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Influence of cyclical electric load on crack growth in piezoelectric ceramics under a constant mechanical load

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Abstract Piezoelectric material has widely used in various applications with its high liable performance and quite smart electro-mechanical characteristics. However, solutions for number of troubles in strength and behavior of fracture have not sufficiently clarified yet. Among these associated solutions, the double torsion (DT) technique is the particular and effective method to measure toughness of fracture and growth behavior of slow crack in ceramic material. From the results of this work, it obtained the practical feasibility of the DT technique for finding growth behavior of crack initiated by kinds of cyclic electric fatigue on piezoelectric ceramics, and found that the initiated crack is able to propagate by using a relatively lower cyclical voltage than before cases under a constant mechanical load if the DT technique is used. In this study, it is also established the experimental method of the crack propagation by cyclic electric fatigue for the piezoelectric ceramics using DT technique, and found the possibility of the power law based on the classical Paris' equation for analyzing the result of electric fatigue crack test.

1. Introduction

The piezoelectric material is the useful smart material broadly utilized in many fields of application because of its unique property of electro-mechanical behavior; however, it has still unknown behavior related to process of strength changing and incident of fracture under the electro-mechanical load. The piezoelectric ceramic commonly used for operating the cyclical electric load in a device; hence, the fatigue cracking of the piezoelectric ceramic caused by the cyclical electric load contributes to degrade electromechanical and mechanical reliability of the device's performance.

Fang et al. [1] found that a crack growth rate of ferroelectric ceramic with pre-crack under pure cyclic electric load was nonlinearly related to the cyclic electric load and a steady crack growth prevail beyond the coercive electric field, E_C of the ferroelectric ceramic. Cao and Evans [2] studied the crack growth behavior in ferroelectric ceramics under large alternating electric fields. Lynch et al. [3] reported that the crack was initiated from the flaw and propagated in the perpendicular direction to voltage drop when a cyclic electric field of magnitude exceeding the coercive field was applied. Schneider et al. [4] examined the fatigue of ferroelectric ceramics under bipolar alternating electric fields which was varied form 0.9~1.5 times the coercive field, E_C and found the crack growth rate decreases with increasing cycle number. Westram et al. [5] obtained the crack propagation data in piezoelectric DCB specimens under cyclic electric loading combined with a constant mechanical load. They found that the fracture quantities were suitable for in cases above the coercive electric field, and found a power law relationship between the crack growth rate and the range of the Mode-IV intensity factor, K_{IV} (or K_D).

According to previous experiments [1-5], cracking in the piezoelectric ceramics subjected to the electric load usually propagated only under the cyclical electric loading shown amplitude near or over their coercive electric field. If alternating electric load with a constant mechanical

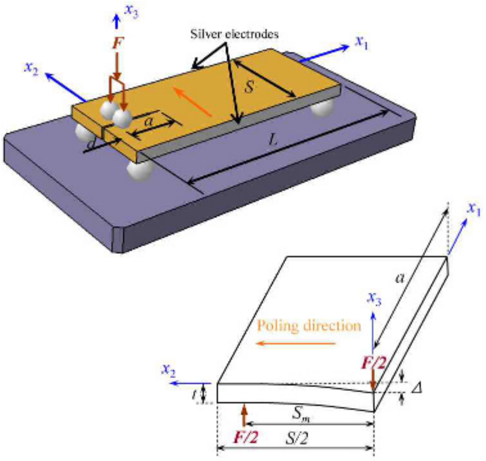


Fig. 1. Schematic of the double-torsion technique and deformation in individual rectangular bars.

load is applied on piezoelectric ceramics, the very lower electric field than the coercive electric field (E_c) is able to propagate an existed crack in piezoelectric ceramics. Double torsion (DT) technique is expected as a most valuable method to measure toughness of fracture and to investigate the growth behavior of slow crack in ceramic materials [6]. An associated study reported that the electric fatigue load under the constant mechanical load using four-point bending test influenced from the propagating velocity of crack and fracture of piezoelectric material has still difficult to find in previous methods [7].

Therefore, this study employs the double torsion (DT) technique rarely used for the experiment of piezoelectric material. Consequently, this research focused on growth behavior of crack initiated by kinds of cyclic fatigue on electric fields generated from the piezoelectric ceramics dominated with constant mechanical load using the DT technique. The law of crack growth, similar to the Paris' law, for the piezoelectric ceramic under cyclical electric load under a constant mechanical load is suggested.

