Effect of Temperature on Transition in Failure Modes for High Speed Impact Test of Solder Joint and Comparison with Board Level Drop Test

Pradosh Guruprasad and James Pitarresi, Binghamton University, USA
Bob Sykes, XYZTEC bv, The Netherlands
Email: pgurupr1@binghamton.edu

Abstract

An effort has been made in this study to evaluate the characteristics of solder joint failure by using a new high speed impact tester. Here, a more thorough understanding of the solder joint behavior is examined by characterizing the behavior with respect to varying temperature and impact profiles. This is done in an attempt to address solder joint failures in actual product that may be under operating temperatures and environments.

Comparison between the high speed pendulum impact test and drop test was primarily made by evaluating the failure modes from these two tests. Energy absorbed by the solder in a single impact has been used to predict the reliability in a board level test. Also the effect of temperature on the reliability of solder interconnects and on the strain rate induced in the PCB during a drop test has been studied.

Introduction

Solder interconnects form an integral part in most of the electronic packages. Soldering technology, in specific lead free solder, is still evolving keeping in pace with the high density arrays of interconnects resulting from the miniaturization of consumer electronic devices. Handheld electronic devices are constantly subjected to high stresses and strains which are induced due to thermal or mechanical shocks resulting from physical handling or their usage. Some of the critical issues surrounding lead free solders is their reliability due to continuous exposure to shocks, vibration and/or high temperature during their service life. Being that solder is a strain rate dependent material, and the varying stresses from end usage of electronics, it is difficult to describe the general reliability of a device. Therefore, different tests like board level drop and vibration, thermal cycling, joint level shear or ball pull are employed to help us better understand the behavior of these solders in any environment, and build reliability models by evaluating the solder performance under different loading conditions.

Transition to lead free solders in electronic packaging has been challenging owing to the fact that lead free solders are more prone brittle failures under high strain rate dynamic loading when compared to lead containing solder. Therefore a good understanding of material behavior under different conditions can help us in building more reliable electronic products.

High speed impact test is steadily gaining ground as a component level quality control test. Employing joint level tests in the reliability assessment of interconnects can be more effective by reducing the time and cost otherwise associated with board level testing. This has spurred a renewed interest in industry as well as academia to research the viability of implementing a cheaper alternative, or complement, to the current board level tests and testing standards. Previous studies have also shown a correlation between various high speed joint level tests and board level shock tests [1-6]. Also the effect of test temperature on mechanical reliability of electronic packages has been documented [7-8].

The goal of this work is to study the solder behavior under simultaneous thermal and mechanical loadings. SAC alloys are widely used in electronic packaging industry as they have been found to be the best alternative to lead solders. Two SAC alloys, SAC 105 and SAC 405 have been used in this study since they have been well characterized and their strain rate dependent behavior is well understood [9]. Hence this provides a good platform to make a comparative study using a novel test method. A new high speed pendulum impact tester has been used to compare the two alloys under impact loadings to board level drop test at both room and elevated temperatures. Since there are no metrics to make a direct correlation between joint level and board level tests, failure modes have been used to make a comparison.

Experiments and procedures

Test Vehicles

The component selected for this test is Amkor CABGA 100 packages utilizing SAC405 and SAC 105 solder bumps with an ENIG pad finish. 450µm solder ball diameter were used in a full 0.8mm pitch, 10 x 10 array. The components were attached to the test board in an air atmosphere with a peak temperature of 245 °C. Components were assembled at symmetric locations on the test board, corresponding to locations U2, U4, U12 and U14, as shown in Figure 1.

The test board was designed per JEDEC standards [10], but modified to a 2-layer design, rather than 1+6+1 buildup. The PCB dimensions are 132 x 77 mm, 1mm thick. The laminate material is a high Tg FR4 resin with 350µm solder mask opening and a CuOSP pad finish. Each of the locations was individually daisy-chained for use of in-situ event detection.

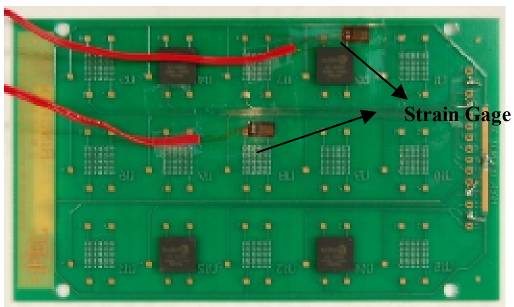

Figure.1 Test Board

High Speed Impact Test

High speed pendulum impact tests were carried out on XYZTEC Condor Impact Measurement Unit. This unit was selected because it has the capability to perform high speed impact tests at elevated temperatures. High speed joint level test is being adopted as a reliability test for electronic packages because testing at traditional speeds of around 1mm/s rarely provides any information on the joints resilience to mechanical shock which is the most common cause of failure as seen in manufacture and end use. The most common of these failures are failures in the intermetallic region formed due to the bonding between the bulk solder and pad. The second failure mode which is commonly seen is the pad cratering. So it is important to distinguish between failure modes seen in manufacture and end use and those seen in an impact test.

