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Four-point bending cycling: The alternative for thermal cycling solder fatigue testing of electronic components

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ABSTRACT

This paper deals with an alternative testing approach for quantifying the life time of board level solder joint reliability of components. This approach consists of applying a relative shear displacement between component and Printed Circuit Board (PCB) through cyclic board bending. During the cycling, the temperature is kept constant, preferably at elevated temperature in order to accelerate the creep deformation of the solder joint. This is done in a four-point bending setup which allows to apply an equal loading on all components lying between the inner bars. The scope of the paper is, firstly, to evaluate if the four point bending testing generates the same fatigue fracture as in thermal cycling; secondly, that the measured life times can be also predicted through finite element simulations; and thirdly if the technique can finally accelerate the cycling frequency to reduce the testing time.

1. Introduction to alternative testing for thermal cycling

Thermal cycling testing is a widely spread method for analyzing the board level thermal cycling performance of printed board assemblies. Thermal cycling testing is part of many qualification standards.

However, thermal cycling testing for analyzing the second level solder joint reliability is a time consuming experiment. Acceleration of the test in order to obtain fast failures is only possible through an increase of the temperature swing. This is done either through increasing the maximum temperature closer to the melt, or decreasing the minimum temperature close to or below the homologous temperature where creep seizes to occur and making the solder more brittle. Both too high or too low temperature can lead to new failure modes which may not be relevant for the operational conditions the system has to work.

In order to cope with these limitations, an alternative testing approach has been developed and evaluated in this work. The method is based on applying four-point bending to the PCB. The bending causes an absolute displacement at the top/bottom fiber of the PCB and as such applies a displacement mismatch with the component which is similar to what is seen during temperature cycling. The bending system is installed in a climatic chamber which allows to combine bending and thermal cycling. This new test method decouples the fatigue failure inducing cyclic mechanical load on the solder joint from the imposed temperature creating an additional degree of freedom the accelerate the test. Additionally, one can now fully explore and exploit the temperature dependence of the material properties especially the increased creep rate at high temperature. In first instance, we kept the temperature constant during the mechanical cycling.

JEDEC provides a standard for Board Level Cyclic Bend Test Method for Interconnect Reliability Characterization of Components for Handheld Electronic Products [1]. It is mentioned that the test procedure is presently more appropriate for relative component performance than for use as a pass/fail criterion. It is also not meant for life time estimations nor for assembly qualifications.

2. Analytical equations relating the applied bending parameters to the local strain on the solder joints

The target of the 4-point bending experiment is to apply mechanically a similar relative shear mismatch between the component and PCB as in thermal cycling. This is illustrated in Fig. 1.

In the thermal cycling experiment with a temperature swing of ΔT, the displacement mismatch between the PCB and component at each

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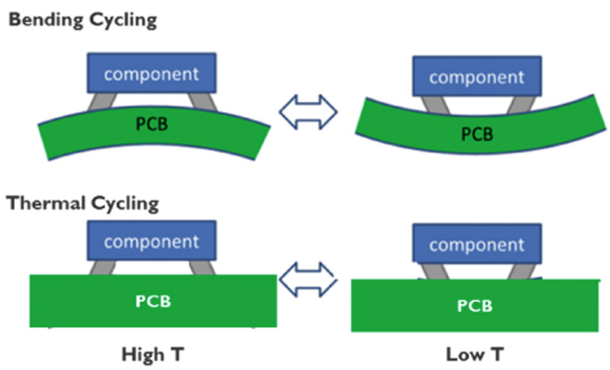

Fig. 1. Illustration of the similarity between thermal and bending cycling.

joint location is calculated in its most simplified form as follows:

$$\Delta l_{PCB-Comp} = DNP^{*}\left(CTE_{PCB} - CTE_{Comp}\right)^{*}\Delta T \tag{1}$$

with DNP the Distance to Neutral Point, typically the center of the component. The Coefficient of Thermal Expansion (CTE) of the PCB is a weighted average of the FR4 laminate and the copper layers, the CTE of the component is also a weighted average, however more difficult to calculate due to the asymmetry of the package build-up. The joints having the highest DNP are typically the corner joints.

