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Investigation of partial discharge in piezoelectric ceramics

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Electrical partial discharges were studied in different piezoelectric ceramics. Epoxy material with micro sized cavities was also tested and compared to the piezoelectric ceramics. It is found that compared to epoxy, partial discharge (PD) occurs at relatively lower electric fields for piezoelectric ceramics. The PD inception voltage was found to be lower for materials with higher relative permittivity. This indicates that the intensification of the electric field within the defects is the main cause for the differences in inception field observed for epoxy compared to piezoelectric ceramics. Furthermore, phase resolved PD pattern analysis was carried out for all materials at elevated electric fields. A broad distribution of the discharge event was observed for both epoxy and hard PZT samples, whereas for soft PZT discharge occurs concentrated at electric fields slightly above the coercive field. This intensification of PDs close to the coercive field suggests that PDs may be enhanced due to an increase of the internal field and electron emission rate induced by the domain switching process.

1. Introduction

The electrical partial discharge test has been widely used to estimate the quality of insulation in high voltage equipment such as cables, capacitors and transformers. It is one of the most commonly used diagnostic techniques to detect flaws e.g. gas bubbles or metal impurities in these systems and analyze the degradation of a range of insulation materials including oils, polymers, composite materials, glasses and ceramics [1–4]. Partial discharge (PD) is defined as a localized discharge which only partly bridges the insulation between the electrodes [5]. It occurs because non-uniformities inevitably exist in insulation systems. In ceramics, these flaws can be small cavities and micro-cracks present within the structure. Under an applied voltage, the electric field across those cavities is higher than that in the surrounding ceramic. Two factors contribute to this localized field enhancement: the geometry of the cavity and the low permittivity of air. Furthermore, the dielectric breakdown strength of air is much lower compared to the ceramic. Consequently, even at a relatively low voltage, discharges can occur across the cavities. Since the discharge is confined within the cavities and not across the whole ceramic structure, it is a partial discharge. Compared to complete dielectric breakdown, PD is usually associated with only a small discharge magnitude in the picocoulomb (pC) range.

A large number of PD studies have been reported on materials or devices such as epoxy, switchgears and transmission lines which are essential elements in high voltage engineering [6]. By contrast, the study of PD on ceramic materials is limited. This arises because usually the PD inception fields for traditional ceramic materials used in high voltage engineering such as alumina and porcelain are very high. Consequently, under common operating voltages, the PD phenomena in these ceramics can be ignored. However, for piezoelectric ceramics, the concern is different.

Piezoelectric ceramics possess good electromechanical properties which are exploited in applications such as actuators and sensors. During operation, piezoelectric ceramics are usually subject to high electrical or mechanical loading. Different from traditional insulation ceramics with relative permittivity usually below 10, the relative permittivity of piezoelectric ceramics can be in the range of 1000. Thus the electric field enhancement in defects such as cracks is much larger compared to traditional insulation materials, and can lead to partial discharge even if the applied external field is below the dielectric strength of air. For $BaTiO_3$ multilayer capacitors with relative permittivity $\varepsilon_r = 60$ and thickness of 50 μm, the PD can be initiated by voltages below 200 V [7]. For bulk $BaTiO_3$ ceramics with thickness of 1 mm, the PD inception electric fields

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were reported to be below 1.5 kV/mm [8]. For a lead zirconate titanate (PZT) ceramic with an indentation crack, the electric field enhancement in the region of a crack tip was evidenced by measuring the electrical potential distribution using Kelvin probe microscopy [9]. In our previous work, we have also shown that the PD inception field for a soft PZT ceramic is as low as 1 kV/mm [10]. Furthermore, it should also be noted that repetitive PDs may cause progressive long-term deterioration of the piezoelectric system when the operating voltage is higher than the PD inception voltage, although a single PD magnitude is small. Partial discharge has been reported to be a reason for electrical fatigue [11], crack growth [12], and electrical failure [13] of piezoelectric ceramics. Hence, it is essential to investigate the PD characteristics of piezoelectric ceramics.

In this study, electrical partial discharge tests using an AC 50 Hz electric field were systematically performed on hard and soft doped piezoelectric ceramics as well as on epoxy, which is one of the most intensively studied materials in the PD literature. It should be mentioned the term "piezoelectric ceramics" is simply used here; however the ferroelectric behaviors of piezoelectric ceramics are the focus. The partial discharge behaviors are contrasted to the microstructural, dielectric and ferroelectric characteristics in order to explore the factors influencing PD. We found that the PDs start at much lower electric field for piezoelectric ceramics compared to epoxy. With increasing electric field, more PDs occur. Moreover, the PDs of soft PZT may be facilitated by local electric fields induced by the domain switching process.