SAC405 and SAC 105 solder bumps on Amkor CABGA 100 packages were tested on the pendulum impact tester. A total of forty measurements were recorded for each condition. A standard shear height of 45µm from the package surface was adopted for all the solder joints tested. The pendulum impact setup is shown in Figure 2.

Impact speeds were selected in such a way to accommodate a sufficient range producing a transition in failure mode from ductile at lower speeds to brittle failures at higher speeds. Test speeds ranged from 0.5m/s to 2m/s. Impact tests were carried out both at room and elevated temperatures (50 and 100°C). Strip heaters were attached underneath the components and the test temperature was controlled by adjusting input voltage to the strip heaters. A thermocouple was placed on the component to monitor any change in the surface temperature throughout the experiment. A 5 minute soak in time was allowed before the start of each test allowing the temperature to stabilize.

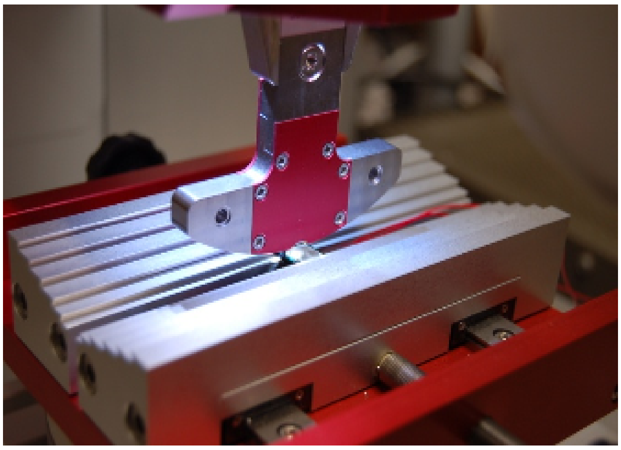

Figure.2 High speed pendulum tester setup

The transducers in the equipment captured impact force and energy data as a function time and displacement The impact energy and failure modes were plotted as a function of temperature and impact speed.

Moiré Interferometry

Moiré interferometry is a whole-field optical interference technique with high resolution and high sensitivity for measuring the in-plane displacement and strain fields [11]. Moiré interferometry has been in use for a long time and is well characterized as a tool to study the in-plane displacements in an electronic package due to thermal loading. Here this technique was used to study displacement behavior of the components to help understand the effects of CTE mismatch induced stresses and mechanical stresses induced on the solder joints at elevated temperatures.

Figure.3 PEMI Moiré interferometry setup

Figure 3 shows the PEMI II system was used for the moiré experiment. This system allows us to view the displacement pattern in a sample in two orthogonal directions separately. Components were cut from the assembled boards and were cross sectioned across the diagonal. The procedure involved applying a very thin layer of epoxy to transfer a 1200 lines/mm grating from an ULE mold on to the cross-section of the specimen at a temperature of 100°C. The deformation at this temperature was used as a zero deformation state. The moiré experiment was performed at room temperature (22°C) and 50°C hence providing a thermal loading of 28°C and 78°C respectively.

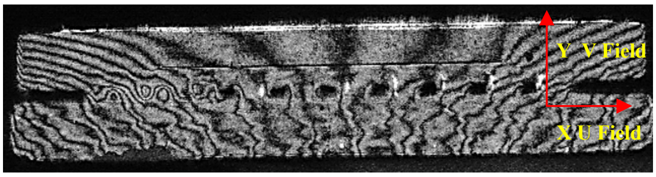

Figure.4 SAC 105 U-field moiré fringe pattern

A fringe pattern obtained from the moiré experiment gives the global deformation information in the x- and the y-planes (or the U and V field) of the sample. The grating frequency of 1200 lines/mm was used to obtain a sensitivity of 417nm per fringe order of in- plane displacement. A U field moiré fringe pattern of the SAC 105 package after a loading of 78°C is shown in Figure 4. Displacement data in the U or V field in this image can be obtained by counting the fringes (N) in the x or y axis respectively.

The following equations can be used to measure the strains in U Field and V Field [11]:

(1)

(2)

(3)

Where - Normal Strain in U Field
- Normal Strain in V Field
- Shear Strain

Due to the non availability of test samples only two packages for each condition was tested. Since strain is maximum at the corner joints stain was computed for two corner joints on each package.

