Impact of Lead Free Solders on MLC Flex Capabilities

Ken Lai [1], Edward Chen [2], John Prymak [3], Mike Prevallet [4]
KEMET Electronics Asia Ltd. [1,2] / KEMET Electronics Corp. [3,4]
3-4F, No. 148, Section 14, Chung-Hsaio E. Rd., Taipei, Taiwan ROC [1,2]
PO Box 5928, Greenville, SC 29606, USA [2,3]
886-2-2752 8585 [1,2] / 864-963-6300 [3,4] (Phone)
886-2-2721 3129 [1,2] / 864-967-6876 [3,4] (FAX)
kenlai@kemet.com [1] /edwardchen@kemet.com [2] /johnprymak@kemet.com [3] /mikeprevallet@kemet.com [4] (Email)

Abstract

Ceramic capacitors have proven themselves very reliable with extremely low failure rates. As processes capabilities and controls continue to improve, reliability of the dielectric also continues to increase, leaving this capacitor type as an extremely reliable selection. This increase in the reliability of the dielectric has created a shift in the categories of main contributors to the overall failure rate. A recent review of field failure analysis of surface mount MLCCs, has shown that "Flex Cracks" account for as much as 40% of ceramic capacitors failures. Flex cracks are created after the component is mounted and a physical displacement of the board generates sufficient stress within the ceramic body to fracture the ceramic material. The generated crack is nearly impossible to detect electrically as the failure shows a time dependence allowing the circuit to be shipped with faulty capacitors on the boards. As the industry moves to lead free soldering systems, which are less ductile, there have been concerns raised concerning the flex capabilities for these new systems. Previous papers have been presented showing that the move to lead-free solders has a detrimental impact on MLC capacitors due to an increase in flex crack occurrences.

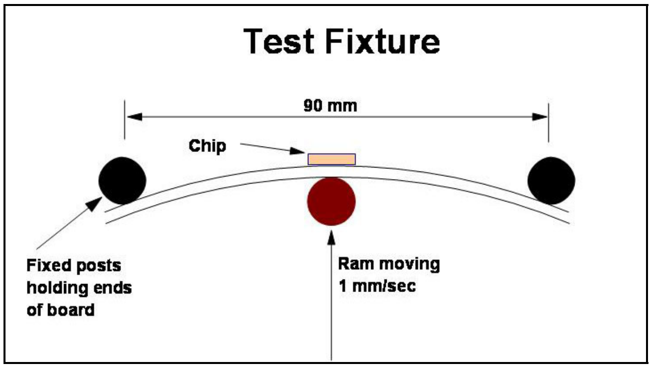


Figure 1. Flex Testing Fixture [1]

This paper was written in response to customer concerns of flex performance as they switch from lead based to lead free soldering processes. In this paper, we present the results of flex testing, comparing standard lead based solders to lead free solders.

Preparation of Samples

The objective of this study is to determine the effects of lead free solders and solder process on the flex crack failure rate. To get an accurate picture of the effects across a variety of sizes, the following case sizes were selected for this study: 0603, 0805, 1206, and 1812. All components were processed in typical fashion, with the terminations finished as 100% Sn plating over nickel. The lead based solder used as a control for this study was a 63-37 Tin Lead (SnPb) solder, and the 'Lead Free' solder (Pb-Free) used was a SAC 305 (SN 96.5%, Ag 3% Cu 0.5%). The solder was dispensed with a metering pump to ensure constant solder amounts. The amount of solder dispensed for each case size was validated before during and after the parts were mounted. The soldering profiles followed the solder paste manufactures recommendation.

