Breakdown Voltages in Ceramic Capacitors with Cracks

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ABSTRACT

Breakdown voltages in 27 types of virgin and fractured X7R multilayer ceramic capacitors (MLCC) rated to voltages from 6.3 V to 100 V have been measured and analyzed to evaluate the effectiveness of the dielectric withstanding voltage (DWV) testing to screen-out defective parts and get more insight into breakdown specifics of MLCCs with cracks. Fractures in the parts were introduced mechanically and by thermal shock stress. To simulate exposure of internal electrodes to environments in fractured parts, breakdown testing was carried out also on cross-sectioned and polished capacitors.

Index terms: **Electric breakdown, ceramic capacitors, defects, reliability.**

I. INTRODUCTION

Most failures of ceramic capacitors are caused either by degradation of insulation resistance that results in unacceptably high leakage currents in the circuit or by electrical breakdown that causes catastrophic failure of the part and can damage the board. Both types of failures are often due to the presence of defects such as voids, delaminations, or cracks. Cracks considered the most insidious defects because they might not lead to immediate failures during the testing, but if remained undetected would cause degradation of performance resulting eventually in failures after months or years of field operation [1].

Cracks in MLCCs might be caused by deficiencies of the manufacturing process or can be introduced during assembly, typically by soldering-induced thermal shock, or after soldering by handling of the board, e.g. by flex cracking of the parts assembled onto printed wiring boards (PWB) [2]. Manufacturing-related defects in capacitors are supposed to be revealed and removed from the production by screening procedures, while robustness of the parts to assembly and handling-related stresses should be assured by qualification testing and by following workmanship guidelines.

It is well known that structural defects such as voids, cracks, and delaminations decrease breakdown voltages in ceramic capacitors [3-4], so one of the techniques that is typically used to screen-out defective MLCCs is dielectric withstanding voltage (DWV) test. 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 because some parts might have the strength of rupture slightly above the test voltage. Experiments show that some lots that passed DWV test failed qualification testing due to 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. Some manufacturers require that the breakdown voltage of high-quality parts exceed the rated voltage more than 5 times [7]; however, Deng reported that excessive voltage during the testing can cause damage to the parts [8].

In this work, distributions of breakdown voltages in 27 lots of fractured and virgin MLCCs rated to 100 V and less were measured and analyzed. Fractures in the parts were introduced mechanically and by thermal shock testing. To simulate exposure of internal electrodes to environments in fractured parts, breakdown testing was carried out also on cross-sectioned and polished capacitors. Mechanisms of breakdown and the effectiveness of dielectric withstanding voltage test to reveal defective ceramic capacitors are discussed.

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II. EXPERIMENT

Twenty seven different lots of chip commercial and military-grade MLCCs rated to voltages from 6.3 V to 100 V were used in this study. The parts were manufactured by five vendors and their Electronic Industries Alliance (EIA) size codes varied from 0402 to 2225. The thickness of the dielectric in the parts (*d*) as determined by cross-sectioning varied from 2.5 µm to 50 µm. Sixteen lots had silver/palladium electrodes (precious metal electrode, PME) and 11 were manufactured with nickel electrodes (base metal electrode, BME).

Capacitors from 14 lots were mechanically fractured (MF) using fine cutters to chip out a corner portion of the part. Cold thermal shock (TS) fractures were introduced in 13 lots of capacitors using the ice water testing (IWT) technique described in [9]. The presence of cracks in TS parts was verified by measurements of leakage currents and vicinal illumination microscopy [10]. After IWT, the parts were baked at 150 ^{o}C for 48 hrs and capacitors with acceptable electrical characteristics were used for breakdown measurements. To measure breakdown voltages on cross-sectioned capacitors (X-sect), parts from 17 lots were prepared by soldering leads, molding in epoxy, grinding and polishing perpendicular to the electrodes. After fracturing and cross-sectioning all parts were verified to have acceptable AC and DC characteristics.

