Measurement of Energy Release Rates for Cracks in PZT under Electromechanical Loads

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Abstract

An experimental method is presented, which allows measuring all components of the total energy release rate under conditions of controlled crack growth in a piezoelectric material. V-notched specimens of PZT poled parallel to the long axis are fractured in 4-point-bending. Additionally electric fields are applied parallel and antiparallel to the poling direction, i.e. perpendicular to the crack surface. To determine the total energy release rate the mechanical and the piezoelectric compliance as well as the electrical capacitance of the sample are acquired continuously. The derivation of the data with respect to the crack surface area allows calculating the mechanical, piezoelectric, and electrical contributions to the total energy release rate. For an electric field of 500 V/mm the electrical contribution is negative and its absolute value is as high as the mechanical one whereas the piezoelectric value is comparatively small. Hence, the total energy release rate almost vanishes under these conditions and cannot be taken as a valid fracture criterion. The expected effect in retarding crack growth has not been observed.

Keywords List

C. Ferroelectric properties, C. Fracture, D. PZT, compliance

Introduction

Piezo- and ferroelectric ceramics are of common interest, since they are used as sensors and actuators in various technical applications [1]. As these materials are often exposed to both mechanical and electrical loading the fracture behavior and the reliability under such conditions are important issues [2].

A large number of theoretical papers on fracture mechanics of piezoelectric ceramics have been published, as e.g. [3-7]. Experiments performed in recent years exhibit different and partly contradictory results [8-14]. For example Park and Sun [8] report that positive electric fields (parallel to the poling direction) promote and negative impede crack propagation. Other authors observed the opposite material behavior. This might be related to different experimental conditions prevailing for the measurements performed. Also the choice of the electrical boundary conditions, especially the permittivity interior to the crack, influences the result. Schneider et al. [15] found experimentally that the assumption of a complete impermeable crack is strongly misleading, since the permittivity in the crack is much higher than that of air. Anyhow, the main question is: What is the influence of an electric field within dielectric or piezoelectric materials on the crack progress?

We present an experimental technique, where all contributions to the total energy release rate in a ferroelectric ceramic are measured simultaneously under conditions of controlled crack growth in a four-point-bending device. This includes the energy components due to the mechanical and the electrical load and a mixed mode term due to the piezoelectric properties of the material. This paper presents the principal idea only. A more detailed description is given elsewhere [16].

Theory

In the following the theoretical basis is explained briefly. Suo [17] has proposed a generalized Irwin-Kies Relation which is valid for linear piezoelectric behavior. If a specimen is loaded by a force F and a voltage V the stored potential energy Π is:

$$\Pi(V,F,A) = -\frac{1}{2}C_e V^2 - \frac{1}{2}C_m F^2 - C_p VF \tag{1}$$

where A, C_e, C_m, and C_p are the crack surface area, the electrical capacitance, the mechanical compliance, and the piezoelectric compliance, respectively. With Q and Δ being the electric charge and the displacement, it is:

$$Q = \left(-\partial\Pi/\partial V\right)_{A,F} = C_e V + C_p F \tag{2}$$

$$\Delta = \left(-\partial\Pi/\partial F\right)_{A,V} = C_m F + C_p V \tag{3}$$

The energy release rate is given by:

$$G_{tot} = -\left(\frac{\partial\Pi}{\partial A}\right)_{F,V} = \frac{V^2}{2}\frac{\partial C_e}{\partial A} + \frac{F^2}{2}\frac{\partial C_m}{\partial A} + FV\frac{\partial C_p}{\partial A} \tag{4}$$

The first, second, and third term on the right hand side of Eq. (4) correspond to the electrical, mechanical, and piezoelectric (mixed) component of G_{tot}, respectively. In order to measure G_{tot} the derivatives of C_e, C_m, and C_p with respect to the crack surface area must be determined. Using Eqs. (2) and (3) the capacitance and the compliances can be calculated by

$$C_e = \left(\frac{\partial Q}{\partial V}\right)_F, \quad C_m = \left(\frac{\partial \Delta}{\partial F}\right)_V, \quad \text{and} \quad C_p = \left(\frac{\partial Q}{\partial F}\right)_V = \left(\frac{\partial \Delta}{\partial V}\right)_F \tag{5}$$

From these equations it can be seen, how the capacitance and the compliances can be obtained experimentally. The mechanical compliance is determined by varying the force by dF and measuring the corresponding change of the displacement dΔ at constant electric load. A similar approach is performed to measure the piezoelectric compliance. Under constant electrical load V, the force is varied and the corresponding electric charge is determined by integrating the electrical current measured in the experiment.

