Has the Electronics Industry Missed the Boat on Pb-Free?
- Failures in Ceramic Capacitors with Pb-Free Solder Interconnects -

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Abstract
In the transition to Pb-free, the electronics industry has devoted extensive resources to ensuring that product reliability will not be comprised. However, the most deleterious effect of Pb-free solders will likely be in the increase of flex cracks in multilayer ceramic capacitors (MLCC). Flex cracks are latent defects that arise during excessive bending of the printed board during manufacturing or use and is a common root-cause of failure in electronic products. This paper builds upon a previous study that used finite element analysis and three-point bend data to develop a flex cracking failure model. Incorporating the lower compliance and higher yield strengths of Pb-free solders, Sn4.0Ag0.5Cu and Sn3.5Ag, it was determined that current bending limits established to prevent capacitor cracking for tin-lead solder are not applicable to Pb-free solders. Results were extrapolated for a variety of EIA case sizes. For a 1206 case size, the deflection required to fail 0.01% of capacitors attached with eutectic solder is predicted to initiate failure in over 10% of the Pb-free soldered capacitors. To maintain a 0.01% failure rate or lower, the maximum board curvature will have to be reduced by approximately 25%. The goal of the study is to provide information that can aid designers in preventing printed wiring board bending failures of capacitors when switching to Pb-free solders.

Introduction
A successful transition to Pb-free products has become one of the overriding concerns of the electronics industry. Membership in academic-industrial consortiums is surging as companies look to minimize risk through the amalgamation of resources. Research topics have focused on process optimization to prevent infant mortality issues and modeling efforts to ensure product wearout does not initiate during the desired lifetime.

These efforts have primarily concentrated on direct effects. Changes to less solderable interconnect and plating materials have led to reformulations of flux chemistries. Higher melting point Pb-free solders create higher reflow temperatures, which has led to the development of new encapsulants more resistant to popcorning. The concern with this approach is that industry is not actually using its experience with field failures to help identify the potential risk points with the transition to Pb-free.

To provide a better framework of where Pb-free might result in the greatest risk, CALCE Laboratory Services reviewed the last 400 services performed for industrial clients. These services included review of electrical and mechanical design, material characterization, supplier benchmarking, accelerated testing, and root-cause failure analysis. Of these 400 actions, 159, or 40%, were identified as analyses of failures during qualification or at a customer site. These failures, representative of over 70 companies, were grouped by failure site and the results are shown in Figure 1.

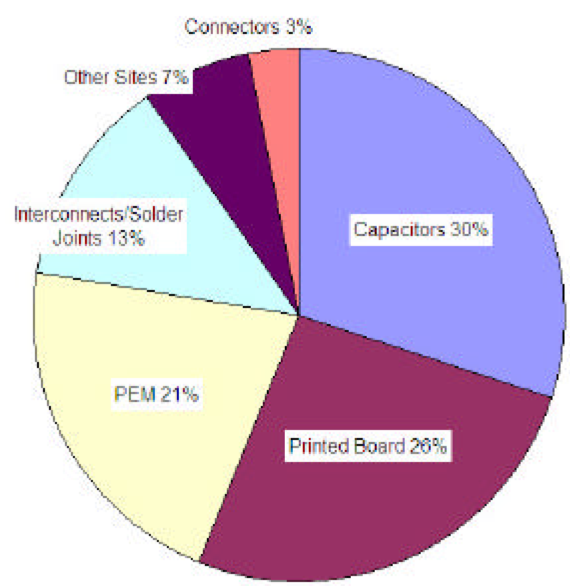

Figure 1: Field failure occurrence by failure site

The most common reason for qualification failures and field returns was failure of capacitors. Further review identified the overwhelming majority of capacitor failures as multilayer ceramic capacitors (MLCCs). This is not a surprising revelation. In the latest generation microprocessors, MLCCs are used at the base of almost every I/O, requiring hundreds of MLCCs for the entire component. In some design, MLCCs can be 80% of the bill of materials.

In addition to their ubiquitous nature, MLCCs have experienced an explosive growth in performance over the past ten years, in some respects easily exceeding Moore's Law. The increasing demand for higher capacitance/volume (C/V) ratios and lower equivalent series resistance (ESR) has placed MLCC manufacturers at the cutting edge of material technology.

A breakdown of the failure mechanisms that plague MLCCs is provided in Figure 2.

