CAPACITANCE MONITORING WHILE FLEX TESTING

Jim Bergenthal & John D. Prymak
KEMET Electronics Corp.
P.O. Box 5928
Greenville, SC 29606
(803) 963-6300

Flex Cracks

As most other modes of failure have been dramatically reduced over the years, cracking due to stresses from boards bending have gained prominence.

The common printed circuit board (PCB) built of G10 or FR4 glass epoxy materials will easily bend under moderate forces. Almost all processes involved in populating these boards can involve bending the board - many times unknowingly. High stresses transmitted to small areas of the board are of greatest concern. Manufacturing efficiencies improved by processing small PCBs as a group of multiple circuits within a singular "mother board." Depanellization, where the individual circuit boards are isolated from the "mother board," is one area where extremely high stress forces can be transmitted to the boards near the edges being cut. "Snap together" methods of assembly are also prone to creating these localized stress areas. The boards may be placed in a holder between process stages, where the outside edges are held and the board is allowed to droop in the middle. The board may be fitted into a cabinet or slot with a force that causes bending near an edge. Communication cables may be mechanically attached to an unsupported edge, translating all forces applied to the cable back to the board. These are just a few of the more common areas where board flexing can occur in assembly. These may be compounded if the board is later worked on in repair - especially by an impatient technician with a rubber hammer.

The bending of the board causes forces to be transmitted through the solder attach fillets to the surface mount chip. These forces are concentrated at the bottom of the chip, where the termination bands end. The mass of solder is important as this material is malleable, and slight amounts will move more freely. Forces applied very slowly will also allow the solder to stretch and absorb some of the force. Also keep in mind that all the thermal shock studies support a moderate amount of solder with excessive solder leading to a greater susceptibility to this fault.

The ceramic material is hard, nonelastic, and brittle. The shear force pulling at the ceramic along the termination edge will lead to a crack if the forces are sufficient. At what force the chip cracks is thought to be dependent upon the ceramic material, the amount of solder, the termination material and amounts, and possible defects or anomalies within the ceramic structure.

Figure 1 details a typical flex crack at one of the termination ends. Remember that this is two-dimensional representation of a three-dimensional phenomenon. The crack always starts near the edge of the termination margin, then extends upward toward the termination face. The angle that this crack takes is usually around 45°. The crack may extend into the termination face, thereby separating a corner section. It may also turn upward, continuing toward the top face of the chip, where it will usually turn out towards the top termination margin's edge. This crack may cause the entire end of the chip to be separated from the main body of the chip.

The angle may change with different dielectric types and applied forces. The crack's exit usually takes place beneath the termination margin and is not apparent with visual inspection. As the force is applied, the crack allows some separation along its path, thereby causing some disconnection of the electrode plates. Be aware that as this force is removed, the separation may be eliminated, allowing the disconnected electrode to return and connect again. Because of this return, it is possible to test a "cracked" chip for capacitance, dissipation factor, and insulation resistance, after momentary exposure to these forces, and still read this unit as a good capacitor with no apparent fault.

Flex Testing

This testing called "flex", "bend", or "warp" testing was instituted to detect a susceptibility to these forces. There were different approaches to what constituted a replication of this force, but the board layout was consistent. As in Figure 2, the board dimensions are 100 mm x 40 mm x 1.6 mm and of the G10 or FR4 type that is detailed in EIA-J RC 3402. The chip is to be mounted at the center of the board, with its opposite termination pads straddling the center line of the board. As with all surface mount applications, the amount of solder and the dimensions and separation of the pads is crucial to obtaining a good mounting of the chip. These pad dimensions varied with chip size but always maintained the chip at the center location of the board.

