The Effectiveness of Screening Techniques for Revealing Cracks in High Volumetric Efficiency MLCCs

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Abstract

Multilayer ceramic capacitors (MLCCs) constitute the majority of components used in electronic assemblies and most of their failures are related to cracks. It is often assumed that dissipation factor (DF), insulation resistance (IR), and breakdown voltage (VBR) are characteristics that are sensitive to the presence of mechanical defects, and screening of capacitors by measurements of these characteristics, and by dielectric withstanding voltage (DWV) testing assures high quality products. This work analyzes the effectiveness of these screening techniques for revealing cracks in high-volumetric efficiency, low-voltage ceramic capacitors. Various types of class II dielectric capacitors with rated voltages from 6.3 V to 100 V, and capacitances from 0.1 μF to 100 μF from different manufactures were used in this study. Fractures in the parts were introduced mechanically and by thermal shock stress. It has been shown that cracking results in relatively minor variations of capacitance and DF. Absorption currents prevail over leakage currents during standard IR measurements at room temperatures, and at high temperatures the intrinsic leakage currents exceed substantially leakage currents caused by cracking thus masking the presence of defects. Analysis of distributions of breakdown voltages in normal capacitors and capacitors with cracks showed that the majority of defective capacitors can pass the DWV testing. New, more effective methods of electrical testing and possible improvement of the existing techniques are discussed.

Key words

Ceramic capacitors, cracking, performance, testing, reliability, degradation.

I. Introduction

Most field failures of MLCCs are related to cracks that are caused either by insufficient process control during manufacturing, by thermal shock associated with soldering or by flex cracking during handling and/or mechanical testing of circuit boards. These cracks, if not identified, might cause failures after months and even years of operation and the failure mode varies from a short circuit to intermittent or “noisy” behavior that in some cases might be misjudged as software failures.

Electrical characteristics of MLCCs are often considered sensitive to the presence of mechanical defects in the parts, and passing the relevant tests is assumed to give assurance that the capacitor is defect-free. These tests include alternative current (AC) measurements of capacitance (C) and DF, and direct current (DC) measurements of insulation resistance and testing for dielectric withstanding voltage.

Standard electrical measurements of C and DF are carried out at 1 kHz, and values of IR are determined as the ratio of the applied rated voltage (VR) to the leakage current measured within 1 or 2 minutes of electrification. It is often assumed that cracks in MLCCs would reduce IR measured at room or at high temperatures and several publications have indicated increased currents in capacitors with cracks [1-2]; however, factors affecting electrical conduction of cracks and the mechanism of the charge transport have not been studied properly yet.

Structural defects such as voids, cracks, and delaminations are known to decrease VBR in ceramic capacitors [3-4], so one of the techniques typically used to screen-out defective MLCCs is DWV test that for low-voltage capacitors is carried out at 2.5VR. However, only a few publications evaluate the effectiveness of the DWV testing to reveal defects in ceramic capacitors. Cozzolino [5] noted that not all defective capacitors will always fail after a single exposure to DWV and some lots that passed DWV test failed qualification testing due to the presence of laminate cracks. Chan [6] analyzed the effect of thermal shock (TS) on electrical characteristics of MLCCs. Capacitors with cracks introduced by cold TS testing had decreased breakdown voltages, from the range of 500 V to 625 V for virgin samples to 250 V to 350 V for the damaged parts, which is far above the DWV test voltage.

In this work, the effectiveness of the existing screening techniques, including measurements of C, DF, IR, and DWV testing for revealing cracks in high-volumetric efficiency, low-voltage ceramic capacitors is analyzed. Improvements for the test methods are suggested and new, more effective screening techniques are discussed.

II. Experiment

A variety of low-voltage (rated to 100 V or less) MLCCs produced by seven different vendors was used in this study. Most of the parts were commercial, high volumetric efficiency, X7R capacitors with EIA case sizes from 0402 to 2225, voltage rating from 6.3 V to 100 V, and capacitance from 1500 pF to 100 μF.

