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FINITE ELEMENT ANALYSIS OF FRACTURE AND POLARIZATION SWITCHING BEHAVIOR IN MODIFIED SMALL PUNCH TESTING OF PIEZOELECTRIC CERAMICS

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Summary The fracture behavior of piezoelectric ceramic was investigated under mechanical and electrical loads utilizing the modified small punch technique. A finite element model was developed to simulate the relation between MSP energy and applied electric field. The strain energy density was also computed. Measured fracture initiation loads and calculated maximum strain energy density are sensitive to the change in the applied electric field and polarization switching.

INTRODUCTION

PZT [$Pb(Zr, Ti)O_3$] is widely used in piezoelectric devices, e.g. transducers, filters, sensors, and actuators. The high mechanical stresses and intense electric fields in the PZT ceramic may cause microcracks to develop which eventually lead to failure of the device. The fracture behavior of PZT under mechanical and electrical loads has been the subject of recent studies [1,2]. Shidno et al. [3] performed the single-edge precracked beam tests on a commercial PZT ceramic, and simulated these tests numerically with the finite element method. Shidno et al. [4] also made indentation fracture tests on the PZT ceramics to estimate the fracture toughness, and employed a three-dimensional finite element analysis to calculate the energy release rate and stress intensity factor. On the other hand, the crack growth in a ferroelectric barium titanate ($BaTiO_3$) ceramic was investigated under applied electric fields up to 4 times the coercive field strength using the Vickers indentation technique. The change in crack length and fracture toughness was discussed in connection with the influence of polarization switching on the crack generating stresses.

In a series of articles, a model was developed to simulate the observed nonlinearities in material behavior [6,7]. The ceramics were considered as an aggregate of many grains which were modeled as single domain with switching. Hayashi et al. [8] investigated the displacement and polarization switching properties of piezoelectric laminated actuators theoretically, numerically, and experimentally. Shindo et al. [9] examined the effects of applied voltage and polarization switching on the electroelastic fields concentrations ahead of electrodes in multilayer piezoelectric actuators in a combined experimental and numerical investigation.

In the present paper fracture behavior of a piezoelectric ceramic under applied electric fields is discussed using the modified small punch (MSP) test technique. The purpose of the present paper is also to present a model for such MSP test. To carry out the analysis a polarization switching model is assumed for the specimen material.

EXPERIMENTAL PROCEDURE

Commercially supplied P-7 (Murata Manufacturing Co., Ltd., Japan) piezoelectric ceramic [3] was selected for the experiment. The coercive electric field E_c is 0.8 MV/m. At least 32 small, thin piezoceramic plate specimens of 10 by 10 by 0.5 mm used for MSP tests were sliced. Poling was done along the axis of the 0.5 mm dimension, and silver electrodes were coated on the two 10 mm × 10 mm surfaces.

Using a screw driven test machine, all MSP tests were conducted. To generate electric fields, a power supply for voltages up to 1.25 kV/D.C. was used to apply positive and negative electric fields of 0.2, 0.4, 0.8 and 1.0 MV/m. Loads which caused fracture were measured for each set of specimens for various electric fields. For 0, ± 0.4, ± 0.8, and ± 1.0 MV/m, four or five tests were performed.

FINITE ELEMENT ANALYSIS

We performed three dimensional finite element calculations to determine the MSP energy and maximum strain energy density for the PZT specimens. A rectangular Cartesian coordinate system (x,y,z) is used with the z-axis coinciding with the poling direction. The analytical model is shown in Fig. 1. A mechanical load was produced by the application of either a prescribed force P_0 or a prescribed displacement u_0 along the z-direction. For electrical loads, a negative or positive electric potential ϕ_0 was added on the surface, $z=h$. The surface $z=0$ is grounded. We use the commercial finite element code ANSYS. Eight-nodes 3-D space solid was used in the analysis. The contact between the specimen and the lower die was modeled using contact elements. Because of the double symmetry of the body and loading only one quarter of the body was modeled.

