Reliability Analysis of Solder Joint Quality on J-Lead Ceramic Oscillators Using Highly Accelerated Life Testing (HALT) with Lead and Lead-Free Compositions.

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ABSTRACT
The reliability of electronic components was investigated using HALT methods to determine the relative reliability of tin/lead soldered part versus lead-free soldered parts. The test process revealed insight into the methods, including the effectiveness of HALT testing and vibration resonance dwell testing. Both lead-free and tin/lead terminations sustained all environmental stresses applied.

Key words: HALT, vibration, lead-free, crystal oscillator, reliability, resonance, resonance dwell.

INTRODUCTION

Electronic manufacturers throughout the world have a long history of using lead-based solders. Such solders have proven to be cost effective and reliable, and are solidly integrated into manufacturing methods and processes. Driven by legislation primarily in the European Union i.e. WEE, RoHS, EEE Directives, manufacturers are paving the way for removing lead solder from all electronics. However, the adoption of lead-free solder poses many challenges.

Conversion to RoHS (Restriction of Hazardous Substance) compliant parts must encompass the entire product development and manufacturing process. To electronics manufacturers, one of the most important aspects in the process is ensuring the lead-free solder joint reliability is equal to or greater than that of their current leaded solder compositions. Manufacturers[10] are working independently to validate reliability for their lead-free electronic components and systems. Likewise, industry organizations[3] and other researchers[2] have developed validation programs that attempt to understand failure mechanism associated with lead-free products, generate reliability acceleration models, and predict the reliability of lead-free solder joints.

Several factors affect solder joint reliability, i.e. part geometry, solder impurities, and external environmental stresses. Rapid thermal cycling has been an effective environmental stimulus capable of inducing fatigue on solder joints, particularly with materials having mismatched thermal expansion coefficients. Mechanically induced vibration is another external stress that effectively evaluates solder joint reliability. Thermal cycling can produce high displacement stresses at low cycle frequencies, whereas mechanical vibration can provide low displacement stresses at high frequencies and high cycle counts.

A particular type of test equipment and methodology capable of applying a combination of rapid thermal cycling and vibration is Highly Accelerated Life Testing[4] (HALT). This experiment attempted to explore the use of HALT to evaluate the reliability of tin/lead vs. lead-free solder joints. For this test, samples of military crystal oscillators were arranged side by side and stress tested on a HALT machine. The test plan included a response where, as samples become displaced from the printed circuit board (PCB), their time to failure would be plotted using Weibull methods. In addition, a solder joint life distribution would be generated describing relative performance between tin/lead vs. lead-free alloys. The outcome of this test did not produce the sequence of failures necessary to plot the life data, however the process of testing revealed insight into the application of HALT and vibration dwell as a technique to compare the performance of PCB soldered components.

HALT TESTING

The test was performed on Elite's Thermotron AST-35 HALT chamber. The HALT chamber is configured with liquid nitrogen cooling and a high power heat bank. It is capable of providing highly responsive and controlled step temperature changes or a 60 ^{o} C /minute thermal shock test environment.

The chamber also generates separately or in combination with thermal testing six-axis pseudo-random vibration.

HALT vibration is generated using pneumatically actuated hammers striking a vibration table. The hammer impacts produce ringing and resonating conditions on the table and induce the pseudo-random vibration input. The table produces vibration excitation from 200Hz to 5,000Hz, which is a frequency range well suited for exciting the inherently high natural frequencies of small components and printed circuit boards. The repetitive shock vibration also produces peak acceleration amplitudes in the range of 5 to 10 times the RMS acceleration. This is higher than the peak acceleration levels on an electro-dynamic machine where the random vibration peak amplitudes are generally limited to three times the RMS value. High peak amplitudes produce correspondingly high displacements and can generate maximum stresses in the parts.

Traditionally, HALT has been applied to overstress prototypes in an effort to find weak components, potential failure modes, and establish design margins. The HALT machine applies environmental stress well beyond the stresses expected during the useful-life of the product. The theory[3] behind this methodology can be summarized with the expectation that field failures occur over a long period of time at much lower stress levels. Therefore, the high stress of HALT compresses the time to failure and provides a more efficient means for discovering product design weaknesses. The root cause of each failure can then be analyzed for design improvements. Such improvements can trigger design changes that improve reliability and make the product more robust.