The apparatus for flexing the chip consisted of a ram along

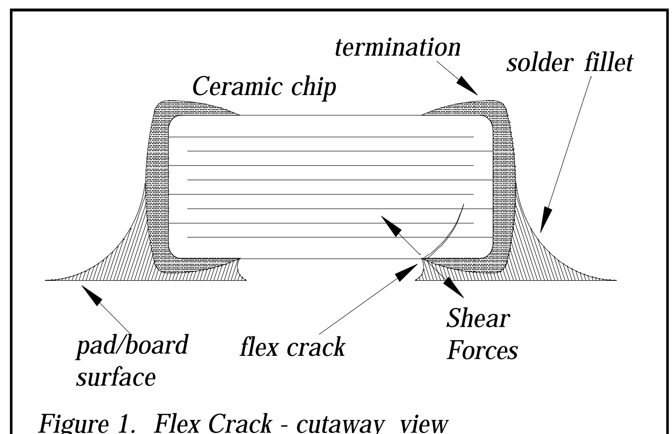


Figure 1. Flex Crack - cutaway view

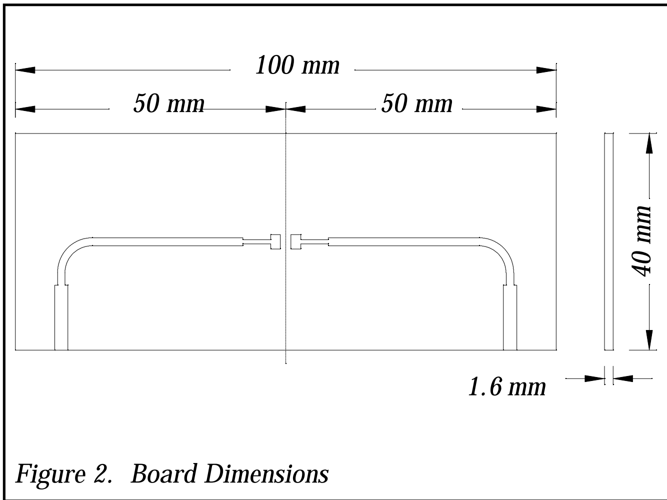


Figure 2. Board Dimensions

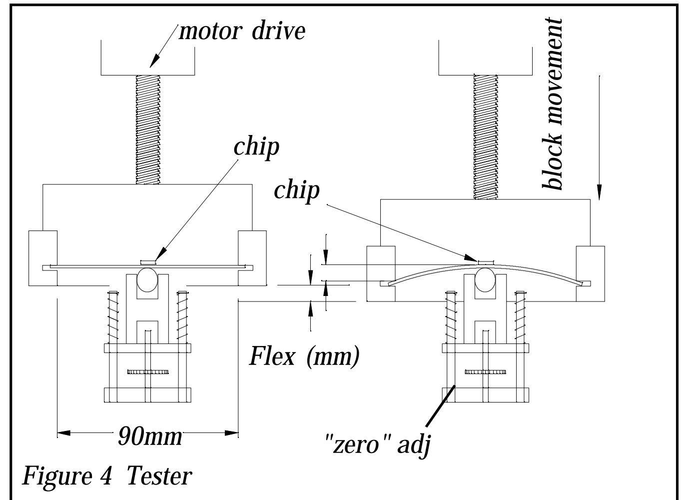


Figure 4 Tester

the center line of the board, pressing into the board at a constant rate. The board was held along its edges, at a spacing of 90 mm as seen in Figure 3. The application of the ram into the board was at a constant rate of 20 mm per minute.

We used a stationary ram and moved the block, holding the board down onto the ram as in Figure 4. The movement of the ram into the board was the result of a motor attached to a screw drive, controlling the movement of the block. The motor was a constant speed DC motor which allowed us to control the direction of the block movement. By selecting the right gears, we were able to achieve a speed of 22 mm per minute.

The specification EIA-J RC 3402 details the ram as having a radius of 340 mm with a 20 mm width. The length of the ram was to be greater than the width of the board, allowing it to extend beyond both edges of the board while applying the force all along the center line. This ram was initially built for applying board deflections of 1 mm, not 12 mm. The higher deflection is required to generate significant numbers of failures. We needed to consistently generate > 50% failures to get an understanding of reliability and to allow comparisons.

There was already some history established with our tester and we were locked into testing for specific customers. Changing the ram from 5 mm to the 340 mm radius also restricts maximum curvature that can be applied to the board. If a board were to bend uniformly between the 90 mm edges, then at 3 mm, the radius of the ram would form a perfect fit for the curved surface of the board. Bending beyond this would cause a concentration of the increasing curvature along the outside edges of the ram, at 20 mm separation (Figure 5). There would be decreasing radius of the board beneath the chip, but this would be indeterminate and unrelated to the travel of the ram.

The proposed EIA specification, EIA Proposed Draft PN-2271, defines the radius of the ram as 140 mm. If the board was to bend uniformly between the 90 mm edges, this ram would form a perfect fit to the surface of the board at 7.5 mm deflection. I have seen papers where this ram was used in testing up to 12 mm of deflection. Testing beyond 7.5 mm now becomes suspect.

The board does not bend uniformly (Figure 6). It will tend to curve more along the edge of the applied force, with decreasing curvature as the distance from its application point increases. Its shape is more parabolic than that of a uniform arc. Because our ram radius of 5 mm is so small, there will never be a point of radius fit to the curvature of the board. The rate of increasing curvature of the board will be at an accelerated rate over that based on the assumptions of an ideally curved board; but the comparisons are all with the same equipment, material, and conditions. In fact, because of this parabolic effect exhibited by the

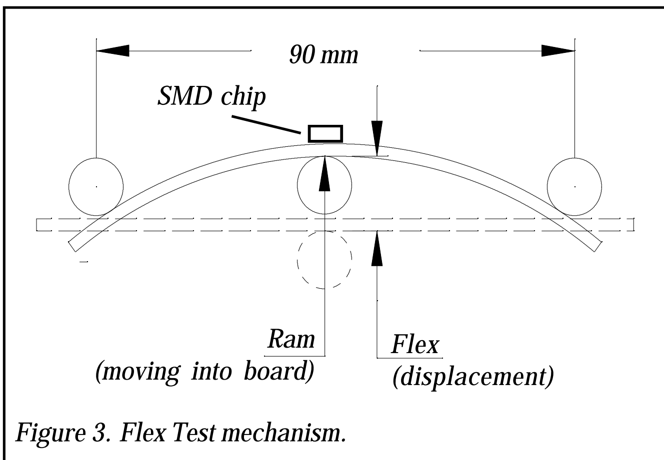


Figure 3. Flex Test mechanism.

