Robustness of Surface Mount Multilayer Ceramic Capacitors Assembled with Pb-Free Solder

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Abstract

The movement to Pb-free soldering will result in solder joints that are significantly stiffer than those of SnPb. Of great concern to the electronics industry is the influence that this will have on some of the most common failures seen in electronic assemblies. One such failure is the cracking of surface mount multilayer ceramic chip capacitors (MLCC) when subjected to board bending events. To investigate the use of tin-silver-copper (SAC) solder on the reliability of MLCC capacitors, a series of printed wiring board flexure experiments were conducted and analyzed. The experimental design consisted of two solders and two capacitor sizes. The first capacitor tested was an 1812 X7R with samples assembled with both Sn63Pb37 and SnAg3.0Cu0.5 solder. Additional flex testing was then conducted on 0805 X7R capacitors assembled with SnAg3.0Cu0.5 solder. Results of the flex testing indicate that capacitors assembled with SnAgCu solder are more robust than those assembled with SnPb solder.

Introduction

The impact of Pb-free on the reliability of electronic assemblies is of great concern to the electronics industry. While many studies have been done to address the reliability and manufacturability of interconnects using tin-silver-copper (SAC) solder, few studies have addressed the effects on components themselves. A survey of failure analyses suggests that the majority of failures seen in electronic assemblies are related to either capacitors or printed wiring boards, as shown in Figure 1. As shown in Figure 2, a high number of the failures of capacitors are due to flex cracking of surface mount multilayer ceramic chip capacitors (MLCC).

This is not surprising given the number of such devices on a circuit board. For example, a cell phone may contain upwards of a thousand components, of which 80 to 90% are capacitors. Of these capacitors, ceramics sometimes comprise up to 60 to 70%. The high number of these devices increases their probability of failure and the probability that they will be subjected to a stress sufficient to cause failure. The concern is how the Pb-free process and materials will affect this probability of failure by printed wiring board flexure.

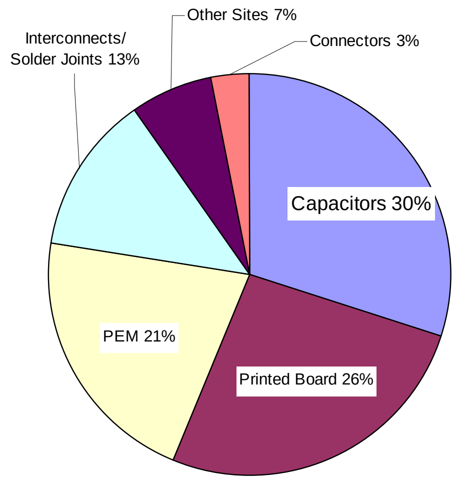


Figure 1: Most common failures by site [1]

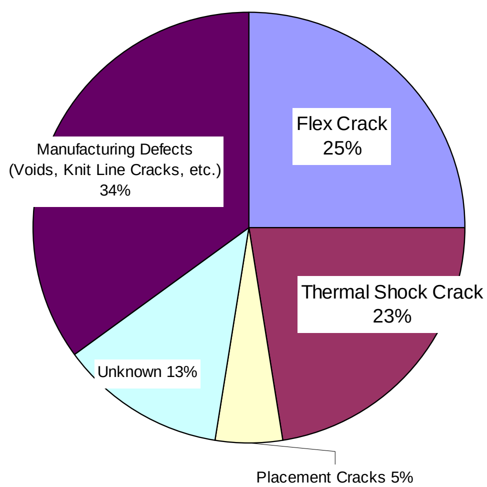


Figure 2: Capacitor failures by type [1]

The flexure of the printed wiring board can occur during de-paneling, connector insertion, screw or standoff attachment, in-circuit testing and customer use. The capacitor manufacturers recognize this and rate the robustness of the capacitors they manufacture using a standard test similar to IEC-384-1. These tests involve subjecting a test board to a three-point bend test, similar to the one shown in Figure 3.

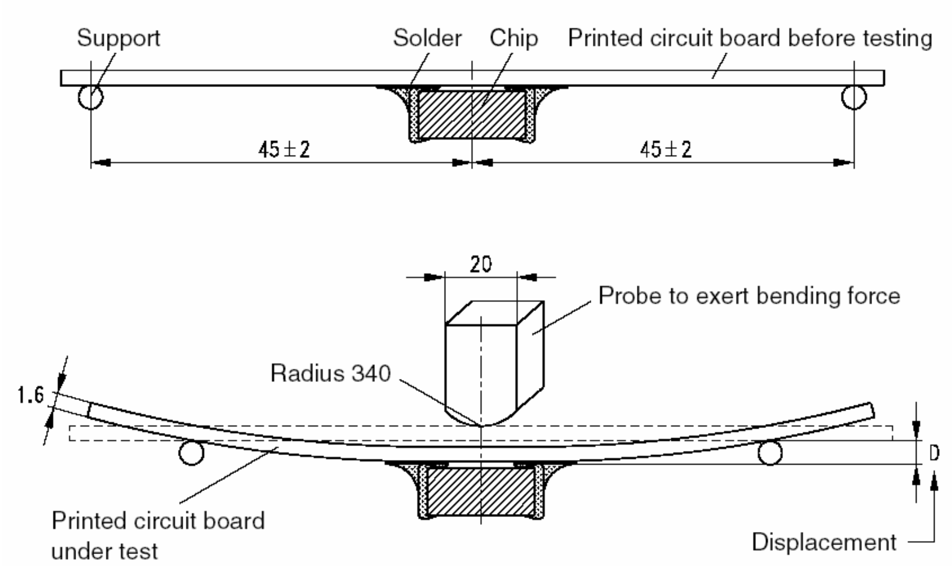


Figure 3: Industry standard capacitor bend test

Depending on the application and the class of the capacitor the displacement amount that is typically specified is either 1 or 2 mm. However, there are some manufacturers that do not provide a displacement specification on their product data sheets. A comparison of some of the displacement specifications provided by various manufacturers is shown in Table 1. The standards state that the capacitor must be able to survive the specified displacement with only a 2.5 to 20% drop in capacitance (dependent on dielectric classification).

The tests performed in this study are based upon the specifications with some minor modifications to increase the number of capacitors tested per printed wiring board coupon.

