Drop Reliability Performance Assessment for PCB Assemblies of Chip Scale Packages (CSP)

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Abstract

Drop impact reliability assessment of solder joints on the chip scale packages is critical for use in miniature handheld products. Replacement of lead-based with lead-free solders requires the need of evaluating its compatibility with existing printed circuit board surface finishes. A 15x15mm fine-pitch BGA with solder ball compositions of 36Pb-62Sn-2Ag and Sn-4Ag-0.5Cu on surface finishes of organic solderability preservative, electroless nickel immersion gold and immersion tin were tested. The results revealed a strong influence of different intermetallic compound formation on soldered assemblies drop durability. The lead-based solder supersedes the lead-free composition regardless of the types of surface finish. Joints on organic solderability preservative were found to be strongest for each solder type. Other factors affecting drop reliability such as component location on the board and drop orientation are reported.

1. Introduction

There is a growing interest and need for the assessment of board assembled Integrated Circuits (IC) packages solder joint reliability under drop impact test. With the decrease in size of consumer products such as cellular phones, PDAs, and camcorders, the frequency of accidental drops increases and will cause solder joint cracks that eventually leads to malfunction of the product. Many research and studies have been conducted for the investigation of the reliability performance of IC packages during drop impact test [1-6]. With the implementation of lead-free solders for the purpose of environmental friendliness, the reliability of lead-free solder joints under drop impact becomes a greater concern. Experimentation and analysis focusing on lead-free solder compositions have also been performed and documented [7-10]. Through finite element modeling and analysis, Wong et al [11] identified three main drivers for board level drop impact failure of interconnections; i) elongation and bending of interconnection due to differential flexing of PCB and package, ii) large inertia force from IC packages, and iii) stress waves generated from impact. Other researchers have worked on developing modeling methodologies for failure prediction of solder joints upon drop test [12-14]. There is however a lack of documentation in the use of lead-based (Pb-based) and lead-free (Pb-free) solder compositions on different printed circuit board (PCB) pad surface finishes, and their influence on drop impact reliability. The recent drop test study on a 35x35mm PBGA by Chong et al [15] showed that different solder alloy of Pb-based and Pb-free when mounted onto different PCB surface finishes resulted in different intermetallics formation and contributed to different failure sites and mode of failure.

Besides solder composition and surface finish influence on drop impact reliability, the placement and layout of the IC packages mounted on the PCB also affect its reliability performance. As reported by Wong et al [11], the package that is mounted near to the support pin of the PCB will subject to exceptionally high acceleration and high magnitude of stress waves transmission through the support pin to the solder joints. Thus the damage may be as significant as the contribution due to differential flexing between the PCB and IC package. Syed et al [13] also showed the joint failure in the IC packages across the PCB is location dependent. The drop orientation of horizontal and vertical will be of interest for drop impact durability. The latter will generate a PCB flexing much smaller than the horizontal, however the stress wave transmission through the support pins may induce large damaging impact stresses in the solder joints of the IC packages placed next to the support.

The current work provides an extension to the study by Chong et al [15]. More and more chip scale packages (CSP) are used in miniature handheld products. A new CSP of 15x15mm fine-pitch BGA (FBGA) with 324 solder ball count is being tested. The solder compositions studied are of Pb-based (36Pb-62Sn-2Ag) and Pb-free (Sn-4Ag-0.5Cu), with surface finishes of organic solderability preservative (OSP), electroless nickel immersion gold (ENIG) and Immersion Tin (Im Sn). The study aims to investigate the strength comparison of PCB assemblies of CSP with Pb-based and Pb-free solders onto different surface finishes. The effect of component placement and location across the PCB will also be studied. A comparison on the drop performance of horizontal and vertical orientations will be briefly discussed.

