STATIC AND DYNAMIC FATIGUE OF CRACKED PIEZOELECTRIC CERAMICS IN THREE-POINT BENDING UNDER AC ELECTRIC FIELDS

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Summary In this study, we report theoretical and experimental examination of the static and dynamic fatigue behavior in cracked piezoelectric ceramics under AC electric fields. Static and dynamic fatigue tests were carried out in three-point bending with the single-edge precracked-beam specimens. A phenomenological model of domain wall motion was also used in finite element computation, and the energy release rate was calculated. The results were then discussed in terms of the lifetime versus energy release rate curve. In addition, the effect of AC electric fields on the critical energy release rate was examined.

INTRODUCTION

The piezoelectric ceramics known as lead zirconate titanate (PZT) have been used as sensors and actuators. The high mechanical stresses and intense electric fields in the PZT ceramics can induce cracking that can lead to premature failure in the piezoelectric devices. The properties of the PZT ceramics are also susceptible to degradation under electromechanical loading. Therefore, an understanding of piezoelectric fracture and fatigue is a key issue for the efficient and reliable design of the piezoelectric devices [1, 2]. Recently, Shindo et al. [3] conducted a theoretical and experimental study of the static fatigue behavior of the PZT ceramics under DC electric fields. Shindo et al. [4] also investigated the dynamic fatigue in cracked PZT ceramics under DC electric fields. In the present paper, the static and dynamic fatigue behavior in piezoelectric ceramics under AC electric fields was studied in three-point flexure using single-edge precracked-beam (SEPB) specimens theoretically and experimentally.

EXPERIMENTAL PROCEDURE

Commercially supplied hard PZT C-203 and soft PZT C-91 (Fuji Ceramics Co. Ltd., Japan) were selected for the experiments. The coercive electric fields of C-203 and C-91 are about 2 and 0.35 MV/m, respectively. Static and dynamic fatigue tests under AC electric fields were carried out in SEPB specimens. Fig.1 shows the testing set-up. PZT ceramics of 5 mm × 5 mm × 5 mm were cut, and the specimen was produced by first poling a PZT and then bonding it between two unpoled PZTs. The size of the specimens was 5 mm thick, 5 mm wide, and 15 mm long. Vickers indents were introduced using a Vickers microhardness testing machine. The specimens were compressed until a precrack was formed. The crack so produced has initial length of about 0.5 mm. Three-point bending apparatus with a span of 13 mm were used for the tests. A 250 N load cell (resolution: 0.01 N) was employed to apply the load to the specimen, and a sine wave electric field at a frequency of 50 Hz or 400 Hz was applied during the test. Time-to-failure under constant mechanical loads and AC electric fields was then measured for the static fatigue test. For the dynamic fatigue test, fracture load under AC electric fields was measured at various load-rates. After testing, a scanning electron microscope (SEM) was used to examine static fatigue and overload fracture surfaces.

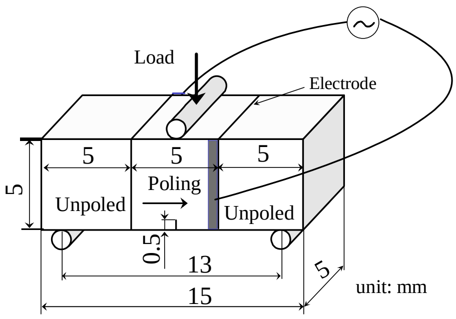

Fig. 1 Testing set-up

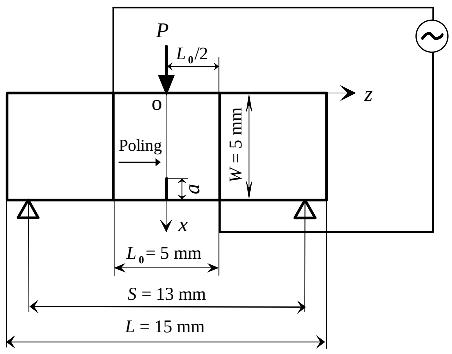

Fig. 2 Finite element model

FINITE ELEMENT ANALYSIS

In order to evaluate the energy release rate G of PZT, plane strain finite element analysis (ANSYS) was carried out for the cracked piezoelectric specimens under concentrated load P and AC electric field $E_0\exp(i\omega t)$; E_0 is the AC electric

