INVESTIGATION OF IMPACT RESPONSE OF Pb-FREE ASSEMBLIES AND COMPARISON OF DROP TEST WITH CYCLIC 4-POINT BEND

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ABSTRACT
The popularity and miniaturization of handheld consumer electronic products such as cell phones, notebook computers, and PDAs has enhanced their probability of being subjected to shock loads; hence making impact reliability study an important area of research. The transition from tin-lead (Sn-Pb) to lead-free (Pb-free) solder has pressed the electronics industry to characterize formulate essential design and process changes to counter the no-lead situation. Investigation and improvement of the performance and reliability of the electronic packages is being addressed by many researchers. This paper deals with the investigation of the impact response, i.e., acceleration, bending strain, impact reliability, and the failure modes of Pb-free test vehicles subjected to high strain-rate environments. The test vehicles were subjected to impact loading conditions including the JEDEC standard impacts of 1500-g, 2000-g and 2900-g and input shocks at nominal amplitude of 1500-g with varying shock periods. Reliability under each shock loading condition was scaled with the relative kinetic energy and a simple relationship predicting failure for the test vehicle was developed. In addition, drop testing is compared with high-speed cyclic 4-point bend test and a scaling factor between the drop and bend reliability is determined. Failure analysis revealed that the failure mode for the test vehicle used in this study was independent of the shock amplitude, shock period, and component location; pad cratering on the board-side solder joint was seen in all the reliability tests. The proposed strategies that scale impact reliability could lead to the minimization of drop testing for design validation and product development, thereby reducing the overall cost and time to market.

INTRODUCTION
Portable electronic products often experience drops and impacts owing to their size and nature of application. They are subjected to vibrations and shocks during manufacturing, transportation, and end use, making it imperative for the design and reliability engineers to understand the dynamics of this phenomenon and implement design modifications for enhanced performance and improved reliability. The development of new technologies and the never-ending demand for newer electronic gadgets has led to the increase in performance and miniaturization of the products. The electronic packages have become small in order to be integrated with the electronic appliance, which by itself, is getting smaller and lighter everyday leading to enhanced vulnerability to shocks [4].

Various techniques are deployed for measuring the impact response of the packages such as product level drop test (actual dropping of the cell phone or PDA) [5, 6], board level drop test (standardized by JEDEC) [1, 7, 8], vibration dwell [22], component level strength tests (i.e., ball shear, ball pull, etc.) [23, 24], and so forth. A product-level test depicts the real-life response of the electronic device but due to complications and difficulties involved in controlling and acquiring data, board-level drop tests are being extensively used for design validation and product qualification in the electronics industry [8, 12]. Wong et al. [13] numerically investigated three significant factors that contribute towards the solder joint failure. 1) Out of plane bending causing normal and shear stresses in the interconnects, 2) inertial forces, and 3) shock stress waves transmitted due to impact. Inertial forces play an important role if the mass of the components is large; otherwise, the PCB bending dominates and constitutes the primary source of failure. Syed et al. [14] demonstrated the effect of component location on impact reliability and proposed a predictive model for shock reliability by scaling solder joint and inter-metallic layer (IMC) stresses to the experimental drops to failure. Luan, et al. [15] studied the effect of drop height, number of felt papers, number of mounting screws and the tightening torque of the screws on the dynamic response of a PCB. Tee, et al. [16]
numerically demonstrated the effect of the drop height and strike surface on the free fall peak input acceleration \( A_0 \) and the shock period \( T \) of the input pulse. Roggeman [17] presented a comparative study of various SAC (105, 205, 305 and 405) and Sn-Pb alloys, and concluded that impact reliability decreases as we go up the SAC family in terms of silver content, except for certain special cases with specific pad metallurgy on each side of the joint. SAC 305 proved to be the most economical and reliable in the Pb-free family. This was one of the driving factors together with the easy commercial availability that SAC 305 BGAs were chosen for this study.