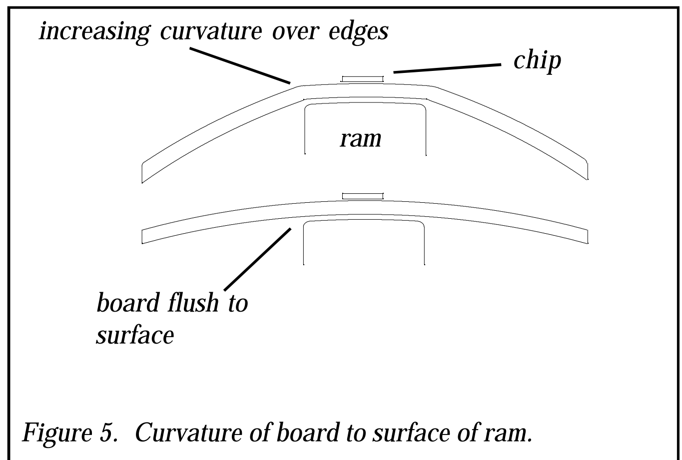


Figure 5. Curvature of board to surface of ram.

©1994 IEEE

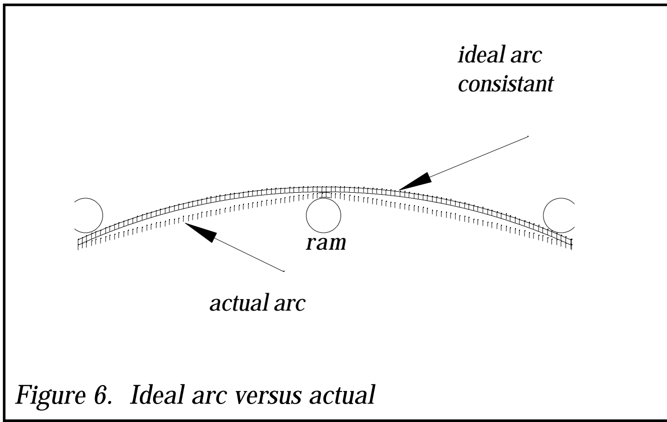


Figure 6. Ideal arc versus actual

board, the 340 mm radius ram will actually fit the board before 3 mm, and the 140 mm ram will also fit before 7.5 mm.

Test Criteria

Now that we have defined the equipment and materials, the procedure for testing and criterion needs to be established. Here is where most of the variations occur with this test. The requirement listed in the JIS C 6429 document details that the board be flexed to 1 mm, held there for 5 seconds, capacitance measured, then returned to a "no flex" state. Capacitance is compared to the initial value to determine if a crack has occurred. With consideration that the X7R, Z5U, and Y5V dielectrics have a high piezoelectric characteristic, they allow the capacitance to change 12% for these devices before it is declared to have failed. For NP0 dielectrics, the allowable change is 5% or 0.5 pF, whichever is greatest. Consider that with any capacitor built with more than eight effective layers, loss of one layer will relate to a capacitance loss of less than 12% and go undetected to the 12% requirement.

One variation of this test was to bend the board a number of cycles and then afterwards, measure for a capacitance shift. Another variation required that the chips, after flex exposure, be placed in a humidity chamber at elevated temperatures and relative humidity, then measured for insulation resistance 24 hours later. Still another variation called for flex exposure in increasing magnitudes of 0.5 mm up to 10 mm, with capacitance checks in between each progressive bend.

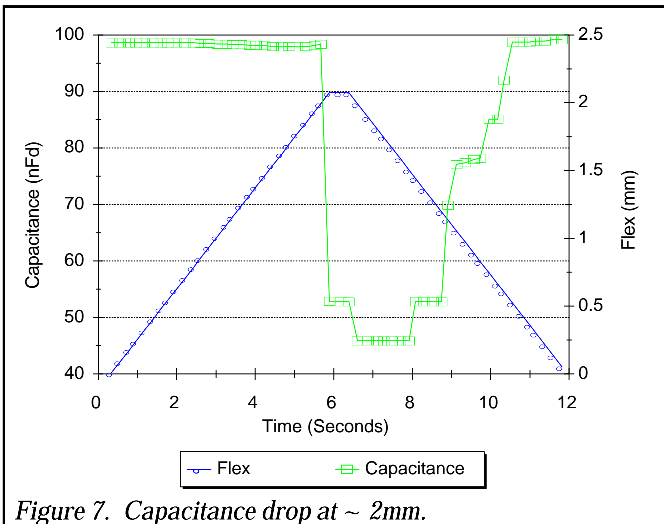


Figure 7. Capacitance drop at ~ 2mm.

The criteria for these methods all resulted in a "go and no-go" declaration. Multiple groups subjected to this testing could result in being "all good" or being "all bad." There was no way of distinguishing among the "all good" batches or among the "all bad" batches. Manufacturing changes involving design, process or material changes were lost many times within these common declarations where there appeared to be no difference among the groups. We needed a more finite declaration of the test to indicate exactly when did each unit fail.

Monitoring Capacitance

The specification JIS C 6429 does outline a procedure where the capacitance is tested while the board is under flex, yet all the published data that I had been aware of ignored this. The boards were built with traces extending to the edges that allowed capacitance or insulation resistance testing of the chips before and after flex exposure; yet these traces could also be used to monitor the unit while it undergoes the flex test. Combining a computer to monitor the capacitance with time allowed an instantaneous translation of time to distance, and a comparison of capacitance with flexure was now available. Using an optically isolated relay board controlled by the computer, the entire test apparatus was automated to allow the computer to control the initiation and then monitor the capacitance versus flex.

A typical response is shown in Figure 7. Each square and circle represents the capacitance from the meter and its associated deflection. At 5.6 seconds into the test, the deflection is ~ 2.1 mm and the capacitance drops suddenly. Prior to this there is some wavering of the capacitance. In many cases, a steady decay in capacitance of nearly 15% will precede the sudden drop. What is most interesting in this response is that, because the unit is monitored throughout the test, the capacitance eventually returns to 99 nF, as if there was no change at all. The change is only +1% based on the initial reading of 98 nF. Initial and post-capacitance measurements would have declared this capacitor as being "without crack." The initial and post-dissipation factor also gave no clue, as it returned to 2.38% from an initial value of 2.42%.