Breakdown voltages (VBR) were measured using two types of test, constant current stress (CCS) and ramped voltage pulse stress (RVPS) test that is a version of commonly used ramp voltage stress technique [11]. A close correlation between average values of VBR measured using CCS technique and RPVS testing at three pulse durations 0.1 sec, 1 sec, and 5 sec (see Figure 1) indicates that all techniques yield similar results.

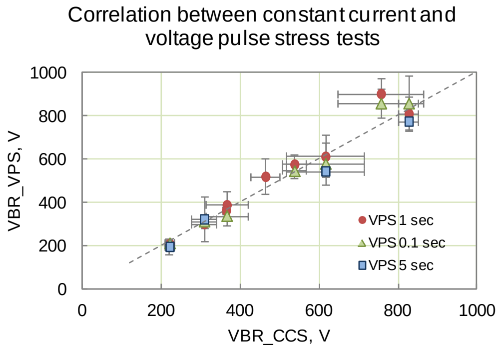

Figure 1. Correlation between average breakdown voltages measured by CCS and RVPS techniques for different types of capacitors. Error bars correspond to the standard deviations of the relevant distributions.

CCS technique allows for more accurate measurements of VBR by monitoring V-t curves and detecting maximum voltage at the curve. This technique was used for majority of the experiments in this work. From 5 to 20 samples were used in each group to determine statistical characteristics for Weibull and normal distributions of breakdown voltages. This technique was used also to characterize I-V dependencies at prebreakdown voltages by forcing different currents in the part and recording saturation voltages at the V-t curves.

III. RESULTS

An example of distributions of breakdown voltages for undamaged (virgin) 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 Figure 2. For virgin, thermally shocked, and cross-sectioned capacitors the distributions could be approximated accurately enough with two-parameter Weibull functions. For mechanically fractured capacitors the spread of the data was typically much greater than for virgin or cross-sectioned parts.

As expected, capacitors with cracks generally had lower values of VBR compared to undamaged parts. However, in four out of 13 groups of capacitors there was no substantial difference between distributions for undamaged and TS stressed parts. In five other groups a large proportion of parts (typically ~50% or more) had breakdown voltages after TS-induced cracking close to undamaged capacitors. Overall, minimal degradation of VBR was observed for parts fractured by thermal shock, and maximum for mechanically fractured capacitors.

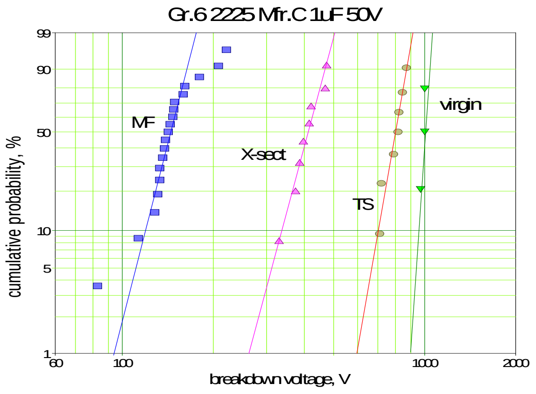

Figure 2. Distributions of breakdown voltages for 1 µF 50 V capacitors.

On average, cracks in capacitors after thermal shock decrease VBR compared to undamaged parts on 23% at a standard deviation (STD) of 28%. Mechanically fractured parts (14 lots) had a decrease in VBR on 69% (STD = 19%) and cross-sectioning of 17 lots reduced VBR to a lesser degree, on 42% at STD of 15%.

Virgin capacitors rated to the same voltage have a wide spread of VBR values, e.g. parts rated to 50 V have VBR in the range from 300 V to more than 1000 V. There was no correlation between the rated and breakdown voltages, which is likely due to a wide spread of the thickness of the dielectric layers for capacitors rated to the same voltage. For example, for 50 V capacitors the value of *d* varied almost an order of magnitude.