2. Drop Impact Test – Test Vehicle and Setup

The Lansmont Model 65/81 drop impact tester (see Fig. 1) was used to carry out the board level drop impact test. The test vehicle used in this experiment is of a 15x15mm FBGA, 324 I/O (input/output) count with solder ball pitch of 0.8mm. The solder ball size is 0.4mm (before reflow). The test package is daisy chained, with full interconnection failure monitoring of the solder balls. Multiple fault isolation pads are designed-in for the purpose of easy identification of failure distribution in the package after the drop test. The packages are mounted on a 77x132mm 2-layer test board with a total thickness of 1.0mm (Fig. 2). Seven packages are mounted in the positions as shown. The solder compositions used in the test are Pb-based of 36Pb-62Sn-2Ag and Pb-free of Sn-4Ag-0.5Cu (also termed as SAC). Five test legs with different PCB surface finishes are divided as follow:

a) Leg 1 - Pb-free on OSP pad finish
b) Leg 2 - Pb-free on ENIG pad finish
c) Leg 3 - Pb-free on Im Sn pad finish
d) Leg 4 - Pb-based on OSP pad finish
e) Leg 5 - Pb-based on ENIG pad finish

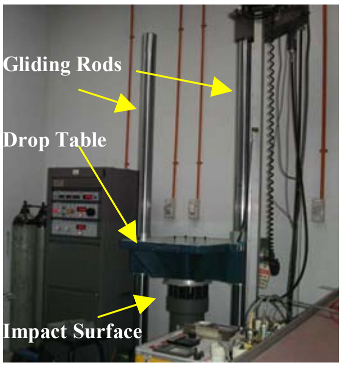


Fig 1. Lansmont Model 65/81 Drop Impact Tester.

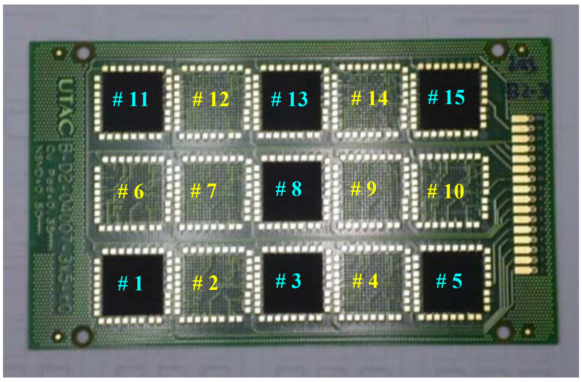


Fig 2. 77x132mm PCB with 15x15mm FBGA Packages.

Due to symmetry of the board, the packages are grouped as listed in Table 1 according to their location and distribution across the PCB. This grouping allows the study of the effect of component placement and location on the solder joint's strength, as well as providing more data points per leg for analysis. Three boards were tested for each leg, with the sample size of six, three and twelve for sets "A", "B" and "C" respectively. The drop height was set at 1.0m with the impact surface covered with felt pads. The drop orientation is of horizontal with packages in a face-down position. The test PCB will be screwed onto the drop table at four support pin locations (see Fig. 3). During the test, the drop table is raised and dropped from the desired height along the two guiding rods of the drop tester onto a rigid base covered with layers of felt. Upon impact, the drop responses of interest are the shock level experienced by the drop table and PCB, the strain experienced at the center of the PCB, and the static and dynamic resistances of daisy-chained solder joints in real-time. The peak input shock pulse of the drop table was about 690g in the form of a half-sine shape with 2 millisecond period as shown in Fig. 4. An accelerometer was mounted on the drop table near to the fixture to measure the input acceleration. Another accelerometer was mounted at the center of the PCB (reverse side of the IC package) to characterize the output acceleration response of the PCB. Strain gauges were mounted on the PCB at the opposite side of the center FBGA package to measure the bending strain experienced during drop impact. For drop test consistency and repeatability, drop responses of input/output acceleration and PCB strain were monitored for one board from each leg. Both the acceleration and strain values were found to be reproducible.

Table 1. Grouping of Test Units on the PCB.

Group	Package Location	Remarks
"A"	3, 13	"Center Edge"
"B"	8	"PCB Center"
"C"	1, 5, 11, 15	"PCB Corner"

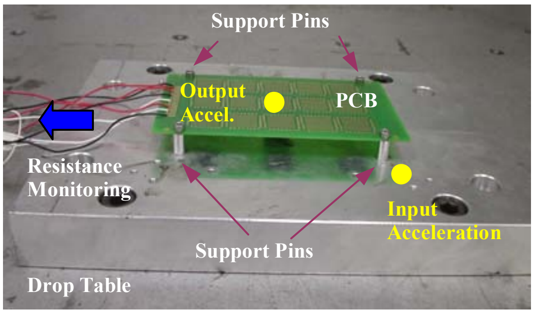


Fig 3. Drop Test Fixture with PCB Mounted onto it.