Our test criteria became any sudden capacitance change between consecutive readings greater than 2% for the higher dielectrics, and 1% for NP0 dielectrics. The return to initial capacitance occurred in about 30% of the pieces tested. Some lots had greater incidence of this while some had no units return to the original reading. We stopped monitoring the capacitance on the return to 0 mm flexure as this appeared to be an insignificant effect. This also allowed us to store the data during the return and to eliminate any delay between loading the next unit for test. We attempted to stop many units when the sudden change may have been 3% to 10%, but because of the lag time with the capacitance meter reading and transmitting the reading, the capacitance usually decayed additionally to near 0. Considering the

©1994 IEEE

elastic nature of the crack propagation, this small capacitance change may have been a momentary change on its way to the larger change, regardless of our response time.

The unit was electrically disconnected as soon as the computer signalled a crack and started to return to 0 mm. The next board was electrically connected and swapped into the fixture as soon as the flexure returned to 0 mm. The operator would start the next board as soon as the computer signaled that it was acceptable to do so. A 50 piece sample could be read in under 30 minutes.

Analysis of the Data

The data was not analyzed while the test was taking place but stored for later analysis. The analysis included ordering, cumulative failure distributions and linear regression to allow projection of the flex needed to achieve 100 PPM failure rates. The coefficient of variance (R^2), had to have a magnitude greater than 95%, and typically, values of 98% were achieved. If the R^2 was less than 95%, then data distribution pattern was reviewed to see if multiple linear regressions would better fit the data. Figure 8 shows the data and the two linear regression fits. Almost all the groups show some sort of bimodal distribution. We have analyzed many groups in an attempt to explain this effect, but we have not been successful to date. In all cases, the slopes decay as the average flexure of each group, within the total distribution, increases.

The number of pieces tested initially was 25, but we soon progressed to 50 pieces to obtain more confidence in the analysis. Sample groups of 100 give even greater credence to the results and are preferred when comparing process or material variations that might lead to minor differences. The data analysis, from input through the first fit, is automated as a macro in the spreadsheet software used. Additional analysis is dependent upon user's input as to what data elements are to be used for each regression.

The end user of these chips is more likely to be concerned where these cracks start than at what flex level the 50% failure is achieved. There are many cases where the 50% failure levels contradict the 100 PPM levels. For these reasons, our comparison of lots is based on the 100 PPM failure rates. For groups with multiple regressions, we use the 100 PPM level indicated by the lower flex group as the comparative number.

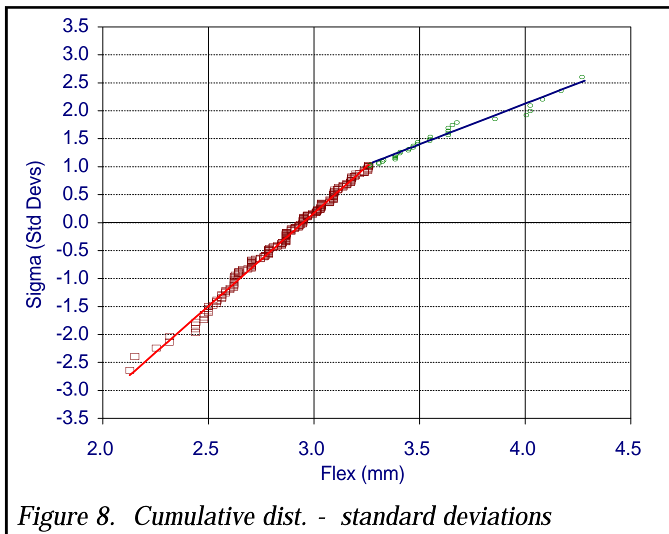


Figure 8. Cumulative dist. - standard deviations

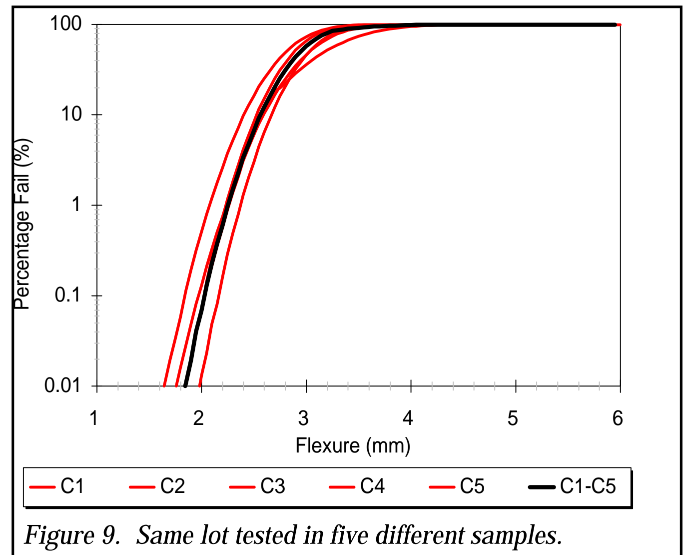


Figure 9. Same lot tested in five different samples.

To establish a consistent test, sample preparation and procedures are important aspects that must be controlled as tightly as possible. The application of the solder to the pads is critical. On the basis of chip size, we used an air-driven dispenser with preset air pressure, nozzle size, and duration for the solder paste application.