There is only a trend of increasing rated voltages (VR) with the thickness of dielectric layers. Analysis showed that VR in low-voltage X7R capacitors is determined mostly by the voltage dependence of the dielectric constant rather than by the electrical strength of ceramic materials.

There is a clear trend of increasing of the normalized breakdown voltage, VBR/VR, with decreasing rated voltages (see Figure 3). For parts rated to 100 V, VBR exceeds VR approximately by a factor of 10, and this ratio increases up to 85 for a relatively low-voltage parts rated to 10 V and 6.3 V. These results are consistent with literature data where VBR was found exceeding the rated voltage for 100 V capacitors by a factor of 10 to 12 [12]. Capacitors rated to higher voltages had lower values of the VBR/VR ratio that decreased to approximately 6 at VR = 200 V, to 1.8 at VR = 2000 V, and to 1.2 for capacitors rated to 4000 V.

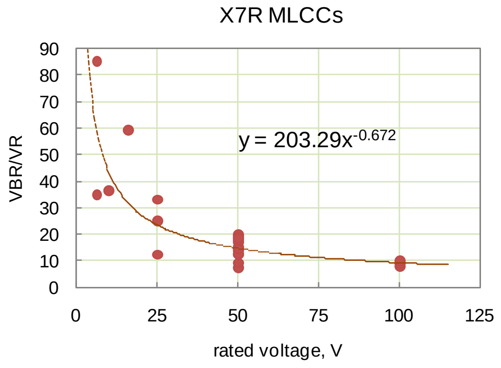

Figure 3. Variations of normalized breakdown voltages with the rated voltage.

Figure 4 shows variations of VBR with the thickness of the dielectric. Although the scatter of the data is rather large, there is a trend of increasing VBR with the thickness at relatively small values of *d*, below ~ 20 µm. In the range of thicknesses from 20 µm to 55 µm VBR apparently levels off stabilizing at approximately 900 V.

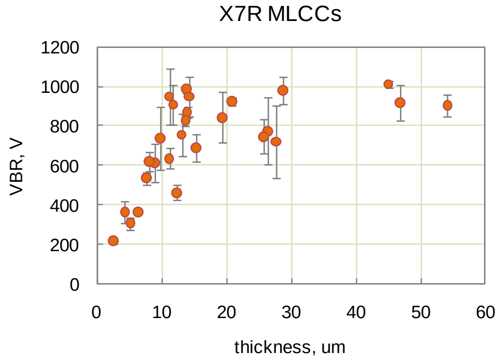

Figure 4. Effect of dielectric thickness on breakdown voltages.

In most cases the slopes of Weibull distributions of VBR for virgin and cross-sectioned parts were similar. There is also a correlation between breakdown voltages in these two groups of capacitors as shown in Figure 5. This indicates that the same factor, most likely the thickness of the dielectric layer, controls breakdown voltages in undamaged and cross-sectioned capacitors.

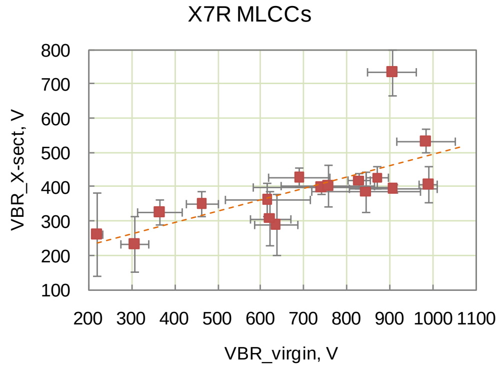

Figure 5. Correlation between breakdown voltages in virgin and cross-sectioned capacitors.

Typically for low voltage capacitors the dielectric withstanding voltage test is carried out at 2.5 times the rated voltage. Based on parameters of the relevant distributions the probability of failure during this test, $P_{2.5}$, can be calculated. For undamaged parts these probabilities were negligibly small and exceeded 0.001% in 6 out of 27 lots only. Even in the worst case, the value of $P_{2.5}$ was relatively small, 0.16%. Surprisingly, the probability of failure during DWV testing for capacitors from fractured lots was not large, averaging for all lots at 11.5%. This shows that even a severely damaged capacitor has a good chance of passing DWV testing. Based on results for parts damaged by cross-sectioning and thermal shock, 65% of the tested lots had the probability of failure during DWV test of less than 1%.