Board Level Drop Test

Board level drop tests were performed at 1500g, 0.5ms according to the test profile stated in JESD22-B111 standard. The drop testing for this work was performed on a Lansmont Model 23® shock test system. Test boards were mounted to the drop table as per the JEDEC standard using standoffs at each corner to allow for board flexure. In-Situ electrical monitoring was attached to the test vehicle via an Anatech Event Detector with a resistance threshold of 900 ohms. The failure criteria followed the definition of "the first event of intermittent discontinuity followed by 3 additional such events during 5 subsequent drops [10]". The setup for the drop test is shown in Figure 5.

The same components used in the impact tests were used for drop test on a JEDEC standard board with a Cu-OSP finish. An insulated heating chamber, controlled by forced hot air using a heat gun was designed and mounted on the drop table enabling a test at higher temperatures. A total of four boards were tested for each condition at room temperature, 50°C and 100°C. The half sine input acceleration pulse was measured at the corner of the drop table using an accelerometer and the temperature was measured by placing a thermocouple at the center of the board.

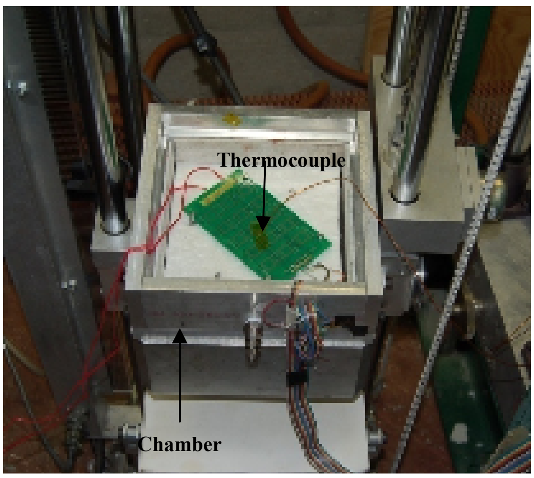

Figure.5 Drop test setup

For the elevated temperature drop test a sufficient soak time of 5 minutes was allowed before the start of each test to allow the temperature to stabilize and the board was maintained at the same temperature for every subsequent drop. Because the change in temperature affects the dynamics of the board, strain measurements were made at room temperature, 50°C and 100°C to characterize the board flexure. Two strain gages were glued on the board at two critical locations as shown in Figure 1. One was glued at the centre of the board where maximum flexure induced and a second one near the outer corner joint of the component where most of the failures are known to occur [12]. A Vishay strain measurement system was used to acquire the strain measurements.

Results and Discussion

High speed impact test

It has been observed for joint level tests, at slow test speeds the predominant failure mode is ductile or bulk solder shear [13]. This failure mode is not representative of the failure modes as seen in manufacture and end use and therefore testing at these speeds has little value when investigating resistance to mechanical shock. It is known that the energy of a ductile failure is more than that of a brittle fracture [14]. The incidence of brittle fracture also corresponds to a decrease in mean energy.

The brittle failures included some portion of bulk solder failure on the opposite side of the pad from the loading direction. This is attributed to the crack propagating through the intermetallic region on the onset of impact and eventually causing the solder joint to hinge on the opposite side. The moment applied at this hinge leads to a small amount of solder to ultimately fail. This effect is shown in the schematic in Figure 6. Therefore the percentage of solder to IMC on each pad for all test conditions has been used as the metric for comparison.

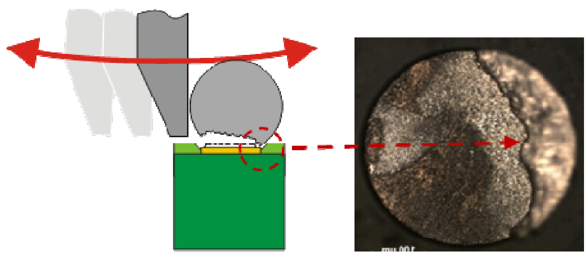

Figure.6 Impact profile High Speed Pendulum Impact Test

The mean impact energy was plotted as function of impact speed as well as test temperature, as shown in Figure 7. At room temperature the impact energy for SAC 105 is higher than SAC 405. This is representative of the low elastic modulus and high compliance of SAC 105 which results in a lower stress induced at the joint interface for the same strain level [9].

