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Tara Niakan, Zarel Valdez-Nava, David Malec. Dielectric Breakdown of Alumina: Effect of Mechanical and Electrical Prestress. 2024 IEEE 5th International Conference on Dielectrics (ICD), Jun 2024, Toulouse, France. pp.1-4, 10.1109/ICD59037.2024.10613248 . hal-04747954

**HAL Id: hal-04747954**

**<https://hal.science/hal-04747954v1>**

Submitted on 22 Oct 2024

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# Dielectric Breakdown of Alumina: Effect of Mechanical and Electrical Prestress

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**Abstract**—This work studies the influence of the mechanical and electrical constraint on the dielectric and mechanical breakdown of alumina ceramics ( $\text{Al}_2\text{O}_3$ ). In this study the dielectric and mechanical breakdown of alumina with different thickness has been characterized and compared with the results obtained with the electromechanical setup. It can be observed that the mechanical prestress of 50% of the mechanical breakdown value, applied to the samples reduces the dielectric breakdown field of the sample of 12%. A similar behavior is observed for the electrical prestress, for 70% of the dielectric breakdown field on the mechanical breakdown strength, resulting a reduction of 30% of the mechanical breakdown strength.

**Keywords**—Ceramics substrate, Alumina substrate, dielectric breakdown, electromechanical breakdown, mechanical prestress.

## I. INTRODUCTION

Power electronics plays a major role in today's world with the use of wide band gap semiconductors such as SiC and GaN, allowing a better efficiency for the energy conversion. One of the elements in this conversion chain is the power module containing substrates, that not only supports all the components, but also has the role of thermal conduction and electric insulator. One of the possible factors of the power module failure is the dielectric breakdown of the substrate. For high power and high voltage modules, the material of choice for substrates are ceramics such as AlN,  $\text{Al}_2\text{O}_3$  and BeO. In the temperature range of [20°C – 300°C], the dielectric breakdown mechanism causing the substrate's dielectric breakdown is the electro-mechanical one. Today there are two main theories about this mechanism: (i) Electrostatic theory [1], [2], [3] and (ii) Crack propagation theory, under a moderated field [4] known as electrofracture for a long term (aging) or under a strong field [5] known as the filamentary breakdown in short term. In this study we will focus on the filamentary theory of the electromechanical breakdown. For brittle materials, the limiting factor is the mechanical breakdown. In the literature, this theory is described as an analogy of Griffith criterion for mechanical rupture. The Griffith criterion [6] states that a defect becomes unstable and material fracture occurs when the change in strain energy resulting from an increase in the growth of the crack is sufficient to overcome the surface energy of the material [7], [8]. Therefore, the electromechanical breakdown in brittle materials is often described as the propagation of pre-existing cracks or defects under the applied electric field till the breakdown is reached. An electromechanical test, combining mechanical and electrical stress, could shed light into the mechanism of crack propagation. The goal of this study is to validate an experimental test bench on which both dielectric and mechanical breakdown tests can be done. Using the setup, the influence of mechanical prestress, aiming to propagate the pre-existing cracks through the sample, on the dielectric breakdown of alumina ceramics can be analyzed.

## II. EXPERIMENTAL METHOD

### A. Samples

The sample used in this study are polycrystalline  $\alpha$ -Alumina plates with 96% purity and different thicknesses (380  $\mu\text{m}$  to 1 mm, Ceramtec). Alumina plates were cut to samples of 10 mm x 45 mm.

### B. Mechanical breakdown setup

The mechanical breakdown experiment was conducted using a 3-point bending test according to standards ASTM C28 and D30, [9], [10] as showed in Figure 1a.

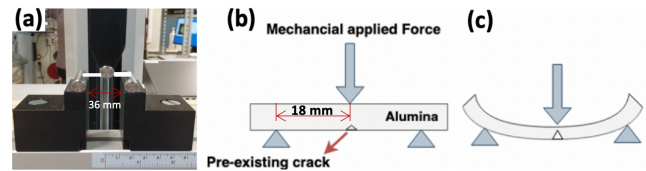


Fig. 1-3-point bending test bench, (a) setup, (b) schematic of 3-point bending and (c) Bending of the sample due to the applied load along with the propagation of the pre-existing crack.

During the 3-point bending test, a force is applied on the sample. As this force increases the sample bends, propagating the pre-existing cracks, until a breaking point, where the mechanical breakdown occurs as shown in Figure 1b and 1c.