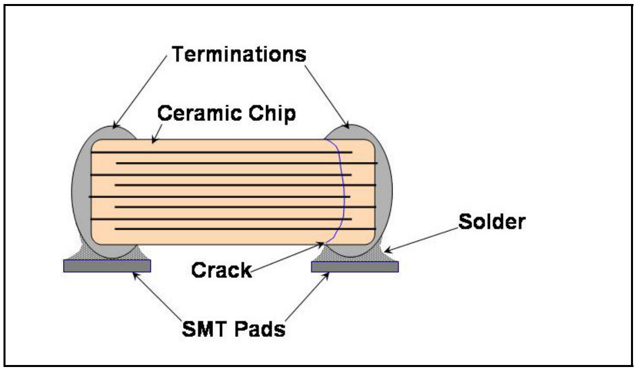


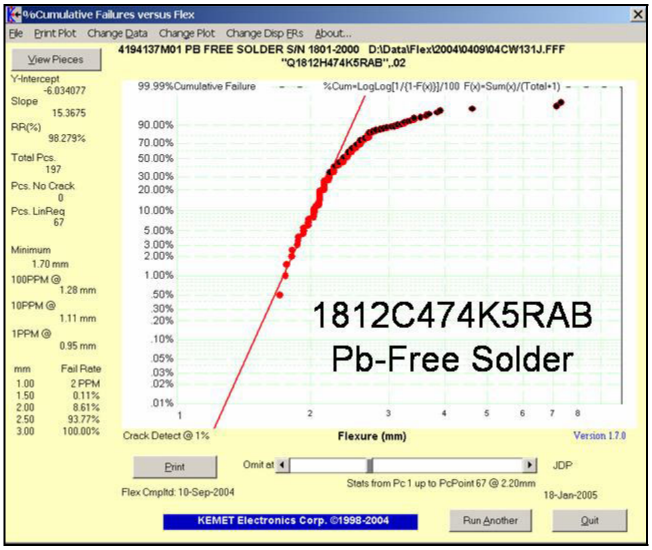
Figure 2. Flex crack signature

The 'Flex Crack'

The flex crack itself is denoted with a specific signature as the crack starts on the bottom side of the chip, at the end of the termination wrap that extends beneath the chip. It always, Always, ALWAYS, starts at this specific point, and then moves as a straight line perpendicular or angled to the bottom face or as a curved arc upward into the capacitor body (Figure 2). The problem is that once the crack is created, it is nearly impossible to detect. All too often, it is a failure found by the circuit's end customer.

Testing

Four-hundred (400) pieces from each part type were mounted on test boards. Two-hundred (200) using Pb-Free solder, and two-hundred (200) using standard SnPb solder. The boards were then flexed at a rate of 1 mm/Second, to a maximum of 10 mm. Continuous capacitance measurements were made and recorded while the part was under test. The flex increases until a crack is detected (a crack is defined as a sudden change of a prescribed limit in capacitance, ±2% in these tests), or until the 10 mm flexure is achieved. [1]



4194137M01 PB FREE SOLDER S/N 1801-2000 D:\Data\Flex\2004\0409\04CW131J.FFF
"Q1812H474K5RAB",.02

Y-Intercept -6.034077
Slope 15.3675
RR(%) 98.279%
Total Pcs. 197
Pcs. No Crack 0
Pcs. LinReq 67
Minimum 1.70 mm
100PPM @ 1.28 mm
10PPM @ 1.11 mm
1PPM @ 0.95 mm

mm	Fail Rate
1.00	2 PPM
1.50	0.11%
2.00	8.61%
2.50	93.77%
3.00	100.00%

Crack Detect @ 1%
JDP
Stats from Pc 1 up to PcPoint 67 @ 2.20mm
Flex Cmpltd: 10-Sep-2004
18-Jan-2005

Figure 3. Weibull plot of 1812, 0.47 uF, X7R

Figure 3 shows the Weibull plot of 'Cumulative Percentage' failures versus Flexure (in mm) for an 1812 capacitor mounted with a Pb-Free solder. By means of linear regression, a calculated failure rate line is generated using the lower end of the Weibull distribution (in this instance, using the lower 67 data points from 197 pieces recorded). This line is used to predict the expected failure rate at a given displacement. Almost all of the data collected in these tests show some tendency for bimodal distributions, and it is on that lower grouping that we will concentrate.

The fitted failure rate line is also used to extrapolate the amount of flex required for 1 PPM, 10 PPM, and 100 PPM failure rates, even though the sample size is only 200 pieces, typical for this test. These are failure points the end user should be most interested in. Comparing these results as one graph to another can get confusing, so the data presented here will compare multiple tests for like components on a single plot.

