Lead Free Solder and Flex Cracking Failures in Ceramic Capacitors

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Abstract

Many companies have experienced failure of multilayer ceramic capacitors due to printed wiring board bending and have placed controls in their manufacturing process to limit the amount of bending (or flexure) of the PWB to eliminate these failures. The shift to Pb-free solders may require these limits to be adjusted to ensure that MLCC bending failures are avoided. Elastic-plastic finite-element simulations were utilized to study the effects that three different solders have on the durability of a 0805 capacitor as it undergoes a standard three point bend test. The solder attaching a MLCC is a critical path in which printed wiring board loads are transferred into the capacitor, therefore the solder properties play an important role in the durability of ceramic chip capacitors.

Introduction

Surface mount multilayer ceramic capacitors (MLCCs) are one of the most common components found on modern circuit card assemblies. They are well known for their reliability and have been rapidly accepted by the electronics industry. The reliability of a nominal MLCC is extremely high, with expected operating lifetimes in the decades, if not hundreds of years. However, because they rely on ceramic for their structure (Figure 1), MLCCs are known to be susceptible to failure during printed wiring board bending events. Capacitor manufacturers recognize this and typically provide information indicating the capacitors durability to printed wiring board bending through the IEC-384-1 specification and similar documents. A typical test set up for capacitor bend testing is shown in Figure 2.

A critical factor in determining if a capacitor will fail due to PWB bending are the properties of the solder joint. With the acceptance of Pb-free solders the chance of capacitor cracking may change because many Pb-free solders are stiffer than standard Sn37Pb solder.

Figure 1: Typical multilayer ceramic capacitor (MLCC) [11]

Capacitor cracks that result from excessive printed wiring board flexure tend to propagate at 45-degree angles from the termination of the end cap. The cracks tend to be large, propagating through the ceramic until it reaches the end cap. A picture of a typical flex crack is displayed in Figure 3.

Figure 2: Standard capacitor bend test [11]
In order to avoid designing, manufacturing or using circuit card assemblies in manner that will induce flex cracking in MLCCs, it is important to determine the failure criterion that will cause flex cracks to initiate and what drivers will increase the susceptibility of capacitors to flex cracking.

**Figure 3**: Example of a flex crack in a MLCC [CALCE EPSC]

**Flex Cracking**

To determine the event that could initiate flex cracking, one must relate the cracking event to a parameter that can be related to its occurrence. In this study the displacement of the printed wiring board is related to the tensile stress in the capacitor using a FEA model. Given displacement failure data from a capacitor manufacturer the failure-stress relationship can be obtained and used to evaluate other types of solders. With this information, an allowable printed wiring board curvature limit can be established that can reduce the occurrence of the flex failures of ceramic capacitors. In this study, a FEA beam model and three point bend failure data [6] from a 0805 capacitor with Sn-37Pb solder interconnects is used to establish the failure stress relationship.

A beam structure is used to approximate the 0805 capacitor mounted to a PWB. The FEA model (shown in Figure 4) uses material properties listed in

**Table 1** and **Table 2**. The length of the printed wiring board is 45 mm and the solder is modeled as an elastic-plastic material using a Ramberg-Osgood model as shown in Equation 1 [12]. The stress strain responses of the solders are based on a best fit of available data as shown in Figure 5.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Modulus (E: MPa)</th>
<th>Poisson ratio (ν)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-37Pb</td>
<td>35810</td>
<td>0.378</td>
</tr>
<tr>
<td>Sn-3.5Ag</td>
<td>39500</td>
<td>0.35</td>
</tr>
<tr>
<td>Sn4.0Ag0.5Cu</td>
<td>41000</td>
<td>0.35</td>
</tr>
<tr>
<td>FR4</td>
<td>17200</td>
<td>0.159</td>
</tr>
<tr>
<td>X7R ceramic</td>
<td>113000</td>
<td>0.34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength coefficient (K)</th>
<th>Hardening exponent (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-37Pb</td>
<td>32.8</td>
<td>0.129</td>
</tr>
<tr>
<td>Sn-3.5Ag</td>
<td>57.0</td>
<td>0.138</td>
</tr>
<tr>
<td>Sn4.0Ag0.5Cu</td>
<td>81.7</td>
<td>0.250</td>
</tr>
</tbody>
</table>

\[ \varepsilon = \frac{\sigma}{E} + \left( \frac{\sigma}{K} \right)^{\frac{1}{n}} \]

*where*

\[ K : \text{strength coefficient} \]

\[ \sigma : \text{stress MPa} \]

\[ n : \text{hardening exponent} \]

\[ \varepsilon : \text{strain} \]

\[ E : \text{Young's Modulus} \]

Since plasticity of the solder is included, the maximum tensile stress that can be generated is limited.
The data in Table 3 indicates that capacitor cracking typically initiates at a flexure of 2.3 mm which corresponds to a tensile stress value in the capacitor of apparently 62 MPa. This compares reasonably well with tensile strength values for BaTiO$_3$ found in the literature [10].