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field amplitude and ω is angular frequency($\omega = 2\pi f$ where f is frequency in Hertz). The specimen and loading geometries are shown in Fig. 2. Let the coordinate axes x and z be chosen such that the y axis coincides with the thickness direction. The z axis is oriented parallel to the poling direction. The three-point flexure specimen with a span S is a beam of width W and length L containing a crack of length a. The length between two electrodes is L_0.
In the finite element analysis, the energy release rates G for the permeable crack model were computed using the path-independent integral approach. Note that the fracture mechanics parameters such as G predicted by the permeable and discharging crack models are not significantly different, using the standard air breakdown field for a critical discharge level within the crack gap [5]. On the other hand, a negative G can be induced with high electric fields in the impermeable and open crack models [6].

RESULTS AND DISCUSSION

Fig. 3 shows the average time-to-failure t_f versus energy release rate G of C-91 under E_0 = 0, 40 kV/m (50, 400 Hz). The G is calculated by the FEA with domain wall motion effect for the piezoelectric specimen with a permeable crack of a = 0.5 mm. Fatigue lives are observed to increase with the decrease in G.
A summary of the results of constant load-rate testing for soft PZT C-91 under electric field E_0 = 0, 40 kV/m (50, 400 Hz) is shown in Fig. 4, where log P_c (fracture load) was plotted as a function of log(dP/dt) (load-rate). Average values of two or three data are shown. The PZT ceramics show a decrease in fracture load as the load-rate decreases. It is shown that the fracture load at load-rate of 0.05 N/s decreases due to applied AC electric fields, and that the fracture load at 400 Hz is lower than that at 50 Hz.

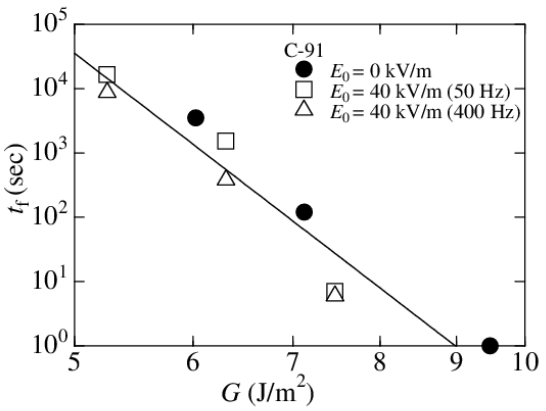

Fig. 3 Time-to-failure vs energy release rate

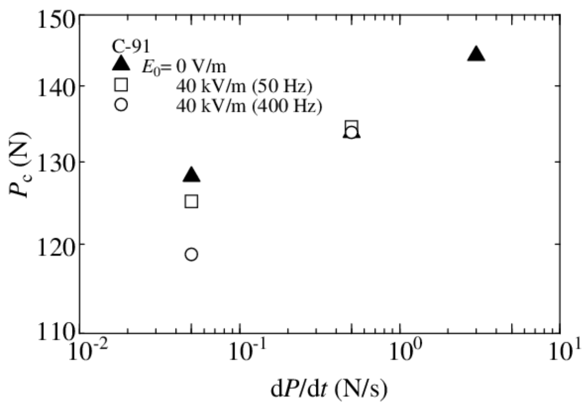

Fig. 4 Fracture load vs load-rate

CONCLUSIONS

The time-to-failure under AC electric fields is significantly lower than that under zero electric field, and the static fatigue curve could be used to judge which piezoelectric ceramics would exhibit good resistance for long time load and which would not. Also, the fracture load of PZT ceramics increases as the load-rate increases, and an overall decrease in the fracture load occurs when testing under AC electric fields.

References

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