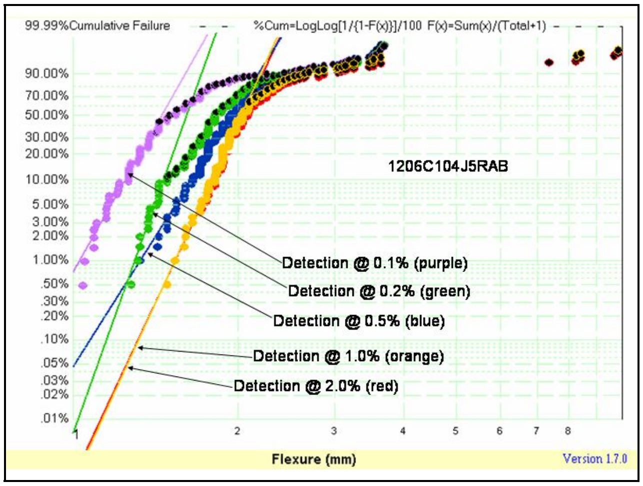


Figure 4. Different detection levels for the same part test data.

Because continuous data for each part is stored, there is an ability to review post-test data to investigate different crack detection limits, as long it is below what the "test" limit was set to. Figure 4 shows the Weibull distribution of a single test group plotted at various detection settings. There is little difference between 2.0% and 1.0% levels, but when 0.5%, 0.2%, and 0.1% levels are analyzed, random noise in the measurement gives a false indication that a crack has occurred. Selecting the appropriate crack detection limit is important. If a chip with 10 layers is flexed and a crack occurs across a single layer will result in a capacitance loss of 10%. Likewise, a crack across a single layer of a capacitor with 100 layers will result in 1% loss in capacitance, a capacitor with 500 layers or more, loss of a single layer will result in less then 0.2% loss in capacitance. It is important to evaluate the design and data to determine the appropriate detection limit. It is also important to realize that the crack may only take a segment of the electrode away, and not the entire electrode. After reviewing all the data, it was determined that a 1% detection limit was acceptable for all but 0603 case size for this study. If the detection level is in the noise region, then continuously decreasing the level will cause a significant shift in the plots. While the detection level is above the noise, the plot displacements should be minor.

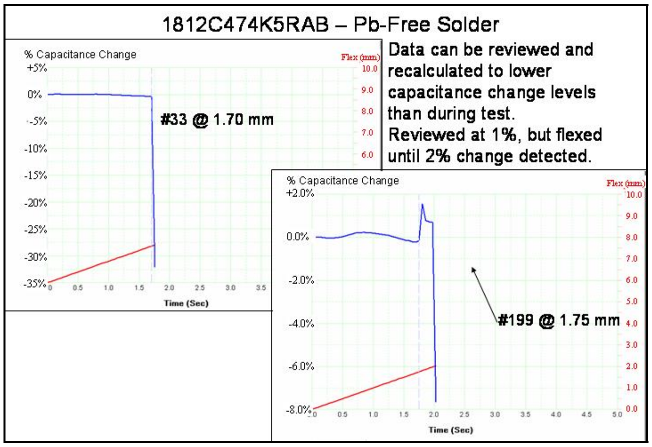


Figure 5. Actual data for the two lowest readings.

Figure 5 shows the capacitance verses millimeters during the application of flexure for the two pieces represented with lowest readings from the sample of the 1812 part types. Because of the piezoelectric effect inherent in high K dielelectrics like X7R, capacitance will typically decrease as physical stress is generated across the capacitor. The sudden decay in capacitance for piece #33 at 1.70 mm shows that the crack has propagated through the electrodes, creating a sudden drop in capacitance, losing nearly 35% capacitance beginning at that specific flexure.

The capacitance monitored looks for any sudden change in capacitance (decreasing or increasing) between sequential or consecutive readings. The 'Capacitance versus Time' plot for piece #199 (plot on the lower right of Figure 5) shows that the capacitance actually increases suddenly at 1.75 mm (+1.5%). This may be the result of the flex crack only occurring in the margin area or in the solder fillet, but not in the active layers of the capacitors. This type of crack may actually allow for a mechanical slip, a result that relieves the cumulative strain generate by the flexure. This release or immediate drop to a lower strain, changes the force applied to the component and through the piezoelectric properties, this results in a sudden capacitance gain.