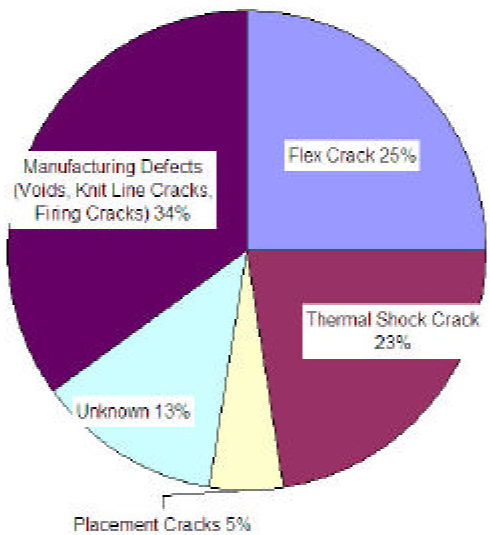

Figure 2: Failure mechanisms in MLCCs

The largest root-cause of MLCC failure is the presence of defects introduced during the capacitor manufacturing process. The occurrence and severity of these failure mechanisms is expected to be relatively independent of solder material being used (eutectic or Pb-free). However, the second most common failure mechanism is cracking of the capacitor due to excessive flexure of the underlying board or substrate. An example of a flex crack is displayed in Figure 3

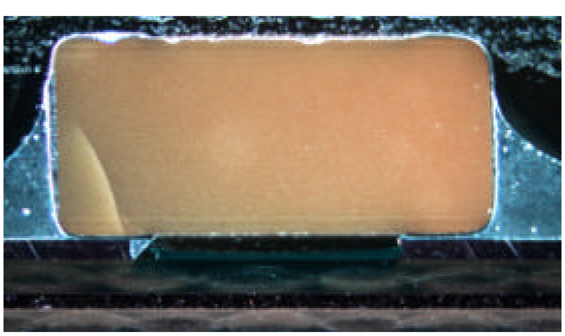

Figure 3: Flex cracking in a MLCC

Flex Cracking of MLCCs

MLCCs are known to be susceptible to failure during printed wiring board (PWB) bending events [1,2]. These bending events can occur during depaneling, connector insertion, screw or bolt attachment, in-circuit testing, and customer use. 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 4.

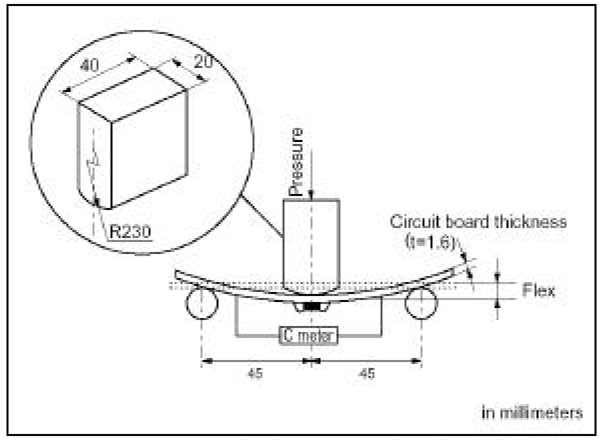

Figure 4: Standard capacitor bend test [3]

A critical factor in determining if a capacitor will fail due to PWB bending are the properties of the solder joint. With the introduction of Pb-free solders the probability of capacitor cracking is expected to increase significantly because most Pb-free solders are stiffer than standard Sn37Pb.

To avoid designing, manufacturing or using Pb-free containing circuit card assemblies (CCAs) in manner that will induce flex cracking in MLCCs, it is important to assess how the use of Pb-free solder will increase the likelihood of this common root-cause of field failures.

Bend Testing: Identification of Failure Criterion

To determine the event that would trigger flex cracking, one must connect crack initiation to the parameter that is the direct driver of the event. For brittle materials, this is the tensile, or Mode I, stress being applied to the crack-initiating flaw. In this study the displacement of the printed wiring board is related to the tensile stress in the capacitor through a finite element analysis (FEA) model. The displacement failure definition is based on three-point bend test data performed by capacitor manufacturers as per IEC-384-1 specification.

In this study, this approach is benchmarked using three-point bend failure data from a 0805 capacitor with Sn-37Pb solder interconnects. Correlation can allow for the extrapolation to capacitors with Pb-free solder joints.

Stress Modeling

A beam structure is used to approximate standard test conditions, consisting of a 0805 capacitor mounted to a PWB. The FEA model shown in Figure 5 uses material properties listed in Table 1 and Table 2.