To restate, the purpose of this test was to develop a life distribution for each solder joint type by applying progressively higher HALT stress levels and bring the parts to the point of failure. More specifically, the focus was on the effectiveness of the six-axis pseudo-random vibration on solder joint fatigue. A five cycle thermal shock test was run to detect any latent defects in the solder joints, but thermal shock was not applied throughout the remaining course of testing.

Test Sample Construction

A total of ten (10) J-lead quartz crystal oscillators (see figures 1 and 2) were soldered to a PCB test vehicle using a tin/lead composition (63Sn/37Pb) while another ten (10) were soldered using lead-free composition (96.5Sn/3.0Ag/0.5Cu). Table 1 provides a summary of notable difference considered prior to using the two solder alloys under test.[5, 6]

Table 1- Solder Alloy Considerations for Test.

Alloy	Solidus (°C)	Liquidus (°C)	Application Comments	ROHS Comments
Sn63 Pb37	-E-	183° C 361° F	Eutectic Tin-Lead solder. Commonly used in Aviation, Space, and Defense electronics.	Unsuitable for products requiring Lead-free solder.
Sn96.5 Ag3.0 Cu0.5	217	215-218° C 419-424° F	Tin-silver-copper near eutectic solder. Currently a leading Lead-free replacement option for Sn63/Pb37.	Suitable for commercial products requiring Lead-free solder. Very little is known about High Reliability field history.

MIL-PRF-55310E, the general specification for military crystal oscillators was referenced as a design and construction guideline.[7] Figure 1 provides a schematic of the J-lead oscillator technology where chip and wire circuitry is constructed over a ceramic substrate. The circuit is enclosed inside a hermetically sealed package. In addition, the quartz crystal blank is also contained inside a hermetically sealed package independent of the oscillator package seal.

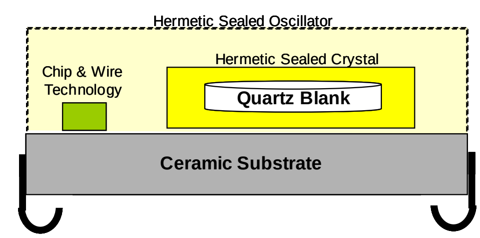

Figure 1 - Visual of J-Lead Oscillator Construction.

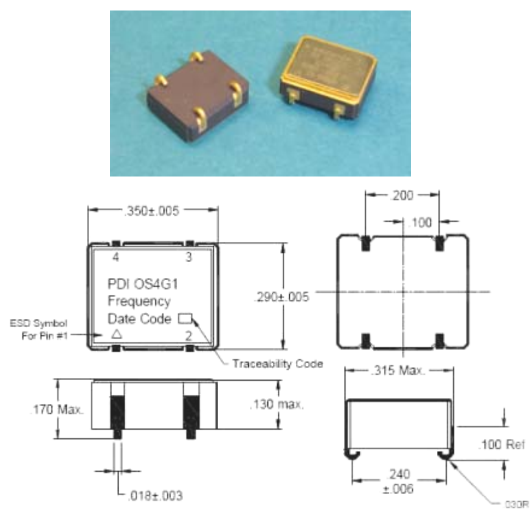

Figure 2 – JL4 Oscillator Package.

TEST VEHICLE

Parts were arranged on a 0.062 inch thick fiberglass epoxy PCB. Hand-soldering techniques for surface mount construction were applied using NASA-STD-8739.3[8].

The traditional tin/lead process was accompanied by the following lead-free process parameters[9]:

Water soluble solder wire:

- Core fluxed, water soluble tin, silver, and copper (96.5Sn/3.0Ag/0.5Cu) solder wire.
- No solvent needed for cleaning.
- Additional time required for bake-out (30 minutes)

Solder iron with temperature LED:

- Solder iron temperature at 350 °C
- The actual temperature at the board is less than 350 °C and the exact temperature is not measurable. It is therefore, critical to control the time of heat exposure to the components.

The printed circuit boards (PCBs) are shown in Figure 3.

