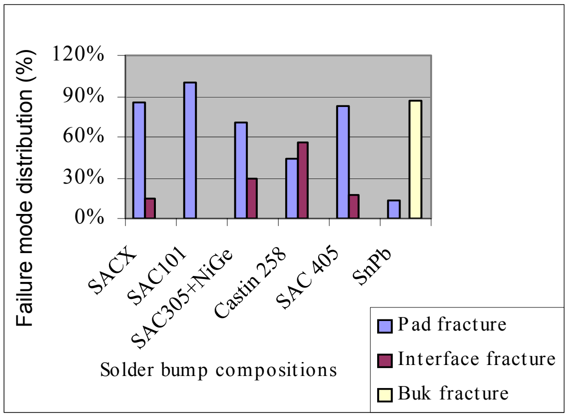


(b) Brittle fracture in Pad/IMC interface

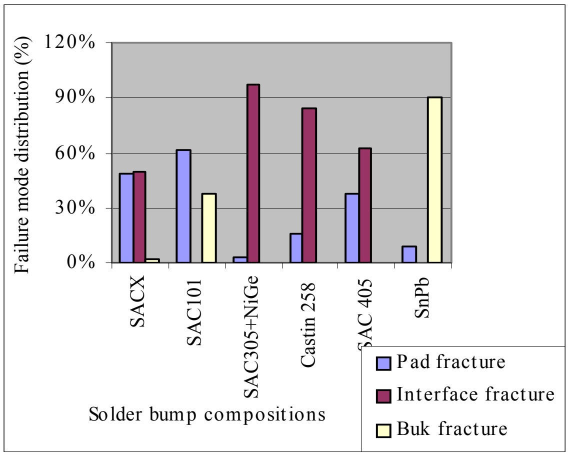


(c) Fracture in substrate bonding pad

Figure 4 Typical fracture modes in the high-speed shear test

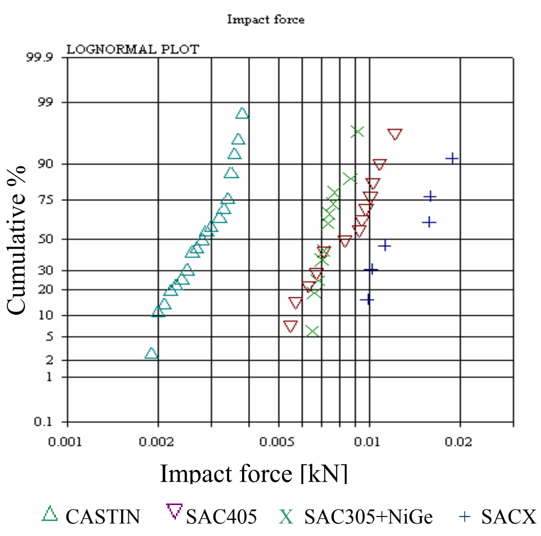


(a) With Sa substrate



(b) With Sb substrate

Figure 5 Failure modes distribution on two substrates with different solder bump compositions



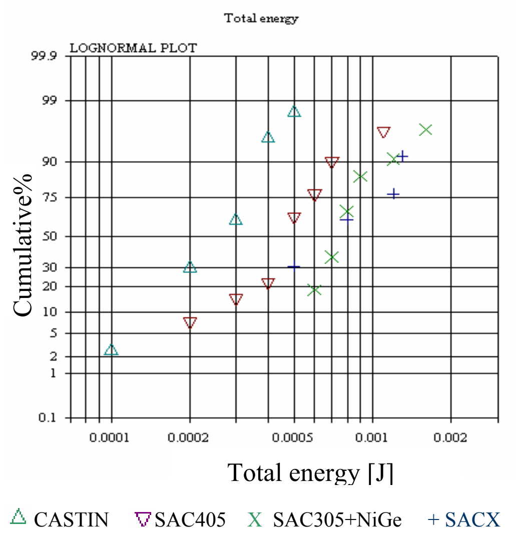


Figure 6 Impact strength and toughness on BGA's with IMC fracture with Sa interposer