2. Theoretical fundamentals

2.1 Double torsion technique

Double-torsion (DT) technique is a powerful testing technique for studying on the slow fracture behavior of brittle materials like as rocks, glasses, ceramics and so on. DT testing methodology was introduced in the late 1960s [8, 9]. DT test configuration is shown in Fig. 1.

The stress intensity factor (SIF) used with common fatigue tests were shown the variation according to the increase of crack length, on the contrary, those used DT test was free from the behavior of cracking length in linear fracture [6]. From the previous our results [10] by using the DT device, it is known that the slopes of load-load point displacement curves under the same electric fields were almost same, but the slope of them were changed depending on the applied electric fields. Hence, the study on behavior of cracking growth in piezoelectric materials has expected better result if tested under the constant mechanical load by using a DT device than other processes. If the mechanical load with electrical fatigue is applying on piezoelectric material, the very lower electric field than the coercive electric field (E_c) is able to growth an existing crack in the piezoelectric material. In other words, by taking full advantage of the DT technique, the influence of the cyclical electric load on the behavior of crack growth in piezoelectric ceramic will be found even if the lower electric field than the coercive electric field of the piezoelectric ceramic is applied under a constant mechanical load. If we can be carried out the desired study without very expensive high voltage apparatus and some dangerous electrical risks.

This study considered the influence of electric fatigue load activated to crack growth of piezoelectric material under the constant mechanical load operated by the DT technique, in terms of application of the lower various cyclical electric fields.

2.2 Linear contributions of cracked piezoelectric ceramics in the double torsion test

With the linearly piezoelectric assumption, the total energy release rate separated as follows [7, 10]:

$$\begin{aligned} G_I^{tot} &= -\left(\frac{\partial \Pi_I}{\partial A}\right) = \frac{F^2}{2}\frac{\partial C_m^V}{\partial A} + \frac{V^2}{2}\frac{\partial C_e^F}{\partial A} + FV\frac{\partial C_p}{\partial A} \\ &= G_m + G_e + G_p = G_M + G_E \\ &= \frac{1}{2}\left(\frac{K_I^2}{c_T} + \frac{K_{II}^2}{c_L} + \frac{K_{III}^2}{c_A} + \frac{K_I K_{IV}}{e}\right) + \frac{1}{2}\left(\frac{K_I K_{IV}}{e} - \frac{K_{IV}^2}{\kappa}\right) \end{aligned} \tag{1}$$

where G_m, G_e, and G_p are the pure mechanical, pure electric, and piezoelectric components of the total energy release rate, respectively, G_M and G_E are the conventional mechanical and electric energy release rates. C_e^F, C_m^V, and C_p are the pure electric capacitance, pure mechanical compliance, and piezoelectric compliance, and italic superscribed "*F*" and "*V*" denoted the values measured at constant force and voltage, respectively. Jelitto et al. [7] considered the mechanical compliance as a variable according to the applied electric fields; however, in the present study the pure mechanical compliance, C_m^V is considered as a constant without electric effects, and corresponds to C_M which includes Δ_l^{P}.

Note that C_e^F and C_m^V are defined as follows from the pure mechanical displacement Δ_l^{F} and the pure electric charge Q_l^{E}, respectively, instead of the total linear displacement:

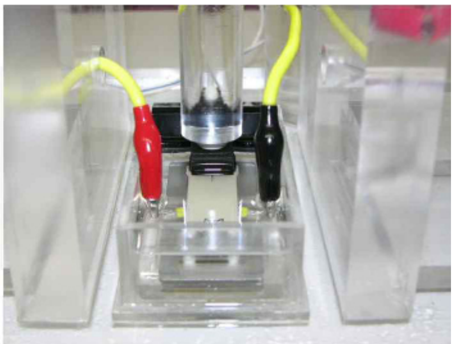
$$\begin{aligned} &C_m^V = \left(\frac{\partial \Delta_l^{\mathrm{F}}}{\partial F}\right)_{A,V}, \quad C_e^F = \left(\frac{\partial Q_l^{\mathrm{E}}}{\partial V}\right)_{A,F}, \\ &C_p = \left(\frac{\partial Q_l^{\mathrm{P}}}{\partial F}\right)_{A,V} = \left(\frac{\partial \Delta_l^{\mathrm{P}}}{\partial V}\right)_{A,F} \end{aligned} \tag{2}$$

The conventional mechanical compliance C_M in the DT technique driven as follows [10, 11]:

Table 1. Material properties for C-82 piezoelectric ceramic using Voigt notation.