Table 1: Manufacturer deflection specifications

	Deflection Specification		
Manufacturer	1 mm	2 mm	Other
AVX [0]		X	X [1]
Vishay [4]	X	X	
SAHA/Susco Components [5]		X	
Cal-Chip Electronics, Inc. [6]		X	
TDK [7]		X	
EPCOS [8]		X	
MuRata [9]	X[2]		
Nippon Chemi-Con [10]	X[3]		
Samsung Electro-Mechanics [11]	X		
Syfer, Novacap [12]		X	X[4]
Johanson Dielectrics [13]	X[5]		X[6]
Panasonic [14]	X		
Philips, Phycomp, now Yageo [15]	X		
KOA Speer Electronics [16]		X	
Maruwa America [17]		X	X[7]
Taiyo Yuden [18]	X		
Walsin Technology Corp. [19]	X		

[1] AVX offers a soft-termination capacitor with a deflection limit of 5 mm
[2] GRM03, GRM15 capacitors, PWB thickness 0.8 mm
[3] Printed wiring board thickness 1.0 mm (1.6 is the standard)
[4] Syfer offers a polymer-termination capacitor with a deflection limit of 5 mm
[5] NPO class dielectrics
[6] X7R, Deflection specification 0.5 mm on FR-4
[7] Flexion termination, 8 mm deflection

Sample Population

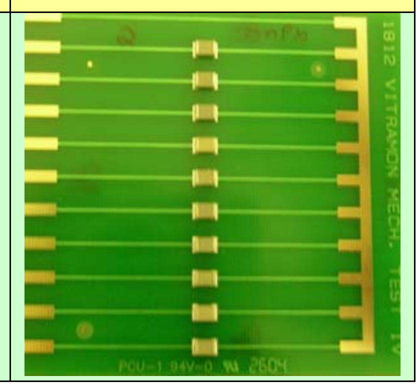
Two capacitor sizes were selected for testing, 1812 and 0805. Both capacitors have X7R type dielectric and are Pb-free parts, having terminations that are 100% tin with a nickel barrier. The nickel barrier had an average thickness of 3 µm and the tin had an average thickness of 7.5 µm before soldering. The capacitors were rated to a 1 mm board displacement specification. To prevent lead contamination the board finish selected for this study was electroless nickel - immersion gold (ENIG), a hot air solder leveled finish (HASL) is typically tin-lead solder and therefore was not selected. Test boards for the 1812 size capacitors were assembled using Sn3.0Ag0.5Cu and Sn63Pb37 solder. A summary of the sample types and quantities is shown in Table 2.

Table 2: Capacitors and solder compositions

Capacitor Type	Capacitance (µF)	Solder Composition	Samples Tested
0805 X7R	0.7	SnAgCu	100
1812 X7R	0.5	SnAgCu	200
1812 X7R	0.5	SnPb	100

The test coupons for the three types of assemblies are shown in Table 3. The boards were assembled by Universal Instruments Corporation and aside from the solder composition and reflow profile, have no other parameters varied.

Table 3: Capacitor test coupons

0805 SnAgCu	1812 SnAgCu	1812 SnPb
		

Experimental Procedure

The test coupons were tested by Vishay Vitramon using a custom three-point bend tester. The bend tester is based upon the industry standard but modified to accommodate a ten-capacitor test coupon. Capacitance measurements were taken at every 0.5 mm displacement and the boards were flexed to an end displacement of 8 mm.

Results

The results of the tests are shown in Table 4 through Table 6. Unlike the industry standard failure criteria of a 10% drop in capacitance, failure was defined as a 5% drop in capacitance. This change was instituted because the relatively stable behavior of MLCCs strongly suggests that any deviation in capacitance is due to the presence of a flex crack. An example graph of the results from one of the tests is shown in Figure 4. Even with this revised failure criteria all capacitors tested met their 1 mm displacement specification regardless of size and solder type.

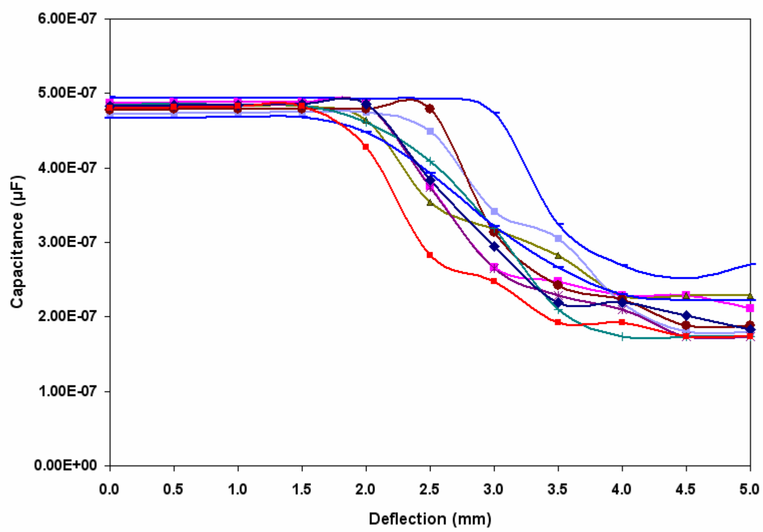


Figure 4: Example of test data, 1812 capacitor with PbSn

Table 4: Flexure failures of 1812 Capacitors with SnAgCu solder

Displacement	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
345(1)		2	3	1									1	2
346(2)		6	2			1								
347(3)		4	3											2
348(4)	3	2	1	1			1	1						
349(5)		2	3	2							2			
350(6)	1	7	1											
351(7)		4	3	2										
352(8)		2	1	3		1					2			
353(9)	1	4	2	2										
354(10)		3	6											
355(11)		4	4		1									
356(12)		5	4											
357(13)			4	1			2	1			1			
358(14)		2	2	2	1					1			1	
359(15)		8	1											
360(16)		4	2						1	2				
361(17)		5	3									1		
362(18)		3	1		5									
363(19)	1	6		2										
364(20)	1	3	3	2										

Table 5: Flexure failures of 1812 Capacitors with SnPb solder

Displacement	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
325(1)	1	5	3											
326(2)	4	3	1	1										
327(3)	3	6												
328(4)	2	4	1	2										
329(5)	6	2	1											
330(6)	2	6	1											
331(7)	1	4	4											
332(8)		5	4											
333(9)	1	6	2											
334(10)	1	7	1											

Table 6: Flexure failures of 0805 Capacitors with SnAgCu solder

Displacement	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
335(1)						2	2		1			1		
336(2)							2			1	1			
337(3)					1				1	1				
338(4)										1	1	1		
339(5)								1			1	1	1	
340(6)							1	1						
341(7)									1	1	1			1
342(8)													1	1
343(9)														
344(10)														

Comparing the data in Table 4 and Table 5, the 1812 size capacitors attached with SnAgCu appear to be more robust than those attached with SnPb solder. A plot of the full data set for the 1812 SnAgCu capacitors is shown in Figure 5.