Intrinsically, drop testing [7, 8, 15, 18], is a very specialized, and time consuming technique for characterizing solder joint performance and measuring the impact reliability of electronic packages. Consequently, there is a need to have an easier and less time consuming methodology for product development. In the recent past, many FE models have been proposed that demonstrate the impact response and failure mode predictions of a test vehicle in high strain rate events [9, 21], but numerical models have their own assumptions, limitations, and accuracy when it comes to predicting life and failure mechanisms. Pitarresi et al. [9] presented a novel block finite element (FE) modeling approach for simulation of complex PC motherboards that resulted in close correlation with experimental acceleration and does so in a 10X reduction of the computational time of the FE model. Pitarresi et al. [10, 11] addressed the random vibration response and shock modeling study of electronic components. In this paper, impact reliability is scaled with the imparted energy and an analytical model is proposed to predict life for a specific failure mechanism. Furthermore, drop testing has been compared with high speed cyclic 4-point bend and a scaling factor between the drop and bend reliability is also determined.

**EXPERIMENTAL DESCRIPTION**

Extensive high strain rate fatigue testing (drop and bend) has been executed in this study to determine correlation, if any, between drop and any other parameter or testing technique, leading to a substantial reduction in the experimental testing time. The out-of-plane displacement measured by High Speed Digital Image Correlation (HSDIC) technique during the drop is used as an input correlation parameter in bend test. Figure 1 shows the cyclic 4-point bend setup. The schematic of the experimental setup for the drop test is depicted in Figure 2.

The printed circuit boards (PCBs) were designed as per JEDEC standard [1] and assembled with CABGA (Chip Array Ball Grid Array) components having 100 I/Os of 0.8-mm pitch and 450 micron sphere diameter each. Pad metallurgy on the component and board-side was ENIG (Electroless Nickel Immersion Gold) and Cu-OSP (Cu-Organic Solderability Preservative), respectively, and the solder alloy incorporated in this research was SAC 305 (Sn 96.5%, Ag 3%, Cu 0.5%). Figure 3 shows the processed assembly with five components as per JEDEC [1] configuration in order to minimize the effect of the clamping stresses at the corner mounting holes and be in accordance with the JEDEC standard for cyclic bend test [2]. Post assembly quality inspection was done on the processed assemblies using X-ray technique to ensure consistency (having fewer variations) with the published standards for consumer electronics [20]. *In situ* failure detection was carried out using an Analysis Tech event detector that measures resistance across each component every micro-second. Any resistance change in the assembly was indicated through the data acquisition system and was referred to as a failure as per the guidelines of JEDEC [1] publication. For reliability assessment using Weibull distribution, the components are divided into
two groups on the basis of out of plane bending experienced by them. As shown in Figure 3, center components form the group I while the four corner ones constitute the group II. Sample size for all the tests was three assemblies per test condition that translated into 3 and 12 reliability data points for group I and II, respectively.

RESULTS
Extensive drop testing was performed on Pb-free assemblies, impact response, i.e., bending strain, acceleration, impact reliability, and the failure modes have been analyzed under various shock loading conditions. Impact response was analyzed and compared as a function of input shock amplitude [3], input shock period at constant nominal amplitude of 1500-g, and component location. Three test vehicles were tested at each data point and reliability was assessed via Weibull distribution (N_{63.2}). Impact reliability has been scaled with imparted kinetic energy to minimize experimental drop testing, resulting in easier product qualification leading to cost reduction, and faster time to market. The dynamic response plots for all the drop scenarios showed that the damage was maximum in the first impact cycle (solder subjected to tension and maximum peak strains) and that it decayed with time, [21] finally going to zero in less than half a second.
Correlation between Energy and Impact Reliability  
Effect of Input Shock Period on the Impact Reliability

Drop testing was conducted at three different conditions with a 1500-g peak nominal acceleration and 0.5-, 0.75- and 1-ms shock periods. From testing, it was observed that the failure mode remained the same for these three conditions; pad cratering at the board-side joint was seen. A plot showing the input excitation pulses for these drop conditions is shown in Figure 4.