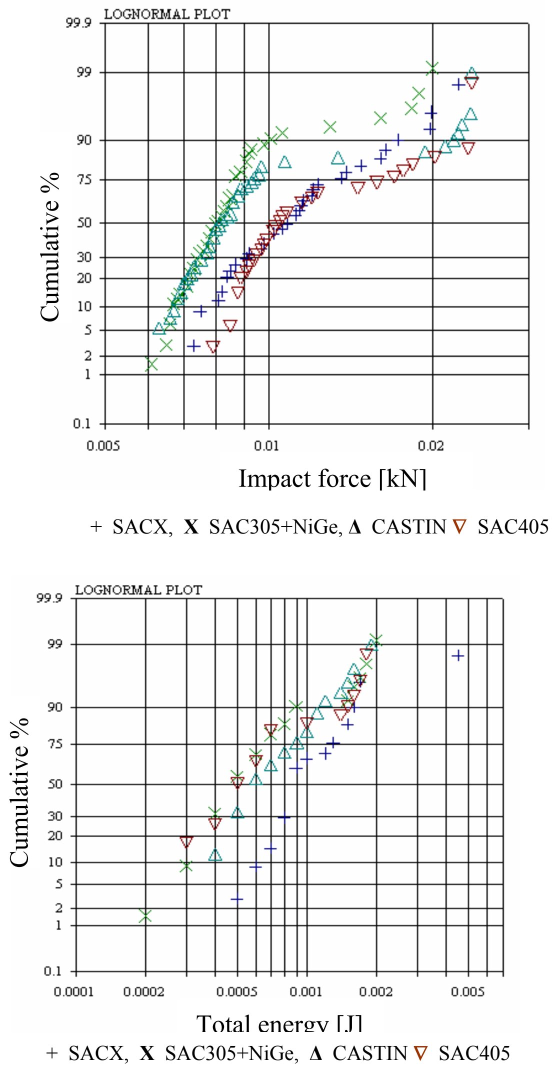


Figure 7 Impact strength and toughness on BGA's with IMC fracture with Sb substrate

High Speed Shear Test II

Another series of tests has been performed with BGA's with NiAu finish from supplier Sb with SAC101, SAC105, SAC305, Sn3.5Ag, and LF35 solder balls and with Cu-OSP finish combined with SAC105 and LF35 solder balls. Figure 8 shows the different failure modes for this 2nd series. It can be seen that, SAC101 and Sn3.5Ag, all fracture in the bulk solder and in the substrate pad wihout any fracture in the intermetallic compound. This indicates that BGA components with these two solder bumps alloys are quite strong to resist a high strain rate impact.

Comparing the NiAu finish with the Cu-OSP finish for LF35 and SAC105 shows that NiAu finish tends to have more intermetallic failure than Cu-OSP finish.

Figure 9 shows the cumulative distributions for the impact force and impact energy for those packages fractured in the intermetallic compound in series 2. Again the Kaplan-Meier method is used to separate the distributions for the different failure modes. From figure 9, no clear trend can be observed.

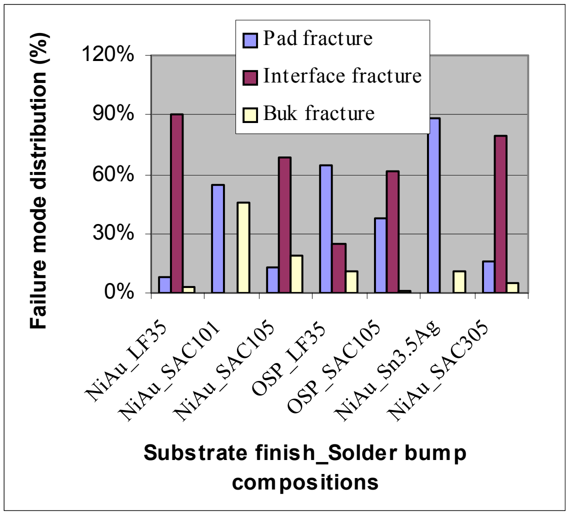
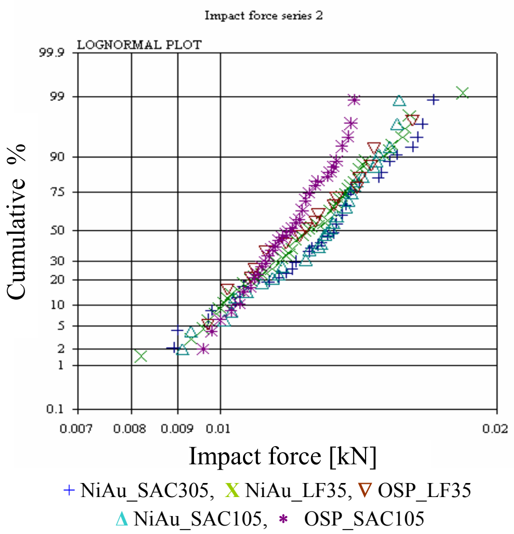