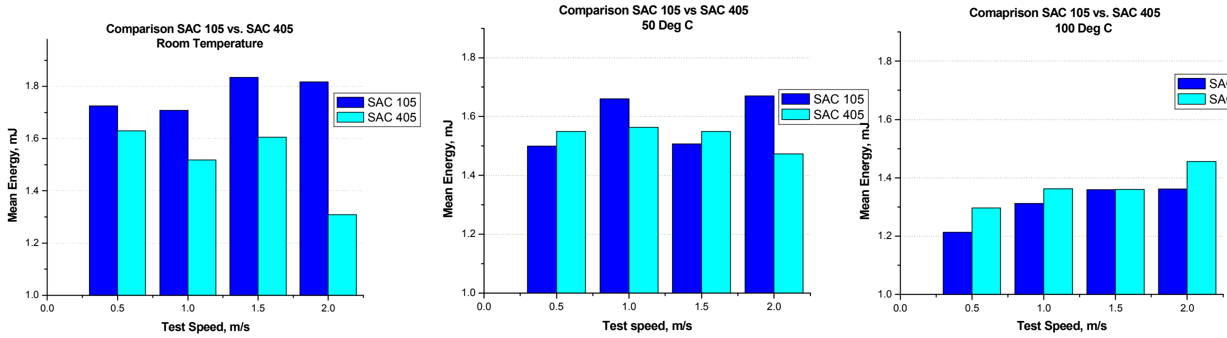

Figure.7 Comparison of mean impact energy for SAC105 and SAC405 at Room Temperature, 50°C and 100°C respectively

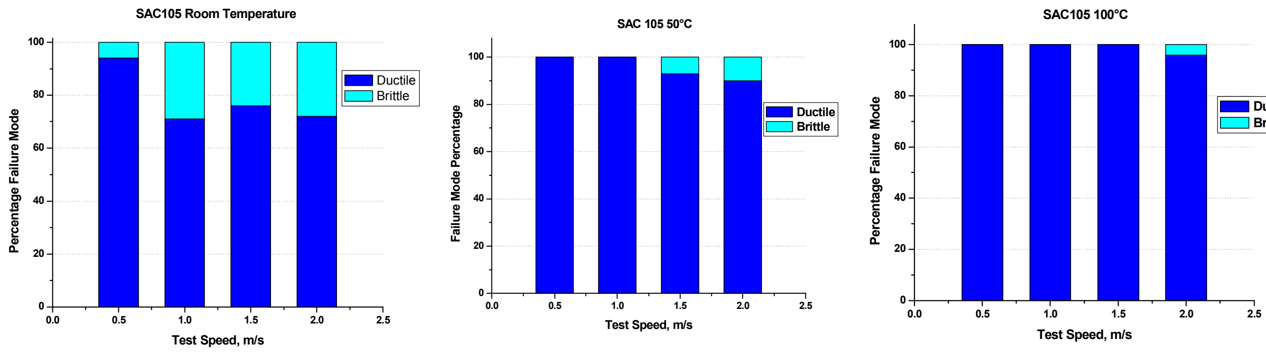

Figure.8 Comparison of Percentage of Failure modes SAC105 at Room Temperature, 50°C and 100°C respectively

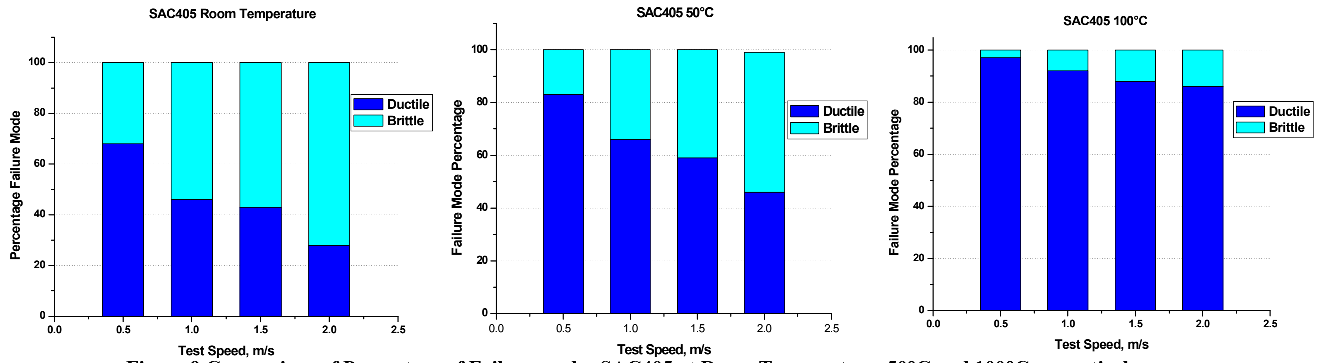

Figure.9 Comparison of Percentage of Failure modes SAC405 at Room Temperature, 50°C and 100°C respectively