Previous studies conducted by J. Bergenthal [22] showed that the failure data for capacitors typically exhibit a bimodal distribution. In his study, the author found it necessary to exclude failures above 50% in order to provide a relevant statistical analysis. To avoid the same bimodal type distribution data above 90% failure (or 4.5 mm displacement) was excluded from the statistical analysis of the 1812 SnAgCu capacitors.

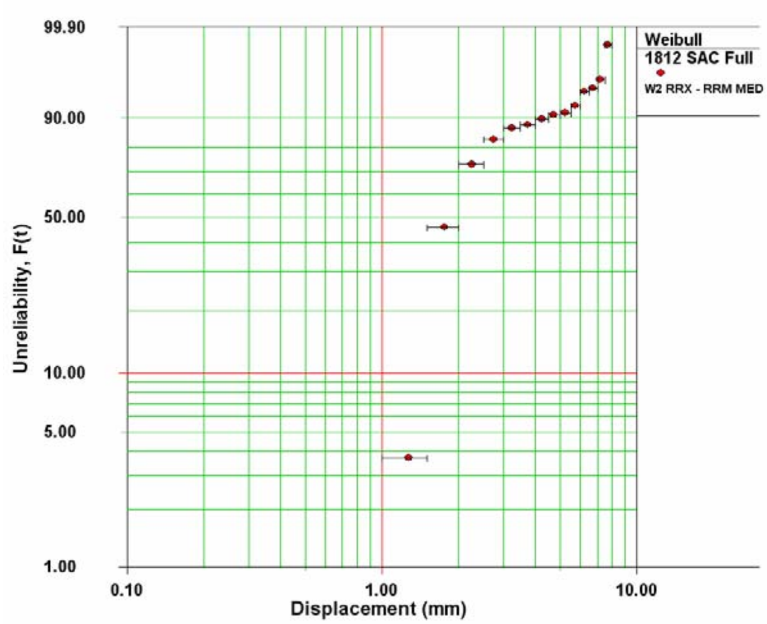


Figure 5: Failures of 1812 capacitors with SnAgCu solder

The additional robustness provided by using SnAgCu is clearly demonstrated by the 2-parameter Weibull plot shown in Figure 6. The characteristic displacement (63% failure point) of the SnAgCu 1812 and the SnPb 1812 was 2.36 mm, and 1.70 mm respectively.

The displacement necessary to induce 5% failure for 1812 capacitors attached with SnAgCu solder was 1.5 mm while those attached with SnPb was 0.85 mm.

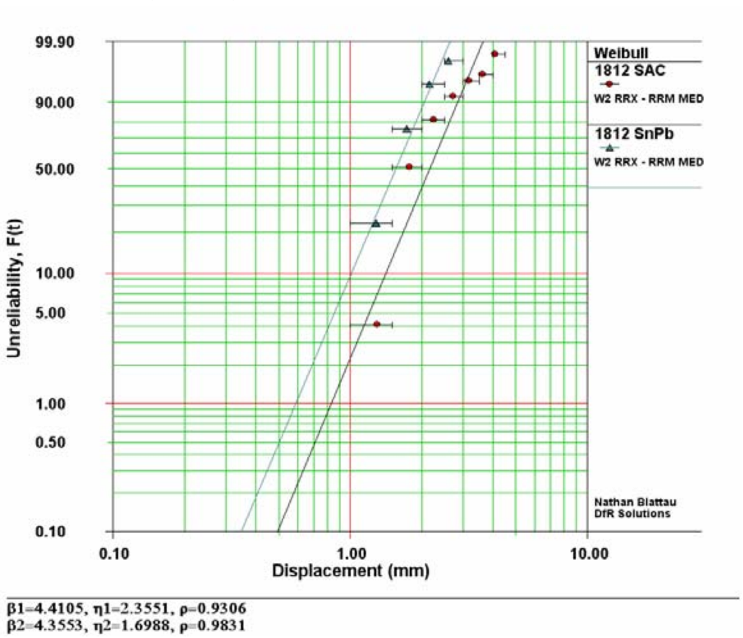


Figure 6: Weibull plot of 1812 capacitor failures

The data from the 0805 tests indicated that only 28 capacitors failed during the testing. The reason for this is discussed in the following section.

Failure Analysis

Selected capacitors from the assemblies were inspected and cross-sectioned to confirm the existence of flex cracks. Solder joint geometries were also compared between the two solder types to see if this contributed to the failure behavior.

Optical images of the failed capacitors are shown in Figure 7 through Figure 9. In these images, flex cracks can be easily identified.

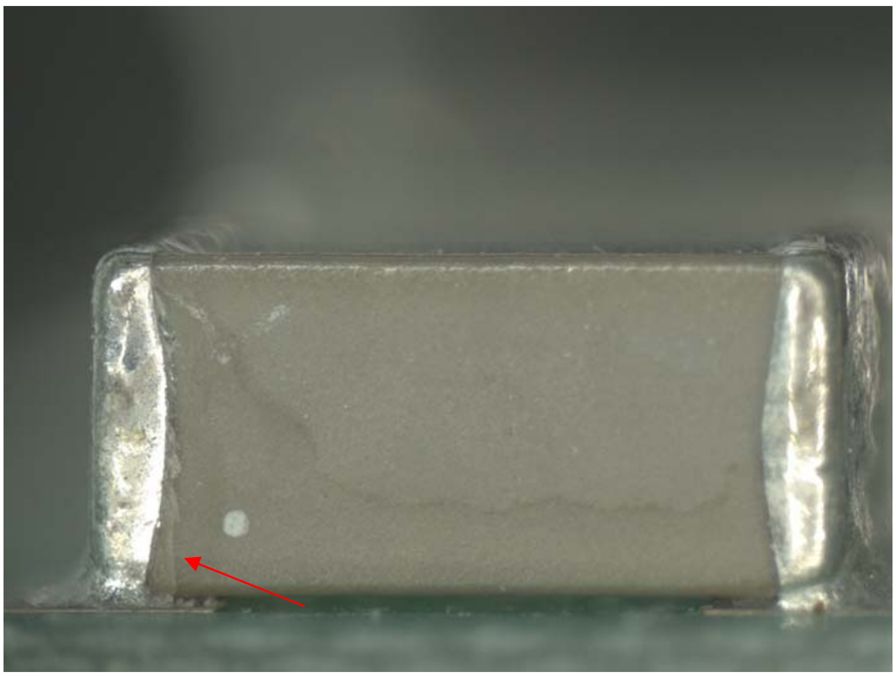


Figure 7: Optical micrograph of a 1812 capacitor attached with SnAgCu solder, flex cracks are identified with the red arrows