The concept of the mechanical cycling test is shown in Fig. 2. The PCB with the soldered components is placed between 4 bars, of which the two inner bars can move up and down. The 4-point bending creates a bending moment acting on the area between the two inner bars which is constant. Important notice is that the two outer and two inner bars should be aligned to the same center line. Therefore, the bending radius and thus the shear loading of the components assembled in this area is uniform.

The parameter which is applied in the four point bending experiment is the displacement δ of the moving inner bars relative to the static outer bars (Fig. 3).

This deflection depends linearly on the applied force according to the following equation:

$$\delta = \frac{F}{E_{PCB}{}^{*}I_{PCB}}\left(\frac{L_1}{2}\cdot\left(\frac{L_2-L_1}{2}\right)^2 + \frac{1}{3}\left(\frac{L_2-L_1}{2}\right)^3\right) \tag{2}$$

with F is the force applied on each of the two inner bars (so total force applied by the motor is 2F), E_{PCB} is the elastic modulus of the PCB and I_{PCB} is the moment of inertia of the PCB.

The bending moment applied to the PCB in the area between the two inner bars is constant and equal to:

$$M = F\frac{L_2-L_1}{2} \tag{3}$$

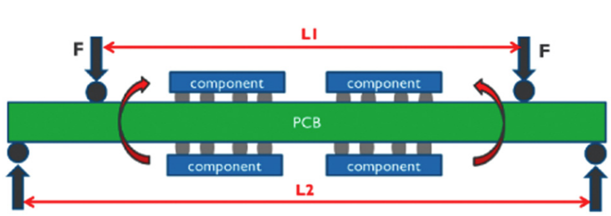

Fig. 2. Concept of the 4 point bending cycling testing of soldered components.

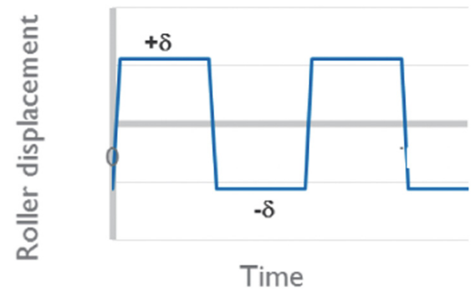

Fig. 3. Representation of the roller displacement during a bending cycling experiment.

This bending moment results in a curvature (in the inner area) equal to:

$$\frac{1}{\rho} = \frac{M}{E_{PCB}{}^{*}I_{PCB}} \tag{4}$$

Combining Eqs. (2), (3) and (4), the curvature can be written as function of the applied bar displacement δ as follows:

$$\frac{1}{\rho} = \frac{24}{\left(3^{*}L_2{}^2 - 4^{*}\left(\frac{L_2-L_1}{2}\right)^2\right)}\delta \tag{5}$$

The applied curvature results in a maximum strain ε_{PCB} at the PCB outer surfaces (top/bottom) equal to:

$$\epsilon_{PCB} = \frac{1}{\rho}\frac{h_{PCB}}{2} \tag{6}$$

with h_{PCB} is the PCB thickness.

Similar to Eq. (1), the strain can be translated into a relative displacement per cycle between component and PCB equal to:

$$\Delta l_{PCB-Comp} = DNP^{*}2^{*}\frac{1}{\rho}\frac{h_{PCB}}{2} \tag{7}$$

The factor 2 is added as in one cycle, the board is bent from −1/ρ to +1/ρ curvature which doubles the relative displacement. Combining Eqs. (5) and (7) results in this relationship between relative shear displacement and applied bar displacement:

$$\Delta l_{PCB-Comp} = DNP^{*}\frac{24h_{PCB}}{\left(3^{*}L_2{}^2 - 4^{*}\left(\frac{L_2-L_1}{2}\right)^2\right)}\delta \tag{8}$$

3. Description of the four point bending testing setup and test vehicle

The four-point bending system consists of four pairs of rollers as shown schematically in Fig. 4. The board under test is clamped between each pair of rollers which are in turn tightened together as shown in Fig. 4 and Fig. 5. An aluminum plate makes the connection of the inner

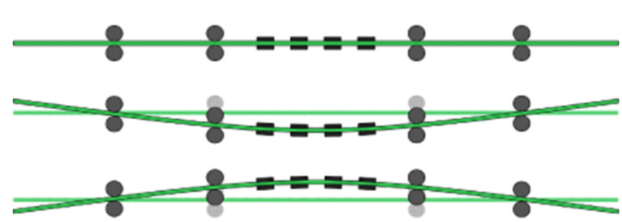

Fig. 4. Schematic drawing visualizing the concept of the four point bending cycling.

