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Thickness-dependence of the breakdown strength: Analysis of the dielectric and mechanical failure

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Abstract

The breakdown strength as well as the mechanical strength of ceramic materials decreases with increasing volume. The volume-effect of the mechanical strength can be explained by the Weibull theory. For the breakdown strength the same explanation has been often assumed. In order to validate this assumption breakdown strength and mechanical strength of alumina samples with defined porosities were compared. Differences in the Weibull moduli of breakdown and mechanical strength distributions indicate that the volume-effect cannot explain the thickness-dependence of the breakdown strength. In particular, the thickness-dependence of the breakdown strength always leads to a Weibull modulus of two which is not in agreement with the measured Weibull moduli for samples with constant thickness. It can be concluded that the thickness-dependence of the breakdown strength cannot be explained by the Weibull concept. A recently developed breakdown model which is based on space charge injection is able to explain the experimental results.

Keywords: Breakdown strength; Thickness-dependence; Weibull modulus; Fracture strength; Volume-effect

1. Introduction

In applications, ceramics are interesting due to their good electrical insulation properties even at high temperatures. Insulators electrically fail when a dielectric breakdown event happens, which leads to a formation of an electrically conductive channel through the insulator. It is assumed that the initiation of breakdown happens, due to a sudden destabilization of trapped charges,[1–3] which causes a current flow through the material. The breakdown strength, E_b, defined as breakdown voltage, V_b, per sample thickness, t, is reported to be dependent on the microstructure,[2–4] sample thickness[5–9] and loading condition.[8,10–12] The influence of the porosity,[2,13–15] grain size,[2–4,13,15–17] purity and secondary phase[2–4,6,7] on the breakdown strength have been investigated. However, no suitable holistic model has been developed, explaining the experimental results.

The thickness-dependence of the breakdown strength ($E_b \propto t^{-1/2}$) has been often explained as volume-effect similar to the mechanical case.[5,18,19]

Mechanical failure of ceramic materials occurs due to microstructural defects. The fracture strength of ceramics shows due to the volume-effect a thickness-dependence, as the probability for a large fracture initiating defect increases with increasing sample thickness and thus its volume.[20] Hence, it was suggested that there is a correlation between electrical and mechanical failure. For hardened gypsum, $BaTiO_3$- and TiO_2-ceramics, the mechanical strength distributions of three- respectively four-point-bending tests and the breakdown strength distributions were evaluated.[21–24] By comparing the mechanical and dielectric Weibull moduli, an analogy between mechanical and dielectric strength distribution was found, whereas Young et al.[25] could not confirm this result based on experiments with $BaTiO_3$ multilayer-capacitors.

A model, which combines electrical and mechanical parameters, is the electromechanical breakdown model originally proposed by Stark and Garton[26] for polymers. This model was further developed by Zeller et al.[27] and Fothergill,[28] who

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introduced, in analogy to fracture mechanics, a Griffith criterion for the growth of a partial discharge channel into the dielectric. The filamentary electromechanical breakdown model, proposed by Fothergill, is in good agreement with experimental results of polymers. But for ceramic materials, it has been shown by Carabajar et al.[29] that there is no good correlation with experimental results. However, if the thickness-dependence could be explained by a volume-effect, a similar dependence would have been measurable when keeping the thickness constant and varying the testing area.[12] This hypothesis could not be confirmed by experiments.[30,31]

The aim of this paper is to compare Weibull moduli of dielectric breakdown tests with Weibull moduli of mechanical "Punch on three Balls" (P3B) tests of alumina samples with defined porosities. The advantage of the P3B-test is that disc-shaped alumina samples can be used with the same geometry as for the electric breakdown test. Additionally, the P3B-test results show high robustness with respect to slight deviations from the ideal sample geometry.[32,33] Using identical processed samples with same geometry for both the electrical and mechanical tests eliminates influences from microstructure and surface finishing. The samples under investigation have defined porosities from 2 to 8 vol%. Assuming that the failure initiating defects for the mechanical and also for the electrical test are identical, the resulting Weibull moduli should be equal within the confidence interval. Furthermore, Weibull moduli of breakdown experiments on alumina samples with increasing thickness (0.3–1.5 mm) were evaluated. If the thickness-dependence of the breakdown strength were due to a volume-effect, a Weibull modulus of two would be expected, as according to the volume-effect the slope of the double-logarithmic E_b–t-curve equals the inverse Weibull modulus.