2. Experimental

2.1. Sample preparation

The piezoelectric ceramic samples were commercial PZT provided by Thales Underwater Systems, Australia. A soft type PZT (TLZ51) and a hard type PZT (TLZ31) were used in this study. "Soft" and "hard" PZT usually refer to PZT with donor and acceptor doping, respectively, which make them different in the electrical properties to meet the requirements for specific applications. Specifically, soft PZT is usually characterized with higher permittivity, larger dielectric loss, lower coercive field and is more susceptible to polarization/depolarization, while hard PZT generally has opposite characteristics. The samples were cut into a rectangular bar shape with dimension of $25 \times 4 \times 3$ mm^3. The 25×4 mm^2 surfaces were polished to a finish of 1 μm with diamond paste. All piezoelectric samples were annealed at 400 °C for 2 h in order to relieve mechanical stresses induced by the polishing process. Silver paste (RS Components, UK) was painted on the polished surfaces as electrodes for further tests. The epoxy resin samples were prepared by a typical solution mixing technique (Epo-Quick, Buehler, Lake Bluff, USA). The mixtures were cured at room temperature for 12 h and then cut to two different geometries – bar shaped and disc shaped. The bar shape epoxy samples had the same dimension as the ceramic specimens. Silver paste was also painted on the 25 mm × 4 mm surfaces. These samples were used as references to make sure that no unintentional PD was produced from the sources outside the tested ceramic materials (e.g. breakdown of the oil, surface discharge across sample edge). Disc samples were prepared with a diameter of 28 mm and approximately 400 μm thickness. Silver paste was painted on both sides with a rim of 3 mm left. The disc shape epoxy sample was used to obtain PD results which are comparable to ceramic samples. As the PD can only be observed at very high electric fields and due to the voltage limit of the PD test system, the thickness of the epoxy sample had to be quite small. The featured properties of the materials used in this study are listed in Table 1.

2.2. Sample characterization

The microstructure of the samples was investigated using an optical microscope (Epiphot 200, Nikon, Japan). The polarization hysteresis loop was characterized using a standardized ferroelectric test system (TF Analyzer 2000 system, aixACCT, Aachen, Germany) with a high voltage amplifier (Trek 20/20C, Trek Inc., Medina NY, USA). A sinusoidal waveform was used with a frequency of 50 Hz and maximum amplitude of 2 kV/mm. The relative permittivity was measured at 1 kHz using an HP 4294A Impedance Analyzer.

2.3. Electrical partial discharge test

The partial discharge test was carried out at room temperature using the direct coupling detection method according to the IEC60270 Standard. The experiment arrangement is illustrated in Fig. 1. In this scheme, C_a represents the test object, C_b is a blocking capacitor, Z_{mi} is a quadripole measuring impedance. Details of the PD system set-up can be found in our previous study [10]. This PD measuring system has a resolution of 1 pC. In this study, the cutoff level of the background noise was set as 2 pC.

The bar samples were all sandwiched between a pair of plane/plane brass electrodes (diameter 50 mm, thickness 10 mm). Six samples were tested for each type of piezoelectric material. The disc samples were clamped between a pair of spherical brass electrodes (diameter 10 mm). Three epoxy samples were tested. All samples were tested in a test cell filled with transformer oil (Shell Diala MX, Melbourne, Australia).

During the PD test, the applied AC voltage at 50 Hz was raised step by step (approximately 80 V for each increment). When continuous PDs were firstly observed in the sample, the applied voltage was reported as the partial discharge inception voltage (PDIV). PD events were recorded for 10 s at the PDIV. The PD events were further recorded at increasing electric fields. This measurement sequence was repeated on each sample. Prior to applying the voltage, off-line calibration was carried out for each sample by low-voltage injection of 50 pC charge. All (sinusoidal) voltage and electric field values reported in this study correspond to the root mean square (RMS) value.

3. Results

The optical surface micrographs of ceramic and epoxy specimens are displayed in Fig. 2. Defects such as pores can be clearly observed at the surface in both ceramics and epoxy. Compared to the transparent epoxy sample, which contains air-filled spherical

Table 1
Characterization of materials.

	Density (g/cm^3)	Relative permittivity ε_r	Average pore size (μm)	Maximum pore size (μm)
TLZ51 (Soft type PZT)	7.6	2100	7.4	48.6
TLZ31 (Hard type PZT)	7.4	1000	5.3	50.3
Epoxy	1.2	4.8	42.0	77.5