Measurements of prebreakdown leakage currents showed that at high electrical fields (>10 V/µm) I-V characteristics in Poole-Frenkel (PF) coordinates, *ln(I/E) vs.* $V^{0.5}$, can be approximated with straight lines as it is shown in Figure 6.

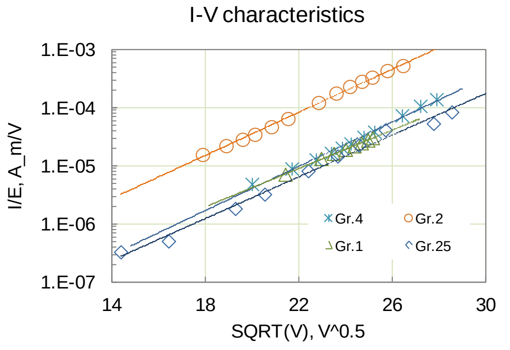

Figure 6. Prebreakdown I-V characteristics for four different part types in Poole-Frenkel coordinates.

The most popular mechanism that describes voltage dependence of leakage currents in barium titanate ceramic capacitors is surface-barrier-limited Schottky conduction [13-14]. However, in some cases experimental data on conduction in ferroelectric materials are better described by the bulk-limited Poole-Frenkel mechanism that is based on a field-stimulated release of electrons from traps located in the conduction band of ceramic materials [15]. Our data are consistent with the PF mechanism. Calculations of high-frequency dielectric constant based on the slopes of the curves in Figure 6 yielded ε ~ 5, which is consistent with the model and literature data [15].

A substantial proportion of large-size capacitors failed at the margin areas near electrodes' terminations and resulted in formation of small craters that exposed melted metallization or semicircular fractures at the terminals. In some small-size capacitors breakdown resulted in formation of cracks along the plates thus indicating that delaminations might be not only the cause, but also a result of failures.

Figure 7 shows typical SEM views of a breakdown area in mechanically fractured ceramic capacitors. This area appeared as a thin glassy layer on the surface with embedded balls of melted and resolidified metal. X-ray microanalysis confirmed that the balls were either silver or nickel droplets depending on the type of electrode materials. The breakdown area was not localized around a single center between two electrodes on the surface as was expected initially, but was spread apparently evenly over several dielectric layers.

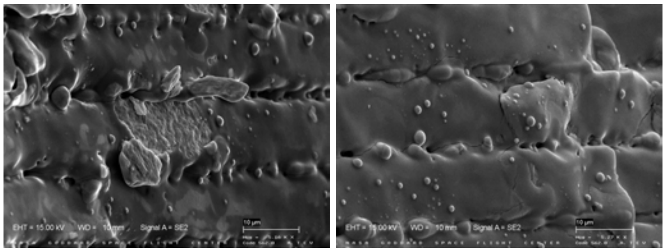

Figure 7. Breakdown-induced damage in mechanically fractured 1 µF 50 V capacitors.

Examinations of cross-sectioned parts showed that similar to mechanically fractured capacitors, the breakdown areas were spread perpendicular to the plates covering from 30% to 100% of the electrodes (see Figure 8). In several cases the breakdown was not limited to one area, but damage consisted of a few spots located 20 µm to 100 µm apart. Similar to mechanically fractured capacitors, breakdown in cross-sectioned parts also resulted in formation of a thin glassy layer with embedded melted balls of electrode material that shorted the parts to the resistance in the kiloohms range.

A large proportion of capacitors (up to 75% for some part types) failed at the margin areas. In some cases breakdown events occurred simultaneously at different margin areas of capacitors. On average, the surface breakdown was observed at the terminal margins in 32% of all tested samples.

