

PB-FREE SOLDER FOR PORTABLE AND HIGH TEMPERATURE ELECTRONIC DEVICES

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Abstract

As the European Union's (EU's) RoHS directives came into force on July 2006, the transition to lead-free solder has occurred at a rapid pace. Many manufacturers have adopted Sn/Ag/Cu (SAC)-type solder alloys as a representative Pb-free solder to substitute the conventional Tin-Lead (Sn-Pb) system with many reliability anomalies unanswered. This paper is an effort to compare solder reliability between the two most popular Pb-free solders SAC305 and SAC 105 for temperature cycling and drop test. Solder reliability for drop test and temperature cycling were determined experimentally and verified using finite element simulations. The results were interpreted and the recommendations for the right Pb-free solder were made for practical applications.

Keywords: RoHS, Pb-free, Drop test, Thermal Aging, Experiment, ANSYS.

Introduction

A semiconductor device as such can be broadly differentiated on the basis of usage as Portable and Hand held devices like cameras, cell phones, iPhones, iPods, etc [1] and as High temperature electronic devices used in industries like Aerospace, Automobile or Oil and Gas industry. The recent directive from RoHS has forced all the companies to ban their tried and tested tin-lead solder and use a Pb-free solder in devices [both Portable and Hand held devices and High temperature electronic devices] using processes that are unproven and, in certain situations, known to be less reliable^[2]. Extensive research has been conducted in the field of lead-free solder to qualify a solder equal to or superior to the tin-lead solder from the reliability aspect. This ongoing research has assisted many manufacturers to streamline the lead-free solder search and find the right substitute for the tin-lead solder system.

Two types of Pb-free solder have been identified as the plausible answer to the RoHS directive. One being the Sn/Ag/Cu (SAC)-solder alloys SAC305 and the other being the SAC105 solder. With the trend to reduce their inventory without sacrificing the reliability, companies are looking for an ideal Pb free solder that caters their business and applications in an optimized fashion. From reliability perspective drop tests for a mobile application and Temperature Cycling for High temperature electronic devices have become one of the crucial tests to qualify any Pb free solder system. A thorough comparison between SAC 105 and SAC 305 on the reliability of drop test is still missing. This paper is an effort to collect the data and compare the results for SAC105 and SAC305 with respect to the following approach for both temperature cycling and drop test:-

- 1) Temperature cycling and drop test failure characteristics for an on-board package were

determined experimentally. Data from these experiments were analyzed using 2-parameter Weibull statistics, and the characteristic life from each set of experiments was determined. The result of 1st failure and 50% failure for SAC 105 and SAC 305 is discussed. Site of failure and intermetallic thickness on the package side were investigated using the cross-sectioned samples.

2) Dynamic simulation of the temperature cycling and drop test were conducted to investigate the stress/strain induced in interconnects using ANSYS. Simulation was done using finite element model to illustrate the temperature flow and stress distribution throughout the joint. The effect of accumulated stress per drop cycle and the hot spot is reported in the paper. The effect of the package integrity and weak joints with respect to drop reliability is also discussed.

Reflow profiles:

Reflow profiles as recommended by the vendor were used for both SAC105 and SAC305 while attaching the packages to the test board. The reflow had a preheat ramp-rate of about 4 °C/sec with 50 and 58 seconds above the reflow temperature and cooling rate of about 3.55 °C/sec and 3 °C/sec for both temperature cycling and drop test vehicles as shown in the figure 1 and figure 2 respectively.

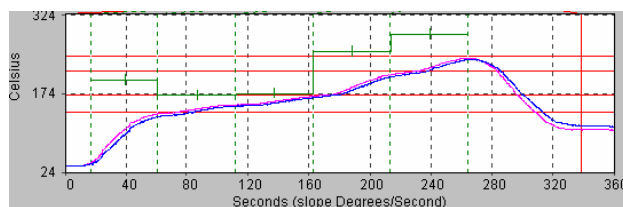


Figure 1: Reflow profile used for the temperature cycling test vehicles.

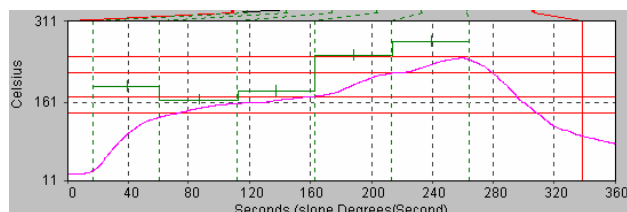


Figure 2: Reflow profile used for the drop-test vehicle.