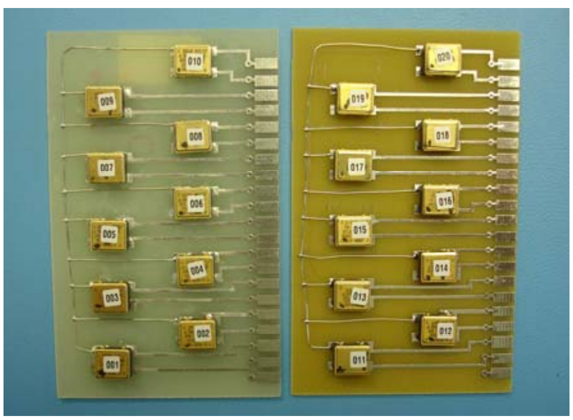

Figure 3 – PCB Test Vehicle.

SOLDER JOINT INSPECTION

Prior to testing, each sample was subjected to a thorough inspection where all solder joints were inspected in accordance with NASA-STD-8739.3 (see figure 4) using a microscope (10 – 60 power).

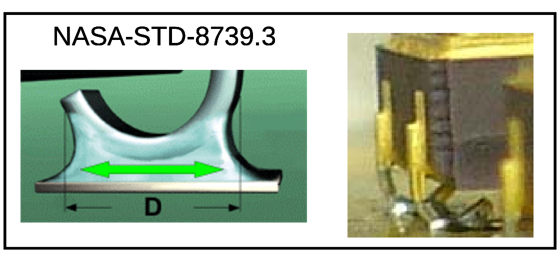

Figure 4 – Solder Joint Inspection Model

No evidence of solder joint cracking, internal metallization, lead separation, component removal, weakened substrate attachment, and/or other degradation characteristics were observed.

DESCRIPTION OF DATA ACQUISITION (DA) SYSTEM

The PCB was constructed with traces to provide power, ground, and signal output to the appropriate oscillator leads. The oscillator signal output leads were monitored with an Agilent multiplexed DC volt meter. The primary function of the data acquisition system was to detect the electrical continuity status of the power, ground, and output solder joints. Therefore, it was not considered necessary to measure the true 127.872MHz clock oscillator signal, rather just the DC bias from the oscillator.

Each PCB was placed on opposite sides of a flat aluminum fixture plate measuring 6" x 6" x 0.75". The PCBs were fixed to the plate with double sided tape and secured on two sides with a washer and bolt connection. The fixture (with PCBs) was then mounted in the center of the HALT vibration table.

To validate the DA system, a single output lead was cut near the board connection to observe the DA system's ability to detect the loss in electrical output. Once the lead was reconnected, the oscillator output resumed registering the same voltage as before being cut.

TESTING

The testing began with a five cycle thermal shock precipitation screen. The purpose of this precipitation screen was to detect any gross issues with the solder joints, as well as with the data acquisition system. No failures were detected, however, after thermal shock an inspection revealed that both PCBs were bowed upward at the center of the board by approximately 0.062 inches for the lead-free and 0.031 inches for the lead solder board.

Next, vibration levels were stepped higher in 10G increments over the period of an hour to the maximum machine throttle level of approximately 55Grms. (The RMS levels were calculated over the range of 10Hz-20,000Hz. The analyzer bandwidth was set at 3.13Hz).

Two parts did fail on the lead solder board. However, the failure mechanism was attributed to a thermal fault specific to these parts and was not directly related to the table vibration acting on the solder-lead connection. A single part came loose from the lead-free board, but this failure was discounted due its failure occurring immediately after the PCB was lifted off the fixture to be reseated with fresh double sided tape. Handling and reseating the PCB may have stressed to failure this single component.

Since it did not appear either of the boards were producing failures after 35 hours of HALT vibration exposure, further analysis was performed to evaluate the characteristics of the HALT vibration stresses. The analysis considered the following questions:

- What was the vibration amplitude and transmissibility at various locations on the PCB, on the fixture, and at other locations on the HALT vibration table?
- How did the applied HALT vibration relate to the resonant characteristics of the PCB and oscillators?

PCB RESPONSE TO HALT INPUT

With parts still on the HALT table, an accelerometer was attached at several locations around the PCB, aluminum fixture plate, and HALT table. The measured vibration RMS amplitudes and power spectral density information was recorded. Figure 5 illustrates the pseudo-random nature of the HALT vibration as well as the high vibration response of the PCB at approximately 725Hz.