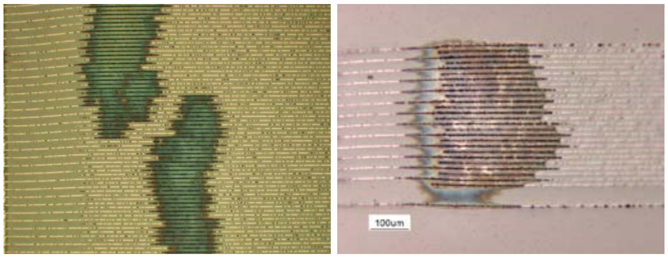

Figure 8. Optical views of breakdown areas in cross-sectioned 1 µF 50 V capacitor.

Typical oscillograms of a breakdown event in cross-sectioned capacitors are shown in Figure 9. The major features of the surface breakdown are similar to those observed for breakdowns in virgin and fractured MLCCs: the duration of the process is ~ 150 ns and the spike consists of several short-duration pulses. However, the amplitude of current spikes for the bulk breakdown was ~ 10 A, whereas for the surface breakdown it was larger, in the range from 40 A to 70 A. This indicates likely that the bulk breakdown contrary to the surface breakdown is localized at a much smaller area of the part.

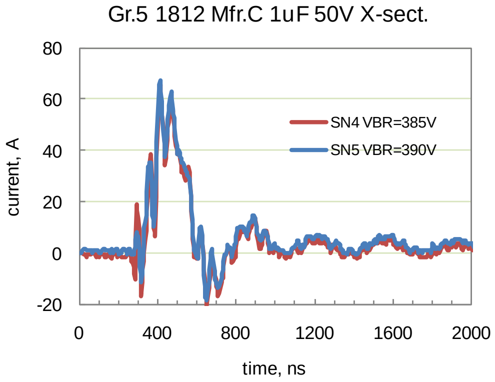

Figure 9. Typical oscillograms of breakdown events in different types of cross-sectioned capacitors.

A self-healing phenomenon, when a capacitor does not fail catastrophically after breakdown but remains operational, was observed in several groups of capacitors (see Figure 10). This phenomenon is well known for different types of capacitors, in particular, high-voltage metalized film capacitors and tantalum capacitors. For polymer capacitors self-healing is explained by evaporation of metal electrode at the local breakdown site and for tantalum capacitors by reduction of the manganese oxide cathode due to local overheating that increase its resistance. In either case the result is electrical insulation of the defective site and prevention of breakdown development and further damage.

The possibility of self-healing for MLCCs has not been discussed in literature in details yet, but it is reasonable to assume that it is related to local evaporation of metallization at the breakdown site. Based on our experience PME parts are more likely to be self-healed compared to capacitors with nickel electrodes, which is probably due to a lower melting temperature of Ag/Pd metallization.

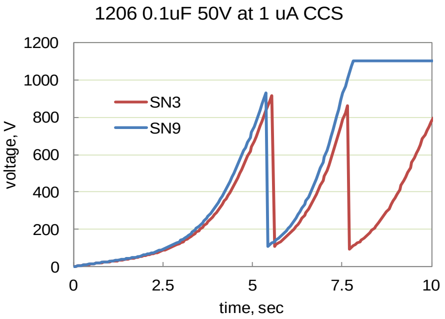

Figure 10. Self-healing during breakdown measurements using CCS technique in a capacitor with Ag/Pd electrodes.

This self-healing phenomenon might have some benefits for applications of capacitors by reducing the probability of catastrophic failures. However, during DWV testing the breakdown might remain unnoticed unless the current is monitored, and a defective part might escape screening.