It is also interesting to note that for piece #199 of Figure 5, the original ±2% limit did not detect the initial point of capacitance change, but captured the secondary, larger expansion of the original crack – one that appears to have severed one or several electrodes at 2.0 mm. With this 2% limit the flex crack was detected at 2.0 mm, but on further investigation, the initial crack occurred at 1.75 mm as the mechanical stress is relieved. A review of the individual plots is also a method used for justifying the change in detection level.

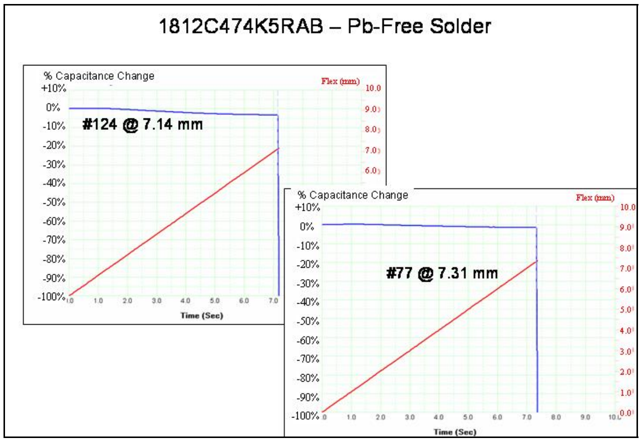


Figure 6. Two of the higher flex failures.

Cracks that occur in the higher flexure regions are most likely to cause severe drops in capacitance, because at this point in the test, there is a huge amount of potential energy in the system, which is suddenly released into the capacitor. The capacitance decays here are sudden and usually drop to near zero capacitance (-100%). This decay to zero is shown in Figure 6 for two of the pieces some of the higher points of crack detected. In both of these examples, the capacitance drops to -100% of the initial value.

Test Results

It is commonly believed that because the Pb-Free solders are less ductile[2], they would be less likely to absorb the forces generated, causing a larger failure rate for a given amount of flexure. When comparing these results, picking points of interest from the data might highlight the differences, but showing the Weibull plots of the cumulative percent failures versus the flexure for the two groups on a single plot might be more revealing.

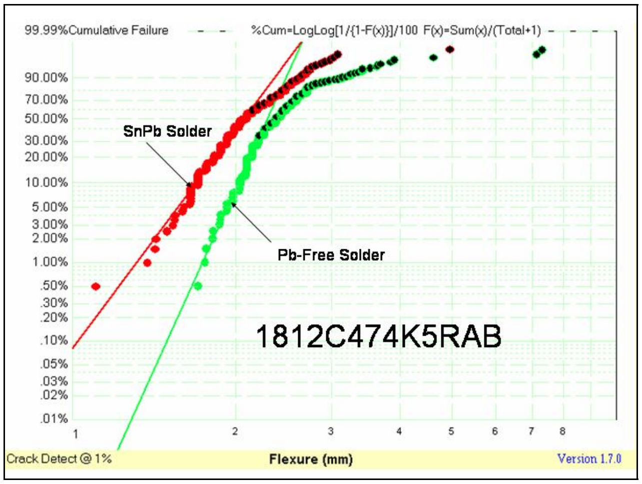


Figure 7. Flex performance 1812, 0.47 uF X7R, Pb-Free vs. SnPb Solders

Consider the plots shown in Figure 7. The data is representative of the two test groups of 1812 capacitors, both of 0.47 uF capacitance, 50 VDC rating, and based on an X7R dielectric. Again, these parts are from the same manufacturing batch, processed through termination (100% Sn plating over nickel) and then randomly divided for these two solder test groups.

The SnPb soldered (63/37) pieces appear as the grouping on the left (lower flexure) and the Pb-Free soldered pieces are part of the grouping on the right (higher flexures). This difference contrasts common belief that Pb-Free solders would cause an increased failure rate at a given displacement, or that their distribution would be lower than the tin-lead soldered pieces. The lowest horizontal line represents 0.01% or 100-PPM failure rate. Looking at the 'Pb-Free' extrapolation of the linear fit in Figure 7 shows the projected 100-PPM failure rate to be 1.28 mm, whereas for the 'SnPb' soldered parts at the 100-PPM failure rate will be well below 1.0 mm (0.80 mm).