Also, overlaid on the HALT data (Figure 5) are results from a resonance search of the PCB. The resonance data confirmed the high Q vibration response at 725Hz. The data also establishes that the HALT vibration table is well suited to deliver high levels of random vibration energy in the resonance range for printed circuit cards and components of this type.

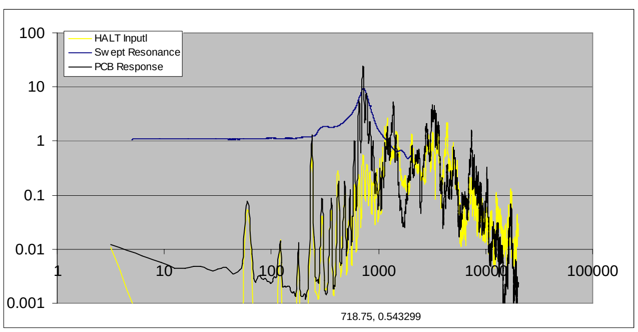

Figure 5- HALT Vibration Power Spectral Density.

For many applications, random vibration testing is preferred because it excites all the natural frequencies associated with the PCB as well as with the parts on the PCB. In addition, the HALT repetitive shock has the advantage of simultaneously exciting resonances in six axes, x-y-z, along with pitch-roll-yaw. However, since random vibration distributes energy across a wide spectrum of frequencies, the amplitude of the RMS vibration delivered at any particular frequency is generally less than that the amplitude which can be achieved by a narrow-band dwell from an electro-dynamic vibration machine. This would imply testing on the HALT machine would eventually fail the part but a longer duration would be required to accumulate the same stress reversals and magnitude of fatigue as would be with a narrow band dwell at high amplitudes.

The vibration amplitude in Grms on the PCB at the resonance frequency of 725Hz can be estimated from the HALT PSD amplitude data (23.33 G^2/Hz) and the measurement bandwidth (3.13Hz):

Response Grms $= \sqrt{(23.3 \times 3.13)}$
$= 8.6$

Referencing previous data[10], it was found that a resonance search and dwell on a similar test vehicle produced failed parts at a 1223Hz and 50gs.

Figure 6 illustrates the variability of acceleration measurements across a single flat plate fixture, as well as across the entire HALT table as measured on a second similar flat plate fixture. Note that in the more traditional role for HALT (i.e. Test, Find, Fix, Test), these variations in test levels generally are irrelevant, since a vibration sensitive latent defect will eventually precipitate to a patent defect regardless of where the part is located on the fixture or table. However, in comparison testing this variability must be considered during test planning and in the results analysis.

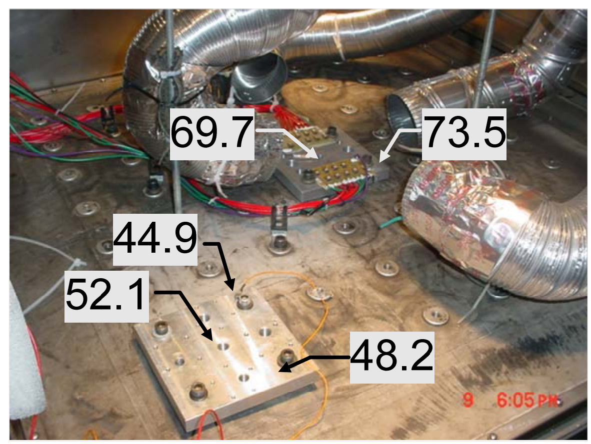

Figure 6- Relative Measures of Grms Levels on Fixture and Across Table.

RESONANCE SEARCH AND DWELL

The HALT vibration portion of this experiment ended because the HALT table was producing very high levels of random vibration and exciting the PCB without precipitating failures. The test was moved to the electro-dynamic table to identify PCB resonance and to determine if vibration at higher amplitudes concentrated at the PCB resonant frequency would be more effective at generating solder joint failures.