Table 3: Results of three-point bend testing of 0805 capacitors [6, 7], test span was 90 mm and test board thickness was 1.6mm

<table>
<thead>
<tr>
<th>Failure Rate</th>
<th>0.01%</th>
<th>0.1%</th>
<th>1%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm/in.)</td>
<td>2.29 / 0.09</td>
<td>2.67 / 0.11</td>
<td>3.14 / 0.12</td>
<td>3.55 / 0.14</td>
</tr>
<tr>
<td>Radius of Curvature (mm/in.)</td>
<td>294.8 / 11.6</td>
<td>252.8 / 9.95</td>
<td>214.9 / 8.46</td>
<td>190.1 / 7.49</td>
</tr>
<tr>
<td>Board-Level Strain</td>
<td>2.71E-03</td>
<td>3.16E-03</td>
<td>3.72E-03</td>
<td>4.21E-03</td>
</tr>
</tbody>
</table>

Changing the material properties for the solder and rerunning the model yields the capacitor tensile stress verse printed wiring displacement shown in Figure 6. Using the capacitor stress failure relationship yields the failure displacement results shown in Table 4.
Table 4: FEA results of three point bend tests for Sn37Pb and two lead-free solder alternatives

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>0.01%</th>
<th>0.1%</th>
<th>1%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn-37Pb</td>
<td>2.29</td>
<td>2.67</td>
<td>3.14</td>
<td>3.55</td>
</tr>
<tr>
<td>Sn-3.5Ag</td>
<td>1.89</td>
<td>2.03</td>
<td>2.18</td>
<td>2.33</td>
</tr>
<tr>
<td>Sn-4.0Ag-0.5Cu</td>
<td>1.86</td>
<td>1.99</td>
<td>2.13</td>
<td>2.28</td>
</tr>
</tbody>
</table>

These results indicate that changing to either Sn3.5Ag or Sn4.0Ag0.5Cu could lead to an increased chance of capacitor cracking related failures. This is not surprising since both these solders are stiffer and have a higher yield stress [1]. The low yield stress of Sn37Pb solder helps relieve some of the forces transferred to the capacitor from the printed wiring board.

Discussion

While measuring printed wiring board displacement is relatively straightforward it is an inadequate parameter for determining the probability of capacitor flex cracking. This is because the displacement is a function of various parameters and therefore doesn’t directly represent the load applied to the capacitor. For example, using simple beam theory for a three point loading, it’s easy to show that the force required to deflect a 2.3 mm board can be 3 times the force required to deflect a 1.6 mm board the same amount.

\[
P = -\frac{48EI\Delta_{max}}{L^3}
\]

\[
I = \frac{bt^3}{12}
\]

Where \( I \) is the moment of inertia of the board, \( E \) is the elastic modulus, \( \rho \) is the radius of curvature and \( M \) is the moment in the board. The curvature can also be related to the strain in the outer fibers of the board by:

\[
\varepsilon_{xx} = \frac{t}{2\rho}
\]

Where \( t \) is the thickness of the board, \( \varepsilon \) is the board strain at the outer fibers and \( \rho \) is the radius of curvature.

The results of the 0805 capacitor three point bend tests and the equivalent printed wiring board radius of curvatures and strains for an allowable failure probability of 0.01% are displayed in Table 5.

Table 5: Allowable limits for a 0805 MLCC at 0.01% failure probability

<table>
<thead>
<tr>
<th>Solder</th>
<th>Sn37Pb</th>
<th>Sn3.5Ag</th>
<th>Sn4.0Ag-0.5Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm)</td>
<td>2.29</td>
<td>1.89</td>
<td>1.86</td>
</tr>
<tr>
<td>PWB Strain</td>
<td>2.714E-03</td>
<td>2.240E-03</td>
<td>2.204E-03</td>
</tr>
<tr>
<td>Radius of curvature (mm)</td>
<td>294.8</td>
<td>357.1</td>
<td>362.9</td>
</tr>
</tbody>
</table>

Conclusion

The results coupled with an appropriate safety factor could be used as a guideline for allowable flexure when using 0805 capacitors on 1.6 mm thick printed wiring boards. However, the experimental data [6, 7] used in this study was from capacitors specified to a 2 mm deflection limit. Therefore, these guidelines are not applicable to capacitors with a lower or no flexure specification limit.
References