Intermetallics:

During the reflow process intermetallics are formed at the package and board side to form a proper bonding between the solder and its respective pads. The intermetallics formed at the package side were Ni_3Sn_4 and $(\text{Cu}, \text{Ni})_6\text{Sn}_5$ and at the board side were Cu_3Sn and Cu_6Sn_5 as shown in figure 4. During the reflow of the package to the board the first intermetallic formed at the board side is Cu_6Sn_5 . But this being an unstable layer, a very thin layer of Cu_3Sn is formed to bring stability to the system. Cu_3Sn formed is orthorhombic in structure and forms a tightly coherent layer with nearly equiaxed grains and Cu_6Sn_5 forms a rough layer with hexagonal prisms that extend into the solder interconnect [3]. On the package side the Au [gold] diffuses into the bulk solder after the reflow process forms Au_4Sn intermetallic that diffuses into the bulk solder. Nickel acts like a barrier layer with the bulk solder for its base metal and forms $(\text{Cu}, \text{Ni})_6\text{Sn}_5$ intermetallic with the bulk solder. This intermetallic layer is observed on top of the Ni_3Sn_4 (adjacent to nickel surface). After the reflow process thin rod shaped brittle Ag_3Sn [4] and Au_4Sn [5] intermetallics are formed in the bulk solder.

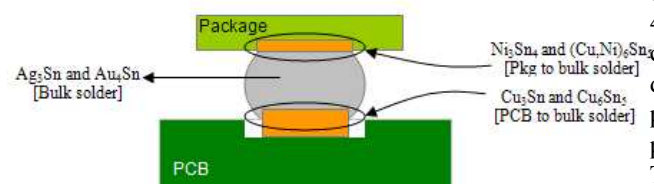


Figure 3: Intermetallics formed for the Pb-free solder alloys.

MECHANISM

Temperature cycling test-

Cyclic loading which is fatigue along with creep is the cause of failure in solder joints during temperature cycling. Mismatch in the coefficient of thermal expansion between the substrate and the board leads to cyclic loading condition. This mismatch constitutes to the shear stress failures on the solder joints. The intensity of this shear stress is proportional to the CTE mismatch between the board and substrate, distance from the neutral point, average diameter of the solder ball and inversely proportional to the square of the

length of the solder ball [6]. Stiffness of the solder ball also constitutes to its ability to resist greater shear force. Most of the failure mechanism in the test vehicle were noticed at the board/solder interconnect system.

Drop test-

It is seen that the test boards subjected to horizontal drop has maximum impact response on an IC package/board [7] and perfectly mimics many drop tests for mobile application. The package and testing board are subjected to different stress when dropped. Several JEDEC standards [8,9] are generally employed as a basis line for the board level drop test, although some customized specifications are usually made to meet the test requirements for specific products. Solder joint interconnects experience the worst stress during the drop test and in most cases leads to primary cause of failure in a package. The levels of stress or strain accumulated in a package again depends on stiffness of the board, interconnects and the package. Stiffer package and board leads to greater amount of load/stress into the interconnects. The stress on interconnects also depends on the symmetry of the package. Typically the corner solder are subjected to a greater load as compared to the center ball and generally leads to open circuit failure. Many times intermetallics also play a dominant role in the failure of an interconnects.

EXPERIMENTAL METHOD

Test vehicle specification:

Temperature cycling test-

The dimension of the packages used for temperature cycling was $(8.15 \times 6.15 \times 1.0)$ mm with 48 ball foot prints and daisy chain interconnects for continuous monitoring of the solder joint resistance during testing to monitor open circuits. The test package is shown in figure 4. This solder mask defined package had a solder resist opening of 400 microns. The pad finish for packages used for the test was ENIG [Ni-Au].

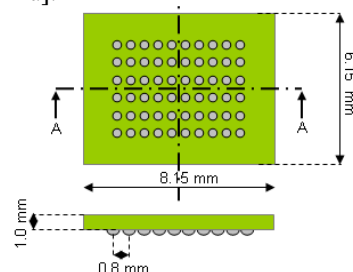


Figure 4: Test package specification: 88 ball PBGA $(8.15 \times 6.15 \times 1.0)$ mm

Six such packages were mounted to the test board as shown in figure 5. The dimensions of the board used for the test was (140×130) mm. Identical test vehicles

were used for the comparison of the two Pb-free solders.