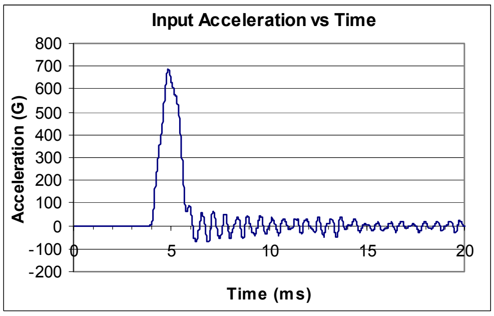


Fig 4. Input Acceleration at the Drop Table Upon Impact.

A dynamic resistance measurement of the daisy-chained solder joints in real-time during drop is used [3,15]. In this method, the dynamic resistance of the joints is represented by a voltage reading on the oscilloscope (four-channels input). With a resistor *Ro* (10Ω) placed in series with the daisy chain solder joints and connected to a DC power supply, the dynamic resistance *Rx* can be described by,

$$R_x = \frac{R_0 V}{E - V} = \frac{R_0}{E / V - 1} \quad (1)$$

where E is the voltage (1.8 volts) of the DC power supply, and V is the dynamic voltage of the daisy chain that changes with its dynamic resistance. When $V \rightarrow E$, $Rx \rightarrow \infty$ (implies an open circuit), it indicates a critical solder joint has failed with crack opening. As there are seven packages on the PCB, the responses of all packages cannot be tracked simultaneously. Channel 1 is reserved for PCB strain measurement. Packages in locations that are prone to early failures will be monitored first by other channels 2-4. The order of failure occurrence among the packages has been pre-tested and determined. Upon failure, the channel will be switched to another package with the next order of failure. This process is continued until all seven packages are captured.

3. Results and Discussion

Three sets of drop impact test data points are presented with reference to their locations mounted on the PCB, namely "A", "B" and "C". For set "B" where the package is mounted directly at the center of the PCB, it will experience the maximum PCB flexing due to pure bending mode upon impact. As the PCB is supported at 4 corners, the longitudinal edge (length-wise of the PCB) will be subjected to an additional twisting mode instead of the bending mode alone. Thus for the "center-edge" location set "A", the deformation will be constituted by both the bending and twisting modes. For set "C" where it is located near to the support pins, PCB flexing and twisting will be minimal. However, it will experience the highest magnitude of stress wave transmission from the drop table during impact where it can be highly detrimental to the solder joints.

The failure due to opening of solder joints is observed through the change in the dynamic voltage reflected on the oscilloscope. Before drop, the solder joint resistance (static) was measured by manual probing to ensure that no failure in the interconnection was observed. In a drop test, the solder joint will exhibit three phenomena of failure. After continuous rounds of drop test, a solder joint system begins to weaken and crack will initiate. Further drops will cause the crack to propagate and eventually results in a full joint crack (termed as *initial* failure). This instantaneous crack can cause immediate malfunction of an IC package if the particular joint is of critical functionality. This crack opens when the PCB flexes leading to a resistance discontinuity but closes back to resume electrical continuity after the flexing of the board has ended. This form of observation will be termed as *intermittent* solder joint failure, where static resistance measurement by manual probing is not able to register any discontinuity. When the crack becomes larger and cannot be closed back even after the impact test, a *permanent* solder joint failure will be resulted (open circuit registered with static resistance measurement). In the current test, the *initial* failure is identified as the failure criteria.