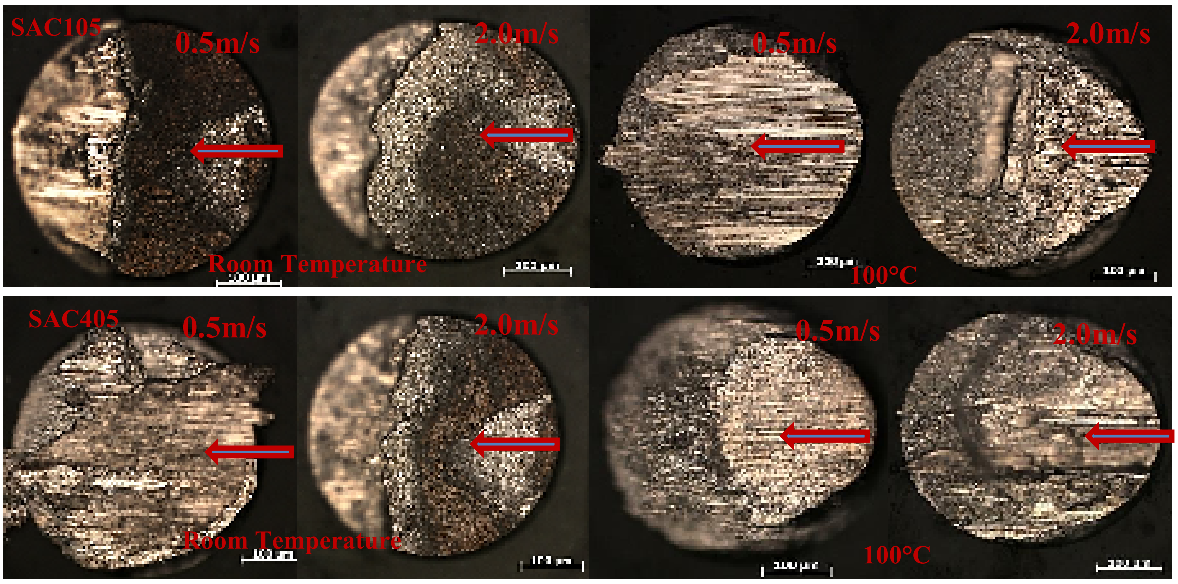

Figure.10 Failure modes at Room Temperature and 100°C SAC105 (top) and SAC405 (bottom)

Comparing the failure modes at room temperature condition for the two test vehicles confirms the fact that the low yield strength of the SAC 105 solder leads to high plastic energy dissipation in the solder and hence we see a higher percentage of failures in the bulk solder. At elevated temperatures the more solder deformation occurs and failure mostly seen through the bulk solder for both the alloys. With an increase in test temperature the transition in failure mode for SAC 405 is more pronounced having ductile failure as the most dominant failure mode. This behaviour can be attributed to the decrease in yield strength and also the stiffness of materials with an increase in temperature. Hence the mean impact energies decrease and are approximately equal for both the alloys at elevated temperatures. The fracture surface for both the alloys is shown in Figure 10.

A higher percentage of solder is seen on the SAC 105 fracture surface for all the test conditions. The failure in the IMC shows two distinct surfaces. One is across between the solder and the IMC and the other is the separation of IMC at the Ni surface.

Moire Interferometry

On thermal loading stresses are induced in the solder joint as a result of CTE mismatch between the component and the printed circuit board. The warpage of the component and the shear strain of the corner solder joint of both packages were obtained from moire interferometry. Measurements were made at 50°C and 100°C corresponding to a thermal loading of 28°C and 78°C relative to the room temperature. Displacement contour of the packages was computed by the phase shifting method. Figure 11 shows the fringe pattern on the SAC105 package upon a thermal load of 78°C.

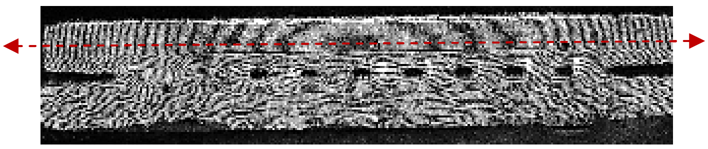

Figure.11 V Field Moiré Fringe pattern at 100C for SAC 105

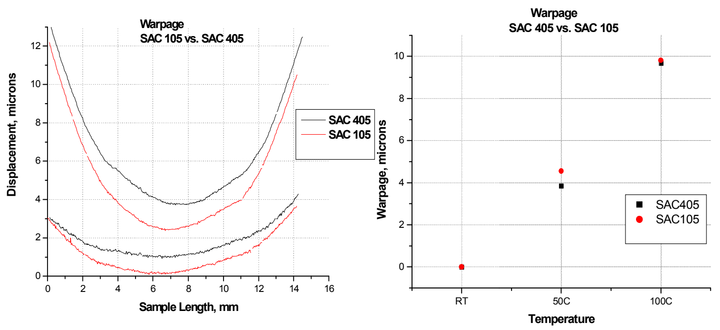

Figure 12 Displacement behavior of component relative to the PCB for SAC105 and SAC405

The relative vertical displacement across the whole length of the sample shows the total warpage of the sample, Figure 12. This was measured across the line as shown in Figure 11 to observe the displacement of the component relative to the board on thermal loading. Warpage for both the packages was found to be similar for both the loading conditions. A maximum displacement of 4 microns at 50°C and 10 microns at 100°C was observed at the center of the package.