Cracks in MLCCs were introduced mechanically or by thermal shock stress using three techniques. (1) Mechanical fracture: a corner portion of the part was chipped-off using fine cutters. (2) Surface cracking: a capacitor was damaged by impact on the surface with a Vickers indenter. (3) Thermal shock: capacitors were stressed either by a cold thermal shock using the ice water testing (IWT) technique or by the hot thermal shock using a solder dip test [7].

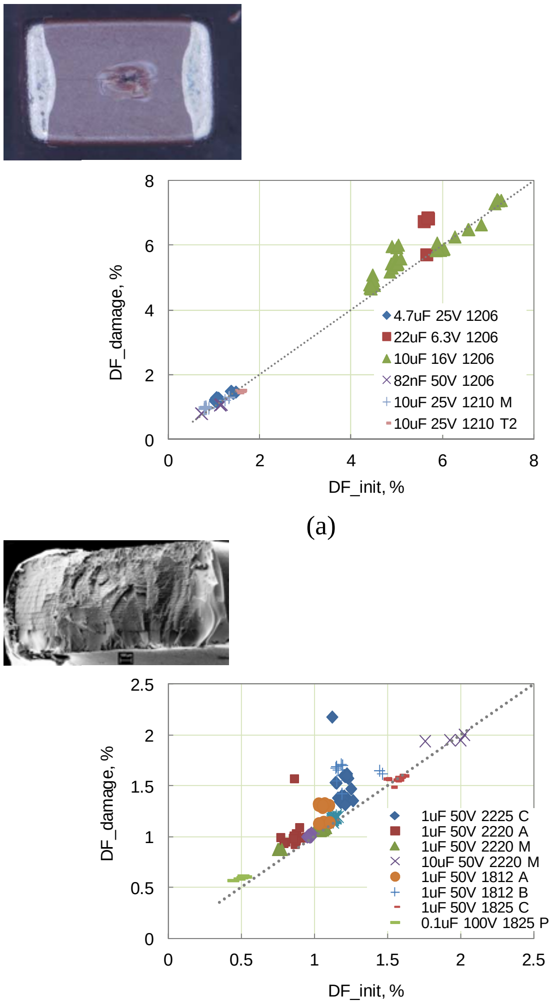
III. Results and Discussion

A. Effect of cracking on C and DF

A correlation between DF measurements before and after fracturing for 15 different types of MLCCs is shown in Fig.1. In most cases fracturing did not result in substantial increasing of DF. On average, the increase was ~15%, but the parts still remain within the specified limits. This suggests that AC characteristics are not sensitive to the presence of cracks, which is in agreement with observations made by Prymak et.al. [8].

Experiments showed that for some capacitors, cracking introduced by the Vickers indenter resulted in increasing the capacitance. This seems counterintuitive, and to get a better understanding of the problem, several 10 μF 25 V and 10 μF 16 V capacitors in cases size 1210 from different manufacturers were hit with an instrument that was used to cause indenter-induced damage to simulate mechanical shock conditions, but without fracturing the parts. Variations of the capacitance and DF with the number of hits and with time after the hits are shown in Fig. 2.

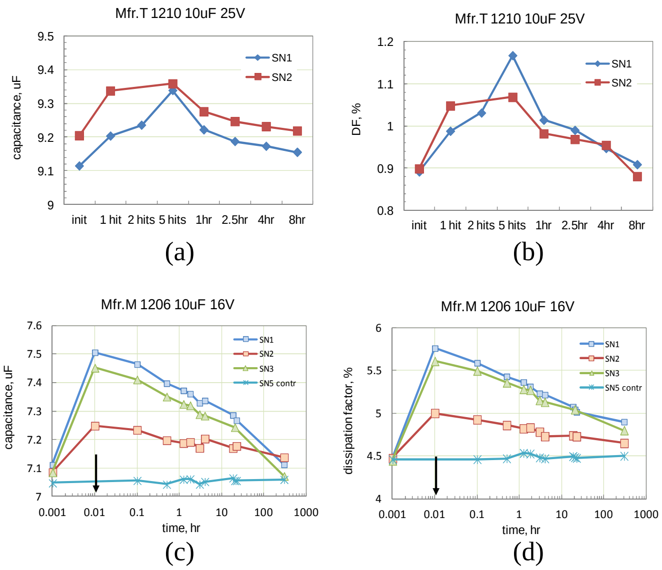
Hitting increases capacitance on 2% to 7% and DF on 20% to 30%, but this increase was reversible: both characteristics gradually decrease with time, and after dozens and hundreds of hours tend to stabilize at the initial level. A decrease of AC characteristics occurs linearly with the logarithm of time.