The polarization of each grain initially aligns as closely as possible with the z-direction. The polarization switching is defined for each element in a material. Boundary loads are applied, and the electroelastic fields of each element are computed from the finite element analysis. The switching criterion is checked for every element to see if switching will occur. After all possible polarization switches have occurred, the piezoelectricity tensor of each element is rotated to the new polarization direction. The electroelastic fields are re-calculated, and the process is repeated until the solution

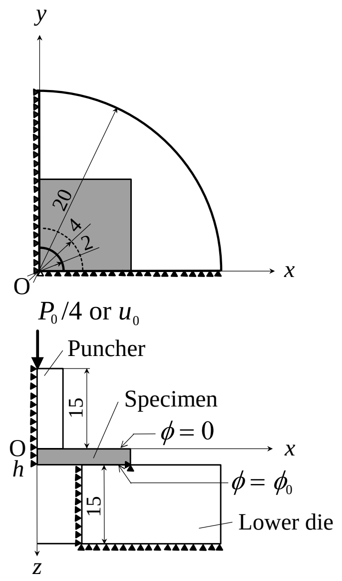

Fig. 1 Finite element model of the MSP test

Table 1 Average fracture initiation loads and statistical deviations under electric fields for MSP specimen

E_0 (MV/m)	P_c (N)	
	Average	Standard Deviation
-1.0	17.7	5.0
-0.8	15.5	2.8
-0.4	13.9	1.6
-0.2	11.9	-
0.0	13.7	0.49
+0.2	15.0	-
+0.4	16.6	2.0
+0.8	17.5	0.35
+1.0	4.79	1.0

converges. The macroscopic response of the material is determined by the finite element model, which is an aggregate of elements.

RESULTS AND DISCUSSION

Table 1 shows the average fracture initiation loads P_c and the statistically-determined standard deviations under different electric fields E_0 obtained from the experiment.

Fig. 2 presents the critical MSP energy E^c_{MSP} including 180° and 90° switching effects (open triangle) for various electric fields E_0. The load-displacement curves were drawn up to the average fracture initiation load P_c using finite element method, and the E^c_{MSP} was calculated from the area under the curve (energy to failure). A similar phenomenon was observed for the maximum energy density. Fig. 3 shows the MSP energy E_{MSP} of the finite element solutions without 90° switching effect under an average fracture initiation load for zero electric field P_0 = 13.7 N and different electric fields E_0, where the result has been normalized by the MSP energy E_{MSP0} for E_0=0 MV/m. Also shown are the prediction with stress effect on polarization switching for the MSP specimen.

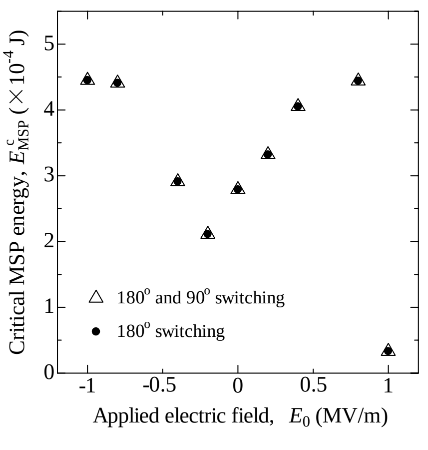

Fig.2 Critical MSP energy vs electric field

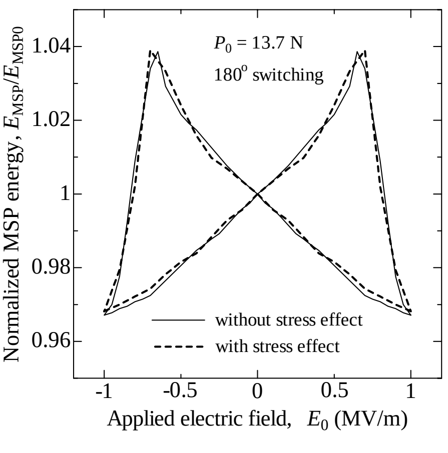

Fig.3 MSP energy vs electric field for applied force

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