Figure 8 Failure modes distribution with different solder bump compositions in series 2



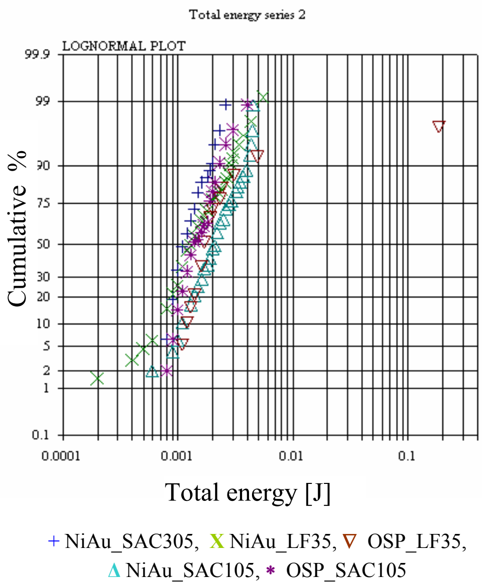
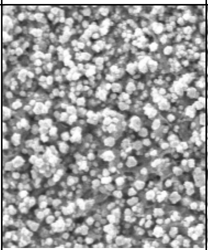
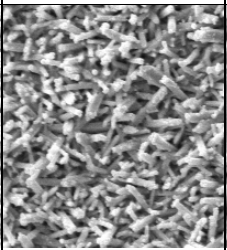
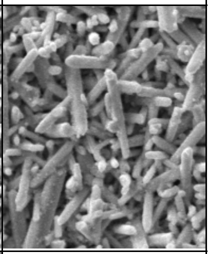
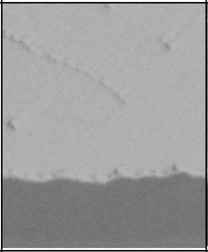
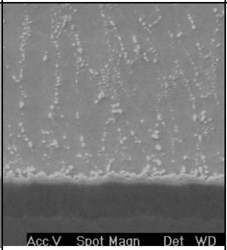
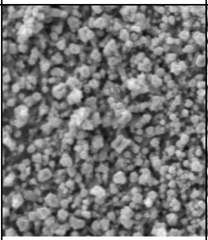
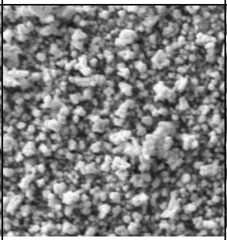
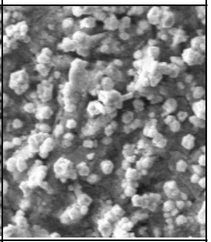
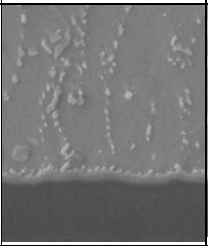
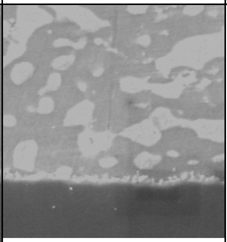


Figure 9 Impact strength and toughness on BGA packages with IMC fracture for Series 2

Table 1 Analysis on interfacial IMC micro-structure

	SAC101	SAC405	CASTIN
Top view			
X-section			
	SAC305+NiGe	Sn63Pb37	SACX
Top view			
X-section			

Interfacial IMC Analysis

Analysis of the interface is done by cross sectioning and by removing the bulk solder via wet etching. The result is shown in table1. From table 1, it is shown that the thickness of the IMC layer for SAC101 is less than for SAC405 and SAC305 + NiGe. Also differences in morphology of the top part of the IMC can be noticed. SAC101, SACX, SAC305+NiGe and SnPb showing more a cauliflower type of structure whereas CASTIN and SAC405 show a needle-like structure.

Drop performance comparison

SAC101 shows a good performance to resist shock impact in two series of high-speed test. This is further evaluated and verified with drop test. BGA240 package with NiAu finished interposer and with two solder alloys SAC101, SAC305 have been evaluated. Results are compared with traditional SnPbAg balls and with SAC101 balls with OSP finished interposer. 15 packages are assembled on a FR4 PCB boards with peak reflow temperature of 245 °C. The board design is based on JESD22-B111 (see figure 10) and the test set up is as shown in figure 11.