![Input pulses at nominal 1500-g and varying shock periods.](image)

The input excitation pulse was integrated using the commercial code MATLAB Simulink and velocity change during the drop was determined. To validate the integration method, the test vehicle was subjected to an input shock of 3-g, and acceleration and velocity was measured using a laser vibrometer. The acceleration measured from the laser vibrometer was integrated using the same technique, and the obtained velocity was compared with the experimentally obtained value. Figures 5 shows the experimental and numerically obtained velocities experienced by the test vehicle for the 3-g input acceleration, respectively.

![Comparison of the simulated and experimental velocities](image)

![Delta v plots for different pulses](image)

The input acceleration measured for different pulses of 1500-g at 0.5-, 0.75-, and 1-ms was integrated and the velocity profile for the entire drop event was obtained, as shown in Figure 6. Kinetic energy is directly proportional
to the product of square of the velocity and mass. Since the mass of the system remained same for all the drop conditions, the relative peak energy factor for each drop condition was calculated by squaring the peak velocity ratio obtained from the response.

Effect of Input Shock Amplitude on the Impact Reliability

The test vehicle was subjected to standard half-sine input pulses of 1500-g, 2000-g and 2900-g at 0.5-, 0.4-, and 0.3-ms, respectively [3]. The dynamic response for initial 10-ms is shown in Figure 7.

As expected, the peak bending strain and acceleration experienced by the test vehicle increased with higher magnitude input shocks. As the change in velocity ($\Delta v$) increased, the energy imparted to the system increased leading to more damage per drop and a lower characteristic life as shown in Table 1; the energy factor is simply the peak velocity squared obtained from integration of the input acceleration pulse.

![Figure 7 Time history plot of bending strain (left) and acceleration (right) for different inputs.](image)

![Figure 8 Comparison of the experimental and analytical life](image)
The best-fit line for the relationship between drops to characteristic life \((N_f(63\%))\) and energy factor \((E \propto \Delta V^2)\) is of the form:

\[
N_f(63\%) = 2729(\Delta V)^{-1.06}
\]

Impact reliability was calculated using the above relationship and compared with the measured data (Weibull characteristic life of the corner components), and is shown in Table 1. Good agreement is observed between the best-fit equation and measured life, with the greatest difference within 16% of measured. Failure analysis revealed pad cratering in all drop scenarios and is shown in Figure 9 below. The crack initiated in the pad (at the board-side joint) and propagated through the PCB resin. No intermetallic brittle failures were seen in any of the drop testing.

<table>
<thead>
<tr>
<th>Drop Conditions</th>
<th>Velocity Change (m/s)</th>
<th>Energy imparted ((m/s)^2)</th>
<th>Measured Characteristic Life (drops)</th>
<th>Predicted Characteristic Life (drops)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500-g, 0.5-ms</td>
<td>3.8</td>
<td>14.4</td>
<td>149</td>
<td>149</td>
<td>0</td>
</tr>
<tr>
<td>1500-g, 0.75-ms</td>
<td>5.3</td>
<td>28</td>
<td>68</td>
<td>79</td>
<td>-16</td>
</tr>
<tr>
<td>1500-g, 1-ms</td>
<td>7.8</td>
<td>56.3</td>
<td>36</td>
<td>34</td>
<td>5.6</td>
</tr>
<tr>
<td>2000-g, 0.4-ms</td>
<td>4.5</td>
<td>20.3</td>
<td>123</td>
<td>103</td>
<td>-16</td>
</tr>
<tr>
<td>2900-g, 0.3-ms</td>
<td>5.1</td>
<td>26</td>
<td>66</td>
<td>72</td>
<td>-9.1</td>
</tr>
</tbody>
</table>

**Table 1** Correlation between experimental life and the best-fit model

![Figure 9](image1)