2. Materials and methods

2.1. Sample preparation

Dielectric breakdown tests and mechanical P3B-tests were performed on cylindrical polycrystalline Al_2O_3 samples with adjusted porosity.

As alumina base powder Taimicron TM-DAR (Krahn Chemie GmbH, Germany) with a purity of 99.99% and a mean particle size of 0.2 μm was used for sample processing. In order to reach a defined porosity, rice starch as pore builder was taken. The rice starch was sieved with 25 μm and mixed with the Al_2O_3 base powder via speed mixer (DAC 150 FVZ, Hausschild, Germany) at 2500 rpm for 1 min. Depending on the porosity that should be reached in the sintered sample different amounts of rice starch were mixed with the alumina base powder. With the aim of reaching 2.5, 5 and 7.5 vol% porosity in the sintered sample, 1, 2 and 3 g rice starch were mixed with the alumina base powder, to a total amount of 100 g mixed-powder. After speed mixing, the powder was sieved with 355 μm for homogenization. In the following, alumina samples without rice starch are labelled as AO-R0, the samples with 1, 2 and 3 g rice starch are labelled as AO-R1, AO-R2, and AO-R3.

Table 1
Sintering cycle for the alumina powder with and without rice starch.

Sample	Sintering cycle
Al_2O_3 without rice starch, AO-R0	10 K/min to 1350 °C for 1 h 10 K/min to 40 °C
Al_2O_3 with rice starch, AO-R1, AO-R2, AO-R3	5 K/min to 700 °C for 1 h, 10 K/min to 1350 °C for 1 h 10 K/min to 40 °C

From these powder mixtures, samples with a diameter of 28 mm were prepared by sequential uniaxial dry pressing at 8.2 and then 17 MPa with the uniaxial press (Uniaxialpresse, Paul Weber GmbH, Germany). This process was followed by cold-isostatic dry pressing (KIPP200ES, Paul Weber GmbH, Germany) at 150 MPa. After pressing, the samples were sintered in a chamber furnace (HT 04/17 Naber, Germany) in air. The sintering cycles for the powders with and without rice starch can be found in Table 1. The sintering cycle for the powder with rice starch differs from powder without rice starch in the first step. For the powder with rice starch the temperature was increased with 5 K/min up to 700 °C, followed by a holding time of 1 h, in order to burn out the rice starch.

After sintering, the samples were ground plan-parallel to a thickness of 1.0 mm with a flat-bed grinding machine (Blohm HFD 204, Hauni, Germany). In order to proof the known thickness-dependence of the breakdown strength[5–9] alumina samples without rice starch AO-R0 were ground to thicknesses of 0.3, 0.5, 1.0 and 1.5 mm. Alumina samples with rice starch AO-R2 were ground to thicknesses of 0.5 and 1.0 mm.

2.2. Sample characterization

After polishing and thermal etching, the grain size of the samples was characterized according to the mean intercept length method. The density was evaluated with the Archimedes method. Based on light microscope images from the polished surface the porosity and pore size were analysed using an optical method via the software ImageJ (developed by W. Rasband, National Institute of Health, USA).

2.3. Dielectric breakdown test

The dielectric breakdown tests were performed using a rectified AC voltage signal as described by Neusel et al.[34] The voltage signal was realized by a 50 Hz voltage pulse, generated by a function generator (Agilent 33220 A, Agilent Technologies, USA), which was stepwise amplified by vacuum tubes, inductors and a transformer coil from low to high voltage.

The tests were performed in a measurement cell, which mainly consists of a brass-made pin electrode as high-voltage electrode and a ground-electrode made of stainless steel. The high-voltage electrode was enclosed by PVC-cylinder to prevent flash-over behaviour from the high-voltage to the ground-electrode. The ground-electrode has a flat surface area with