Fig. 5. Realization of the four point bending setup in the thermal chamber.

rollers to the linear actuator. The outer rollers are fastened to a thick aluminum plate which is clamped inside the climate chamber. By moving the actuator either up or down, the board is bended in the likewise direction.

The displacement of the board is measured on the inner rollers which are attached to the actuator by an aluminum plate.

The bending test board measures 450 mm by 280 mm and is 2.5 mm thick. The daisy chain Chip Scale Package (CSP) components are located in the spacing between the load anvils, which is about 210 mm wide. On each side of the board, 20 daisy chain components have been placed in an array of 4 columns and 5 rows. This number is limited by the number of channels of the measurement equipment, not by the space. It was chosen to have the same component soldered at both sides in order to have a symmetric build-up. This is important for the bending experiment in order to guarantee that the neutral fiber remains in the middle of the PCB. (See Fig. 6.)

4. Comparing 4 pt bending with thermal cycling testing for a Chip Scale Package assembly

The same component assembly has been tested under isothermal temperature cycling and 4-point bending cycling. The details of the test conditions are summarized in Table 1. Also the induced relative displacement for the outer joints is shown in this table. In the bending cycle, a shear strain is applied which amounts to about half of the thermal cycling strain. While thermal cycling induces almost a pure shear load, the bending cycling also results into a normal relative displacement of about 1.8 μm maximum, with the realistic assumption that the rigid CSP remains flat, and the PCB can freely bend.

The results of the cycling tests are shown in the Weibull distribution of Fig. 7. This graph shows the distribution of the number of cycles to failure of the CSP assemblies in the daisy chain. Despite the lower shear displacement in the 4 pt bending test, still these samples are failing much earlier than the samples in the thermal cycling test.

Cross-sections of failed samples for the two testing methods show a similar fatigue fracture in the solder joint, located close to the CSP (see

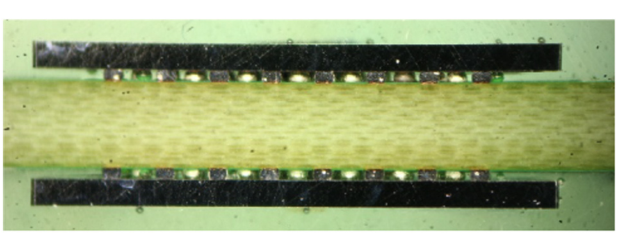

Fig. 6. Cross-section (over the diagonal) of the CSP's soldered at both sides of the 2.4 mm thick PCB.

Table 1
Conditions for thermal and bending cycling.

Test	Conditions	Relative Displacement ($\Delta l_{PCB\text{-}Comp}$)
Thermal cycling	0 to 100 °C cycling 20 min dwell time	$\Delta l_{shear} = 6.6$ μm $\Delta l_{normal} \sim 0$ μm
Bending cycling	$T = 100$ °C $\delta = 5.6$ mm (roller displacement) 20 min dwell time	$\Delta l_{shear} = 3.5$ μm $\Delta l_{normal} = 1.8$ μm

Fig. 8 and Fig. 9). So it can be concluded that two testing methods induce the same failure mode.

There are several factors which explain why the bending cycling shows much earlier failures than thermal cycling. **Firstly**, the bending test is performed at a constant temperature of 100 °C, allowing the material to have equal amounts of creep deformation at both extremes of the mechanical cycle which is not the case in the thermal cycling test (much lower creep at minimal temperature.

Secondly, the bending also causes additional normal stress in the solder joint corners as the PCB is bending. This is due to the stiff CSP which hardly bend. In the thermal cycling test, both PCB and CSP remain flat due to the back-to-back assembly of the CSPs.