The accelerometer placements and results from the resonance search testing are presented in Figures 7 and 8. The results indicate that the resonant frequency characteristics and response amplitudes depend on the accelerometer placement location on the PCB. For location #2 the first PCB resonance was measured at approximately 175Hz to 200Hz, with a more significant resonance at approximately 845Hz. Also, at 845Hz , location #3 measured an apparent anti-node thus confirming multi-moding on the PCB.

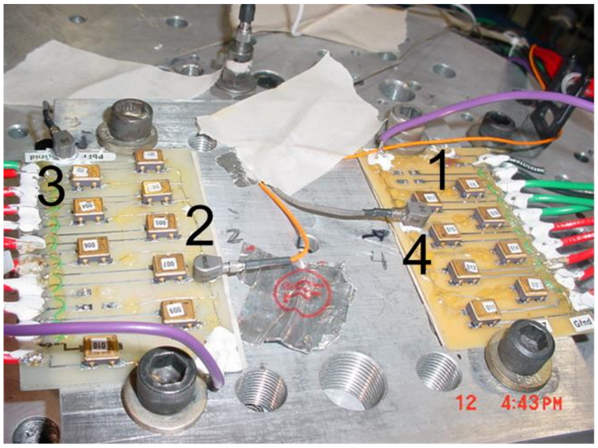

Figure 7- Locations of accelerometers.

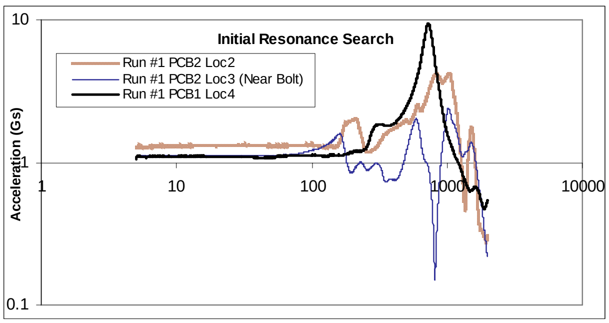

Figure 8- Initial wept Resonance Data.

The data illustrates the center location on the board #2 and #4 had higher acceleration levels than at the location near the bolt #3. The multi-moding of the PCB, as observed with a strobe light, produces acceleration amplitudes that vary depending on locations around the PCB. In one respect, having the board flex with high displacement is desirable in order to apply high levels of stress and quickly evaluate the solder joint stresses. However, because stresses at the center of the PCB were much higher than at the sides and different frequency and amplitudes between boards, the conclusions drawn as a result of failures can become skewed. When conducting comparison testing, the results should take these resonance conditions and response variations into consideration.

In addition to measuring the PCB resonance, an accelerometer was placed on an oscillator to record its resonance characteristics. Since the mass of the accelerometer was nearly equal to the mass of the oscillator, the resonance search was repeated with a portion of bees wax placed on top of the accelerometer. The purpose of adding wax was to use its weight to estimate the relative shift in oscillator resonance from placing accelerometer mass on the oscillator. The results in Figure 9 indicate a slight shift in the resonance frequency and suggest that the mass of the accelerometer will slightly impact the measurement.

Note: At this stage of the experiment, resonance testing was temporarily delayed and the fixture was removed from the electro-dynamic machine. Several days later, the test resumed and the resonance search was repeated. It was observed that the resonances shifted.

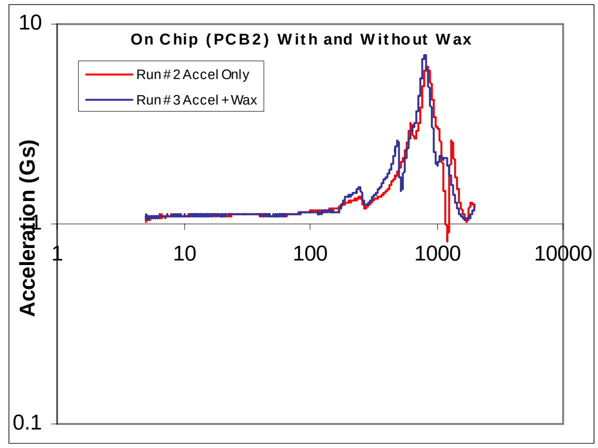

Figure 9- Swept Resonance Measured On Oscillator.