(a)

(b)

Fig. 1. Effect of fracturing on dissipation factors of small size (a) and large size (b) ceramic capacitors. The lines correspond to the no-change values. Inserts show examples of fractured capacitors used in this study.



(a) (b)

(c) (d)

Fig. 2. Variations of capacitance (a, c) and dissipation factor (b, d) for 1210 10 μF 25 V (a, b) and 1206 10 μF 16 V (c, d) capacitors during and after the hitting. Arrows indicate the moment of hitting and the 0.001 hr measurements show the initial data.

This phenomenon is likely related to the aging processes that are due to gradual changes in the domain structure of the dielectric as a result of the stress relaxation. It is possible that mechanical stresses associated with the acoustic waves, which are formed during hitting, disturb the domain structure that afterward relaxes with the time. More analysis and experiments are necessary to get a better understanding of this phenomenon. The results show that mechanical stresses can change AC characteristics of X7R capacitors and this effect, similar to the microphonic effect, should be considered for sensitive circuits.

B. *Effect of cracking on IR*

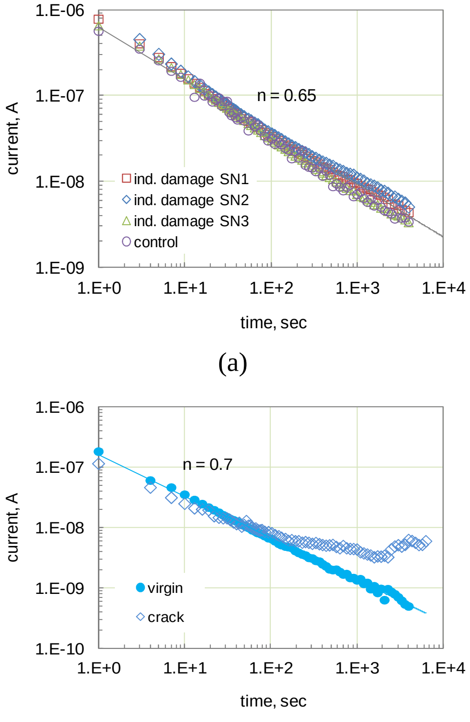
Currents in MLCCs were measured with time at different voltages and temperatures for a variety of normal quality (virgin) ceramic capacitors and for cracked capacitors. In all cases, except for a few involving severely damaged capacitors, currents were similar for virgin and damaged parts. Examples of these measurements at room temperature are shown in Fig. 3. For case size 1812, 1 μF 50 V capacitors, the normal quality and cracked capacitors had similar currents within a one-hour period of polarization (Fig.3.a). Similar to data in Fig.3a, current relaxations for all virgin capacitors at room temperature follow the empirical Curie von-Schweidler power law:

$$I(t) = I_0 \times t^{-n}, \qquad (1)$$

where I_0 and n are constants, and n is close to 1.
This behavior is due to the dielectric absorption phenomenon that is known for most dielectric materials employed in different types of capacitors, including MLCCs [9-11].

Fig. 3.b presents an example of current relaxations when leakage currents in a capacitor with cracks exceeded currents in a normal part. However, some difference can be observed only after ~ 100 seconds of polarization. This makes the presence of the defect undetectable by regular IR measurements.