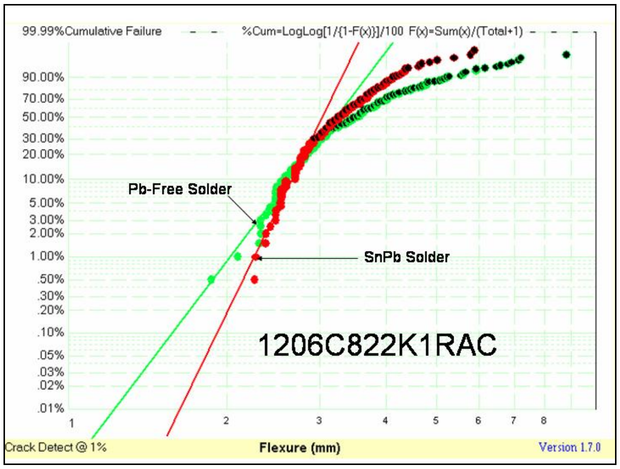


Figure 8. Flex performance 1206, 8.2-nF, X7R, Pb-Free vs. SnPb Solders

Moving down in chip size to 1206, the Weibull plots for the 8,200 pF, 100 VDC, X7R parts (Figure 8) show a comparison that contradicts the previous part type. Although the fitted lines cross near the 30% 'Cumulative Failure' rate, it would be hard to imagine any manufacturer satisfied with this level or above. The focus must be with the lower failure rates. In this region, at 1% and lower failure rates, the 'SnPb' soldered parts define an advantage over the 'Pb-Free.' Again, looking at the bottom line (100-PPM) of the plot, the difference between the Pb-Free (at 1.22 mm) and the SnPb (at 1.63 mm) highlights the difference between these two groups. In this group, the SnPb pieces have to be flexed to a higher amount to create the same 100-PPM failure rate as the Pb-Free.

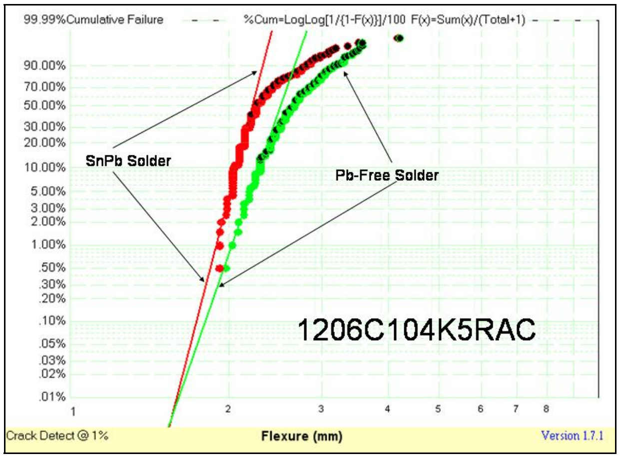


Figure 9. Second 1206 sample of higher nominal capacitance.

This 1206 size chip (Figure 8) represents a higher voltage and lower capacitance than typical for this device. We also tested a lower voltage, higher capacitance unit, of 0.10 uF and 50 WVDC. This device showed a distinct separation between the 'Pb-Free' and the 'SnPb' solders at the higher failure rates (>1%), the median failures, and up through the higher failure rates (Figure 9); but the distributions begin to be very similar in the lower failure rates (near 100-PPM).

The next smaller size chip involves the 0805 style as shown in Figure 10. This device is a 0.22 uF, 25 VDC, X7R capacitor. In this plot, the results for the two groups are separated into two distinct, parallel distributions: the Pb-Free data consistently to the right (higher flex capability) of the SnPb distribution. The 100-PPM points are 2.37 mm for the Pb-Free, and 2.07 mm for the SnPb groups.