To establish what consistency we had achieved, a sample was divided into five distinct batches. The first three, C1 through C3, were mounted to the test boards, all on the same day. The fourth lot, C4, was mounted a week later, and the last lot, C5, was mounted a week after C4. Two of the first three lots, C1 and C2, were flex tested 24 hours after mounting. Lots C3 and C4 were flex tested 24 hours after C4 was mounted. Lot C5 was tested 24 hours after it was mounted, one week after C3 and C4. Additionally, all the data from lots C1 through C5 was combined to analyze the overall data compared to the individual groups. C1 through C3 were to give us an idea of consistency for the test process and the additional groups of C4 and C5 were to give us an indication of our mounting consistency.

The results of the consistency test are depicted in Figure 9. The variations are fairly minor and can easily be attributed to sample variations. Table 1 lists some of the more important aspects of each of the groups, including 100 PPM failure flex (mm), average failure (mm), and the flex (mm) needed to achieve 0.1-%, 1-%, 5-%, and 10-% failure rates.

Variations in Manufacturing

Once we established what our consistency in testing revealed, we needed to look at the consistency that was achievable with a given product manufactured over a period of time. From production batches spanning a 25 week period, we gath-

©1994 IEEE

Sample	100PPM @	Avg @	0.1% Flex	1.0% Flex	50% Flex	10% Flex
C1	1.83	2.97	2.02	2.26	2.47	2.58
C2	1.84	2.89	2.01	2.23	2.42	2.52
C3	1.75	3.03	1.97	2.23	2.46	2.59
C4	1.98	3.03	2.15	2.37	2.56	2.66
C5	1.64	2.81	1.83	2.08	2.29	2.40
C1-C5	1.84	2.95	2.02	2.25	2.45	2.56

Table 1. Repetetive testing - 1206 X7R 104 50V.

ered 11 groups of 1206 and 8 groups of 0805, X7R, 104 chips. Figure 10 depicts the range in the calculated linearizations for these groups and Table 2 lists the same parameters as used in Table 1, for the best and the worst of these 11 groups. This variation is not much greater than our consistency spread and leads us to believe that our materials and process result in a fairly

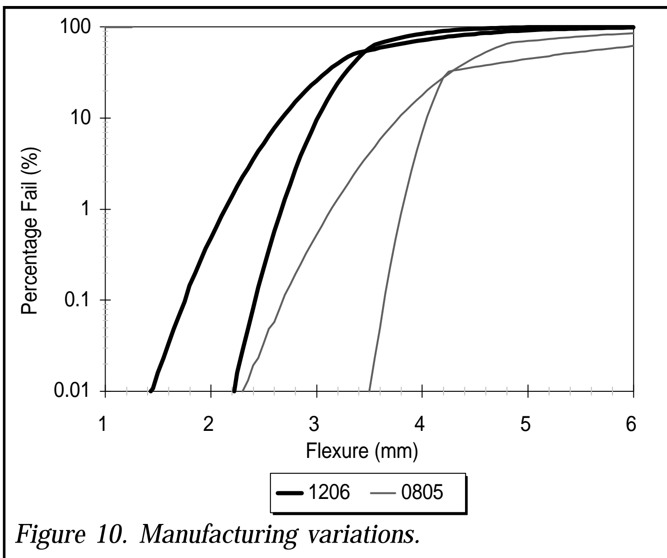


Figure 10. Manufacturing variations.

Lot	100PPM @	Avg @	0.1% Flex	1.0% Flex	50% Flex	10% Flex
1206 Best	2.21	3.43	2.41	2.67	2.89	3.01
1206 Worst	1.41	3.33	1.73	2.13	2.48	2.67
0805 Best	3.50	4.33	3.64	3.81	3.96	4.04
0805 Worst	2.29	4.55	2.67	3.14	3.55	3.77

Table 2. Manufacturing Variations - 1206 X7R 104 50V.

consistent product.

Effects of Chip Size on Flex Strength

The movement in the industry is towards smaller chip sizes. The 1206 chip is being replaced by the 0805, 0603, and 0402 sizes. Data from five groups of 0805, X7R, 104 chips were combined to show the difference between these groups and the 1206 data previously established. The 1206 data is the same C1-C5 data discussed earlier. These chips are of the same material and capacitance, with the design changed in the smaller chip to a thinner dielectric thickness.

It is readily apparent in Figure 11 on the following page that the smaller chip has a greater flex capability. The thinner dielectric is not the cause of the increased flex capabilities, as parallel experiments showed this to be of indiscernible effect. To understand why the increase in flex capability exists, consider that the distance between the terminations has decreased with the 0805 from the 1206. The flexure force, as an increasing curvature between two fixed points, generates a stress force that is proportional to the increasing arc distance between these points. The growth can be seen as fractional, and with the larger separation of the 1206 chip, the growth in the length of the arc is greater than with the 0805.

If the forces were truly proportional to the distance between the separations, then we should be able to establish this effect with a known group, terminated with varying margins. We created two additional test batches from the same production lot of chips used for the C1-C5 experiments. With one group, we attempted to create smaller margin overlaps, or bands by dipping the chip ends in the silver paste termination material to a depth ~ 2.5 mm less than standard. Large overlaps or bands were created by dipping the chips in the silver termination paste to a depth ~ 5 mm deeper than standard. The cumulative change in separation for these narrow and wide band chips was ~ 15 mm between them, or ~ -5 mm for the narrow band and ~ +10 mm for the wide bands over the standard termination bands. Figure 12 shows the results plotted for this study. From left to right, the three curves represent the narrow termination bands, the normal bands, and the wide termination bands.