The line plot in Figure 14 represents the relative horizontal displacement across the vertical height of the joint as shown in Figure 13. The trend of these lines suggests that the total displacement behavior of the component relative to the PCB as function of temperature is very minimal and is not dependent on the alloys for this test vehicle.

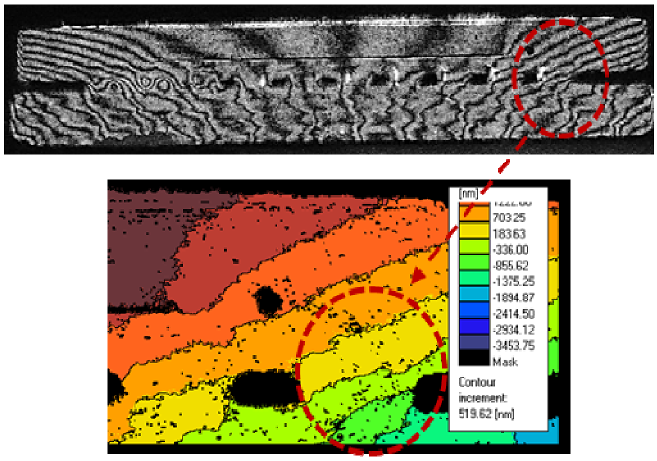

Figure.13 U Field Moire Fringe Patter at 100C for SAC 105

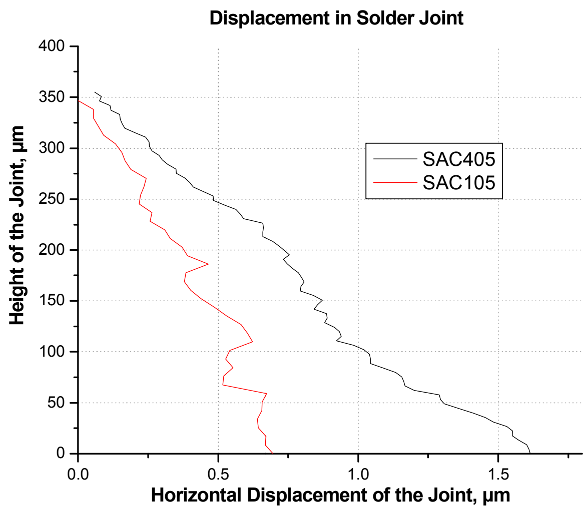

Figure.14 Horizontal displacement across the vertical height of the joint

Board Level drop Test

Temperature can affect the dynamics of the board on shock loads. For this test vehicle the strain response on the board as shown in Figure 15 suggests similar maximum strain at the center and the corner location. However, multiple strain peaks were seen during the first oscillation at the corner, whereas the center location did not show this effect. These high strain rate events could lead to different reliability behavior at the center vs. the corner of the board near the supports. This was consistent for all the test temperatures indicating a minimum influence on failure lifetime.

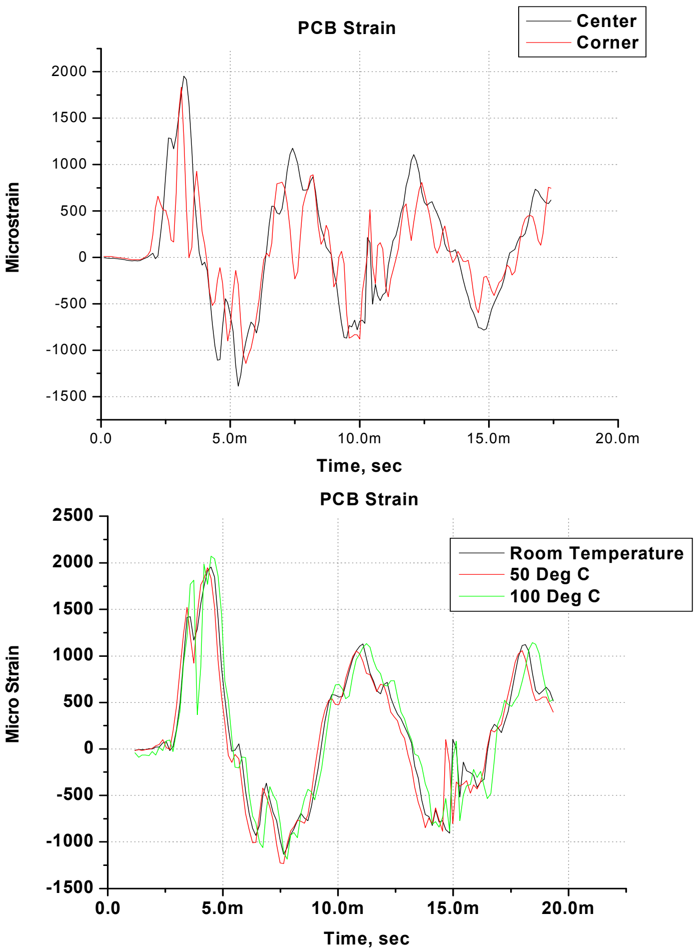

Figure.15 PCB strain Measurement (a)Comparison between center and corner location (b) comparison at different test temperatures