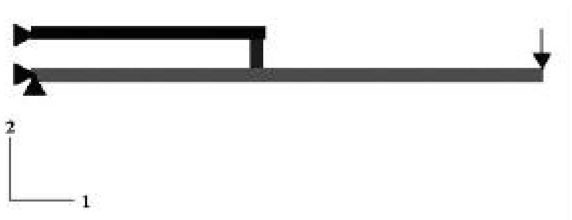

Figure 5: FEA beam model of 0805 capacitor

The length of the printed wiring board is 45 mm and the solder is modeled as an elastic-plastic material using the Ramberg-Osgood model shown in Equation 1. The stress strain responses of the solders are based on a best fit of the data shown in Figure 6.

Table 1: Material properties, linear elastic [4]

Material	Elastic Modulus, E (MPa)	Poisson ratio (ν)
Sn-37Pb	35810	0.378
Sn-3.5Ag	39500	0.35
Sn4.0Ag0.5Cu	41000	0.35
FR4	17200	0.159
X7R ceramic	105000	0.34

Table 2: Material properties, nonlinear [4]

Material	Strength coefficient (K)	Hardening exponent (n)
Sn-37Pb	32.8	0.129
Sn-3.5Ag	57.0	0.138
Sn4.0Ag0.5Cu	81.7	0.250

$$e = \frac{s}{E} + \left(\frac{s}{K}\right)^{\frac{1}{n}}$$

Equation 1

where

K : strength coeffiecient

s : stress MPa

n : hardening exponent

e : strain

E : Young's Modulus

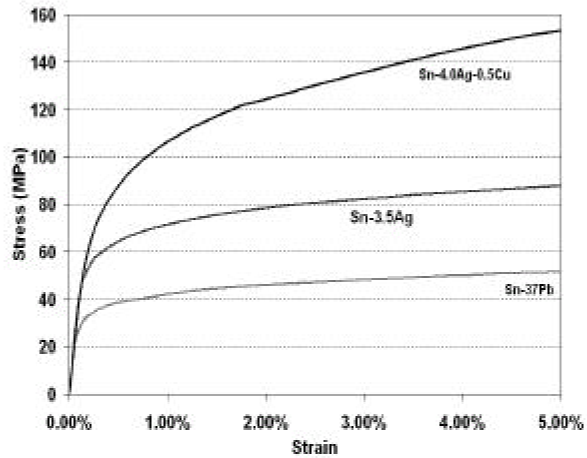

Figure 6: Stress strain curves for three solders, Ramberg-Osgood model of available data [4]

Since plasticity of the SnPb solder is included, the maximum tensile stress that can be generated is limited. This can be seen in the results of the FEA stress analysis, displayed in Figure 7.

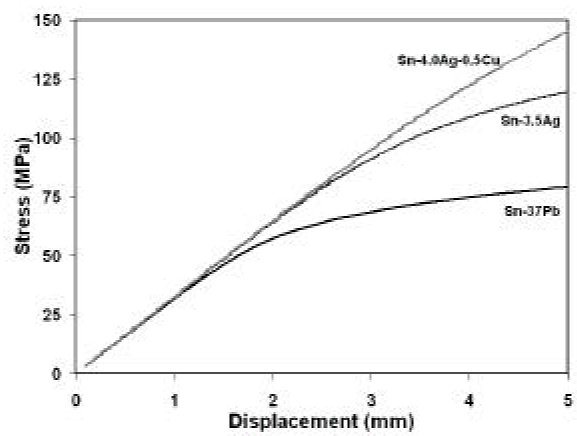

Figure 7: Maximum tensile stress in a 0805 capacitor as a function of pwb flexure/displacement and solder type

By comparison, experimental data from a capacitor manufacturer is displayed in Table 3. These results are from a standard test, which specifies a test span of 90 mm and test board thickness of 1.6mm. The data shows that capacitor cracking typically initiates at a flexure of 2.3 mm. Based on the stress analysis shown in Figure 7, this displacement results in a tensile stress value in the capacitor of about 62 Mpa. This compares reasonably well with the tensile strength values for barium titanate found in the literature [5].

By using the results shown in Figure 7 and the experimental test results shown in Table 3 a stress failure relationship for the 0805 capacitor can be developed and used as a failure prediction model for other solder materials (Figure 8).