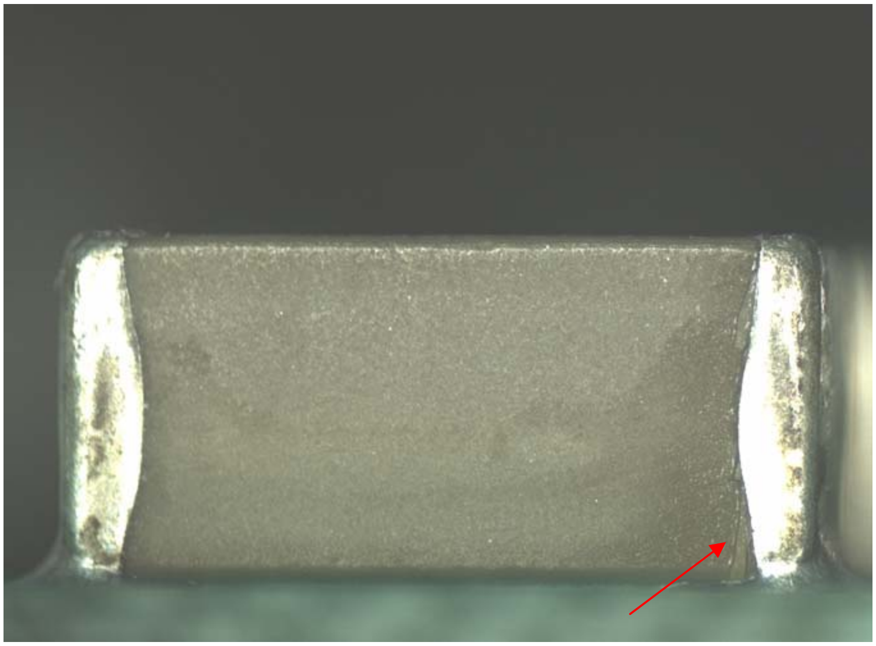


Figure 8: Optical micrograph of a 1812 capacitor attached with SnAgCu solder, flex cracks are identified with the red arrows

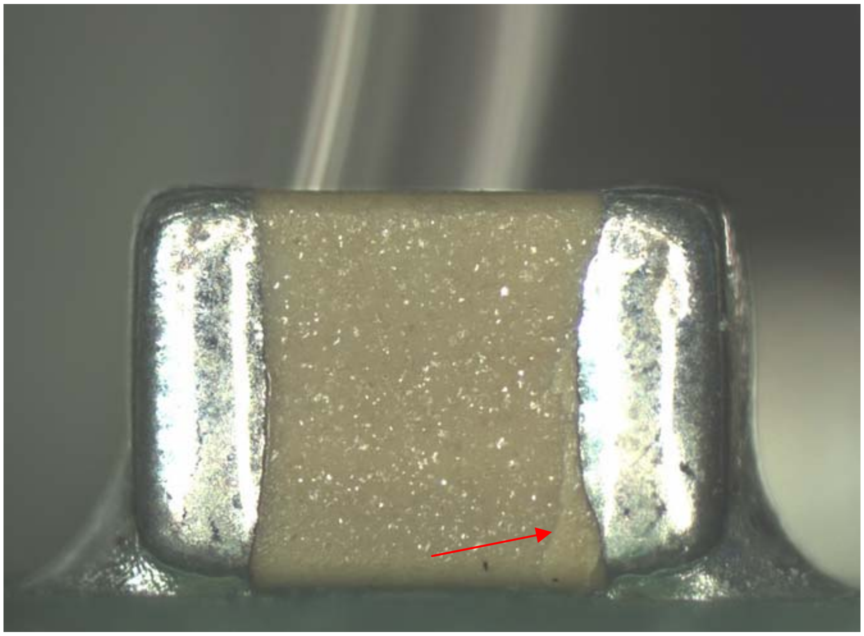


Figure 9: Optical micrograph of a 0805 capacitor attached with SnAgCu solder, flex cracks are identified with the red arrows

Failed 1812 capacitor cross-sections are shown in Figure 10 and Figure 11. The first one is that of a failed capacitor with SnAgCu solder and the second is one with SnPb solder. As shown by the figures, the fillet shape and height are similar. This indicates that the failure behavior is unlikely due to geometric parameters. The morphology of the cracks is typical of flexure fractures of ceramic capacitors.