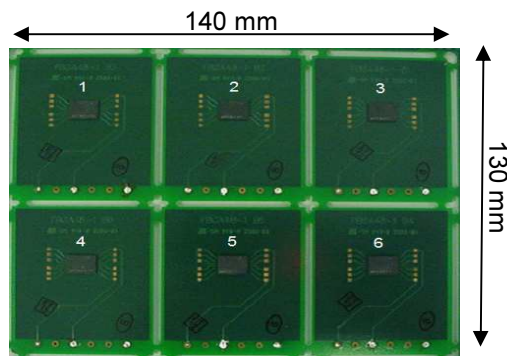


Figure 5: Temperature cycling vehicle used for SAC105 and SAC305 comparison.

Drop Test-

The dimension of the packages was (11 x 8 x 1.2) mm with 88 ball foot prints and daisy chain interconnects for continuous monitoring of the solder joint resistance during drop impact testing. The test package is shown in figure 6.

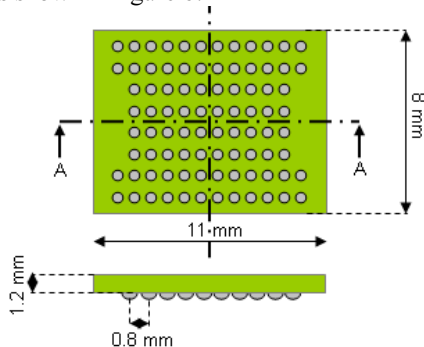


Figure 6: Test package specification: 88 ball PBGA (11 x 8 x 1.2) mm

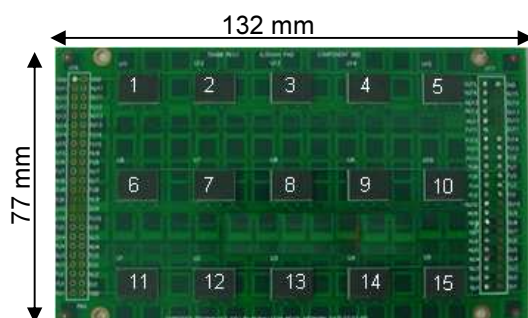


Figure 7: Drop test vehicle used for SAC105 and SAC305 comparison. [10]

This solder mask defined package had a solder resist opening of 400 microns. The pad finish for packages used for the test was ENIG [Ni-Au]. 15 such packages were mounted to the test board as shown in figure 7.

JEDEC Standard JESD22-B11 drop test board was used for the test. The dimensions of the board used for the test was (132 x 77) mm. Identical test vehicles were used for the comparison of the two Pb-free solders.

Experimental setup and profile:

Temperature cycling test-

Four test boards with twelve packages (double side SMT, 6 units on each side) on each board were used for the test for both SAC 305 and SAC105 packages. The resistance was monitored with the help of the daisy-chain per package during the test. Resistance measurement with more than 1000 ohm



Figure 8: Thermal cycling test chamber and data monitoring system

lasting for 1 microsecond or longer was considered as a failure and the corresponding number of drops was noted. The board was subjected to a cyclic loading between -25 to 125 °C from room temperature with a dwell time of about 5 mins. The total cyclic time was for 20 minutes. The temperature cycling chamber is shown along with the resistance measurement system is shown in figure 8. The ramp-rate and profile used are shown in figure 9.

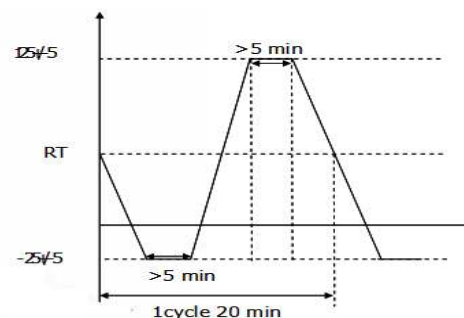


Figure 9: Temperature cycling test set-up

Drop test-

Four test boards with 15 packages on each board were used for the drop test for both SAC 305 and SAC105 packages. The drop test apparatus setup

is shown in figure 9. The resistance was monitored with the help of the daisy-chain per package after each drop cycle. Resistance measurement with more than 1000 ohm lasting for 1 microsecond or longer was considered as a failure and the corresponding number of drops was noted. Test drop duration was for at least 30 drops or until 80% of all devices failed or which ever was earlier. Acceleration used for the test was 1500g with a pulse time of 0.5 ms. The calibration profile used for the drop test is as shown in figure 10.