### C. Dielectric breakdown setup

The dielectric breakdown experimental setup consisted of a high voltage transformer driven by a motorized autotransformer (AC, 50Hz). A current probe is used to detect any dielectric breakdown in the sample and turn off the high voltage, with the current threshold of 15 mA. The measuring cell has already been introduced by Malec et al. [11]. Ground electrode has 18 mm of diameter and the high voltage electrode has 5 mm in diameter. An insulating liquid is used to avoid surface flashover (Galden HT55, Solvay).

### D. Electromechanical setup

The Electromechanical experiment can be done in two ways, (i) Separated setup and (ii) ElectroMechanical Test Bench (EMTB). The separated setup tests consist of using the dielectric breakdown measuring cell and 3-point bending setup separately, i.e., a mechanical prestress will be done and the sample will be removed and placed in the dielectric cell. These tests would be limited since no simultaneous experiment can be done. The EMTB tests however, allow a variety of configurations, including the combined electrical and mechanical. Figure 2 shows the Electromechanical setup, consisting of a container where the 3-point bending is set. There is a planar electrode facing the high voltage/mechanical load electrode connected to the ground. This electrode is supported by a spring to allow the vertical displacement. Other components are made of insulation materials (Poly-methyl methacrylate).

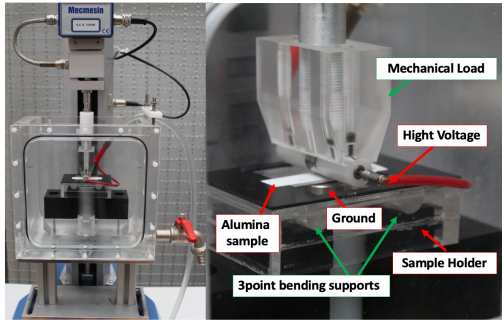


Fig. 2 Electromechanical setup

The cylinder used for the electrical and the mechanical load application is a rod with a 5 mm cylinder, as shown in Figure 3. The container is filled with the same type of liquid insulator as mentioned above.

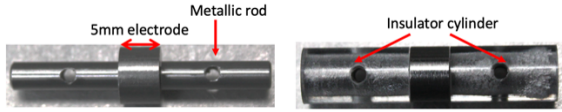


Fig. 3 The upper electrode of the electromechanical setup

Multiple test scenarios are possible with the electromechanical test bench, illustrated in Figure 4.

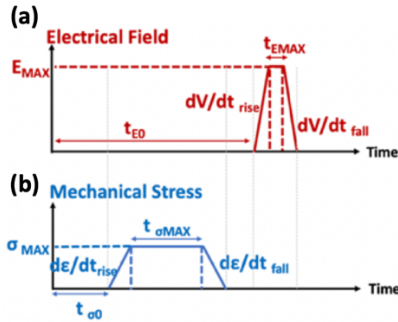


Fig. 4 Different configurations for electromechanical tests, (a) the electric field conditions and (b) Mechanical stress conditions.

TABLE I. ELECTROMECHANICAL TEST CONDITIONS

Test conditions	Dielectric breakdown with mechanical prestress	Mechanical breakdown with electrical prestress
$t_{\sigma 0}$	0 min	>1 min
$d\varepsilon/dt_{rise} = d\varepsilon/dt_{fall}$	1 mm/min	1 mm/min
$\sigma_{max}$	210 MPa	Breakdown
$t_{\sigma MAX}$	1 min	0 min (Breakdown)
$t_{E0}$	>2 min	0 min
$dV/dt_{rise} = dV/dt_{fall}$	1.5 kV/s	1.5 kV/s
$E_{max}$	Breakdown	12.5 kV/mm
$t_{EMAX}$	0 min (Breakdown)	20 s

The parameters are the maximum field and stress applied, with  $E_{max}$  and  $\sigma_{max}$ .  $dV/dt$  and  $d\varepsilon/dt$ , are the voltage rising rate and the loading rate,  $t_{E0}$  and  $t_{\sigma 0}$  the time before the test starts and  $t_{EMAX}$  and  $t_{\sigma MAX}$ , the hold time of the constraints.