Once the resonance search was completed, the tin/lead board was removed and the lead-free board was configured alone on the fixture. The vibration dwell was set at the frequency which exhibited the highest amplitude resonance, in this case 748Hz. The dwell amplitude was gradually increased and the parts were observed until failures occurred. The test levels for the lead-free board are indicated in Table 2. The tin/lead board was similarly configured with the highest amplitude resonance measured at 548Hz. The subsequent tin/lead board dwell test levels are listed in Table 3.

Table 2 - Lead-Free Board Resonance Dwell Durations and Amplitudes (at 748Hz).

Loc 2 (Gs)	Control (Gs)	Loc 3 (Gs)	Dwell (Min)
25	3	-	10
50	5.6	-	10
97	10	6.3	10
217	20	26	10
433	40	78	10
513	50	106	10
560	60	129	7
Total			67

Table 3 – Tin/Lead Board Resonance Dwell Durations and Amplitudes (at 548Hz).

Loc 4 (Gs)	Control (Gs)	Loc 1 (Gs)	Dwell (Min)
25	1.8	2.3	10
50	3.4	4.2	10
98	7	8.9	10
202	15.7	21.2	10
386	35	47.7	10
451	45	61	10
510	60	75	4
Total			64

As can be observed in the data, even after a significant application of vibration, concentrated at the PCB resonance, neither the lead-free nor the lead solder composition board failed resonance dwell testing.

CONCLUSION AND LESSONS LEARNED

Each sample was subjected to nominal supply voltage and load power in accordance with the design and performance specification. Respective post-test samples continued to oscillate with no performance irregularities observed.

The initial objective of this experiment was to use HALT vibration to establish the relationship between the life of similar parts soldered with different solder compositions. The results proved inconclusive for the primary purpose of lead-free versus tin/lead solder joint fatigue life. Both compositions demonstrated extremely robust performance and the results may suggest that with respect to this abbreviated vibration fatigue test, solder joint reliability is nearly equal between the two compositions (see figure 10). No samples were separated from the test vehicle as a result of the stresses applied.

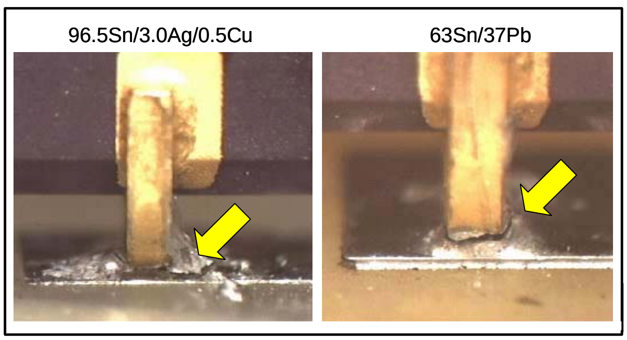

Figure 10- Worst Case Solder Joint Fractures.

However, the test process revealed insight into HALT and resonance dwell test methodologies and suggested factors which can affect results when soldered components are being compared.

First, printed circuit board dynamics must be understood and controlled so that acceleration hot spots and nulls are made more equal in amplitude. A flexible PCB will deflect and produce bending stresses suitable for evaluating stress on solder joints. But with a flexible board, multi-moding and acceleration uniformity become difficult to control and make a comparison test less objective.

Second, HALT random vibration is a good methodology for generating multi-axis broad spectrum energy for PCBs and their components. The repetitive shock technique excites resonances in each of 6 axes. However, the spread of energy may dilute the acceleration intensity required at the part resonance to create a failure in a short time.

Third, relying on a resonance search and dwell has the benefit of focusing an enormous amount of vibration energy at a specific frequency. However, the selection of a resonance frequency to dwell at can bias the test to a particular type of component or the location of the component on the PCB.

For either the HALT or the resonance dwell, neither technique could create solder joint failures. Further testing is suggested with the following recommendations:

- Perform a resonance search and dwell with the PCB in the X and Y axis. This test step may evaluate the effects of over turning moments of the part relative to the PCB.

- Perform a resonance dwell at one of the lower resonant frequencies. The lower frequency may generate greater displacements and higher stresses.

- Develop a stiffer PCB and secure it in a manner to eliminate the moding on the PCB.

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