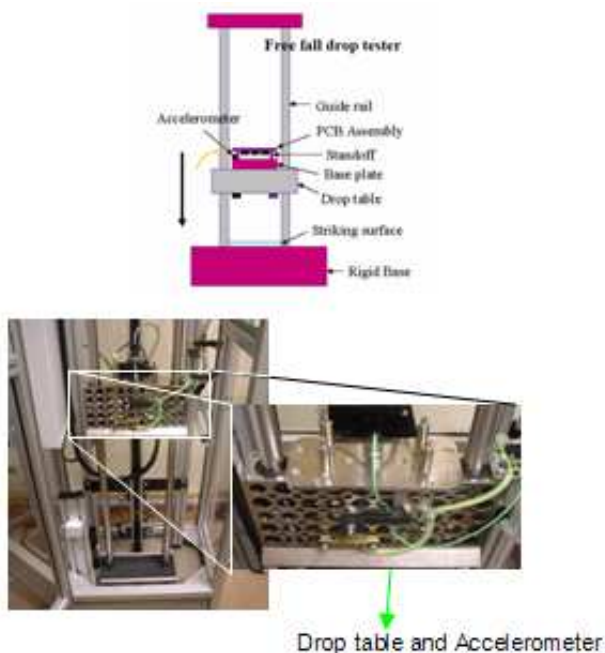


Figure 9: Drop test set-up

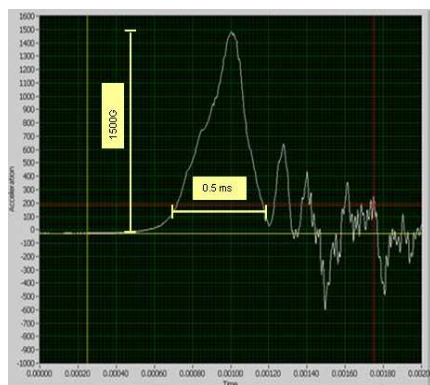


Figure 10: Drop Test Calibration Profile

Experimental Results:

Temperature cycling test-

SAC305 solder failure-

SAC 305 had failures at the Intermetallic layer on the board side as shown in figure 11. On the

package side there was no crack initiation or failures seen. On the board side the crack seems to have originated at the interface of the copper pad and the bulk solder [between Cu_6Sn_5 and the bulk solder] propagating through its interface and bulk interface. Identical failures were seen in other SAC305 packages.

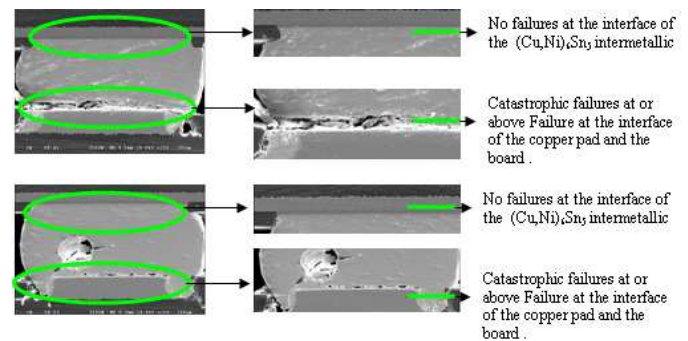


Figure 11: SAC 305 typical solder failures for temperature cycling test

SAC105 solder failure-

SAC 305 had failures at the Intermetallic layer on the board side as shown in figure 12. On the package side there was no crack initiation. On the board side the crack seems to have originated at the interface of the copper pad and the bulk solder [between Cu_6Sn_5 and the bulk solder] propagating through its interface and bulk interface or failures seen. This crack initiation and propagation was very similar to SAC305 failures. Identical failures were seen in other SAC105 packages.

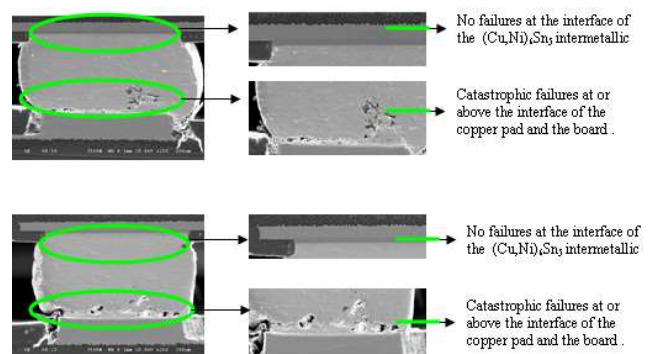


Figure 12: SAC105 typical solder failures for temperature cycling test

Drop test-

SAC305 solder failure-

SAC 305 had failures at the Intermetallic layer on the package side and the through the laminate

beneath the pad location on the board side as shown in figure 13.