In order to quantify both effects, a thermo-mechanical simulation using finite element modelling was performed for these testing

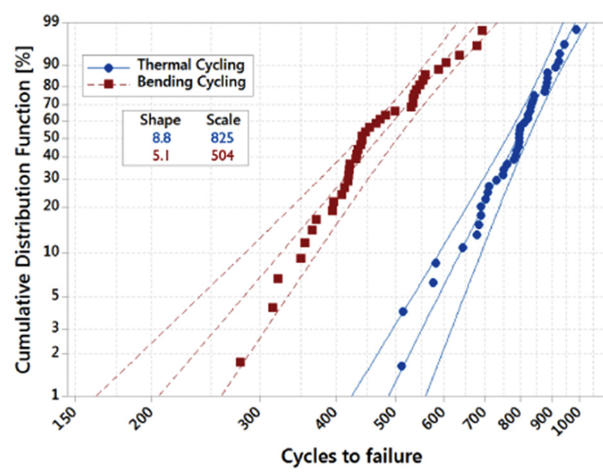

Fig. 7. Weibull distribution for the two cycling techniques.

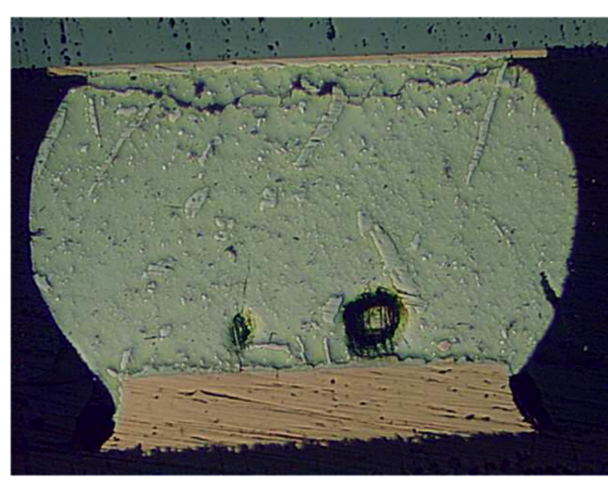

Fig. 8. Cross-section of failed solder joint after thermal cycling testing.

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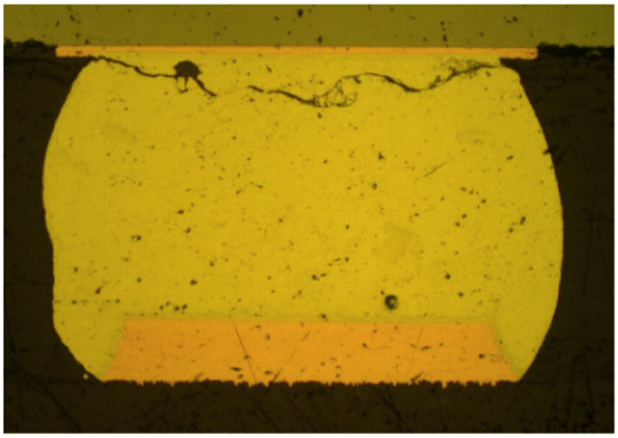

Fig. 9. Cross-section of failed solder joint after 4 pt bending cycling testing.

conditions. The simulation model for 4 pt bending test is shown in Fig. 10. The SAC305 solder material is modeled using the Anand based equations defining the viscoplastic behavior as function of temperature and stress [2]. Viscoplasticity is defined as unifying plasticity and creep via a set of flow and evolutionary equations where a constraint equation is used to reserve volume in the plastic region.

The output of interest from this simulation is the creep strain distribution induced in one thermal (Fig. 11) or one bending (Fig. 12) cycle.

In the thermal cycle, the corner joints see the highest creep strains. This is in agreement with the experiments showing the first failures in one of the four corners. In the bending cycle, the two outer rows are equally stressed. Also this confirmed by the cross-sections.

Comparing the creep strains to the thermal cycling case, the strains are about 10% more stressed in the 4 pt bending case. This already confirms the trend seen in the experiments. However the little difference in creep strain per cycle cannot explain the difference in the life time.

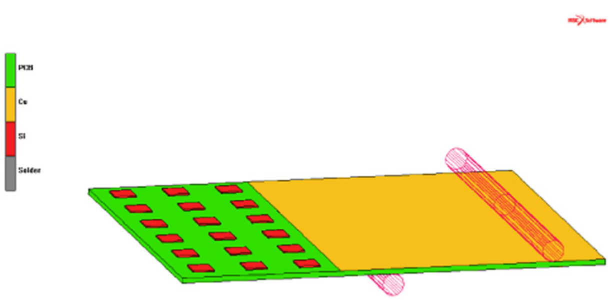

Fig. 10. Finite Element Model simulating the 4-point bending test.