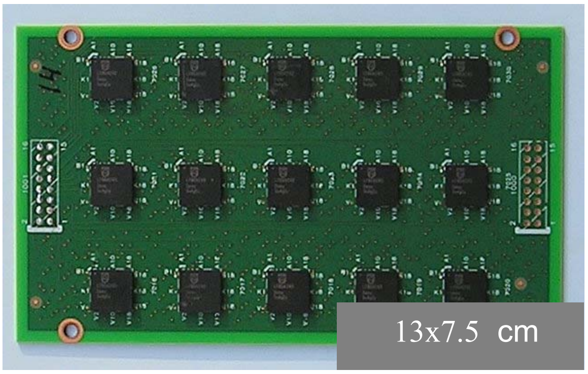


Figure 10 Designed test boards based on JESD22-B111

A half-sine pulse of 0.5ms with acceleration of 1500g is applied and measured at the base plate. Test duration is at least 30 drops. Failure criteria are that daisy chain resistance is larger than 500Ω for a time longer than 0.2µs and the first event of intermittent discontinuity is followed by 3 additional such events during 5 subsequent drops. 6 boards are dropped for each type of package.

The drop test result is analyzed in figure 12 and in table 2. It shows that SAC101 outperform SAC305 largely to resist drop impact and is even slightly better than SnPbAg. This is in line with what is found from previous high-speed shear test. In addition, it shows that BGA packages with Cu-OSP finished substrate are better than those with NiAu finish to resist shock impact. Also this is in line with the high speed shear test and with what can be found in literature [?].

Failure analysis was done on those failed samples from drops, see figure 13. It is found that for package with NiAu finished SAC101, fractures happens in the intermetallic compound with the PCB (Cu/Cu_6Sn_5) and the component substrate Ni/Ni_3Sn, either in the IMC layers or between the IMC layer and the Pad, and in the PCB itself. For OSP finished SAC101, fractures mainly happens in the PCB, and sometimes along the IMC at the component and PCB sides. NiAu finished SAC305 mainly fractures along the IMC at component side. NiAu finished SnPbAg often fractured in the PCB, and some with fractures along IMC at component and PCB side.

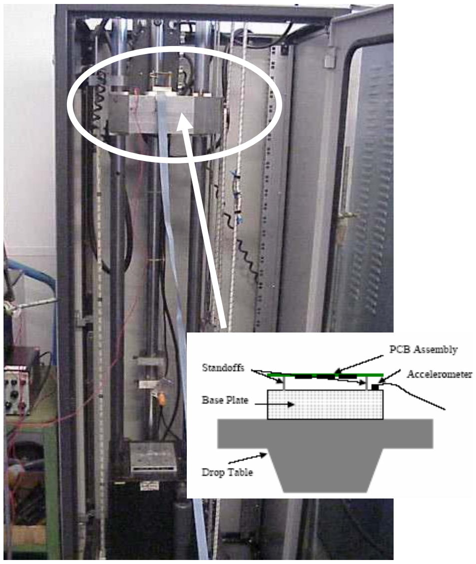


Figure 11 Set-up for drop test

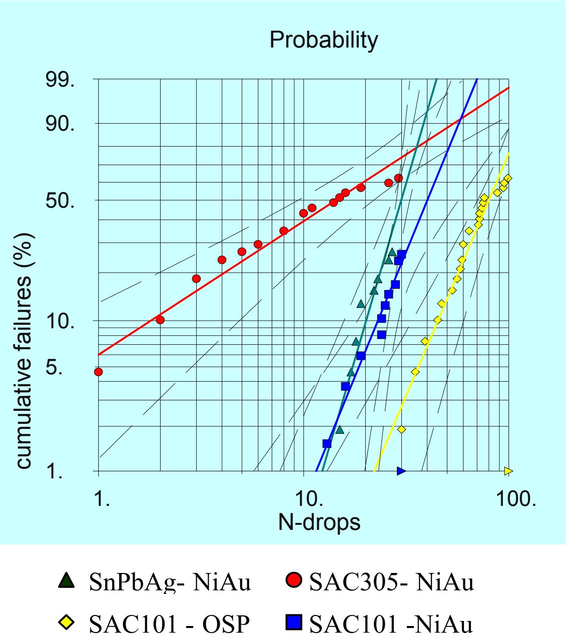
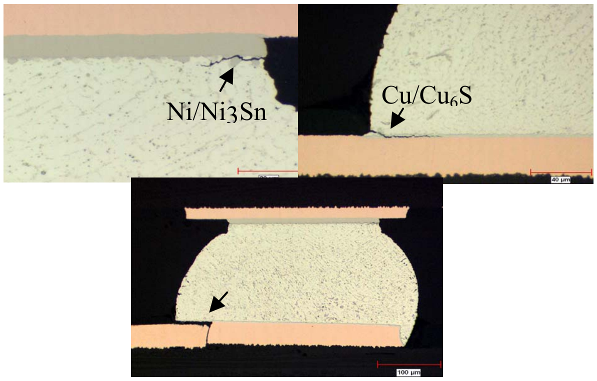