Elastic stiffness constants (10^9 N/m^2)					Piezoelectric stress constants (C/m^2)			Dielectric permittivities (10^{-9} C/Vm)	
c_{11}	c_{12}	c_{13}	c_{33}	c_{44}	e_{31}	e_{33}	e_{15}	κ_{11}	κ_{33}
13.8	9.2	9.1	12.0	2.2	-5.2	26.5	17.0	13.6	11.2

(a) Experimental layout



(b) Detail of A

Fig. 2. Photographs of experimental layout.

$$C_M = \frac{\Delta}{F} \approx \frac{3S_m^2 a}{St^3 \bar{C}_{cm}^* \psi(\tau)} \quad (3)$$

Therefore, the crack length *a* measured at $V = 0\,(E = 0)$ expressed as follows:

$$a = \frac{St^3 \bar{C}_{pm}^* \psi(\tau)}{3S_m^2} \frac{\Delta^{\mathrm{F}}}{F} = St(S,t) \cdot \frac{\Delta^{\mathrm{F}}}{F} \quad (4)$$

2.3 Fatigue crack growth law for impermeable crack

The crack growth rate in a piezoelectric ceramic recognized as a function of the amplitude of electric displacement, if the crack propagated by the cyclic electric fields under a constant mechanical load.

Suo [12] proposed that dielectric remotely applied electric fields E_2 perpendicular to the so-called impermeable crack (i.e., with zero electric displacement *D* inside the crack perpendicular to the crack surface) lead to a singular electric displacement around the crack tip.

$$D(r) \propto \frac{K_D}{\sqrt{2\pi r}} \quad (5)$$

With the so-called EDIF, K_D $(\text{or } K_{IV})$ able to present as follows:

$$K_D = D_2^\infty \sqrt{\pi a} = \kappa_{33} E_2^\infty \sqrt{\pi a} \quad (6)$$

The law of crack growth for the piezoelectric ceramic under cyclical electric load under a constant mechanical load commonly introduced the electric displacement intensity factor (EDIF), K_D. Therefore, the following power law based on the classical Paris' equation is suggested as:

$$\frac{da}{dN} = C(\Delta K_D)^m \quad (7)$$

Coefficients *C* and *m* is similar concept in the classical Paris' law for crack fatigue test.

3. Experimental procedure

3.1 Specimens

Early DT specimen commonly have a guide groove along the line of crack, but Non-groove specimen were used recently because the presence of the groove leads to effects that are still not fully characterized [6]. Therefore, non-groove samples were used in this study for the DT test, C-82 piezoelectric ceramic (Fuji Ceramics Ltd. Co.) is main material widely applied in medical probes, various actuators, and dynamic devices associated with relatively high value of d_{33}. Properties of C-82 PZT ceramic for the test are listed in Table 1, the coercive electric field E_c was acquired as 880 kV/m. Photograph of the experimental layout using the DT test for this study is shown in Fig. 2. The specimens prepared from the wire-cutting process into dimensions having 40×16×2 mm (*L*×*S*×*t*), the total crack

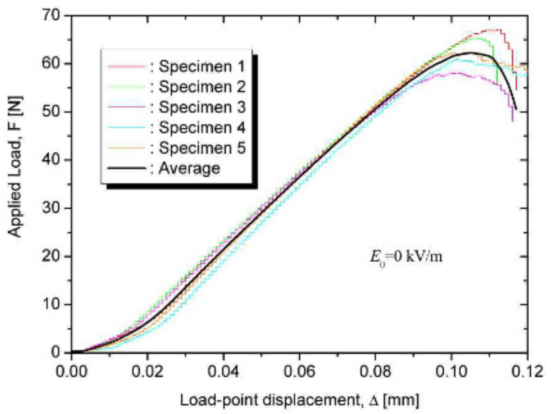


Fig. 3. Raw load-point displacement curve at V_0 = 0 kV(E_0 = 0 kV).