Figure 16 shows the Weibull plots for drops of failure for SAC 105 and SAC 405. The test was conducted in a controlled environment but the range of data obtained is typical of drop test with multiple failure modes. But from this data a certain trend emerges as the test temperature is varied. At room temperature condition the drops to failure for SAC105 is almost twice that of SAC405 but with the increase in test temperature the difference in characteristic life between them decreases, Figure 17. The trend is similar to that in the high speed impact energy results which also show a convergence between the alloys as the temperature was increased.

As discussed earlier from the moiré experiment, the displacement of solder joint as a function of temperature is not dependent on the alloy for this test vehicle. Also the difference strain on the PCB at the onset first impact in the drop test did not change much with the change in test temperature. Therefore the primary reason for this increase in lifetime for this test vehicle can be only explained by the solder joints absorbing more impact energy as a result of decreasing stiffness with increasing temperature. Again this increase in lifetime is more pronounced for SAC405.

Failure analysis was done to study the primary failure mechanism on these boards. Dye and pry technique was used to locate the failure sites. Once the failure sites were known

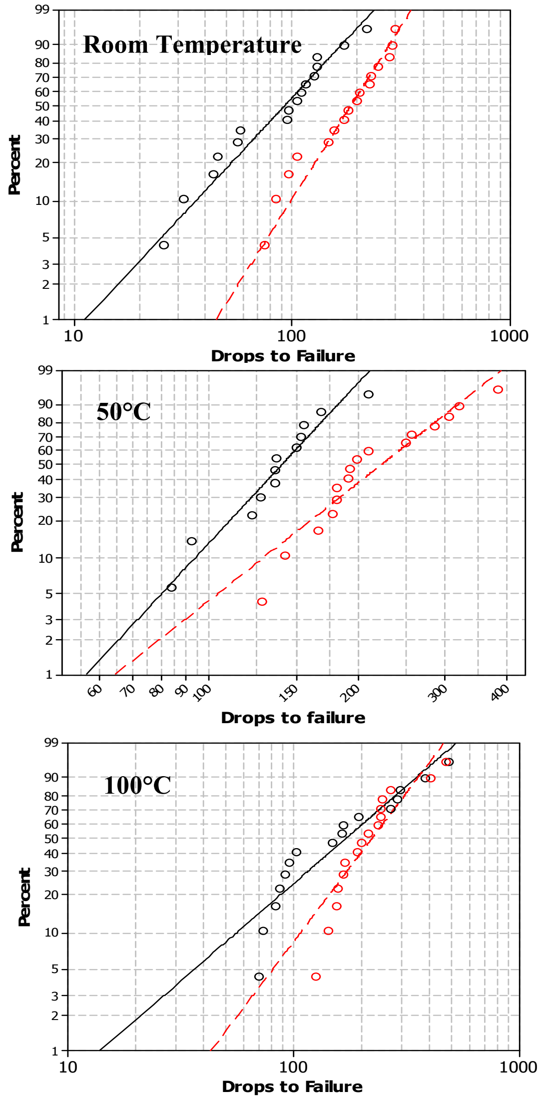

Figure.16 Weibull plots for drop test

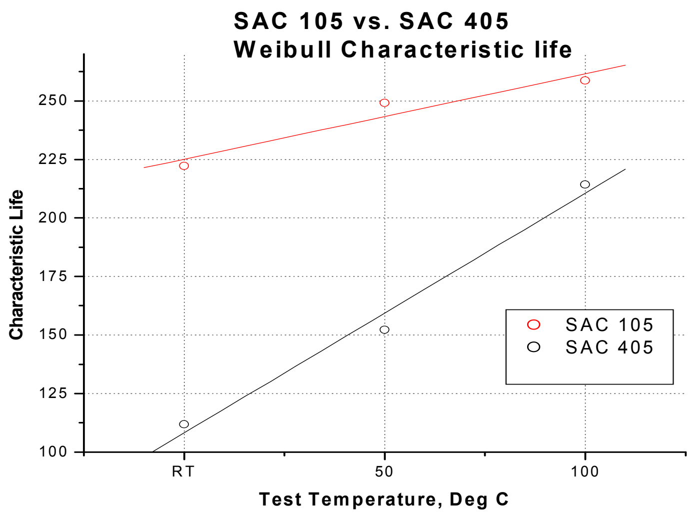

Figure.17 Comparison of characteristic life in drop test for SAC105 and SAC 405 at Room Temperature, 50°C and 100°C.