### III. RESULTS AND DISCUSSION

#### A. Results of mechanical breakdown strength

The 3-point bending test is used to characterize the mechanical strength of the alumina samples. According to

Anderson [8], this bending test is most suitable for crack propagation in brittle materials such as Alumina ceramics. The mechanical breakdown strength of Alumina ceramics can be observed in Figure 5 for both setups. The strength,  $\sigma$ , was calculated according to the standard ASTM D7264 [10],

$$\sigma = \frac{3FL}{2wd^2} \quad (1)$$

where  $F$ , is the applied force,  $L$ , the support span length,  $w$ , the sample's width and  $d$ , the sample's thickness. Figure 5 shows the stress-strain graph obtained from the mechanical breakdown of 1 mm Alumina using the 3-point bending and the electromechanical setup.

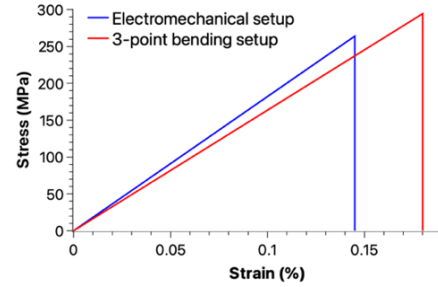


Fig. 5 Stress-strain graph for Alumina with 1 mm thickness using the 3-point bending setup and the electromechanical setup (loading rate=1 mm/min,  $L=36$  mm).

The comparison of the breakdown strength of both setups are in agreement, meaning that the electromechanical cell is compatible for both dielectric and mechanical tests.

#### B. Results of dielectric breakdown strength

The results of the dielectric breakdown field obtained with a plane-plane electrode using the dielectric breakdown cell and the electromechanical setup is shown in Figure 6. These results are statistical values of 10 samples per thickness, analyzed by the two parameter Weibull distribution with a 90% confidence bounds, given by,

$$F(x) = 1 - e^{-\left(\frac{x}{\alpha}\right)^\beta} \quad (2)$$

Where  $F(x)$  is the cumulative probability of failure,  $\alpha$  is the scale parameter (kV/mm) correlated to the probability of failure  $F(\alpha) = 63.2\%$  and  $\beta$  is the shape parameter.

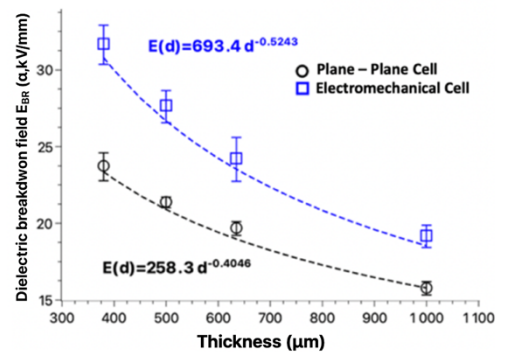


Fig. 6 Dielectric strength ( $\alpha$ ) of polycrystalline Alumina samples versus thickness, with  $n_{Plane-plane\ cell} = 0.4046$  and  $n_{EMTB} = 0.5243$ . Error bars represent 90% confidence bounds.

Owate and Freer [12], Malec et al. [11] and Neusel et al. [13] al. have demonstrated that the dielectric breakdown field,  $E_{DB}$ , and the thickness,  $d$ , follow the relation  $E_{DB} = Ad^{-n}$ , with both  $A$  and  $n$  ( $\approx 0.5$ ), parameters related to the purity. It is observed from Figure 6 that the dielectric breakdown field

of the electromechanical setup is coherent (same tendency and order of  $n$ ) with the expected results and the same tendency can be found.

The difference between the dielectric breakdown field of the two setups is due to the volume of field interaction within the sample. The sample volume in interaction with the electric field is much lower for the electromechanical one compared to the dielectric measuring cell. For calculating this volume, the electrostatic field was simulated using Comsol Multiphysics v.6.1. The volume under high field in the electromechanical setup is  $8.6 \text{ mm}^3$  while for the plane-plane cell it's  $15.6 \text{ mm}^3$ . This was obtained by calculating the surface of the ceramic that was under the same electric field. Diahm et al. [14] and Block et al. [15] showed that the dielectric breakdown field decreases with the increase of the electrode area for the same thickness. Hence the dielectric breakdown occurs at a higher value of the electrical field for the electromechanical setup, in the region that the dielectric breakdown field is dependent of the thickness.

### C. Results of the electromechanical test

The electromechanical tests in this paper are consisted of a mechanical prestress followed by the dielectric breakdown or an electrical prestressed followed by a mechanical breakdown. In the Separated setup, both tests were conducted, however there were no impact of the mechanical prestress on the dielectric strength, nor any impact of the electric prestress on the mechanical breakdown strength, observed on Figure 7.