Competitive Analysis

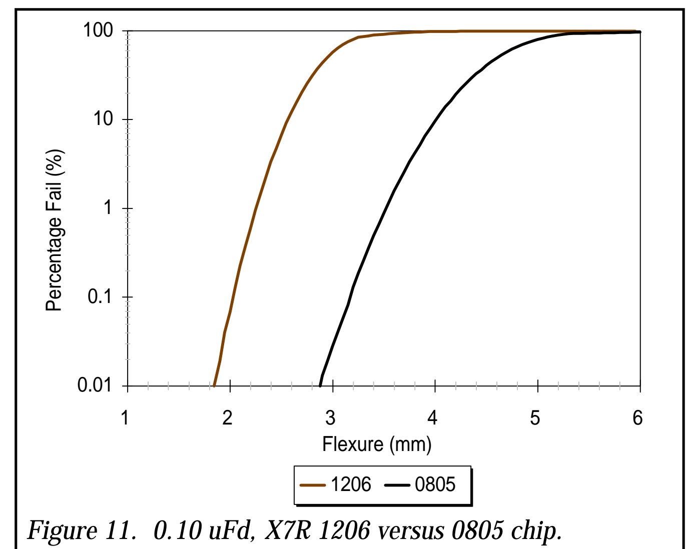


Figure 11. 0.10 uFd, X7R 1206 versus 0805 chip.

©1994 IEEE

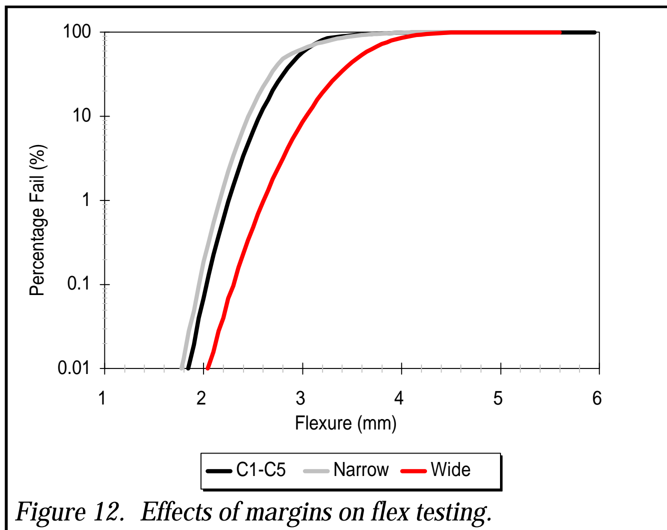


Figure 12. Effects of margins on flex testing.

We tested eight different groups of 1206, X7R, 104 chips from five different vendors, and six groups of 0805, X7R, 104 chips from five different vendors. The range of best to worst for each of the chip sizes is shown in Figure 13. These wide ranges of response deal with raw material formulations and process conditions that may vary considerably from our own and among these manufacturers. The crossing response in the 0805 chip ranges highlights that there are very significant dissimilarities. This comparison allows us to judge the effectiveness of our product compared to others for flex strength considerations.

Electrode Plane Considerations

In the analysis of the 0805 chips, we found some of the groups whose chips had thicknesses very close to their widths. With all the testing to this point, the chips had thicknesses that were considerably less than their width. As such, when mounted in their lowest profile, the electrode planes were always oriented to be parallel to the plane of the board. With those chips whose width and thickness were not distinct, there was no way of knowing what the electrode plane orientation was. Mounting was usually a 50/50 distribution of chips with electrode planes parallel to the board and those with electrode planes perpendicular.

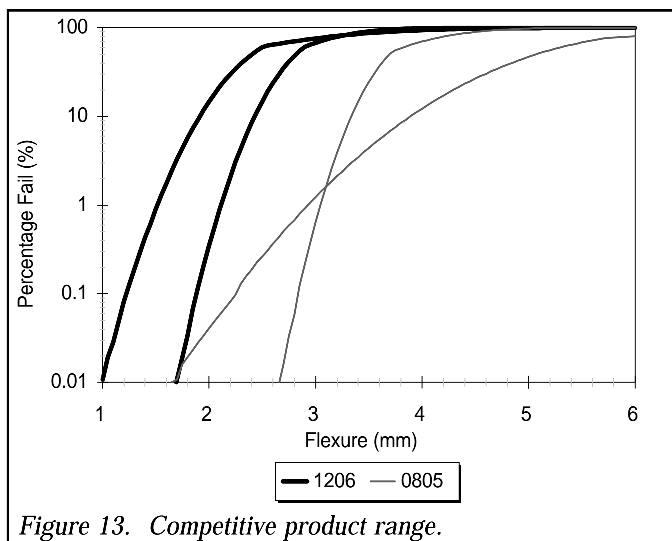
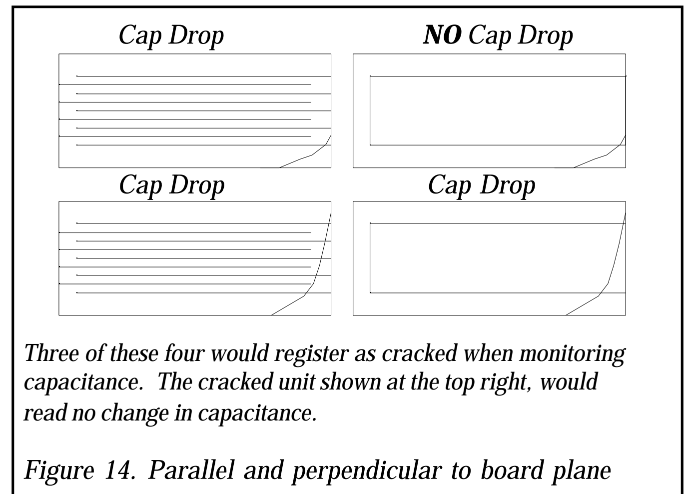


Figure 13. Competitive product range.