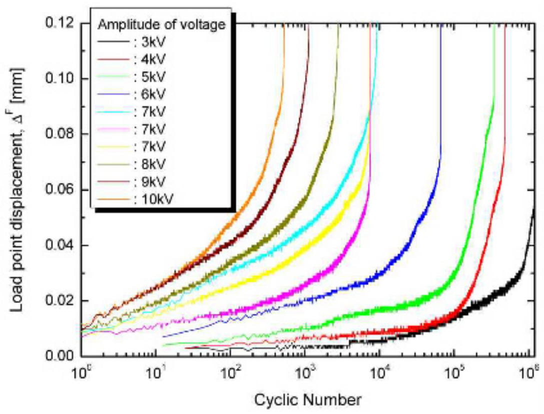


Fig. 4. Raw load-point displacements with cyclic number for each amplitude of applied voltages (Width of 16 mm, F = 40 N).

length, $d + a$ fitted around 12 mm included the effective length, a , of 9 mm. After the process of cutting, specimens were poled along the x_2 -axis using electrodes coated with silver at side surfaces (Fig. 1). A thin and 11 mm-long notch was cut in an end side of PZT sample using the diamond coated saw blade having thickness of 0.18 mm. The sharply propagated 'natural' crack on specimens measured in the range of 0.9~1.1 mm generated by a device for crack manufacturing. After all, the total length of notch included with crack measured to 12 mm long. For more precise and correct acquisition of data, samples shown a crack line deviating over 0.1 mm from the center of slit notch were totally abandoned, in other words, specimens with almost no curvature of crack line were selected for the test.

3.2 Experimental device and method

Figs. 1 and 2 depicted a schematic drawing and a photograph of the experimental setup for the DT test used herein, respectively. All experiments performed in an acrylic box filled with silicon oil to prevent electric shocks.

The cracked DT test specimen located at a distance of d = 3 mm from the edge of the acrylic specimen guide, and supported with the 4 mm-size ceramic balls. Specimens pushed by concentrated loads using two ceramic balls of 3 mm-diameter having magnitude of each $F/2$ at x_1 = 0 mm, x_3 = 3 mm, and x_2 = ±1.5 mm in a screw-driven testing machine (AutoGraph AG-IS 500N, Shimadzu Co., Japan).

The moment arm S_m fixed at a distance of 5 mm with the acrylic supporting ball guide and the stainless steel loading ball guide. Silicon oil used for the electrical insulation and ceramic balls had role to keep from direct contact on metallic conductor, stainless steel plates, which high strength used to reduce the deformation caused by the contact stresses.

A high-voltage amplifier controller (Model 610E, Trek Co., Japan) and a frequency generator for voltages up to ±10 kV/dc was used to apply cyclic electric fields of E_0 and selected a range of positive and negative electric fields of 625 kV/m (10 kV/16 mm).

4. Results and discussion

Fig. 3 shown the associated curves between the load-point displacement and loads at V = 0 kV (E_0 = 0 kV/m). As shown in Fig. 3, linear relationships between the load-point displacement and the applied load were appeared in the range of displacement of 0.02 to 0.09 mm.

It applied on all samples having the dimension with 40 × 16 × 2 mm and a = 9 mm under same experimental conditions alike earlier studies [10] to find relative factors between displacement and crack length of DT test proposed in Eqs. (3) and (4). And then, Eq. (8) represented the relation between the load-point displacement and the crack length was obtained from the average data of Fig. 3 using the Eqs. (3) and (4).

$$a = St(S,t) \cdot \frac{\Delta^F}{F} \quad \text{with} \quad St(S,t) = 6676.6 \text{ N} \tag{8}$$

The raw load-load point displacement curve with a cyclic number depicted on Fig. 4 shows the understanding of characteristics in electrical fatigue crack, resulted from the condition under a constant mechanical load (F = 40 N) with an electrical fatigue that applied various amplitudes. The results showed that the propagation of the electrical fatigue crack of piezoelectric material could analyzed without an electric field value higher than ΔE_0 = 0.8 E_C~1.2 E_C (E_C : The coercive electric field of the piezoelectric material), as usual. Half size of the amplitude of applied voltage in sine signal designates (e.g., ΔV_0 = 5 kV in the case of the input as V_0 = ±5 kV) in Fig. 4. It should be noted that the applied voltage, ΔV_0 = 5 kV is ΔE_0 = 625 kV/m (10 kV /16 mm) because the width of specimen is 16 mm and the E_C of C-82 is 880 kV/m. As shown in Fig. 4, by using the suggested DT technique, it can be observed that the propagation of crack in piezoelectric ceramic can be sufficiently available even if the lower electric field than the coercive electric field of the piezoelectric ceramic is applied under a constant mechanical load, and found the velocity of crack growth increases with increasing the amplitude of applied voltage.