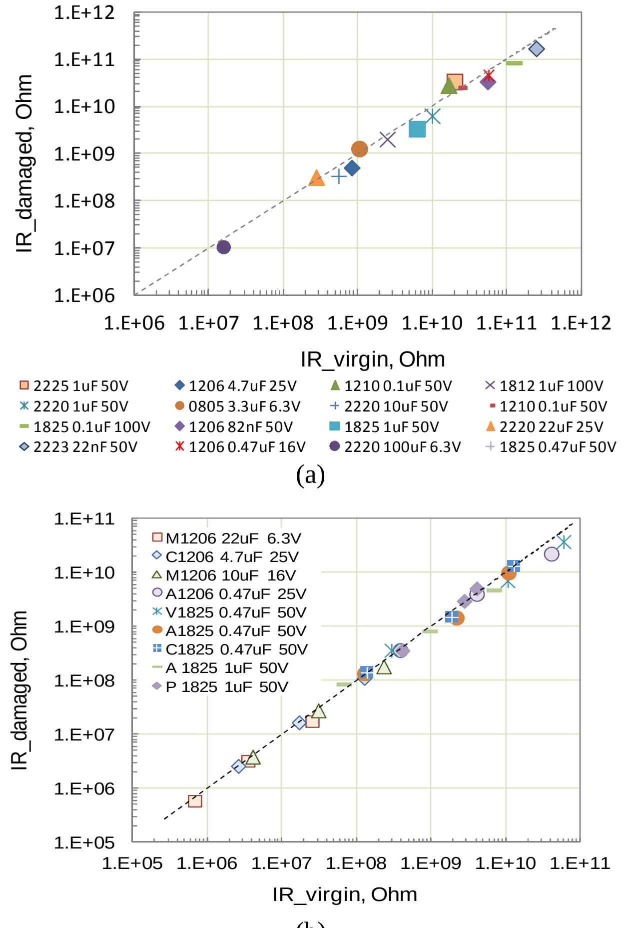
Fig. 4.a shows a correlation between IR values measured after 120 seconds of electrification for 15 different types of virgin and fractured capacitors at room temperature. The data are closely correlated, indicating no substantial change in the resistance values. This also shows that IR screening at room temperature would not detect fractured capacitors.



(a)

(b)

Fig. 3. Relaxation of currents in normal and fractured capacitors at room temperature and rated voltages. (a) Case size 1812, 1 μF, 50 V capacitors. (b) Case size 0805, 3.3 μF, 6.3 V capacitors.



(a)

(b)

Fig. 4. Effect of cracking on insulation resistance in different types of ceramic capacitors. The dashed line corresponds to no-change values. (a) Room temperature measurements. (b) Measurements at 85°C, 125 °C, and 165 °C.

It is often assumed that IR measurements at high temperatures, typically at 125 °C, are more sensitive to the presence of defects, and thus are more effective for the quality evaluation. To assess the effectiveness of high-temperature measurements in revealing dielectric cracks, nine types of virgin and fractured capacitors were measured at 85°C, 125°C, and 165°C. Results of these measurements are shown in Fig. 4.b. High temperature IR measurements were also closely correlated, indicating that the temperature increase does not assist in revealing mechanical defects in MLCCs.

The values of activation energy, E_a, for the intrinsic leakage currents reported for X7R capacitors by Lee, Burton, et al. [11-12], are in the range from 1.2 eV to 1.3 eV. At these values, intrinsic leakage currents increase at high temperatures by 3 to 7 orders of magnitude compared to room temperature and, as experiments show, prevail over the absorption currents. Leakage currents associated with cracks are not activated with temperature to the degree of the intrinsic leakage currents. For this reason, high-temperature currents exceed substantially the currents associated with cracks and thus mask the presence of defects in capacitors. This indicates that attempts to screen-out damaged capacitors by IR measurements at high voltages and/or temperatures are not effective.

Based on our results, crack-related leakage currents at room temperature, in most cases, are below the absorption currents. Some improvement of the sensitivity of IR measurements to the presence of cracks might be achieved by increasing the duration of the electrification period. For example, an increase from 1 minute to 1 hour would reduce I_{abs} approximately 60 times and increase the possibility of detecting excessive currents in the capacitors substantially.