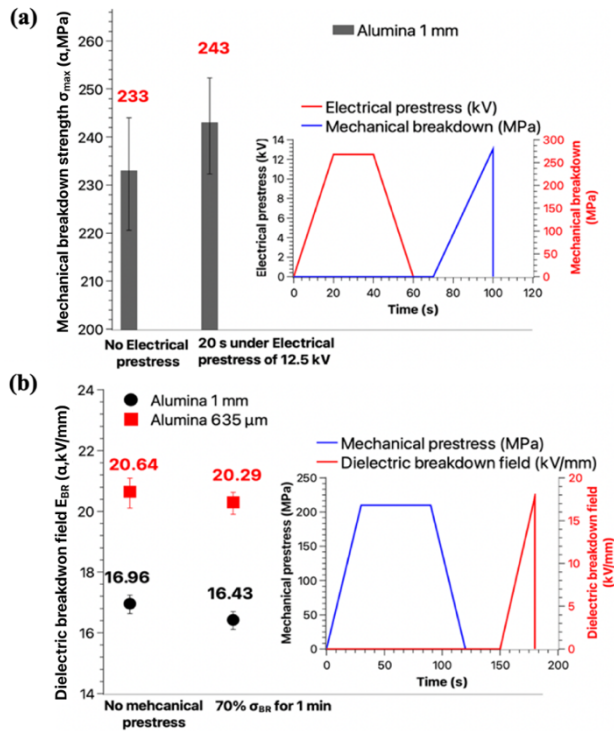


Fig. 7 Influence of prestress on breakdown, (a) Mechanical breakdown ( $\alpha$ ) of 1 mm Alumina vs the electrical prestress and (b) Dielectric breakdown ( $\alpha$ ) of 1 mm and 635  $\mu\text{m}$  Alumina versus the mechanical prestress, applied for 1 min Error bars represent 90% confidence bounds.

The mechanical prestress was applied for 70% of the mechanical breakdown strength,  $\sigma_{BR}$ , for a duration of 1 min, using the 3-point bending setup. The sample was removed and put into the dielectric measuring cell. As for the electrical prestress, the samples underwent 12.5 kV, 70% of  $E_{BR}$ , during 20 s in the measuring cell and then put into the 3-point bending

setup, undergoing the mechanical breakdown. These results are statistical values of 10 samples for each point, analyzed using Eq (2).

Since there was no impact of the prestress on the breakdown, in the Separate setup, it is crucial to be able to use the electromechanical setup, where the sample will not be removed from one test to the other. For the mechanical prestress in the EMTB configuration, two main prestresses were chosen, 70% of breakdown constraint  $\sigma_{BR}$  and 50%  $\sigma_{BR}$ . Table II, gives a summary of the different test configurations used on the ceramic. The first configuration is the pristine Alumina sample undergoing dielectric breakdown with no mechanical prestress.

TABLE II. MECHANICAL PRESTRESS CONFIGURATION

Test conditions	Configuration 1	Configuration 2
$t\sigma_0$	0 min	0 min
$d\epsilon/dt_{rise} = d\epsilon/dt_{fall}$	1 mm/min	1 mm/min
$\sigma_{max}$	70% $\sigma_{BR}$	50% $\sigma_{BR}$
$t\sigma_{MAX}$	>1 min (Breakdown)	5 min
$t_{E0}$	1.50 min	>6 min
$dV/dt_{rise} = dV/dt_{fall}$	1.5 kV/s	1.5 kV/s
$E_{max}$	Breakdown	Breakdown
$t_{EMAX}$	0 min (Breakdown)	0 min (Breakdown)

Configuration 2 consist of applying the mechanical prestress and then the dielectric breakdown test, while for configuration 1, the dielectric breakdown test will occur under mechanical constraint, therefore, the mechanical load will hold till the breakdown, only possible with the EMTB.

The dielectric breakdown versus the different configurations of mechanical stress application is shown in Figure 10 for two different thicknesses of Alumina. Using 10 samples for each point, analyzed by the two parameter Weibull distribution with a 90% confidence bounds. It is observed in Figure 8 that both Alumina 635  $\mu\text{m}$  and 1 mm follow the same tendency, applying the mechanical constraint decreases the dielectric breakdown.