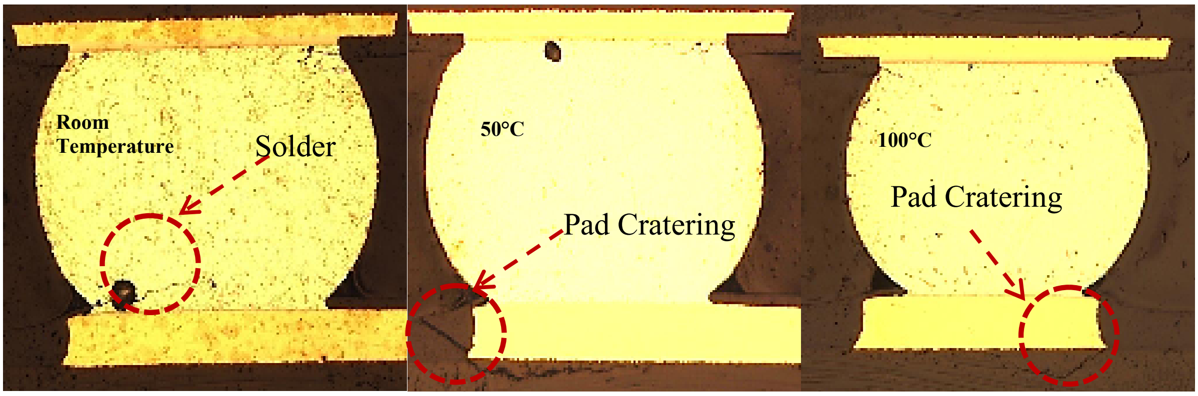

Figure.18 Drop test failure locations for SAC 105

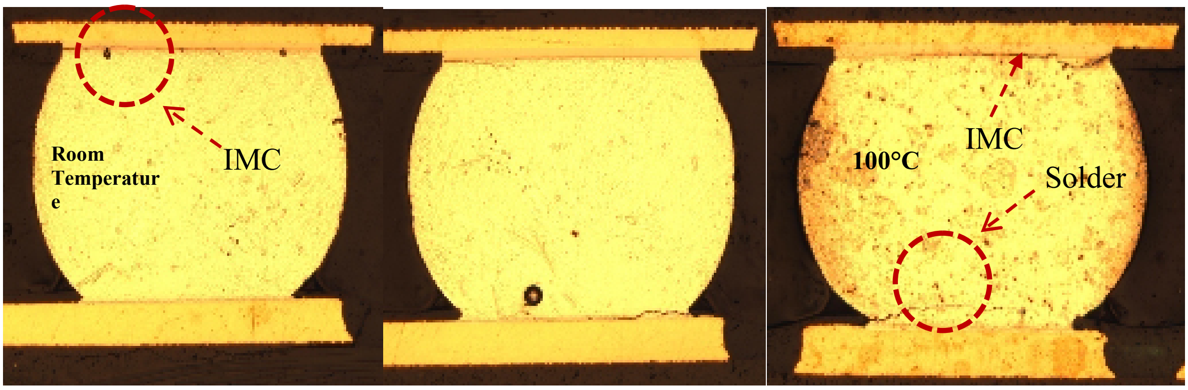

Figure.19 Drop test failure locations for SAC 405

the boards were cross sectioned to analyze the cracks in these joints as seen in Figure 18 and 19.

The primary failure mode on all the SAC105 systems was seen in the bulk solder. Pad cratering was also seen on most of these boards without a discontinuity in the traces, hence failures due to pad cratering can be ruled out. The primary failure mode on the SAC405 systems at room temperature was cracking in the IMC at the package side. But at elevated temperatures mixed mode failures were observed, with predominant cracking in bulk solder at 100°C.

Observing a similar trend in the high speed impact test where at room temperature SAC105 showed a higher percentage in ductile failures than SAC405 implying a tendency to absorb more impact energy for the same strain level. But with increasing temperature ductile failures in the bulk solder was more prominent for SAC405 suggesting a transition from brittle to ductile failure mode.

Conclusion

Solder joint reliability in a mechanical test at elevated temperature is a function of more than just the solder property changes. For the high speed impact test SAC 105 showed more ductile failures for all test conditions. SAC405 transitions from brittle to ductile failure with increasing temperature. As a result the difference between alloys observed during high speed impact test and board level drop test decreased with increasing temperature.

For board level drop test the board strain did not change much with the change in temperature. Drop reliability went up with increasing temperature for both alloys. SAC 105 performed better than SAC 405 at room temperature.

But again the difference in their performance greatly decreased at the elevated temperatures. This might not always be the case as literature [7-8] shows conflicting data suggesting a complex interaction between materials and component types. More work is needed to understand the effect simultaneous interaction of thermal and mechanical loading on the reliability of the solder joint.

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