Results of one-hour IR measurements before and after fracturing for nine part types are shown in Fig.5 and indicate a substantial, up to two orders of magnitude decrease of IR in capacitors with cracks. However, based on IR values, the majority of the fractured capacitors would be considered acceptable and pass the screen. This indicates that both the existing testing technique and the requirements should be revised.

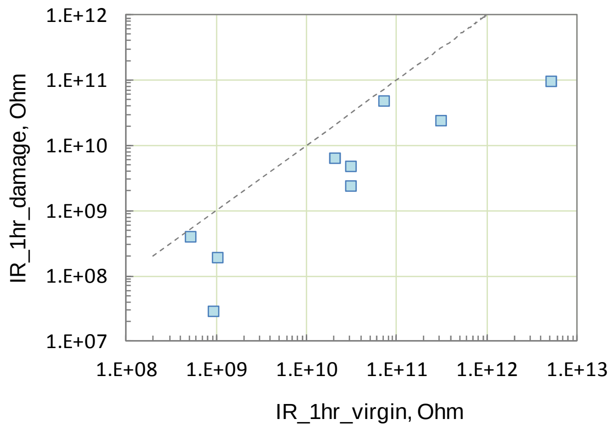


Fig. 5. Correlation between IR values in virgin and fractured MLCCs calculated based on currents measured after 1 hour of electrification.

C. *Effect of cracking on VBR*

An example of distributions of breakdown voltages for undamaged 1 μF 50 V capacitors and for parts after mechanical fracturing (MF), thermal shock (TS), and cross-sectioning (X-sect) is shown in Weibull coordinates in Fig. 6. As expected, capacitors with cracks had lower values of VBR compared to undamaged parts. However, the majority of capacitors with cracks had VBR exceeding 125 V. This means that most of the parts with defects would pass DWV testing.

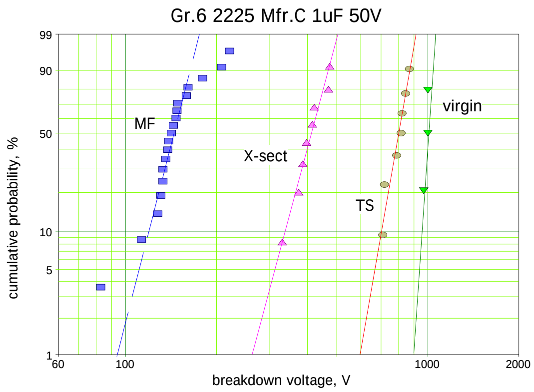


Fig. 6. Distributions of breakdown voltages for case size 2225, 1 μF 50 V capacitors.

Testing of 27 types of various low-voltage capacitors [13] showed that on average, cracks in capacitors after thermal shock decrease VBR compared to undamaged parts ~ 23%. Mechanically fractured MLCCs (14 lots) had a decrease of VBR ~ 69% at a standard deviation (STD) of 19%. Cross-sectioning of 17 lots reduced VBR to a somewhat lesser degree, ~ 42% at STD of 15%. However, in all cases VBR in fractured MLCCs remained substantially greater than 2VR.

Analysis indicates that the majority of defective parts would pass DWV testing, so the effectiveness of this test to screen-out low-voltage capacitors with fractures is not acceptable. This testing can be made more useful if the test voltage, VBR_{test}, is increased. To avoid damage caused by applying excessively high voltages to capacitors, VBR_{test} should have a substantial margin to VBR. For this, VBR_{test} should be determined by the distribution of VBR for virgin capacitors that can be characterized by an average value, VBR_{avr}, and standard deviation, σ. A 50% margin to the fifth percentile of the VBR distribution seems to be sufficient to assure a safe application of high voltages:

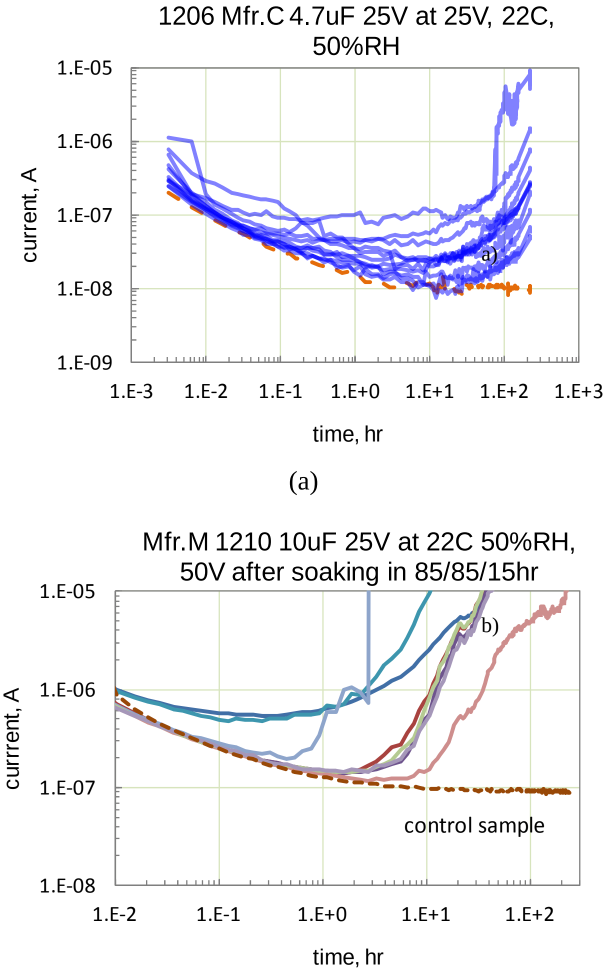
$$VBR_{test} = 0.5\times(VBR_{avr} - 2\times\sigma) \tag{2}$$

For the case shown in Fig.6, VBR_{test} = 475 V, and the DWV testing would detect all mechanically fractured capacitors.

D. Degradation of leakage currents with time.

Preliminary results show that the relative humidity (RH), even at moderate levels of ~ 50%, might strongly affect the behavior of MLCCs with dielectric cracks. Fig. 7 shows degradation of leakage currents at room temperature and 50% RH for two groups of capacitors damaged by the Vickers indention. The first group had 15 samples of 4.7 μF 25 V capacitors, and the second had 9 samples of 10 μF 25 V capacitors from a different manufacturer. One sample in each group was not damaged and used as a reference. Both groups manifested a substantial, more than two orders of magnitude degradation of leakage currents that started after ~ 1 hour of testing. Increasing of the testing voltage from VR to 2VR and preliminary soaking of the parts in a humidity chamber at 85 °C, 85% RH for 15 hours appear to result in a more significant degradation.

Note, that per IR requirements, the currents after 120 sec (0.033 hr) for 4.7 μF 25 V capacitors should be below 1.2×10^{-7} A, so all 15 parts with cracks would be considered acceptable. Based on results for 10 μF 25 V (Fig.7b), the majority of the fractured parts would be accepted if tested at the rated voltage.



(a)

(b)

Fig. 7. Long-term degradation of leakage currents in MLCCs with cracks at room temperature and 50% RH. The dashed lines correspond to reference parts. (a) Case size 1206, 4.7 μF 25 V capacitors at 25 V. (b) Case size 1210 10 μF 25 V fractured capacitors at 50 V.

Monitoring of leakage currents with time at room temperature and voltages from VR to 2×VR during or after exposure to humid environments might be a useful technique to reveal capacitors with cracks.

IV. Conclusion

- Cracking in MLCCs results in a relatively minor, on average ~15%, increase in DF indicating that AC characteristics of low-voltage capacitors are not sensitive to the presence of mechanical defects.
- Capacitance in class II dielectrics might increase 2 % to 7 % as a result of mechanical hits. The mechanism of this phenomenon needs more analysis.
- The effectiveness of the existing IR and DWV testing to reveal cracks in low-voltage MLCCs is low. Increasing the testing voltage for DWV test, and time of electrification for room temperature IR measurements can improve the value of these tests.
- Increasing temperature or voltage during IR measurements does not increase the sensitivity of the testing to the presence of cracks.
- The effectiveness of a new testing method that is based on monitoring of current degradation at room temperature is currently being evaluated.

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