3.1. Dynamic Responses and Observations

In any drop, the solder joints resistance (or "voltage") for the FBGA packages and PCB bending strain were captured. A typical curve response is showed in Fig. 5 where it can be divided into two regions, before impact (static) and after impact (dynamic). Test result for Leg 5 (Pb-based/ENIG) at the 78th drop is used for illustration. Channel 1 is used for dynamic strain measurement at the PCB center upon impact. Channels 2, 3 and 4 are measuring the dynamic voltages of package units 1, 8 and 15 respectively. One large division in the y-axis of the oscilloscope corresponds to 1.0 volt (V). Before impact, the PCB strain is zero while the static solder joint resistance is similar to the value measured by manual probing. Each package location has its own zero-reference voltage and initial voltage reading of 0.6V [$Rx(initial)$ = 10/(1.8/0.6 – 1) = 5Ω] as indicated. With reference to channel 3 (unit 8) a peak voltage was registered after impact, indicating that an *initial* failure in a solder joint has occurred. The following fluctuation in peaks was constituted by the downward/upward flexing of the PCB leading to the opening/closing mode of the crack. When flexing of the board has ended, static resistance measurement by manual probing was not able to register any discontinuity. This observation describes the *intermittent* solder joint failure. With it, unit 8 of Leg 5 registered a failure at the 78th drop. At subsequent drops, unit 8 would register fluctuation in voltage reading. At the 89th drop, it registered a maximum voltage of 1.8V [$Rx(final)$ = ∞]. The discontinuity was confirmed by manually probing with an open circuit being measured, thus implying that the joint opening is *permanent*. Similar observation was made for unit 15 of channel 4. Joint failure also occurred at 78th drop. For channel 2 (unit 1), the solder joints remained intact as there was little change in the resistance responses before and after the impact.

Fig. 6 shows another response curve for the same leg and test board at the earlier drop sequence of 45th drop. It can be seen that constant voltage (0.6V) was registered before and after impact for unit 8, revealing good solder joint integrity before reaching 78 drops. Attention is now placed on channel 4 (unit 13). It had registered a maximum voltage of 1.8V before impact, fell to 0.6V after impact and fluctuated between these two values subsequently. For this case, solder joints in unit 13 already failed permanently before 45 drops. The cracks opened and closed due to the downward/upward flexing of the PCB after impact. All test legs displayed similar response curves as in Figs. 5 and 6. The drop cycles constituted to the *initial* failure of the solder joint was recorded for results compilation and analysis.

High speed digital camera has been employed to capture the drop impact images of the test boards upon impact. Fig. 7 shows the PCB bending sequence upon impact. The drop table will be put to a sudden stop upon impact with the rigid base, whereas the PCB continues to travel downwards leading to the concave bending mode of the board. Due to its inertia and flexibility, the PCB will reflex back to a convex bending mode. This concave/convex bending mode will continue and eventually subside after sometimes due to damping effects experienced by the PCB. The amplitudes of the initial concave and convex bending are the highest, corresponding to Figs. 7b and 7c respectively.

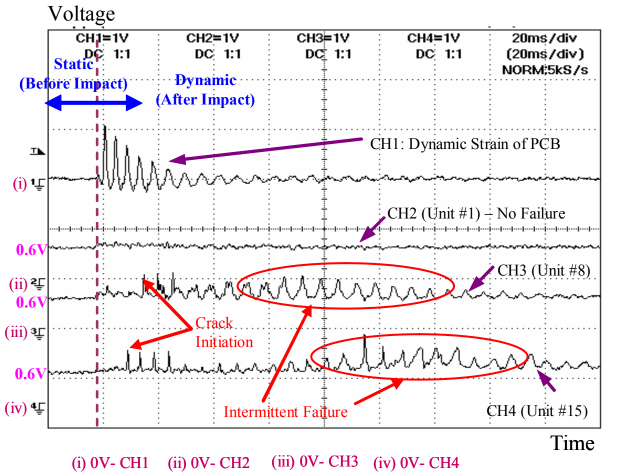


Fig 5. Typical Dynamic Responses for Drop Test - Leg 5 (Pb-based on ENIG) at 78th Drop.