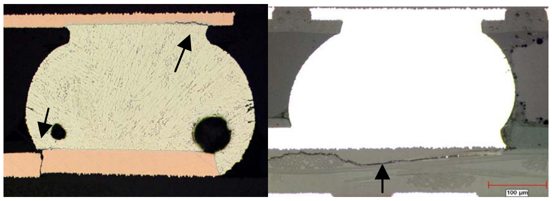
Fig.12 Drop test failure rates of BGA240 packages with different solder compositions and substrate finishes (Weibull)

Table 2 Analysis on the test result in figure 12

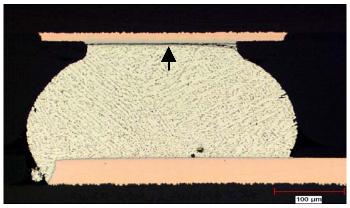
Alloys	SnPbAg	SAC305	NiAu - SAC101	OSP- SAC101
β	4.8	0.9	3.4	3.3
α	32	22	45	89
1%	12	0.1	12	22
50%	30	14	40	80



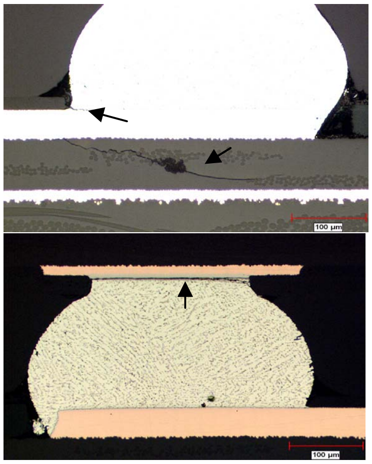
(a) With NiAu finished SAC101



(b) With OSP finished SAC101



(c) NiAu finished SAC305 fracture in the IMC at comp. Side



(d) With NiAu finished SnPbAg

Figure 13 Typical failure modes found in drop tests

Because a lot of failure happens in the PCB and the number of cross-sectioning samples is limited, the drop test result may not be sufficient to evaluate the effect of solder ball compositions on the shock impact resistance. But it can tell at least SAC101 is better than SAC305 to resist the shock impact because almost no complete fracture happens along the IMC at component side for SAC101, whereas most fractures along IMC for SAC305. In addition, PCB strength may be another critical point to be improved to resist the shock resistance, at least for the evaluation of the shock performance of different solder compositions, a high strength PCB need to be designed so that most fractures can happen in the solder joint purposely to assure enough data for comparison.

Discussion

The shear test provides the possibility to access directly the interface between a substrate or interposer and a solder ball. When using high shear rates, failure modes can be addressed that correspond with brittle failure modes that are observed in the field e.g. issues with BGA's with missing balls from handling and/or transportation. The high speed shear tester gives two levels of results. The first level is a qualitative level: the test allows creating realistic failures and based on that, to make failure mode distributions. For the different solder alloys and interposer finishes that have been evaluated in this study, the percentage of brittle failures indicates that interposer material from supplier Sa with Ni/Au finish performs better than interposer material from supplier Sb, that a Cu-OSP finish on the interposer performs better than a Ni/Au finish (also reported for printed circuit boards) and that SAC101 outperforms the other Pb-free solder alloys on shock impact robustness and behaves comparable with eutectic SnPb. All three elements are confirmed by either results in the field (material supplier difference) or by comparison of the shear test results with board level drop test results. The high speed shear test, however, has also the capability to generate values for maximal strength and maximal fracture energy. This allows getting quantitative data for the quality of the interface, e.g. the energy needed to create brittle failure in the intermetallic layer. The data obtained in this study for maximal strength and maximal fracture energy, however, are not consistent. Maximal fracture strength and maximal fracture energy don't show the same trends for different solder alloys and values obtained during the 2nd run differ from the ones obtained in the first run. This is because the resolution of the prototype tester that was used is too low. Information from the equipment supplier indicates that the current generation of testers allows getting better quantitative data. At this moment, it is not clear yet which is the right criterion that can be used to quantify the shock performance of a package in a high-speed shear test either. Considering the dynamic character of shock impact, the impact energy, that is the total energy to shear the solder ball off, is expected to be a better criterion in dynamic test. With the current resolution of the test, it is recommended to limit to a qualitative analysis, like the frequency of occurrence of intermetallic compound fracture, as the criterion to compare the solder bump effect, instead of doing a quantitative analysis. With this criterion, in substrate Sa, SACX has the lowest frequency to IMC fracture while the CASTIN has the highest frequency. SAC305+NiGe and SAC405 are in between while SAC305 +NiGe is better than SAC405. In substrate Sb, SACX has the lowest frequency to IMC fracture while the SAC305 +NiGe has the highest frequency. CASTIN and SAC405 are in between while SAC405 is better than CASTIN. On both of substrate, SAC101 has no IMC fracture, indicating the best performance to resist shock impact. SACX ranks in the second position.