**Figure 9** Representative images showing pad cratering.

**Comparison of drop with high speed cyclic 4-point bend**

The full-field dynamic response during the drop test at 1500–g, 0.5-ms was measured using the HSDIC technique. HSDIC results were validated by comparing bending strain (in-plane) data with the reference strain gages at the locations situated on the two sides of the TV. Bending strain correlated well as revealed by Figure 10. Out-of-plane displacement measured by the HSDIC technique during the drop was used as the input parameter in the displacement control bend test. Bend testing was performed at 7 Hz (max possible to achieve the required displacement on the available MTS M/C) with the peak displacement of 2.2 mm at the loading knife in order to correlate with the drop test. It was made sure that the board was being displaced (out-of-plane) with the same magnitude at 7 Hz (61.32 mm/sec) in bend as experienced in drop at approximately 200 Hz or more.
Failure analysis for bend tested assemblies revealed mixed failures (exclusive pad cratering and pad cratering/intermetallic failures in few samples) as shown in Figure 11. While there was evidence of intermetallic cracking in this case, all electrical failures were the result of pad cratering.

A 2-D finite element (FE) model was used to approximate the bend phenomenon of the test vehicle. In particular, it was used to study the stress distribution and verify the location of primary failure mode in the joint. Material properties were used from the existing literature [21]. The FE simulation results in Figure 12 indicate stress concentration in the pad region of the board-side joint as opposed to much lower stresses towards the component side (areas of interest, where failures were seen in the experimental tests, refer to Figure 11). Therefore, the primary failure mode in bending is pad cracking (board-side joint) and characteristic life between drop and bend is shown via Weibull in Figure 13.
This correlation between drop and bend for this specific test vehicle (consistent PCB, Pad metallurgy, etc.,) under a specific drop scenario (1500-g at 0.5-ms input shock) was found to exist with a scaling factor of 25X in the characteristic life.

CONCLUSION
In this study, extensive impact testing has been performed on consistent test vehicles and possible strategies to minimize experimental drop testing have been proposed. These strategies would lead to substantial time and money savings towards product development, resulting in the optimal cost, and faster time to market. Impact reliability is found to be inversely proportional to the imparted energy for drop conditions including the standard JEDEC shocks [3], varying input shock periods with constant nominal amplitude of 1500-g, and the failure mode was seen as pad cratering (at the board-side joint). Since the failure mode was constant all throughout, impact reliability was scaled with kinetic energy and a best fit reliability prediction model was proposed for the boards considered in this study. The model is only valid for this specific test vehicle as it does not take into consideration PCB type, component type, pad metallurgy, dimensions, and so forth. A more comprehensive model could be

Figure 12 von Mises stress distribution in the solder joint

Figure 13 Weibull plot for the drop and bend tested assemblies

This correlation between drop and bend for this specific test vehicle (consistent PCB, Pad metallurgy, etc.,) under a specific drop scenario (1500-g at 0.5-ms input shock) was found to exist with a scaling factor of 25X in the characteristic life.
developed if reliability is correlated with the output energy at the board (which will consider all the factors and different test vehicles could be compared and analyzed).

Characteristic life of the group I was slightly less than that of the group II owing to the higher out of plane displacements at the center, strengthening the fact that cyclic out of plane bending dominates as the primary cause of failure in high strain rate environments; failure mode was independent of component location.

Correlation between drop test and high speed cyclic 4-point bend is seen in the failure modes. Pad cratering (board-side joint) was seen in both the mechanical tests and a scaling factor of 25X was determined between the characteristic lives at specific drop and bend condition. This is an initial platform to estimate impact reliability by performing bend test, but in order to achieve general correlation more experimentation on a spectrum of assemblies with different solder alloys, pad finishes, and PCBs is required.

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REFERENCES
1. JEDEC Standard for Board Level Drop Test Method of Components for Handheld Electronic Products: JESD22-B111.
3. JEDEC Standard for Mechanical Shock: JESD22-B104C.