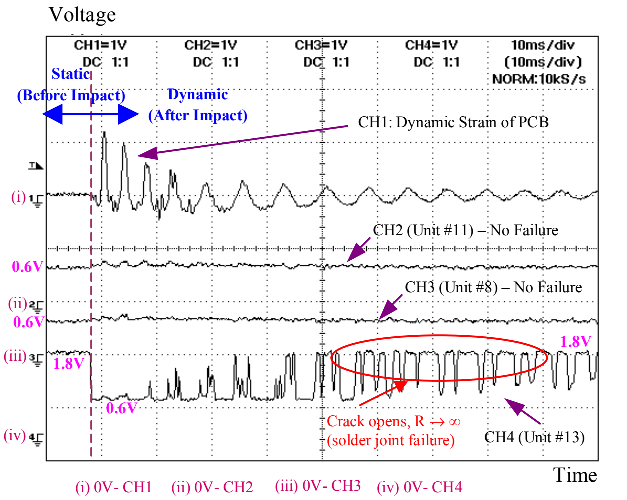


Fig 6. Dynamic Responses for Leg 5 at 45th Drop.

A vertical orientation drop has been conducted by mounting the drop fixture perpendicularly to the drop table. Fig. 8 shows the PCB bending images upon impact. The amplitudes of the flexing are much smaller compared to the horizontal drop. Thus joint failure due to differential flexing will be minimal. It is however anticipated that packages mounted near to the support pin will subject to as high magnitude of stress waves transmission through the support pins to the solder joints (as of horizontal drop). And units in group “C” will register similar drop cycles to failure as to horizontal drop. Nonetheless, there existed no solder joint failure after a total of 150 drops. There could be two possible explanations. Firstly as shown in Fig. 9, stress wave transmission will be largest in the direction of drop. Thus stress wave transmitted to the solder joints of corner packages mounted horizontally would be significant. But for a vertical drop, stress wave transmission could be greatly reduced due to a change in direction, thereby minimizing the impact on corner packages. Secondly, although the solder joints will be subjected to a shear force upon impact due to the IC package’s mass and inertia in a vertical drop, the shear stress generated may be of less detrimental compared to the tensile stress experienced in a horizontal drop (thus tearing the joints apart). The current finding presents some differences in the results with work done by Lall et al [5,14]. In their work, the PCB is dropped vertically onto an impact surface thereby introducing great stress wave transmission into the solder joints through the PCB. Large PCB deformation and flexing was also observed, with failure of the CSP solder joints tested occurred at as low as ten cycles.

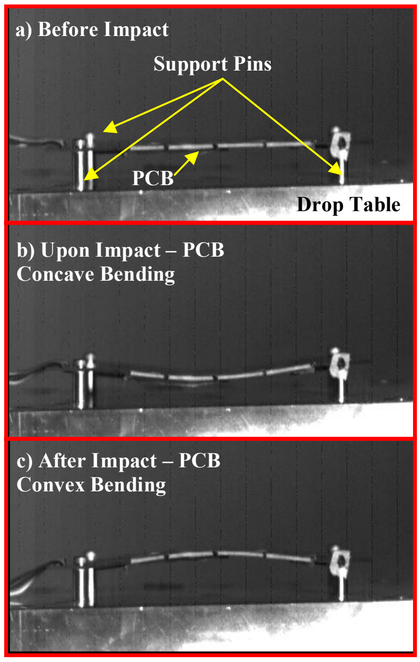


Fig 7. High Speed Digital Images of PCB Bending for Horizontal Orientation Drop.

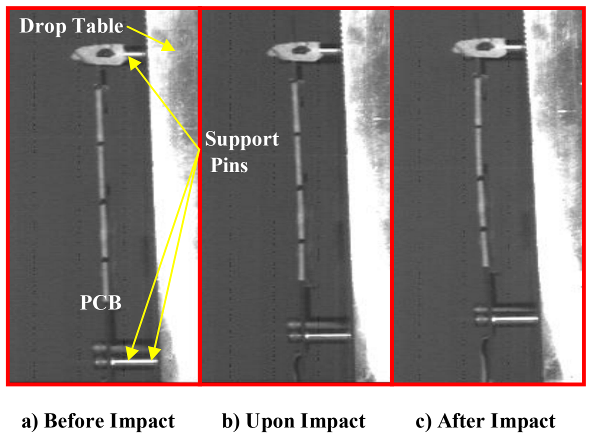


Fig 8. High Speed Digital Images of PCB Bending for Vertical Orientation Drop.