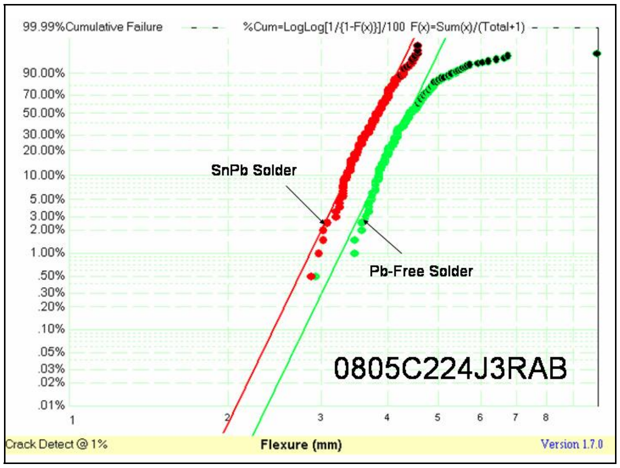


Figure 10. Flex performance 0805, 0.22 uF, X7R, Pb-Free vs. SnPb solders.

The two Weibull plots for smallest of the capacitor size tested, the 0603, 0.22 uF, X7R plots (Figure 11) are overlaid and shows that there is almost an equal performance between Pb-Free and SnPb solders at the bottom of the graph. Since this is a high capacitance part number with many layers, the crack detection limit was set to 0.5%. The crossover point appears to be near 200-PPM (0.02%) with very little difference at levels near and above or below the crossover point. In this comparison, the SnPb group shows slightly better performance for the 100-PPM and lower failure rate levels.

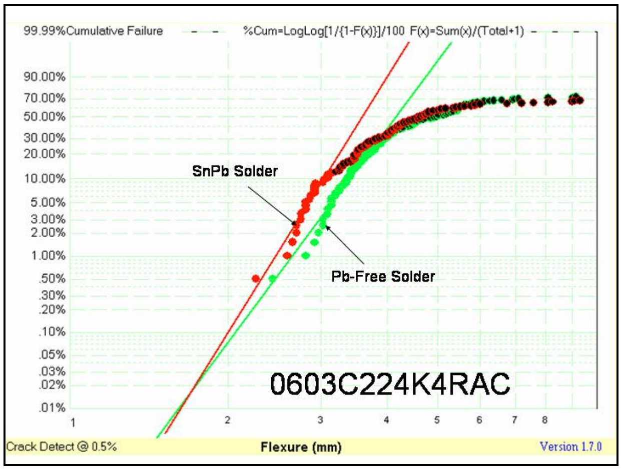


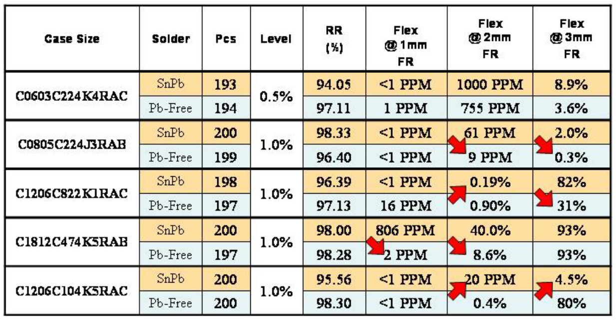
Figure 11. **Crack detection changed to 0.5% for the high layer count of the 0603 chip.**

Summarizing the calculated flex to achieve the lower levels of PPM (Table 1) shows that in one case (1206 small capacitance) the 'SnPb' solders performed significantly better (higher flexure to achieve specified failure rate), while in two other case sizes (1812 and 0805), the 'Pb-Free' solders performed significantly better. The remaining test (0603 and large capacitance 1206) did not show a discernable advantage of one over the other. The red arrows note where one solder type had a clear advantage over the other.

Case Size	Solder	Pcs	Level	Minimum Detected (mm)	100-PPM FR (mm)	10-PPM FR (mm)	1-PPM FR (mm)
C0603C224K4RAC	SnPb	193	0.5%	2.25	1.62	1.32	1.07
	Pb-Free	194		2.42	1.61	1.26	0.98
C0805C224J3RAB	SnPb	200	1.0%	2.86	2.07	1.76	1.50
	Pb-Free	199		2.92	↘ 2.37	↘ 2.01	↘ 1.71
C1206C822K1RAC	SnPb	198	1.0%	↗ 2.25	↗ 1.63	↗ 1.38	↗ 1.17
	Pb-Free	197		1.86	1.22	0.95	0.73
C1812C474K5RAB	SnPb	200	1.0%	1.10	0.80	0.62	0.48
	Pb-Free	197		↘ 1.70	↘ 1.28	↘ 1.11	↘ 0.95
C1206C104K5RAC	SnPb	200	1.0%	1.92	1.59	1.46	1.34
	Pb-Free	200		2.03	1.66	1.48	1.31