Three of these four would register as cracked when monitoring capacitance. The cracked unit shown at the top right, would read no change in capacitance.

Figure 14. Parallel and perpendicular to board plane

This variation did show significance in some of the tested lots. In the bimodal distributions, it was noted that a large percentage of those pieces with very high flex strength had their electrodes perpendicular to the plane of the board. This alone did not define the bimodal effect, as there were many units with electrode planes perpendicular to the board distributed among the lower flex failures.

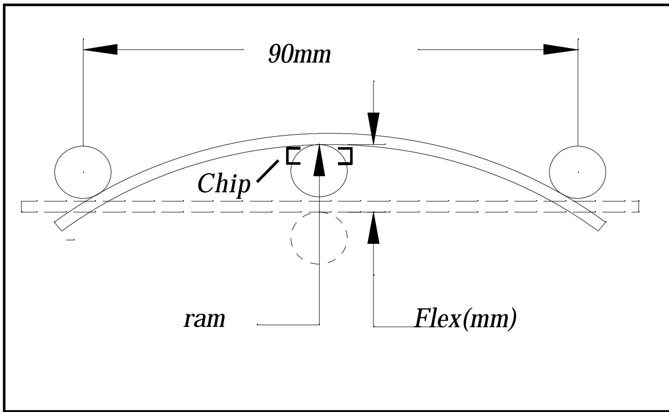
This effect does point out a deficiency in this test. Looking at Figure 14, and remembering that this is a two-dimensional representation of a three-dimensional effect, the unit in the upper right corner would show no loss of capacitance in this test. If the corner of the electrodes in the adjacent planes were severed by this crack, the loss in capacitance would probably be less than 2%. (Remember that the crack would extend into and out of the two-dimensional cutaway view, and the electrodes in the adjacent planes are connected to the opposite termination end.) The crack would have to extend upward into the chip, high enough to sever the electrode completely as in the lower right chip. The undetected crack that traverses electrodes offers the same insidious potential of failure as any crack detected, irrespective of the capability of detection in this test.

Reverse Flex

Chips have also been tested with the board reversed, so that the chip is on the concave side of the flexed board (Figure 15). A slot in the ram allows spacing between the ram and the chip, preventing physical contact between the two. In this test, the ram was driven to a flexure of 10 mm, held for 2.5 seconds , then gradually withdrawn as the data of Figure 16 represents. We also ran this test with an increase in the hold to 10 seconds as indicated in Figure 17. In every case, the chip failed during the withdrawal of the ram and relaxation of flexure. With a 2.5 second dwell at the maximum flexure (Figure 16), the failure occurred at 6 mm into the withdrawal. With the longer dwell the failure occurred sooner, at 4 mm into the withdrawal. Averages for 10 pieces tested in each condition were:

Condition	Distance to Failure
Reverse Flex (10 mm), 2.5 sec. dwell	5.2 mm from peak
Reverse Flex (10 mm), 10 sec. dwell	4.7 mm from peak
Normal Flex (10 mm maximum)	4.4 mm from start

©1994 IEEE



Acoustic Emission Monitoring

Another method proposed for crack detection deals with acoustic emissions detection. The crack will generate a high frequency, low level acoustic scream as it jumps through the dielectric. With the use of a transducer and the appropriate amplifying equipment, these acoustic sounds can be readily detected. This can detect cracks if they do not traverse electrodes and regardless of electrode orientation, but may also capture false triggers as crack initiations.

As the board is held at the separation of 90 mm during the bending, its arc length is a greater distance between these points. The distance at 0 mm flex is 90 mm, but at 10 mm flex, the arc length is now 92.9 mm between these two fixed points. During the transition from 0 to 10 mm flex, the board will slide along the edges to allow for this greater length requirement. This slide is not continuous and smooth but jumpy, occurring intermittently through the transition. These jumps will translate a sudden stress change to the capacitor under test. If the dielectric has a potential for piezoelectric noise, the resulting ring within the ceramic could be interpreted as an acoustic signature from a crack.

There is also the possibility that a benign crack would cause determination of failure. Such a crack could start as all flex

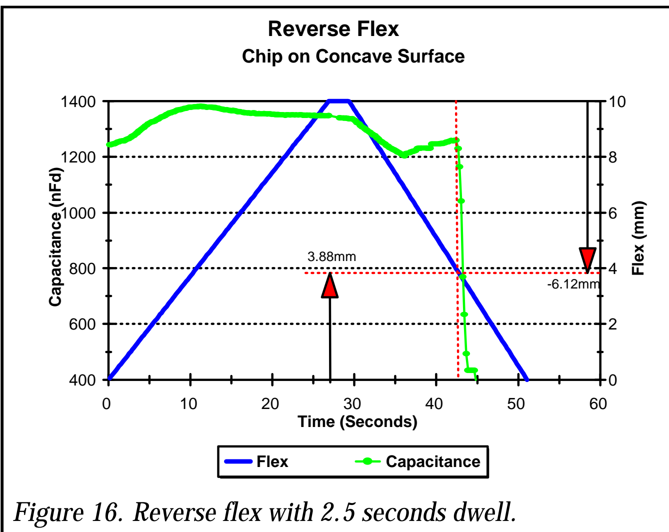


Figure 16. Reverse flex with 2.5 seconds dwell.