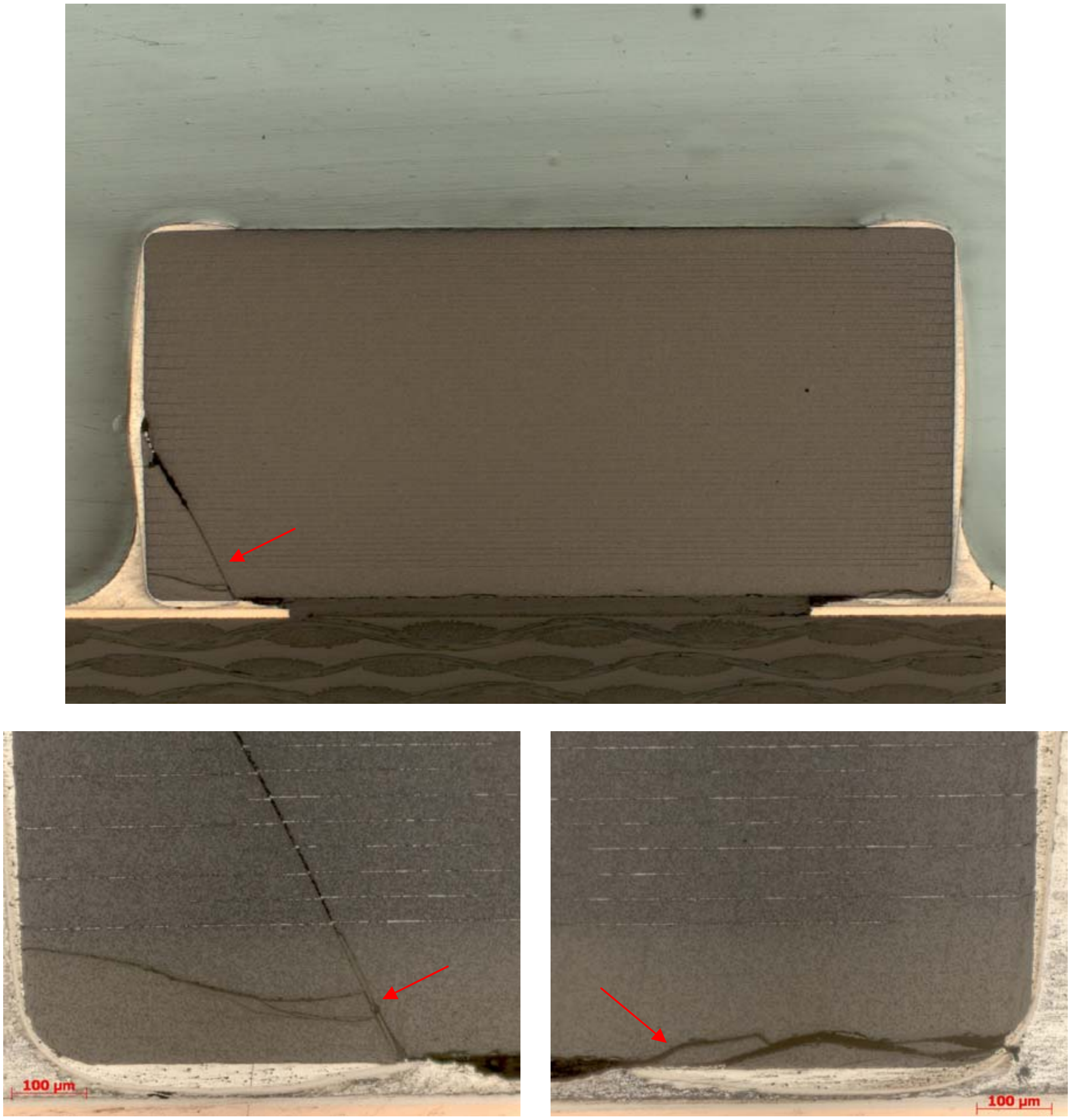


Figure 10: Optical micrograph of a cross-sectioned 1812 capacitor attached with SnAgCu solder, flex cracks are identified with the red arrows

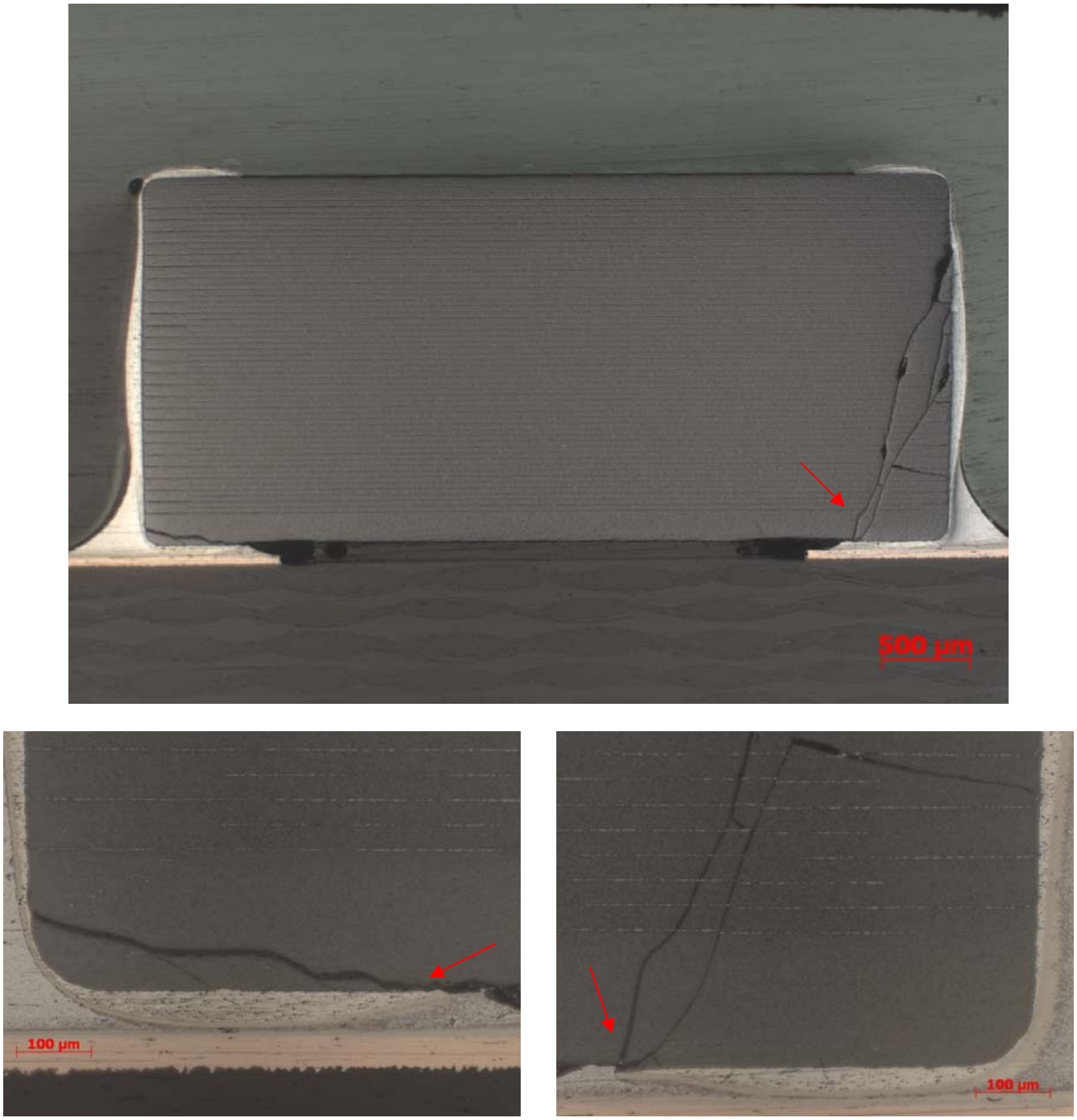


Figure 11: Optical micrograph of a cross-sectioned 1812 capacitor attached with SnPb solder, flex cracks are identified with the red arrows

A failed 0805 capacitor cross-section is shown in Figure 12. The 0805 capacitor shown in Figure 13, while cracked did not register as a failure during the testing. This is due to the orientation of the plates, which prevents the flex crack from fully separating from the terminations.