Table 1. **Extrapolated PPM Failure Rate Flexures**

Another way to look at the data is to calculate the failure rate at 1mm, 2 mm, and 3 mm of flexure. There are still many customers defining 2 to 3 mm flex tests for X7R and C0G, respectively. Using this method, only at lower stress levels and even then only half the trials we see an improvement of one soldering system over another. There is no clear-cut winner. The results for the 1206 chip size flip-flop comparing the failure rates at 2 mm and 3 mm. The 0603 has no significant differences, while the 0805 and 1812 show significant advantages for the Pb-Free solder type.



Case Size	Solder	Pcs	Level	RR (%)	Flex @ 1mm FR	Flex @ 2mm FR	Flex @ 3mm FR
C0603C224K4RAC	SnPb	193	0.5%	94.05	<1 PPM	1000 PPM	8.9%
	Pb-Free	194		97.11	1 PPM	755 PPM	3.6%
C0805C224J3RAB	SnPb	200	1.0%	98.33	<1 PPM	61 PPM	2.0%
	Pb-Free	199		96.40	<1 PPM	↘ 9 PPM	↘ 0.3%
C1206C822K1RAC	SnPb	198	1.0%	96.39	<1 PPM	0.19%	82%
	Pb-Free	197		97.13	16 PPM	↗ 0.90%	↘ 31%
C1812C474K5RAB	SnPb	200	1.0%	98.00	806 PPM	40.0%	93%
	Pb-Free	197		98.28	↘ 2 PPM	↘ 8.6%	93%
C1206C104K5RAC	SnPb	200	1.0%	95.56	<1 PPM	20 PPM	4.5%
	Pb-Free	200		98.30	<1 PPM	↗ 0.4%	↗ 80%

Table 2. **Calculated Failure Rates for given flexure.**

Upon investigating the solder joints, it was noted that the SnPb solder had a better wetting over the whole pad area when compared to the Pb-Free solder (Figure 12). The reduced wetting with the Pb-Free solders effectively reduces the pad width. Pad width is known to have an impact on flex performance [4]. A pad that is smaller then the termination width will have a better flex performance then a pad that is larger then the width of the termination. This effect of wetting may explain the improved performance Pb Free solder over the SnPb solder in some of the experiments.

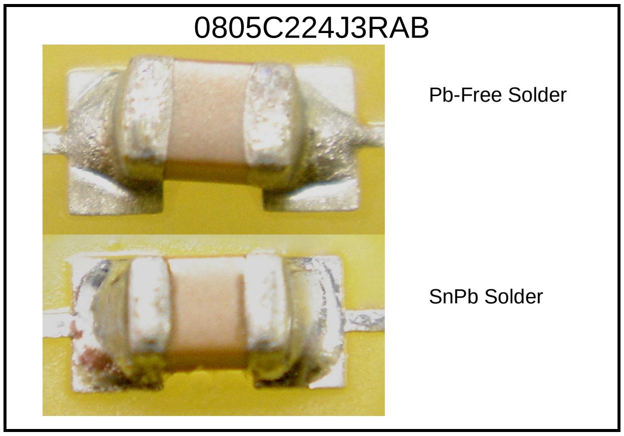


Figure 12. **Solder fillet difference.**

Conclusions

There have been concerns that moving away from lead based solders to Pb-Free solders will increase the flex failure rate. In this paper, we showed the results are mixed, and that there is no clear-cut winner a majority of the time. With some cases sizes, the Pb-Free solders performed better and other parts the SnPb parts performed better. And in one instance, the SnPb solder parts perform better at low flex and at a higher level, the Pb-Free based solders perform better. There may be other factors that may affect flex performance, including wetting of the solder, and pad layouts, that may have an interaction and affect the flex performance.

References

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