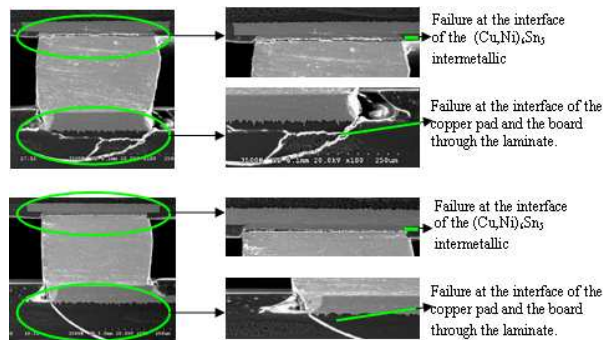


Figure 13: SAC 305 typical solder failures for drop test

On the package side the crack seems to have propagated through the weak interface of the $(\text{Cu,Ni})_6\text{Sn}_5$ intermetallic. The interface between the Ni_3Sn_4 and $(\text{Cu,Ni})_6\text{Sn}_5$ is proven to be a weak interface^[11]. This might be a possible reason for the stress riser and crack initiation during the drop test near the package. On the board side the crack seems to have originated at the interface of the copper pad and the laminate and seems to have propagated through the laminate structure inside the board. Identical failures were seen in other SAC305 packages.

SAC105 solder failure-

SAC 105 had failures through the laminate beneath the pad location on the board side as shown in figure 14.

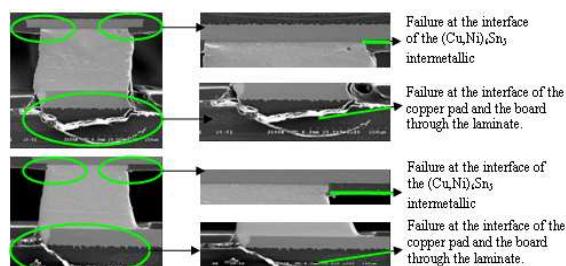


Figure 14: SAC105 typical solder failures for drop test

On the package side the crack seems to have propagated from either direction at the interface of $(\text{Cu,Ni})_6\text{Sn}_5$ intermetallic. But this crack on the package side seems to far less critical as compared to SAC305 package. On the board side the crack seems to have originated at the interface of the copper pad and the laminate and seems to have propagated through the laminate structure inside the board. Identical failures were seen for the other SAC105 packages.

Intermetallic thickness

Temperature cycling test-

For SAC305 intermetallic layer Ni_3Sn_4 and $(\text{Cu,Ni})_6\text{Sn}_5$ formed at the package end after the reflow was about 2.36 microns [avg] and that for SAC 105 was about 2.38 microns [avg] as shown in figure 15 and 16.

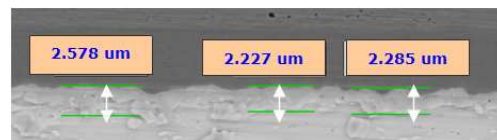


Figure 15: Temperature cycling- $(\text{Cu,Ni})_6\text{Sn}_5$ Intermetallic at the package side for the SAC 305 alloy.



Figure 16: Temperature cycling- $(\text{Cu,Ni})_6\text{Sn}_5$ Intermetallic at the package side for the SAC 105 alloy.

The reason for poor performance for the SAC105 in temperature cycling can be attributed to its stiffness as compared to SAC305. The failure modes were common for both the solders SAC305 and SAC105 [right through the interface of Cu_6Sn_5 and the bulk solder]. The failure might be due to a weaker copper intermetallic interface with bulk solder acting like a stress riser and a site for crack initiation during the temperature cycling.

Drop test-

For SAC305 intermetallic layer Ni_3Sn_4 and $(\text{Cu,Ni})_6\text{Sn}_5$ formed at the package end after the reflow was about 3.652 microns [avg] and that for SAC 105 was about 2.24 microns [avg] as shown in figure 9 and 10.

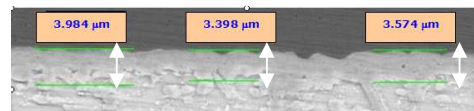


Figure 17: $(\text{Cu,Ni})_6\text{Sn}_5$ Intermetallic at the package side for the SAC 305 alloy.