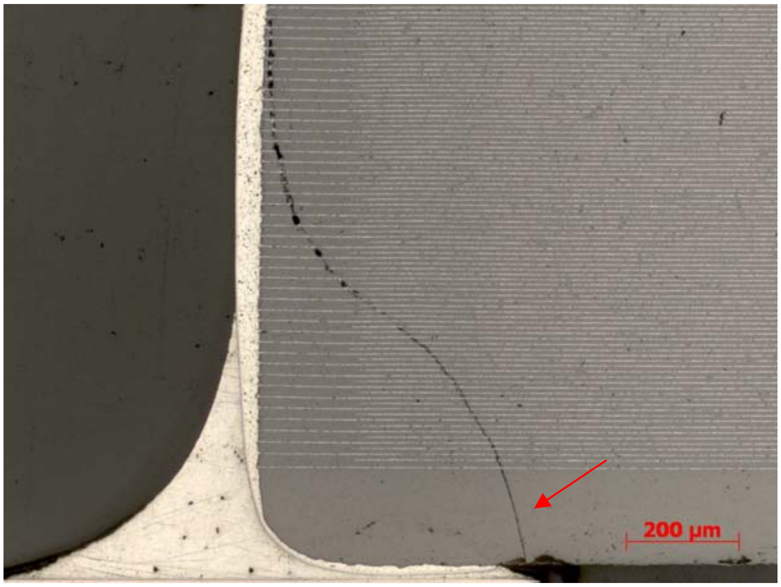


Figure 12: Optical micrograph of a cross-sectioned 0805 capacitor attached with SnAgCu solder, flex cracks are identified with the red arrows

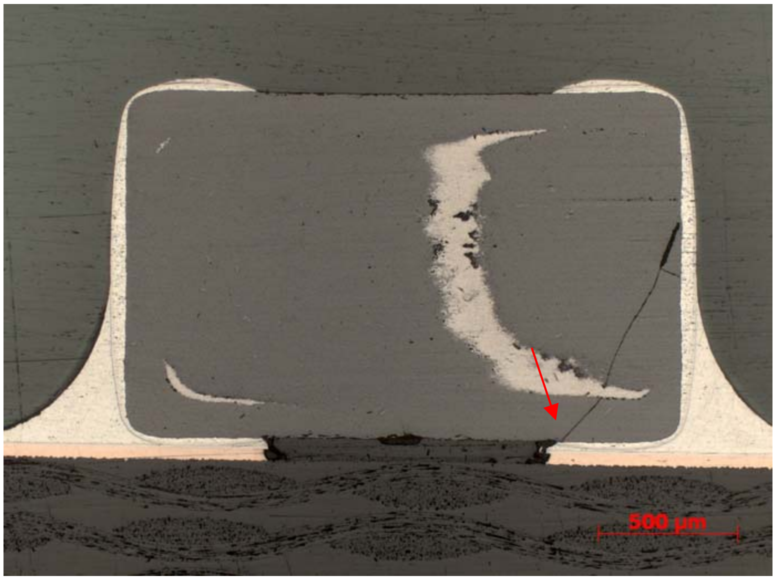


Figure 13: Optical micrograph of a cross-sectioned 0805 capacitor attached with SnAgCu solder, flex cracks are identified with the red arrows

Discussion

For a ceramic chip capacitor, failure due to printed wiring board bending usually manifests itself as a crack in the body of the capacitor, as shown in Figure 14. The crack may intersect the electrodes of the capacitor causing a decrease in capacitance or an increase in leakage current. Many times the failure is catastrophic with opposing electrodes shorting together and destroying the capacitor. The use of an open-mode ceramic capacitor can significantly decrease the probability of a catastrophic failure if a flex crack occurs.

The probability of the capacitor cracking is a function of the stress applied and the distribution of flaws present at the crack initiation site. This makes predicting the failure of ceramic probabilistic based upon the applied stress and the defects as first proposed by Weibull [20].

The results of this study indicate that the Pb-free assembly process will not have a negative impact on the reliability of the ceramic chip capacitors even though the solder is stiffer and the capacitor will be subjected to higher reflow temperatures. This contradicts some previous modeling studies.

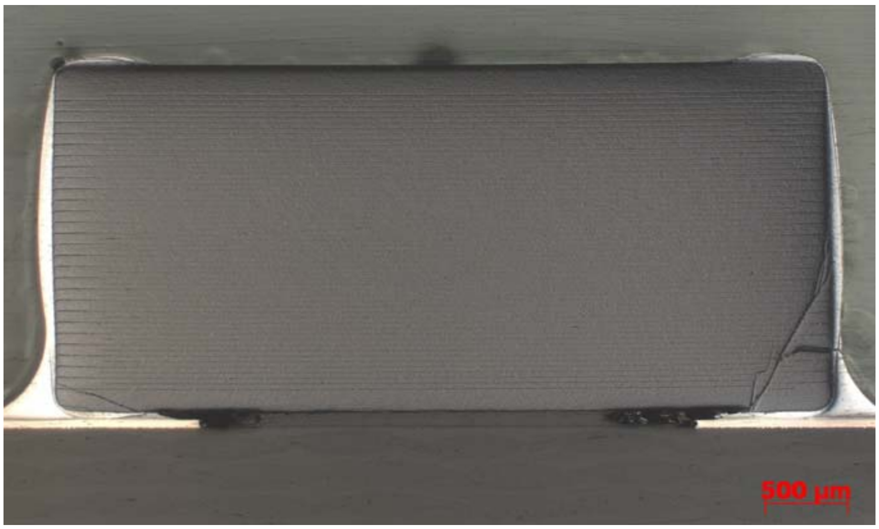


Figure 14: Flex cracking in a capacitor

Previous modeling using finite element analysis indicated that the stresses developed in the capacitor during bending would be higher due to the increased stiffness of the solder, which would lead to more flexural failures [0]. These models assumed that the solder was fully stress relaxed after the assembly process. However, this is not the case with Pb-free solder, as the creep rates for SnAgCu are much slower than that of SnPb. This places the capacitor under compression after assembly. This effectively increases the force required to fail the capacitor, much like the pre-stressed concrete beams used in bridges.