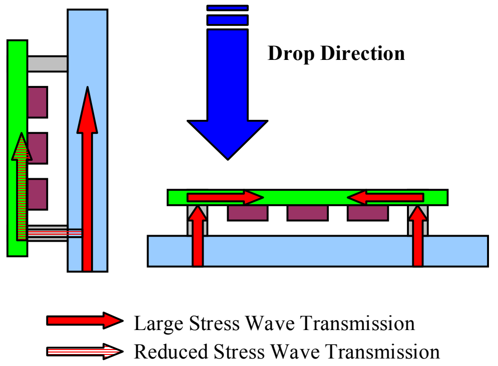


Fig 9. Stress Wave Transmission for Vertical and Horizontal Orientation Drops.

3.2. Drop Test Results and Trends

The drop test was conducted until all the units on the board had failed. The average number of drop cycles to *initial* failure for each group in different legs is reported. The failure trend for the five legs are plotted in Fig. 10, with the drop performance of each test leg revealed. In the first instance, drop reliability of the Pb-based solder composition supersedes the Pb-free composition regardless of the types of surface finish. The solder joint formation (both Pb-based and Pb-free) on OSP finish was found to be strongest as compared to ENIG and Im Sn. For the Pb-free legs, Im Sn surface finish generated the lowest drop cycles to failure. The above failure trend can be attributed to the type of intermetallic compound (IMC) layer formed at the solder joint interface with the PCB copper pad, and will be discussed in the next section.

The drop test results also captured the location dependent failure trend of the solder joints. Packages in group “A” located at the PCB center edge suffered the most drop impact damage. Due to the large deformation constituted by both the bending and twisting modes, the solder joints experienced the highest level of stress where all the solder joints failed below the drop cycles of twenty. Study by Syed et al [13] revealed similar observation. In their test the PCB is fully populated with fifteen components, and solder joints at location #14 (refer to Fig. 2) failed earlier than of #8. In the current test with no component mounted at locations of #2, 4, 12 and 14, units #3 and 13 took the additional stress induced by the twisting mode of the PCB. Packages at the PCB center and corner were found to exhibit equal chance of joint failure. Crack failure in packages at the PCB center was caused by the pure bending of the board, with the tensile stress experienced tearing the joints apart. For packages at the PCB corner, PCB flexing and twisting will be minimal. The solder joints were damaged by the impact stress waves transmitted from the drop table through the support pins. In addition, the PCB adjacent to the support pins could experience up to a thousand times acceleration (1000g) and similarly for a package near to it. Whereas a package located at center on the same PCB, its acceleration could only be in the range of hundreds of gravitational acceleration. Thus given the same mass, interconnects in the package placed near the support will be subjected to a larger tensile stress and eventually lead to impact failure.

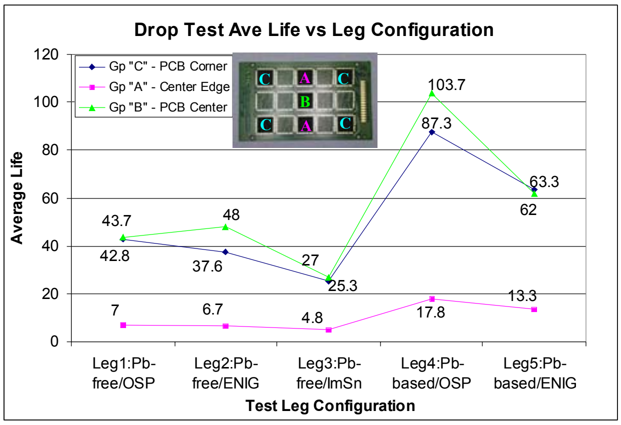


Fig 10. Drop Test Failure Cycles for Different Test Legs.

Fig. 11 shows the solder joints failure distribution across the PCB. Due to pure bending mode in location “B”, joints at corner of the package failed as a result. Damage by stress wave transmission through the support pins was evidently demonstrated for units in group “C”, where joints at the package corner had failed. For group “A”, failure was registered at left and right rows of the package. The failure location mapping was preformed after all units in a single board had failed. Thus it may have failed to capture the first solder joint crack occurring at the corner of the package (shaded in green). The subsequent drop cycles resulted in adjacent joints to fail. Similar failure distribution was observed in all test legs.