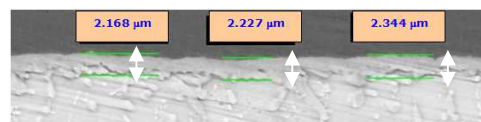


Figure 18: $(\text{Cu,Ni})_6\text{Sn}_5$ Intermetallic at the package side for the SAC 105 alloy.

The reason for poor performance for the SAC305 can be attributed to the formation of a thicker intermetallic layer of Ni_3Sn_4 and $(\text{Cu,Ni})_6\text{Sn}_5$ [package side] as compared to SAC105 package as shown in figure 9 and figure 10. The failure might due to the greater mismatch between the Ni_3Sn_4 and an overlying $(\text{Cu,Ni})_6\text{Sn}_5$ layer which might lead to a weaker interface and there by acting like a stress riser and a site for crack initiation eventually during the drop test.

Weibull plot

Temperature cycling test-

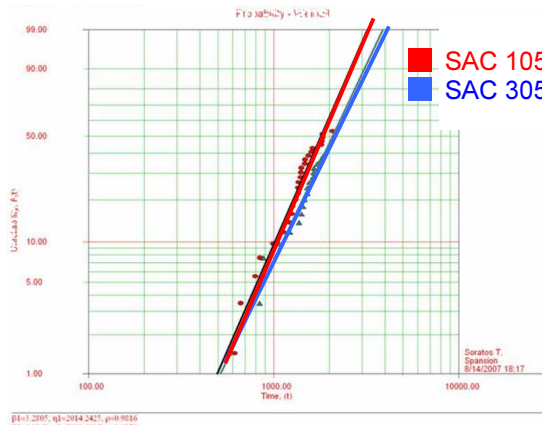


Figure 19: Temperature cycling weibull plot comparison of SAC 105 v/s SAC305

	1 st failure (no. of cycles)	63.5% failure (no. of cycles)
SAC 305	610	2500
SAC 105	580	2000

Table 1: Temperature cycling- No of cycles to failure

Weibull graph was plotted to find the mean time to failure [t_{50}] for both SAC105 and SAC305. SAC305 performed better than SAC105. SAC105 had the first failure at 580 cycles as compared to 610 cycles for SAC305. Similarly SAC305 [2500 cycles] had 20% better performance for the mean time to failure [t_{50}] as compared to SAC305 [2000 cycles] as shown in figure 19.

Reason being SAC305 is much stiffer as compared to SAC105. Lower modulus solder [SAC105] has lower stiffness and thus more susceptible to early failures due to cyclic loading and continued shear stress.

Drop test-

Weibull graph was plotted to find the mean time to failure [t_{50}] for both SAC105 and SAC305. It was very clear from the data that SAC 105 had a much better performance in the drop test as compared to SAC305.

SAC105 had the first failure at 38 cycles as compared to 10 cycles for SAC305. Similarly SAC105 [110 cycles] had 45% better performance for the mean time to failure [t_{50}] as compared to SAC305 [60 cycles] as shown in figure 19.



Figure 19: Drop test Weibull plot comparison of SAC 105 v/s SAC305

	1 st failure (no. of cycles)	63.5% failure (no. of cycles)
SAC 305	10	60
SAC 105	38	110

Table 2: Drop test- No. of cycles to failure

Reason for poor performance of SAC305 Pb-free solder is its stiffness as compared to SAC105 i.e. SAC 305 has higher modulus of elasticity than SAC105. Lower modulus solder has lower stiffness and thus greater capability to absorb large amounts of shock. This allows the SAC105 Pb-free solder to accumulate lower strain energy per drop cycle as compared to SAC305 and thus resulting in an enhanced life. Also lower silver concentration in SAC105 solder help in producing less brittle intermetallics [Ag_3Sn] and thereby reducing stress risers in the bulk solder.

SIMULATION METHOD

Model Approach

Temperature cycling test-

The solid model was identical to the experimental test board with a 0.8 mm ball pitch. Similar dimensions were used to simulate the model. In order to save computation time, a quarter symmetry FEA model-ANSYS model for the package was used for the simulation as shown in Figures 20. Same model with different material properties for the solder were used for comparing SAC105 with SAC305 solder.