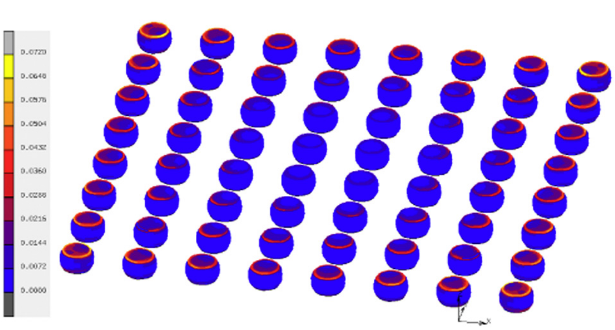

Fig. 11. Creep strain in the solder joints induced over one thermal cycle (0 to 100 °C).

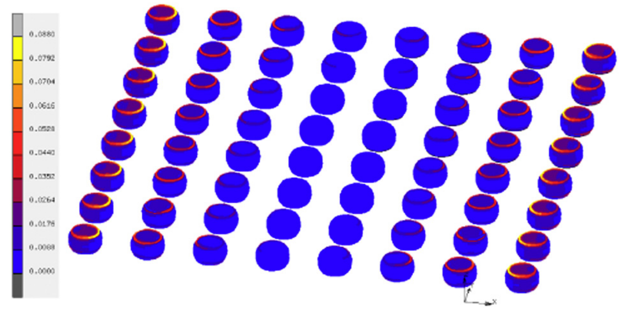

Fig. 12. Creep strain in the solder joints induced over one bending cycle (see Table 1 for exact conditions).

There is also a **third** factor needed to explain the trend, namely the statistics for the daisy chain testing. In the thermal cycling, the four corner joints are equally stressed. In the four point bending cycling, in total 16 joints are seeing the highest stress. As the daisy chain fails when one joint is fractured, it is expected to have faster failures in a larger population.

In the case of Weibull distributions [3], the reliability as function of number cycles t for a system with one joint is equal to:

$$R_1 = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (9)$$

with η is the scale parameter and β is the shape parameter in a 2 parameter Weibull distribution.

Now, for a system of n independent solder joints, subjected to the same stress, the reliability of a daisy chain "system" R_s with n joints in series becomes:

$$R_s(t) = (R_1(t))^n$$

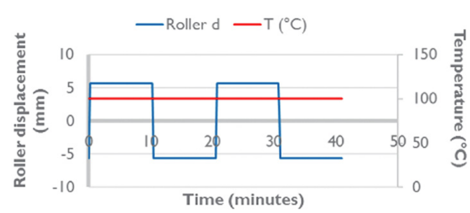

Fig. 13. Loading conditions for the dwell time parametric study(in this graph, dwell time is 10 min).

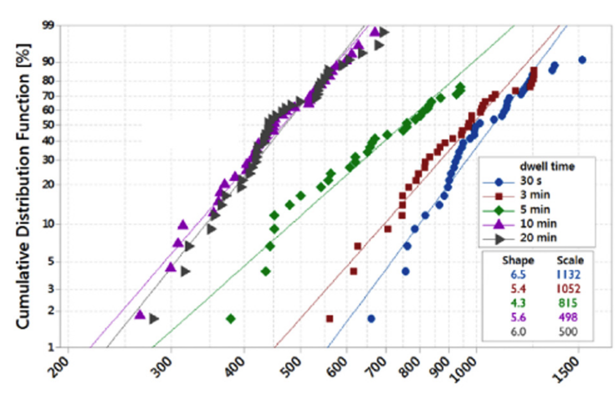

Fig. 14. Weibull plot for 4 point bending cycling tests with different dwell times.

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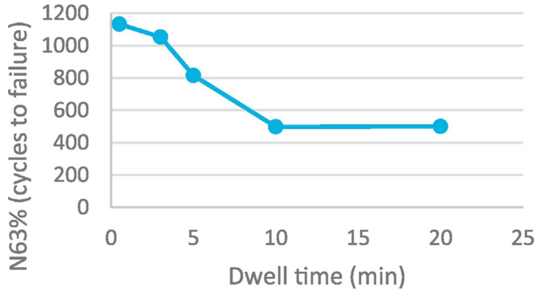

Fig. 15. Relation between characteristic life and dwell time during the 4 pt bending test.