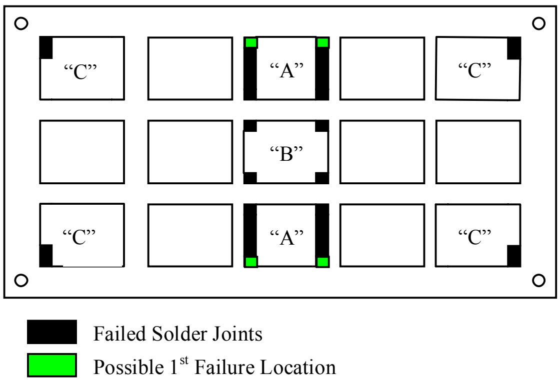
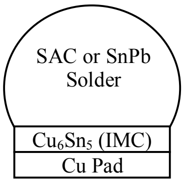


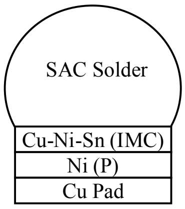
Fig 11. Solder Joints Failure Distribution Across the PCB.

3.3. Failure Analysis of Solder Joints

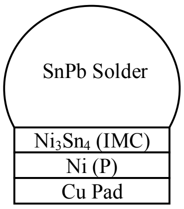
Solder joints corresponded to failed locations in Fig. 11 were sent for cross-sectioning to determine the failure sites. The test results revealed the solder joint’s strength in the rank of: Pb-based/OSP > Pb-based/ENIG > Pb-free/OSP > Pb-free/ENIG > Pb-free/Im Sn. Chong et al [15] reported the influence of IMC formation on solder joint drop durability. The different IMC layer formations are illustrated in Fig. 12. When Pb-based or SAC solder reflowed over an OSP copper pad, the OSP coating is evaporated and allows the interaction of the solder with copper to form a binary intermetallic of Cu_6Sn_5 [16-18]. For SAC soldered onto Im Sn surface finish, intermetallic of CuSn would be formed as well. During soldering process onto the ENIG finish, the gold plating (usually < 1um) will dissolve rapidly into the solder. And the nickel barrier layer forms a binary and ternary intermetallic of Ni_3Sn_4 [19] and Cu-Ni-Sn [11, 20-21] for the Pb-based and SAC solder compositions respectively.



a) OSP/Im Sn Pad Finish (Legs 1, 3 & 4)



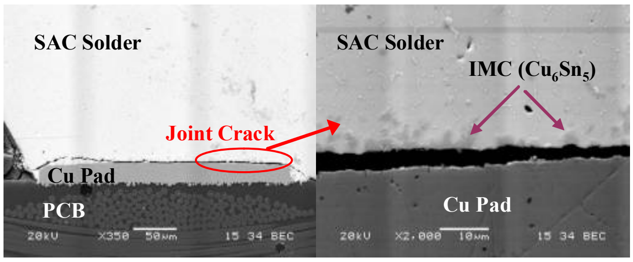
b) ENIG Pad Finish (Leg 2)



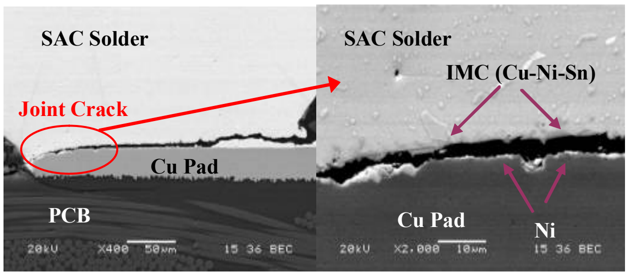
c) ENIG Pad Finish (Leg 5)

Fig 12. Intermetallic Compound Layers Formation for Legs 1-5.