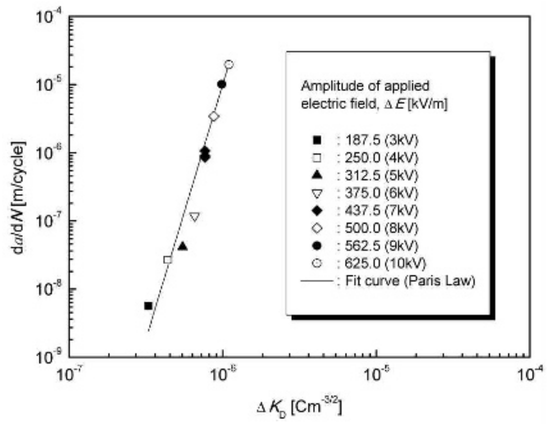


Fig. 5. Crack growth rate versus cyclic EDIF for different amplitude of applied electric fields.

Therefore, if the suggested DT technique is applied, it is really helpful for study on the behavior of crack propagation of piezoelectric ceramic depending on cyclical electric load without a dangerous expensive high voltage apparatus.

Fig. 5 shows da/dN versus ΔK_D in double logarithmic plots for the C-82 ceramics with silicone inclusion. Different amplitudes of the applied electric field are described with different symbols. Herein, da/dN's were obtained from each linear range of all cases in the Fig. 4, and EDIF ΔK_D's were also calculated from Eqs. (6) and (8) using the experimental data of Fig. 4. As mentioned earlier, the SIF resulting from the DT test was independent of (or has a weak dependence on) the crack length in linear fracture behavior. Therefore, the amplitude of electric field (ultimately, that is related with ΔK_D) played as a main important role on the crack propagation in this case.

Coefficients *C* and *m* obtained by fitting the data linearly as the Paris' equation in a classical fatigue in the figure. A quantitative description for the C-82 ceramics suggested and given as follows:

$$\frac{da}{dN} = C(\Delta K_D)^m \ , \ C = 7.15\times10^{39} \text{ and } m = 7.48 \quad (9)$$

Fig. 5 depicts that the above relation faithfully matched with all the experimental data plotted in the figure for the whole range of amplitude of the applied electric fields. We evaluated the crack growth rate by ΔK_D in the framework of the linear electro-elasticity.

As shown in Fig. 5, it can be seen that the crack growth rate da/dN increases with increasing amplitude of the EDIF ΔK_D, and that the same electric field tends to be similar. Therefore, this study can confirm that the proposed DT technology is valid for slow crack propagation testing by electrical fatigue of piezoelectric ceramics. It can also be seen that crack growth rate is significantly affected by the magnitude of the applied electric fields (that is, one of the EDIF).

From these results, it was found that the proposed DT technology in this study could achieve crack propagation by applying very less cyclical electric voltage than that of the previous work [1-5] applied only by applying conventional pure electrical fatigue or through a four-point bending experiment, and useful results could be obtained from crack propagation experiments on electrical fatigue for piezoelectric ceramics.

5. Conclusions

Behaviors of fatigue crack growth in the piezoelectric ceramic driven with various cyclic electric fields under a constant mechanical load were investigated by the double torsion technique. Highly effective application of DT technique to find unique property of piezoelectric materials has established, as a result, a proper method to evaluate the associated propagation of crack on piezoelectric material using lower voltage - safer level - than the common case under a constant mechanical load (constant mechanical SIF condition) obtained follows:

(1) From this work, DT technique used in this study was quite useful to investigate the influence the electric fatigue load on the behavior of slow crack growth in piezoelectric ceramic without a dangerous and expensive high voltage equipment.

(2) The relation between load-load point displacement and crack length tested with the DT test was able to obtain under raw load-load point displacement at V_0 = 0 kV (E_0 = 0 kV) without the electric field.

(3) Cracks grown in slow state at the early stage and at the final stage, the other range shown normal state of steady-state crack growth.

(4) Coefficients *C* and *m* acquired using the curve fitting of the traditional Paris' equation, which is included the related factor between growth rate of fatigue crack and intensity of electric displacement.

(5) The growth rate of fatigue crack quantitatively suggested with the intensity factor of electric displacement in the linear electro-elastic framework.

The DT technique was used electric fields lower than that for other method to find the propagation of the electrical fatigue crack on the piezoelectric materials. The next improved study will find the crack growth behavior of the piezoelectric ceramic under various constant mechanical loads with fully reversed cyclic electrical loading and pure positive or negative cyclic electrical conditions.

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