The maximum decrease in the dielectric breakdown was for configuration 2, where a mechanical constraint of 50% of  $\sigma_{BR}$  was applied for 5 min followed by the dielectric breakdown. There is a slight decrease of the dielectric breakdown strength for Alumina 1 mm samples, in configuration 1, which means that the dielectric breakdown occurred during the appliance of the mechanical constraint. The dielectric breakdown value with no prestress is used at reference. The main difference between configuration 1 and 2, other than the value of the mechanical constraint and hold time, is that in configuration 1, the dielectric breakdown occurs under the mechanical prestress. After observing the effect of the mechanical constraint on the dielectric breakdown strength of Alumina ceramics, the influence of the electrical prestress on the mechanical breakdown was studied.



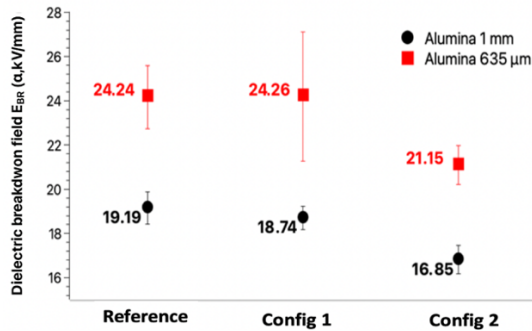


Fig. 8 Effect of mechanical constraint on the dielectric strength ( $\alpha$ ) for polycrystalline Alumina with two different thicknesses. The reference is the dielectric breakdown ( $\alpha$ ) of pristine samples using the EMTB. The dielectric breakdown field is plotted for 3 different configurations. Error bars represent 90% confidence bounds.

The Alumina samples with 1 mm and 635  $\mu\text{m}$  thicknesses was electrically prestressed with 12.5 kV and 9 kV respectively, which is equivalent of 70% EBR for each thickness, for 20 s. The results are shown in Figure 9, where 10 samples were used for each test condition, analyzed by the two parameter Weibull distribution with a 90% confidence bonds. It can be observed that in contrast of the Separated setup test, the electrical prestress reduced the value of the mechanical breakdown strength, meaning that the electrical field was able to propagate the pre-existing micro-cracks inside of the ceramic, hence the mechanical resistance to the flexural test decreases.

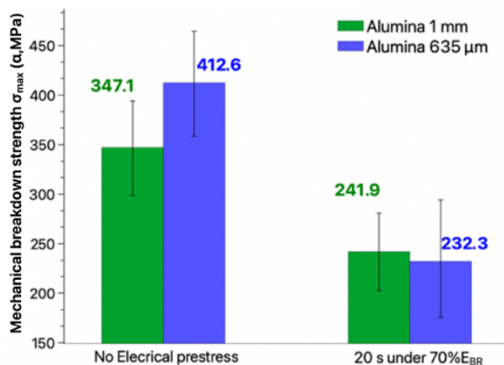


Fig. 9 Mechanical breakdown ( $\alpha$ ) of 1mm and 635 $\mu\text{m}$  Alumina vs the electrical prestress using the electromechanical breakdown setup. Error bars represent 90% confidence bounds.

The pre-existing micro-cracks could have a length of 10 – 20  $\mu\text{m}$  which is proposed to be the size of the original defects in ceramics[16]. Cook et al. [17], demonstrated that the increase in initial crack length decreases the mechanical strength, and since the mechanical breakdown strength after the electrical prestress has decreased, it can be related to the electric field interaction with the pre-existing micro-cracks.

#### IV. CONCLUSION

Both mechanical and electrical experiments, can be conducted in a single electromechanical test bench. The results obtained from the electromechanical experiments, shows that there is an impact of the mechanical or electrical pre-conditioning of the sample on the dielectric or mechanical breakdown limits, respectively. The effect of the electrical prestress on the mechanical breakdown is also observed, which points to a probable crack propagation under the electrical field, since the value of the flexural test after the electrical prestress was reduced drastically. Further studies

must be conducted to explore the other configurations possible with the EMTB. These measurements and complementary microstructural analyses could give additional information on the current electromechanical model and the scenario occurring during breakdown.

#### ACKNOWLEDGMENT

The authors acknowledge the fruitful discussions and exchange with Dr. Francis AVILES, from CICY, Mexico on the fracture mechanics of ceramics. Assistance from Mr. Sorin DINCULESCU and the mechanical services of LAPLACE is also recognized for the design and integration of the EMTB.

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