A qualitative analysis with the frequency of occurrence of brittle fracture in IMC layer is highly recommended to compare the impact resistance with different solder ball compositions in a high-speed test. This can avoid the "noise" with impact force or impact energy as criteria. The failure mode can be easily checked and summarized during the high-speed shear test, and the frequency can be easily calculated. This is one advantage of high-speed shear test to the board level drop test. With this criterion, SAC101 is found to outperform other Pb-free solder compositions and the result correlate with the drop test result very well. This indicates the frequency of occurrence of IMC fracture can be a good parameter to characterize the mechanical robustness of electronic packages.

The fracture interface analysis indicates that the shock resistance of a BGA package can be related to the IMC grain size and morphology and by the IMC thickness. SAC101 has slower IMC growth compared with SAC405 and SAC305 + NiGe and a cauliflower top morphology of the IMC layer. Interconnect with SAC405 and CASTIN shows needle shape grain in the IMC layer and the layer is relatively thicker. Both IMC thickness and morphology can affect the interface strength. The thicker the IMC layer is, the higher the risk for brittle fracture. A needle like morphology can easily induce crack formation. Sung reported that a lower Ag content decreases the formation of large Ag_3Sn needles[12]. The amount and size of the Ag3Sn needles is also depending on the cooling rate. This explained the better performance in temperature cycling in his study [12] for Pb-free solders with lower Ag-content. From [13] it was shown that the morphology of the IMC changes from aging. The effects from processing, aging and from morphology of the intermetallics are important factors and have to be explored further.

The drop test shows a lot of failures in the PCB. This indicates that the board design is critical. In addition, a lot of cross sections are needed to analyze the failure mode.

Conclusions

A high speed shear test was used to evaluate the shock resistance of BGA ball to interposer interconnects. During the test, three failure modes are observed, fracture in IMC, fracture in bulk solder and fracture in PCB pad. Given the current measuring resolution of the prototype tester that is used in this study, the frequency of the occurrence of IMC fracture is selected as a criterion for the interface robustness. Pb-free solder alloy compositions with different Ag and Cu-content have been evaluated: SAC405, SAC305 with NiGe addition, Castin 258 (2.5Ag-0.8Cu-0.5Sb), SAC105 (1.0Ag-0.5Ag), SAC101 (1.0Ag-0.1Cu-0.02Ni-xIn), SACX (0.3Ag-

0.7Cu-0.1Bi), LF35 (1.2Ag-0.5Cu) and Sn3.5Ag. SAC101 and Sn3.5Ag are the only Pb-free alloys that show no fracture in the IMC layer, indicating that these alloys have the most robust interface between solder ball and interposer and that they have similar strength to traditional SnPb. SACX shows a lower occurance of IMC fracture than SAC305+NiGe, CASTIN and SAC405. Solder ball attachments to Ni-Au finished interposers from supplier Sa show less IMC failure in the high speed shear test compared with attachments to interposers from supplier Sb. Experience from the field confirms the better performance of interposers from supplier Sa.

A JEDEC based board level drop test was done. The test result confirms that SAC101 outperforms the other Pb-free solder compositions to resist the shock impact and that it has comparable robustness as SnPb. Both high speed shear test and drop test also show that the packages with Cu-OSP finished interposer have a more robust ball to interposer interface than NiAu finished interposer under drop impact.

Interfacial IMC analysis shows that SAC101 has slower IMC growth compared with SAC405 and SAC305 and that no Ag_3Sn needles are formed. Together with the ductility of the alloy, these factors contribute to the interface robustness. Factors that influence the morphology of the IMC are processing and aging. These factors have to be explored further.

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