IV. DISCUSSION

A. *Effect of thickness of dielectric on VBR*

Analysis of the breakdown field, $E_B = V_{BD}/d$, dependence on the thickness of the dielectric shows a substantial increase of E_B as d decreases (see Figure 11). In the range from 3 μm to 60 μm variations of E_B with d can be approximated with a power law $E_B = A \times d^n$, where constant A = 211.4, n = -0.56, d is measured in μm, and E_B is in V/μm. For relatively thick dielectric layers, in the range from 25 μm to 50 μm, E_B is in the range from ~30 V/μm to ~20 V/μm. However, for thin layers, from 3 μm to 5 μm, the breakdown field is almost 4 times greater and reaches ~ 90 V/μm.

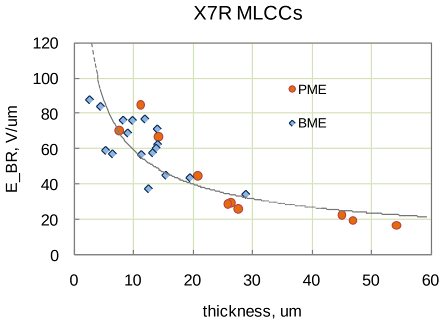

Figure 11. Variation of the breakdown field with the thickness of the dielectric in X7R MLCCs.

The level of E_B reported in literature varies in a wide range from ~2 V/μm for relatively thick layers (30 μm to 120 μm) [6] to more than 100 V/μm for dielectrics with a thickness of a few micrometers, which is in agreement with our data. An increase of E_B with decreasing of the thickness of ceramic layers was observed by Maher et al. [16] and was related to better thermal conditions for thinner dielectric layers. Another possible reason for the improved electrical strength is a reduced number of flaws in thin dielectrics. It is known that the density of structural defects is generally increasing with the thickness (volume) of material [4], and VBR is generally lower for capacitors with larger values of capacitance and surface area of electrodes [17].

The thickness of the dielectric is only one of the factors affecting E_B and the electrical strength of barium titanate ceramics depends also on the composition [18], grain size [19], specifics of microstructure, and material of metal electrodes [20]. A relatively large scatter of the E_B data in Figure 11 is most likely due to a variety of different factors affecting breakdown strength in different types of capacitors manufactured by different vendors.

According to Lee [20], variations of the composition of silver/palladium electrodes in MLCCs from Ag80/Pd20 to pure silver decreased E_B for 30 μm dielectrics from 51.5 V/μm to 39.7 V/μm. This was explained by migration of pure silver into dielectric layers along the grain boundaries during co-firing and thus effectively reducing the thickness of the dielectric. Although it is difficult to compare values of VBR for PME and BME capacitors used in this study because other factors are also changing, our data do not show any substantial difference in E_B for PME and BME capacitors (see Figure 11).

A large proportion of undamaged capacitors fail at the electrode margin areas likely for two reasons. First, the electric field at electrode edges is enhanced thus increasing the current density and the probability of a local breakdown. Second, margin areas are highly stressed mechanically [21] and have a relatively large proportion of structural defects that can also facilitate electrical breakdown.

B. *Mechanism of breakdown in fractured capacitors with exposed electrodes*

The appearance of breakdown areas in mechanically fractured and cross-sectioned capacitors was similar and clearly indicates a surface breakdown. This breakdown could be due to a flashover that depends on the physical and chemical characteristics at the surface of ceramics. Another possibility is a direct breakdown between electrodes in the air gap that at atmospheric pressure varies with the distance between electrodes according to the Paschen's law. However, Paschen's curve describes breakdown in a gas gap with flat electrodes and relatively sharp edges of electrodes on the surface of fractured capacitors might reduce VBR compared to the Paschen's values.

Typically, flashover occurs in vacuum systems and is related to the field emission of electrons at the triple junction (interface of metal electrode, vacuum, and surface of the dielectric) that promotes the secondary electron emission from the surface of the dielectric and results in positive charging of the surface. This creates an electron avalanche across the surface towards the anode, which is followed by an electrical breakdown and plasma generation on the surface of the dielectric [22]. The voltage of this flashover breakdown is assumed to be less than for the gas breakdown between the electrodes with the equivalent gap.