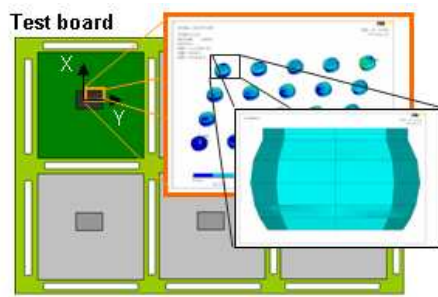


Figure 20: Quarter symmetry model for the temperature cycling

Drop Test-

The solid model was based on the JEDEC Standard JESD22-B11 drop test board with a package as explained earlier [(11 x 8 x 1.2) mm with 88 ball foot prints and 0.8mm ball pitch]. In order to save computation time, a quarter symmetry FEA (ANSYS) model was used for the simulation as shown in Figures 12. During the drop as the test boards were hinged at the 4 corners the center experiences the maximum deflection. As the center package of the test board was subjected to maximum deflection/stress, only the quarter symmetry of this package was modeled for the simulation [12, 13, 14]. Same model with different material properties for the Pb-free solder system were used for the comparison of SAC105 and SAC305 solder.

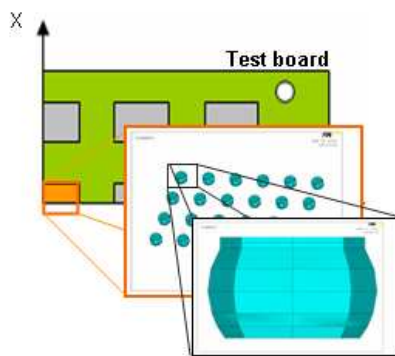


Figure 21: Quarter symmetry model for the drop test

Loading Conditions

Temperature cycling test-

Similar loading condition as shown as in figure 9 was used for simulation. Anand's model [15] was used as a constitutive equation to solve this model. Three cycles were simulated to corroborate the simulation results or trend with the experimental data. Data points at time chosen to evaluate the two SAC solder during the cycle is as shown in figure 22.

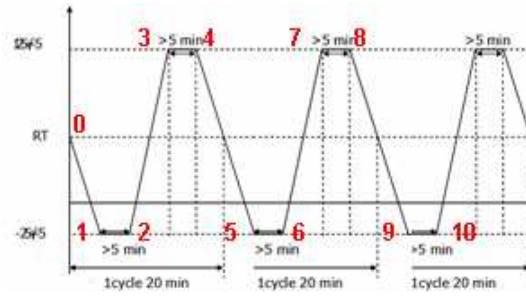


Figure 22: Loading condition for the temperature cycling

Drop test-

The first half-sine G-curve with a peak acceleration of 1500G and duration of 0.5ms was used as the input loading for the drop test simulation to mimic the actual test conditions as shown in figure 23. As it is very difficult to capture the strain energy accumulated in solder ball per cycle for the drop test elastic work was assumed for the simulation. The displacement at the center of the board during the drop test is shown in figure 24.

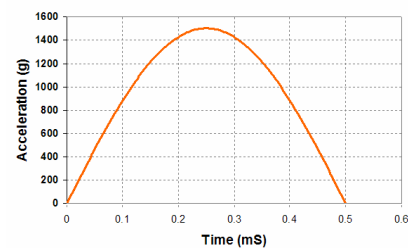


Figure 23: Loading condition for the drop test

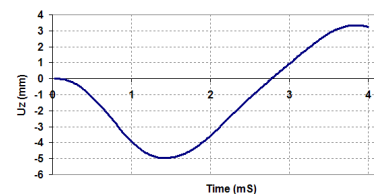


Figure 24: Displacement of the center of the board

Simulation Results:

Temperature cycling-

In order to compare the reliability of SAC105 to SAC305 for temperature cycling, a parameter, $K = W/E$, was defined. W is the plastic work density and E is the Young's modulus of the material. Figure 25 shows the growth in W/E as a function of the time (or number of cycles) for both SAC305 and SAC105. As SAC305 is stiffer than SAC105 the parameter K is lower for SAC305 as compared to SAC 105.

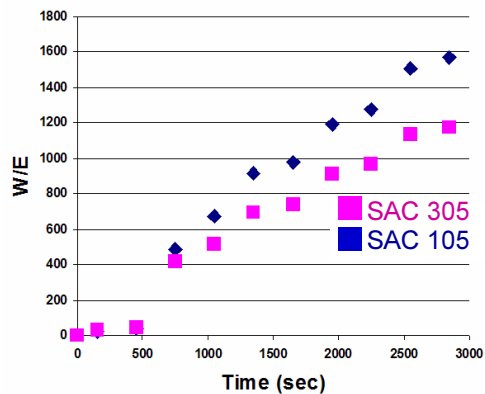


Figure 25: Plastic work density/Modulus of Elasticity v/s Time (sec) for temperature cycling

This illustrates that the SAC105 is likely accumulate more K per cycle and hence is likely to fail sooner than SAC305 during temperature cycling. This is in agreement with the experimental data. The corner solder balls of the package were subjected to maximum stress during the temperature cycling as in figure 26. The model also mimics the solder joint crack initiation site at the PCB and the bulk solder interface.