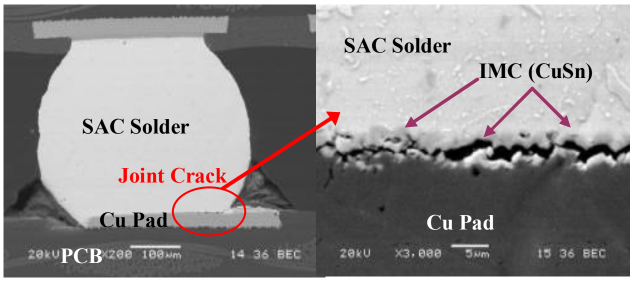
Brittle fracture is promoted through the suppression of plastic deformation under high strain rate test situations [22]. Thus with drop test for soldered assemblies which is of high strain rate in nature, it usually causes brittle failure in the IMC layer instead of ductile failure in the solder. Fig. 13 describes the different failure sites of the FBGA package solder joints. Solder joint crack at the interface of solder to PCB copper pad were found in all the legs, with the exception of Leg 4 (Pb-based on OSP). It is postulated that the Cu_6Sn_5 IMC formed due to Pb-based solder on OSP finish is much thinner as compared to SAC solder reflowed on OSP and Im Sn surfaces. A higher reflow temperature is required for the SAC solder (typically 260°C peak vs 225°C for Pb-based solder), thus it may promote thicker IMC growth in Leg 1. For SAC solder reflow on Im Sn surface (Leg 3), the Sn existed on the copper pad would further aggregate the formation of thick Cu_6Sn_5 layer. The extra thick and brittle Cu_6Sn_5 layer could result in quick damage under impact loading thus generating a worse off drop performance. Instead of joint interface failure at the PCB side for Leg 4, the crack has migrated to PCB resin and joint interface at the package side. Similar explanation could be offered for solder reflow on ENIG surface finish. IMC of Ni_3Sn_4 and Cu-Ni-Sn are both very brittle in nature. Thus a thicker layer of Cu-Ni-Sn formed in Leg 2 will be more prone to impact failure as compared to Leg 5. PCB resin crack was also observed in Leg 5. Further work on microstructure analysis at the joint interface and failure mechanism investigation is in progress.



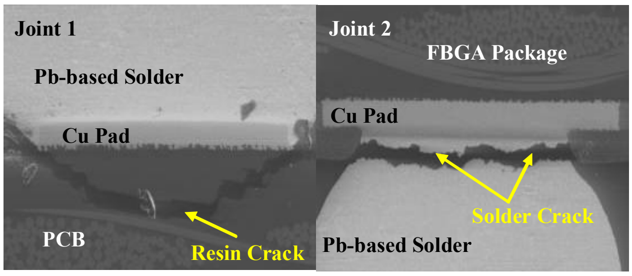
a) Leg 1 – Pb-free on OSP



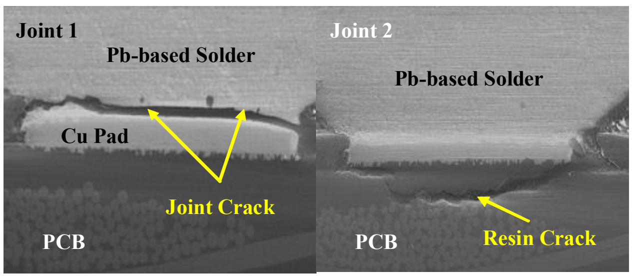
b) Leg 2 – Pb-free on ENIG



c) Leg 3 – Pb-free on Im Sn



d) Leg 4 – Pb-based on OSP



e) Leg 5 – Pb-based on ENIG

Fig 13. Cracks and Failures Found in the Solder Joint System.

4. Conclusions

The drop impact reliability performance of the 15x15mm CSP (FBGA type with 324 solder balls) has been assessed for solder compositions of 36Pb-62Sn-2Ag and Sn-4Ag-0.5Cu onto surface finishes of OSP, ENIG and Im Sn. The drop responses mechanism, failure distribution and sites have been analyzed. The following conclusions can be drawn:

i) Combination of bending and twisting modes in the PCB during drop impact will constitute to the highest level of stress leading to early joint crack failure.
ii) Pin-supported vertical drop of PCB generated much lower PCB flexing and impact stress damage to the solder joints as compared to horizontal orientation drop.
iii) Failure rate and distribution of the IC packages mounted onto a PCB is location dependent.
iv) A strong influence of different IMC formation on soldered assemblies drop durability.
v) The solder joint formation (both Pb-based and Pb-free) on OSP finish was found to be strongest as compared to ENIG and Im Sn.
vi) Based on current test vehicles, drop reliability of the Pb-based solder composition supersedes the Pb-free composition regardless of the types of surface finish.

Acknowledgments

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