The flashover at atmospheric pressure is not a fully understood phenomenon [23-24]. Surface charging might depend strongly on the type of gas and as was shown in [23] the path of the arc changes for air and nitrogen environments. In the case of ceramic capacitors the flashover process might be facilitated by a high efficiency of ferroelectric materials for electron emission [25]. It is possible that fractured ceramics have much greater emission efficiency compared to the surface of grounded and polished ceramic materials that is oxidized by water and contaminated by materials used for grinding and polishing. A higher emission of electrons from the freshly activated surface of mechanically fractured capacitors might explain lower breakdown voltages in these parts compared to the cross-sectioned capacitors. This effect is seen in Figure 2 where the spread of breakdown voltages is relatively small and slopes of distributions for the major portion of the MF capacitors is close to the one for the cross-sectioned parts.

A dependence of breakdown voltages measured in cross-sectioned capacitors on the thickness of the dielectric is shown in Figure 12. This figure shows also the Paschen curve calculated in the assumption that the air gap is equivalent to the distance between electrodes. The experimental data follow closely the Paschen's curve thus indicating that the mechanism of the surface breakdown might be the same as in the air gap with the distance between electrodes equal to the thickness of the dielectric.

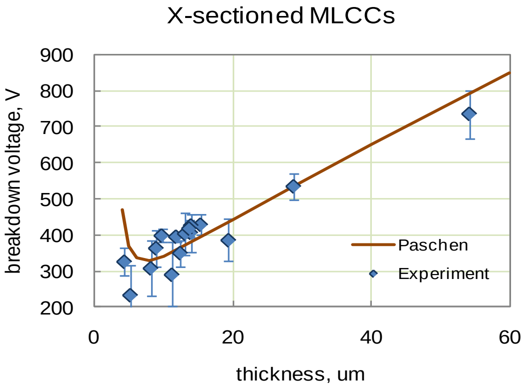

Figure 12. Variation of breakdown voltage in cross-sectioned capacitors with the thickness of the dielectric layers. The marks are experimental data with error bars equal to standard deviations; the curve represents Paschen's law.

Experimental data can be approximated with the Paschen's curve down to the distances between electrodes about 7 μm. For smaller distances the probability of ionizing of gas molecules that would cause avalanche breakdown became low, so higher voltages are necessary to initiate breakdown and Paschen's curve has a minimum at ~ 7.6 μm (327 V). All cross-sectioned capacitors in this study, including those with the smallest thickness of the dielectric, had evidence of surface breakdown. This indicates that the surface flashover can occur at voltages below those predicted by the Paschen's curve.

Note also that the Paschen's law is not applicable when the separation between the electrodes is comparable to the mean free path of electrons in air that is approximately 0.5 μm [26]. Direct experiments showed that the Paschen's curve provides accurate estimations of VBR for a relatively large gap size only (>10 μm) [27]. At lower distances breakdown voltages instead of increasing as required according to the Pashen's curve, are further decreasing and stabilize around ~100 V in the range from ~ 5 μm to ~ 0.3 μm.

Both, bulk and surface breakdown increase with the dielectric thickness and both have a relatively small spread of the data. This explains correlation between VBR for virgin and cross-sectioned capacitors (see Figure 5).

Oscillograms of the surface breakdown indicate a substantial noise in the signal thus suggesting that the breakdown is a combination of multiple discharges. The duration of a gas discharge in a small gap is about a few nanoseconds, which is in agreement with [28], so dozens of local discharges that are spread over a relatively large surface area contribute to the surface breakdown resulting in total duration of the process of ~ 150 ns.

Surface breakdown in a large proportion of cross-sectioned capacitors occurred at the end of electrodes near the margin areas. The reason for this is likely similar to the bulk breakdown and is due to the increase of local electric field at the edges on the surface.