Experimental setup

The 4-point-bending device has support distances of 10 and 20 mm and is placed in a very rigid metal frame which enables controlled crack growth (Fig. 1) as proposed by Fett et al. [18]. The morphotropic PZT specimen used (PIC 151, PI-Ceramic, Lederhose, Germany) are $3 \times 4 \times 28$ mm^3 in size, poled in longitudinal direction, and have notch depths of about 1 mm. During the experiment they are loaded with an electric field up to 500 V/mm parallel and antiparallel to the poling direction, i.e. perpendicular to the crack surface. A similar experiment using the same geometrical arrangement has been performed previously [14], but with the difference that the samples were cracked by fast uncontrolled fracture in a universal testing machine.

The development of the present setup was insofar challenging, as changes of very small quantities like the capacitance of a few pF have to be acquired under high electric loads up to 14 kV. Furthermore the displacement of the upper support rollers must be measured to determine the corresponding energy quantities correctly. Therefore, two V-shaped rods are connected movably by an axis and transfer the displacement of the upper support rollers to the position encoder positioned below the specimen (Fig. 2). The electrical insulation on the high voltage side of the specimen is achieved by a coating of thermoplastics.

In the fracture experiment the crack length is determined using an optical microscope (Wild M3Z). For determining the R-curve behavior the mechanical load F is measured as well. The outstanding advantage of the presented setup is now that all quantities necessary to determine the energy release rate are acquired additionally and simultaneously with only a minimum of additional time exposure. These quantities are: the displacement Δ, the charge Q, the capacitance C_e, the mechanical compliance C_m, as well as the piezoelectric compliance C_p of the specimen.

Results and discussion

Fig. 3 represents the mechanical and the piezoelectric compliance and also the capacitance of the PZT-specimen as a function of the crack length for a constant applied electric field of 500 V/mm. With a specimen width of about 4 mm the crack growth can be controlled up to the top side of the specimen.

At the beginning the mechanical compliance increases slightly. At higher crack lengths the slope increases strongly (Fig. 3a). As expected the capacitance decreases, because the dielectric constant in the crack is smaller than that of the PZT material (Fig. 3c). The piezoelectric compliance decreases monotonic and reveals a zero-crossing at a certain crack length. This can be qualitatively understood. For an ideal bending bar in principle the piezoelectric compliance is zero, since the charges generated in the compression and in the tension zone compensate each other. In the present case the bending bar is single edge notched, which leads to asymmetric behavior. This asymmetry probably changes its characteristic, when the crack proceeds through the specimen, which explains the tendency in Fig. 3b.

In order to calculate the derivatives of these data, an averaging procedure over 10 neighboring measuring points is applied. Thus, we get the three contributions G_e, G_m, and G_p (right side of Eq. (4)), which add up to the total energy release rate G_{tot}, for an electric field of 500 V/mm (Fig. 4a). It should be mentioned, that in the literature, as e.g. in Ref. [8], the mechanical and the electric energy release rate are defined slightly different, namely as $G_m + G_p/2$ and $G_e + G_p/2$, respectively. For a better evaluation the corresponding R-curve is displayed below (Fig. 4b). Theoretically, the stress intensity factor K_I is independent from the applied electric load under the prevailing conditions [14]. Thus, the fracture toughness K_{IC} in Fig. 4b is calculated using the formula given by Munz and Fett [19] for pure mechanical loading. (Note, that the measured data in Figs. 3 and 4 are based on a single specimen.) Although G_{tot} is approximately zero (Fig. 4a), an effect in retarding crack growth has not been observed. The average value of the mechanical part $\langle G_m \rangle$ for crack lengths between 0.5 and 1.5 mm is about 13 J/m^2. This corresponds well to the value of 12 J/m^2 found by Heyer et al. [20] for the same material but for a conducting crack. A detailed description of the technical and experimental aspects and other experimental results are given in Ref. [16].

Summary

An experimental method for the simultaneous measurement of all components of the total energy release rate under combined electromechanical loading is presented. This is realized using a rigid four-point-bending device which allows controlled cracking of PZT-specimens under applied electric field. During the measurement of an R-curve the mechanical and the piezoelectric compliance as well as the capacitance are acquired simultaneously as a function of the crack length. Therefrom the mechanical, the electrical, and the piezoelectric contribution to the total energy release rate is derived. For the PZT-material used the total energy release rate, i.e. the sum of the three components, is zero or even negative for an applied field of 500 V/mm. This implies that the total energy release rate is not appropriate as fracture criterion, whereas its mechanical part is more likely from an empirical point of view.

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Figure Captions

Figure 1: Four-point-bending device in a rigid frame in order to enable controlled crack growth.

Figure 2: The four support rollers, specimen and small construct for transferring the displacement of the upper support rollers to the position encoder. At the right end of the specimen the insulation with thermoplastics can be seen.

Figure 3: Measured compliances and the capacitance as a function of the crack extension at 500 V/mm. (The sum of crack extension and notch depth is the crack length.)

Figure 4: a) The different contributions G_m, G_p, and G_e to the total energy release rate G_{tot} vs. crack extension at 500 V/mm. b) Corresponding R-curve.