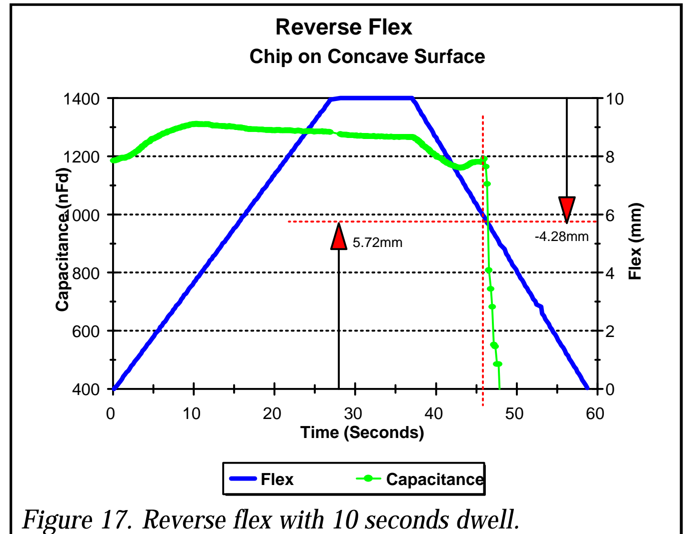


Figure 17. Reverse flex with 10 seconds dwell.

cracks but jump immediately to the termination face without traversing any electrodes (Figure 19). This crack would never in itself lead to a failure, but the acoustic emission test would regard it to be an equal failure to the unit where the entire termination end is severed from the main body of the chip.

The availability of this acoustic emission equipment is not widespread and would require all vendors and users to purchase some equivalent equipment to establish required testing by the manufacturer and independent testing by the user. The simple RLC meter is a common piece of equipment.

Conclusion

This testing establishes a tool to allow us to continue our efforts to continually offer the best product available. It is readily available to manufacturers and users alike. With the considerations presented, the results are very repeatable and the test is consistent.

References

EIA-J RC 3402, "Multilayer Ceramic Capacitors (Chip Type)"; December 1983

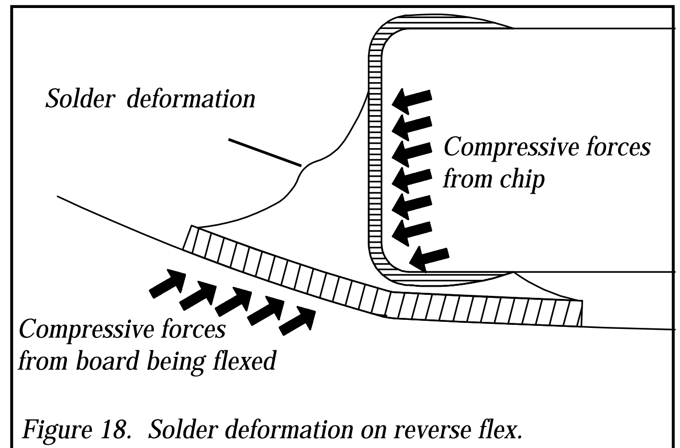


Figure 18. Solder deformation on reverse flex.

©1994 IEEE

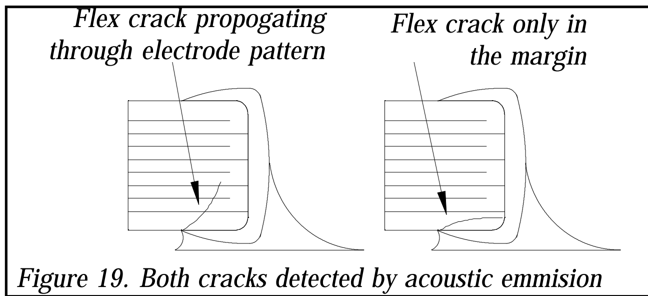


Figure 19. Both cracks detected by acoustic emmision

JIS C 6429, "Fixed Multilayer Ceramic Chip Capacitors for Use in Electronic Equipment", Japanese Standards Association; 1989

EIA Proposed Draft PN-2271, Rev G, Electronic Industries Association; 1993

“Important Factors in Board Flexure Testing of Surface Mount Capacitors”, Craig Nies, AVX Corp.,and John Maxwell, JMA; CARTS ASIA, Singapore; 1991

“Flex or Bend Testing”, KEMET TechTopics, Vol. 3, No.7; Prymak, John; KEMET Electronics Corp.; September 1993

"Flex Test While Monitoring Capacitance", 44th Electronic Component & Technology Conference, Bergenthal, Jim and John Prymak, Wasington, DC, May 1994, pp. 864-870

"Flex II", KEMET TechTopics, Vol. 4, No.6; Prymak, John; KEMET Electronics Corp.;October 1994

"Capacirtance Monotoring While Flex Testing", KEMET Engineering Bulletin F-2110, June 1995

©1994 IEEE