C. *Effectiveness of the DWV testing for screening of MLCCs*

Parts after mechanical fracture had the largest probability of breakdown during DWV testing, but even for these groups of parts the average proportion of samples that would be rejected by this test was only ~20%. Capacitors damaged by cross-sectioning had very small values of $P_{2.5}$ averaging at 0.25%. A substantial proportion of lots (31% of lots after TS and 47% of lots after cross-sectioning) had a negligible level of $P_{2.5}$ of less than 0.001%.

A large percentage of capacitors with tiny cracks created by thermal shock testing did not decrease VBR compared to virgin parts. Most likely gas ionization processes in capacitors with cracks of a thickness that is close or less to the free path of electrons in air (~0.5 μm) would not develop and breakdown voltages in such parts would not be affected any substantially.

This analysis indicates that majority of defective parts would pass DWV testing, so the effectiveness of the existing DWV test to screen-out low-voltage capacitors with fractures is not acceptable. To improve its effectiveness, the test voltage should be increased and prebreakdown currents should be monitored to check for possible self-healing. To avoid damage caused by applying high voltages to capacitors, the test voltage should have a substantial margin to VBR, and using test voltages equal to 50% of the first percentile of the VBR distributions seems to be reasonable and consistent with literature data [6-7].

To assure that a lot of MLCCs is not susceptible to cracking caused by soldering-induced thermal shock (especially in the case of manual soldering) and/or flex cracking, breakdown voltage testing is recommended during qualification inspections. Comparative analysis of distributions of breakdown voltages before and after the stress would allow revealing potentially weak lots of capacitors.

V. CONCLUSIONS

1. Analysis of breakdown voltages in X7R ceramic capacitors showed the following:
   a. Breakdown voltages substantially, by a factor of 10 to 85, exceed rated voltages, and the ratio VBR/VR increases as VR decreases. Rated voltages in MLCCs are limited mostly by the non-linearity of polarization and are not related to their electrical strength.
   b. Breakdown electrical field decreases from ~90 V/ μm to ~ 20 V/ μm as the thickness of the dielectric increases from 4 μm to 60 μm and does not depend substantially on the type of electrodes used (BME or PME).
   c. Breakdown in a large proportion of capacitors is localized at the margin areas, likely due to the field enhancement at the electrodes' edges and high mechanical stresses at the margin areas of MLCCs.
2. Distributions of VBR in capacitors with cracks and appearances of the breakdown areas were evaluated with the following results:
   a. A large proportion (~50%) of capacitors in 13 different lots that had cracks induced by thermal shock testing did not change their breakdown voltages compared to undamaged parts any substantially.
   b. Variations of breakdown voltages in cross-sectioned capacitors with the thickness of the dielectric could be accurately enough approximated by the Paschen's curve down to the thickness of ~ 7 μm.
   c. Breakdown in mechanically fractured and cross-sectioned capacitors was not local, but spread over a large portion of the exposed electrodes resulting in formation of a thin glassy layer on the surface with embedded balls of molten electrode materials. In a large proportion of cross-sectioned samples the breakdown areas were located near the terminals.
   d. The mechanism of breakdown in capacitors with exposed electrodes is likely a surface flashover that is initiated at the weakest spot on the surface between two electrodes, and then spreads along the electrical field to the neighboring areas. The process is facilitated by high field emission of electrons from ceramic and consists of multiple local discharges with duration of a few nanoseconds.
3. The effectiveness of the existing DWV testing to reveal capacitors with cracks is low. Even parts with gross defects, caused by rough mechanical fractures have the probability of failing the test of ~20% only and for parts with fine cracks this probability is less than 1%. To make DWV test more effective, it should be performed at higher voltages that can be determined based on analysis of the distribution of breakdown voltages for the lot.
4. Breakdown voltages in low-voltage MLCCs are sensitive to the presence of cracks and are measurements of VBR for low-voltage MLCCs is useful for assessment quality of the parts. Measurements of VBR are recommended during qualification testing to assure adequate robustness of capacitors to soldering and assembly related stresses.

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