Therefore, we can derive:

$$R_s(t) = \left(e^{-\left(\frac{t}{\eta}\right)^{\beta}}\right)^{n} = e^{\left(-\left(\frac{t}{\eta}\right)^{\beta}\right)n} = e^{-n\left(\frac{t}{\eta}\right)^{\beta}} = e^{-\left(\frac{t}{\eta}\,n^{1/\beta}\right)^{\beta}} = e^{-\left(\frac{t}{\eta\,\left(\frac{1}{n}\right)^{1/\beta}}\right)^{\beta}}$$

This can be simplified to:

$$R_s(t) = e^{-\left(\frac{t}{\eta_s}\right)^{\beta_s}}$$

In the thermal cycling, 4 joints see the maximum stress. Therefore, a chain with 4 equally stressed joints, the corresponding reliability function R_4 becomes:

$$R_4 = e^{-\left(\frac{t}{\eta_4}\right)^{\beta}} \text{ with } \eta_4 = \eta\left(\frac{1}{4}\right)^{1/\beta} \tag{10}$$

For a daisy chain with 16 joints, the reliability function R_{16} is:

$$R_{16} = e^{-\left(\frac{t}{\eta_{16}}\right)^{\beta}} \text{ with } \eta_{16} = \eta\left(\frac{1}{16}\right)^{1/\beta} \tag{11}$$

Using a shape parameter β of 6 and combining Eqs. (10) and (11), the relationship between the scale parameters for a daisy chain of 16 vs 4 joints is given by:

$$\eta_{16} \cong 0.8^{*}\eta_4$$

So combining the 10% higher creep strain per cycle for the critical joint and the 20% lower scale parameter (N63%) for a chain of 16 joints with 4-point bending cycling, the 40% lower characteristic life for 4-point bending cycling is clarified.

5. 4 pt bending tests with varying dwell time

The major advantage of the 4-pt bending test would be that cycling could be done faster since the whole test can be performed at high temperature where the creep velocity is high and the dwell time can be kept low. In order to quantify this impact, bending fatigue tests have been performed on the same component assemblies with dwell times varying from 30 s to 20 min (Fig. 13).

The results are shown into a Weibull plot (Fig. 14). There is no difference seen between 20 and 10 min dwell time at 100 °C, as shown in Fig. 15. This can be explained as 10 min seems to be sufficient to have complete relaxation of the solder joints. With fast cycling (30 s), the life time increases by about a factor 2.

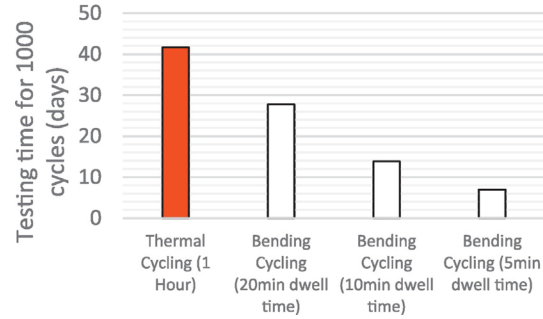

Fig. 16. Testing time for 1000 cycles: thermal cycling versus bending cycling.

For this specific CSP assembly, we could say that 10 min dwell is more than sufficient. Calculating the time needed for testing 1000 cycles (Fig. 16), bending cycling with 10 min dwell time can reduce the testing time to 1/3 compared to thermal cycling.

This statement is obviously temperature dependent as at other temperature, creep of the solder is different and therefore could need more or less time to have full relaxation of the solder joint.

6. Conclusions

4-point bending experiments have been performed on test boards with 40 soldered daisy chain WL-CSP's. Solder joint fractures are seen after a number of bending cycles and are similar to fractures induced due to temperature cycling. The time to failure of the PCB could be related to the applied bending strain. As it is also the objective to reduce the testing time, the effect of the dwell time is measured, showing an increase in number of cycles for a dwell time below 10 min. As such, a considerable faster time-to-failure at even lower strain levels in bending test compared to thermal cycling test is demonstrated.

The decoupling of the mechanical loading from the imposed temperature allows to study the temperature dependence of the solder properties. It is therefore a suitable technique to derive temperature dependent acceleration models.

Future work will be focused on applying the same bending cycling test to other components such as QFN's and BGA's. At the end, these are of high interest for the industry.

Acknowledgments

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