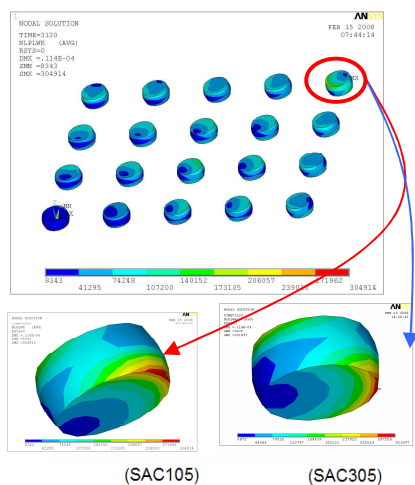


Figure 26: Nodal contour plot for corner solder ball for temperature cycling [SAC305 v/s SAC105]

Drop test-

The corner solder balls of the package were subjected to maximum stress during the drop test for both SAC305 and SAC105 solder balls as shown in figure 15. Different maximum stresses were noticed for the corner solder balls in a package at time 0.1425E-2 second for both SAC105 and SAC305 Pb-free solder. SAC105 induced 15% less stress as compared to SAC305. This may be attributed to the stiffness of the joints. Maximum stress was seen at the interface of the

solder ball and the package as shown in figure 16. The current model replicates the behavior of a solder joint crack [stress riser] at the interface of the package and the solder interconnect.

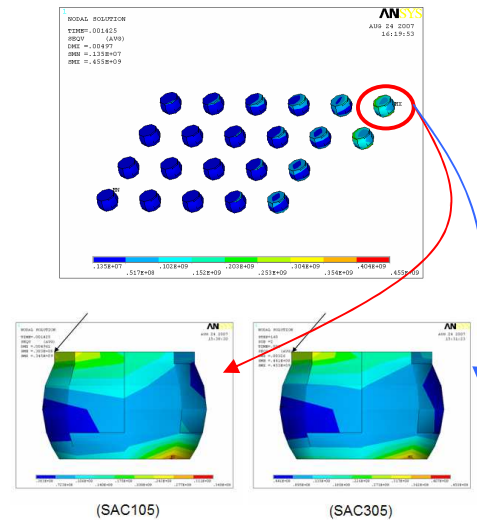


Figure 27: Nodal contour plot for corner solder ball for drop test [SAC305 v/s SAC105]

Conclusion:

Temperature cycling-

1. Experimentally it was seen that SAC305 has 20% better performance than SAC105 for temperature cycling test [mean time to failure].
2. Cu_6Sn_5 intermetallic and bulk solder interface [board-side] seems to be susceptible to crack initiation. Interface of Cu_6Sn_5 and bulk solder [board-side] seem to have weaker interface than Ni_3Sn_4 and $(\text{Cu},\text{Ni})_6\text{Sn}_5$ intermetallic layer interface [component-side].
3. From the simulation it was seen that higher accumulation of plastic work density/young's modulus per cycle for SAC105 might be the reason it to fail earlier as compared to SAC305.
4. SAC305 has better performance than SAC105 for the temperature cycling and might be suitable for high temperature applications.

Drop test-

1. Experimentally it was seen that SAC105 has 45% better performance than SAC305 for drop test [mean time to failure].
2. Thicker interface of Ni_3Sn_4 and $(\text{Cu},\text{Ni})_6\text{Sn}_5$ intermetallic layer is susceptible to crack initiation. Interface of Ni_3Sn_4 and $(\text{Cu},\text{Ni})_6\text{Sn}_5$ [component side] intermetallic layer seems to have a weaker interface as compared to Cu_6Sn_5 , Cu_3Sn and bulk solder interface [board-side].
3. From the simulation it was seen that corner solder balls for SAC 305 experienced 15% more stress at the

interface of the package and solder interconnect as compared to SAC 105.

4. SAC105 has better performance than SAC305 for the drop test results and might be a suitable candidate for mobile and hand held devices.

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