The test results and analytical equations were used to determine the relative magnitude of the residual compressive stresses. These stress and failure equations were utilized with increasing amounts of compressive stresses until the failure behavior matched that of the test results.

The analytical equations used to calculate the stress in the capacitor and have been extensively validated with finite element analysis. The failure equation then uses this stress to make reliability prediction using a model based upon the Weibull modulus and the width of the capacitor. The failure model differs from the test specification because it uses crack initiation as the failure criteria. This yields much more conservative estimates of the reliability of the capacitor.

The key is that any cracks in capacitors should be avoided, not just those that are so large as to cause a significance capacitance decrease. The existence of cracks, even small ones in the capacitor, could be a reliability concern in the field, especially if the capacitor is subjected to vibration or thermal cycling. The analytical equations used to predict the stresses and the failures of ceramic capacitors have been incorporated into a web based calculator. The predictions of capacitor failures for 1 mm board deflection are shown in Figure 15 and Figure 16. The residual stress required to match the behavior of the test results for the SnAgCu was determined to be between 15 and 20 MPa. The 1812 SnAgCu test results verses the predictions are shown in Figure 17. The 1812 SnPb test results verse the analytical equation predictions are shown in Figure 18.

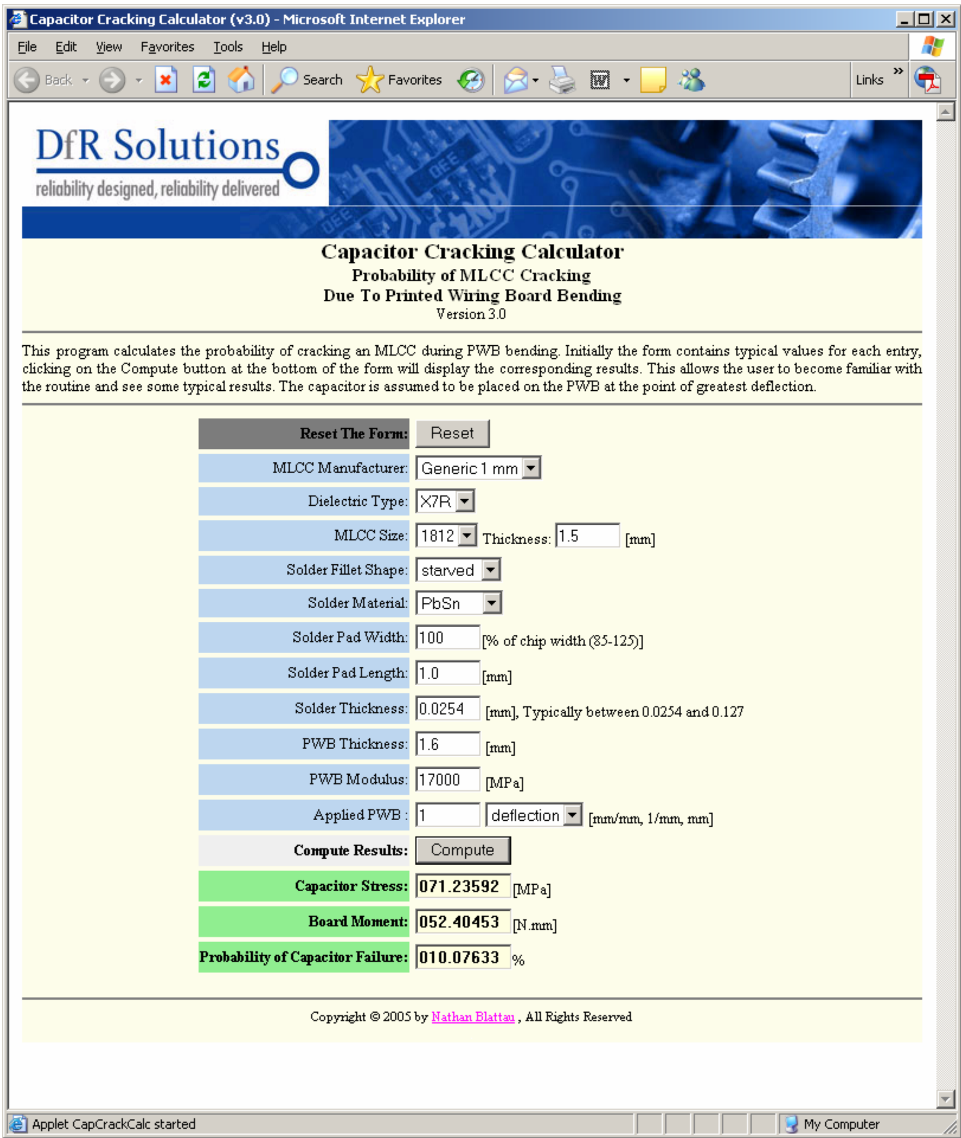


Figure 15: Capacitor calculator predictions with PbSn solder

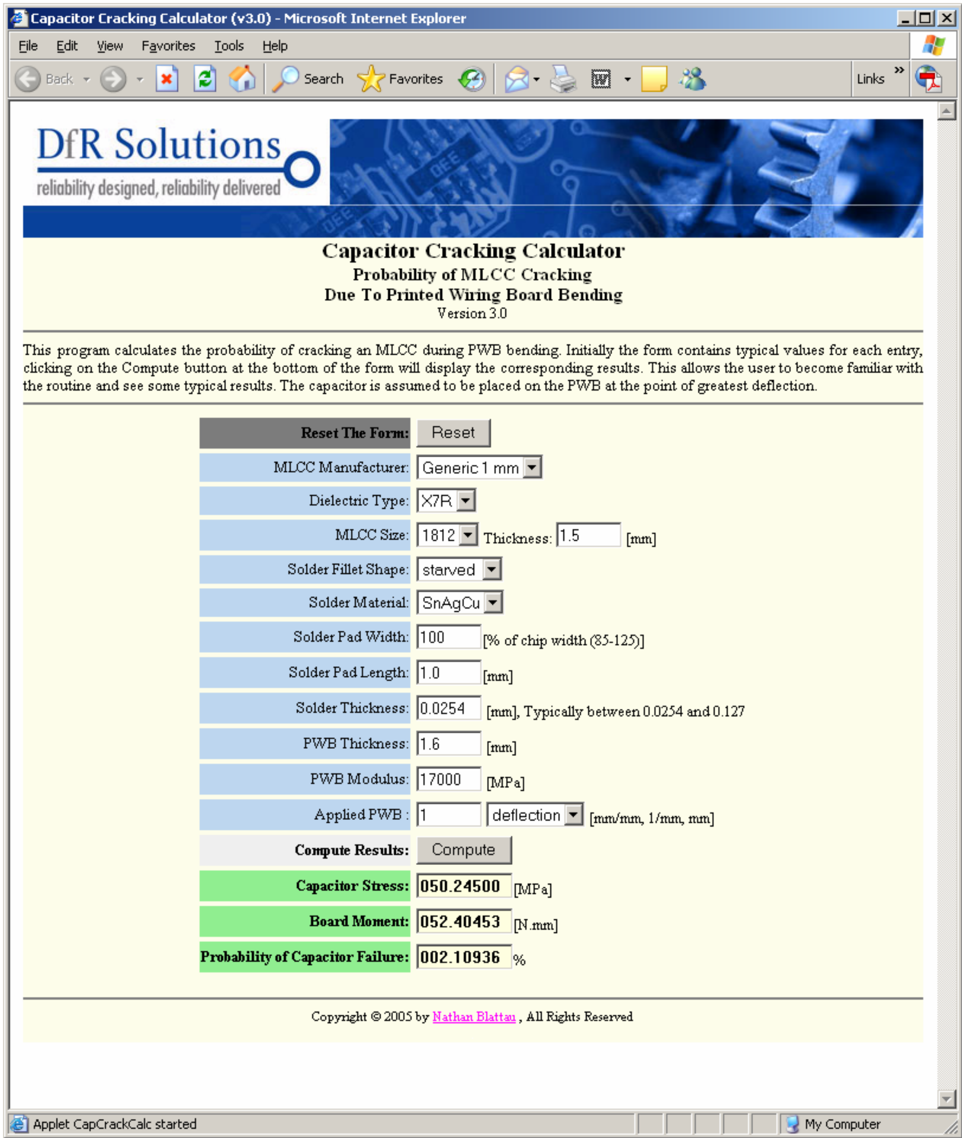


Figure 16: Capacitor calculator predictions with SnAgCu solder

SnAgCu solders can hold significantly higher residual stresses than PbSn [21]. The residual stresses reported were around 18 MPa after 8 hours at 21˚C. The time between manufacturing and testing was much greater than 8 hours and further investigation is warranted. A possible additional explanation for this behavior is the amount of Ni_3Sn_4 intermetallics in the solder joint between the capacitor and the copper bond pad.

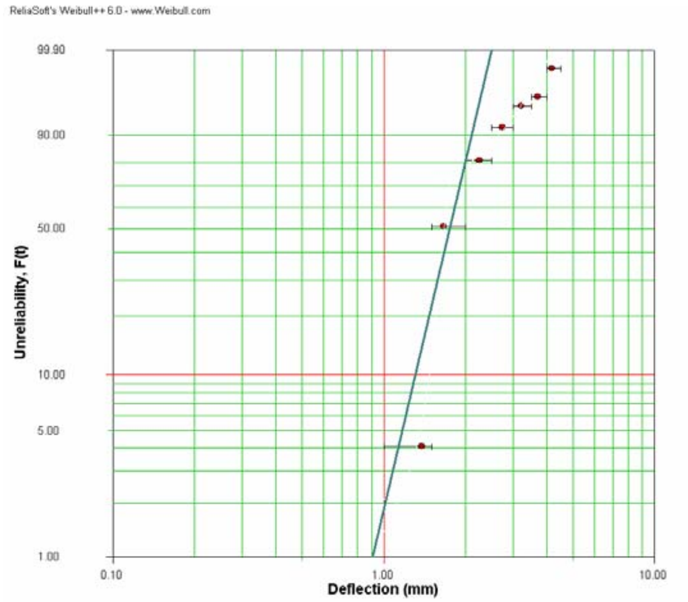


Figure 17: 1812 SnAgCu model predictions (blue line) verses test data

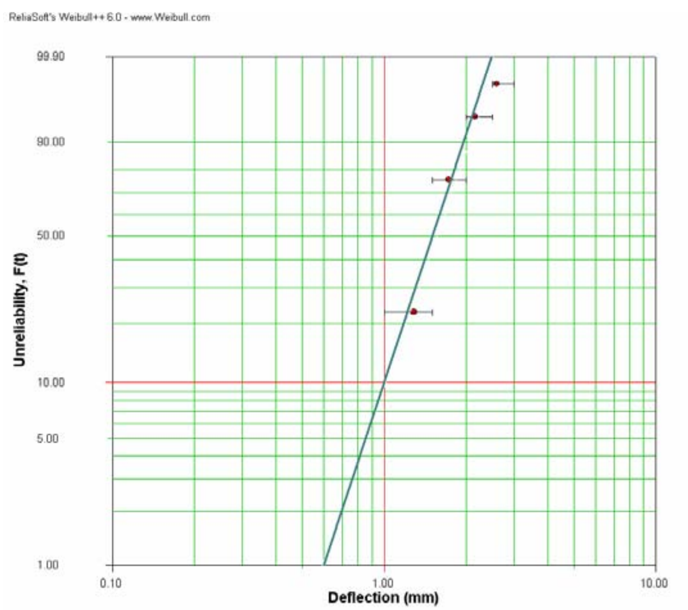


Figure 18: 1812 SnPb model predictions (blue line) verses test data

Conclusion

The extra robustness of ceramic capacitors soldered with SnAgCu is encouraging for the electronics industry. However, the role of residual stresses may raise additional concern with regards to components that may be subjected to residual tensile stresses after reflow. It also raises some concern over the reliability of reworked ceramic capacitors, since reworking may subject the capacitor to tensile residual stresses. The recommendation is that board assemblers not modify their board flexure limits with concern to ceramic capacitors when switching to SnAgCu.

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