Table 3: Results of three-point bend testing of 0805 capacitors [6, 7]

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

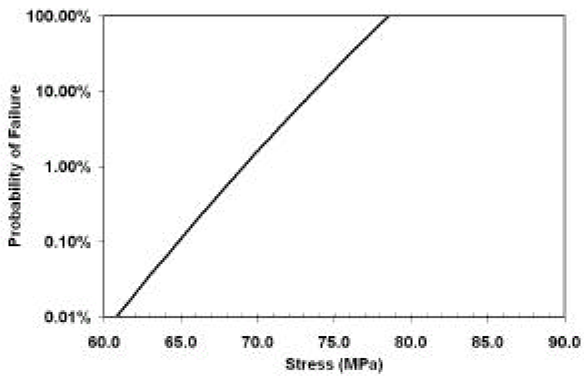

Figure 8: Probability of failure as a function of stress, developed from experimental data and FEA results for the 0805 capacitor with Sn37Pb solder joints

Using the fundamental driver, tensile stress, as the failure criteria in simple FEA models allows for risk assessment for a variety of designs, loading environments, and materials, including the use of Pb-free interconnects.

Two Pb-free solders, Sn04.0Ag-0.5Cu and Sn-3.5Ag were studied using the above failure prediction approach. The capacitor tensile stress verses PWB displacement plot in Figure 7 includes the results for these two Pb-free solders. Using the stresses in the failure model yields the failure displacement results shown in Table 4.

Table 4: FEA results of three point bend tests for a 0805 capacitor attached with a variety of interconnect materials

Probability of Failure	0.01%	0.1%	1%	10%
Solder	PWB Flexure (mm)			
Sn-37Pb	2.29	2.67	3.14	3.55
Sn-3.5Ag	1.89	2.03	2.18	2.33
Sn-4.0Ag-0.5Cu	1.86	1.99	2.13	2.28

These results indicate that changing to either Sn3.5Ag or Sn4.0Ag0.5Cu could lead to a greatly increased chance of capacitor cracking related failures. For some situations, the effect could be dramatic. As an example, at 2.3 mm of displacement, a 0805 capacitor soldered with Sn-37Pb solder has a 100-ppm likelihood of failure. Considering variability in flex events and the limited area of effect for these maximum displacements, this could result in an undetectable level of field failures due to flex cracking.

However, as shown in Table 4, at 2.3 mm of displacement the probability of failure for the Pb-free solders is almost 10%. This is not surprising since both these solders are stiffer and have a higher yield stress. 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 displacement is a function of various parameters and therefore does not directly represent the load applied to the capacitor. For example, using simple beam theory for a three point loading it is 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.

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

$$I = \frac{bt^3}{12}$$

Equation 2

where *I* is the moment of inertia, t is the thickness, E is the elastic modulus, b is the width, L is the span, and ? is the displacement [8].

It is therefore necessary to use a parameter that is directly related to the forces in the printed wiring board. Assuming the PWB behaves as a beam, a parameter that directly represents the load applied to the capacitor would be the radius of curvature. The moment in the beam is directly related to the radius of curvature by:

$$\frac{1}{r} = \frac{M}{EI}$$

Equation 3

where ? is the radius of curvature and M is the moment in the board. The curvature can also be indirectly related to the strain in the outer fibers of the board by

$$e_{xx} = \frac{t}{2r}$$ **Equation 4**

Where *t* is the thickness of the board, *e* is the board strain at the outer fibers and *?* is the radius of curvature.

Use of radius curvature allows for the establishment of more definitive design and process guidelines for avoidance of capacitor flex cracking. The results of the 0805 capacitor three point bends tests and the equivalent printed wiring board radius of curvatures and strains for an allowable failure probability of 100 ppm are displayed in Table 5.

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

Solder	Sn37Pb	Sn3.5Ag	Sn4.0Ag 0.5Cu
Displacement (mm)	2.29	1.89	1.86
PWB Strain	2.71E-03	2.24E-03	2.20E-03
Radius of curvature (mm)	294.8	357.1	362.9

Conclusion

The results of this study indicate that the switch to Pb-free solders will dramatically reduce allowable PWB flexures. The results in Table 5 indicate that allowable the amount of flexure could be reduced by over 20% with the switch to the two Pb-free solders studied. The allowable flexure will be further reduced if the capacitors used are specified with a 1-mm deflection limit, as the data used in this study was from capacitors specified to a 2-mm deflection limit.

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