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The electric field induced strain behavior of single PZT piezoelectric ceramic fiber

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Abstract

In this paper, the electric field-induced strains (S-E) of a single PZT piezoelectric fiber were measured using a micro-displacement sensor. Various factors that could affect S-E behavior, such as, amplitude and frequency of applied electric field, temperature and uniaxial compressive stress were investigated. The results demonstrate that the S-E behavior is strongly dependent on these factors. Both the maximum strain (S_{max}) and depoling field increase with the increase of applied electric field. The S_{max} value increases with the increase of frequency and remains constant after the frequency exceeds 20 Hz. Meanwhile, the remnant strain (S_{rem}) continues to increase, due to the mismatch between the strain response and loading rates. The recoverable strain (S_{max}-S_{rem}) goes up with the increase of temperature and reaches the maximum value at 140 °C. Under an increasing uniaxial compressive stress, both S_{max} and depoling field increase and reach the peak value at 3 MPa, and then decrease with further increase of stress.

Key words: Piezoelectric, PZT, single fiber, electric field induced strain

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1. Introduction

Piezoelectric materials are materials that produce an electrical charge when they are placed under mechanical stress and vice versa, they will change shape slightly (a maximum of 4%) if an electric field is applied to these materials. Piezoelectric materials, due to high actuation capability and sensing ability, have received vast interests in a wide range of intellectual applications. Piezoceramics, one of widely used piezoelectric materials, have excellent piezoelectric properties but suffer from inherent brittleness which restrains their applications in the areas, such as curved or irregularly shaped surfaces and flexible structure [1]. New piezoelectric materials and novel designs have been explored in order to break through these limitations in some applications [2]. Piezoelectric fibers are embedded in polymer matrix, forming the piezoelectric fiber composites (PFCs) with both high piezoelectric properties from fibers and flexibility from polymer. These composites have the enhanced strength, conformability and toughness compared with pure piezoceramics. The performance of PFCs depends on the properties of piezoelectric fibers to a great extent.

The uses of piezoelectric devices, such as, sensors and actuators, in various conditions and environments are required. Therefore, it is necessary to evaluate the performance of piezoelectric fibers under different conditions. Over the last several decades, an increasing number of investigations on electric field-induced strain (S-E) behavior of piezoelectric ceramics [3], single crystals [4] and composites [5] have been conducted. The results for piezoelectric ceramics and single crystals reveal that the domain switching induced by applied electric field [6], temperature [7] or stress [8] is the main reason causing S-E behavior change, for example. electric field-induced phase transitions, tetragonal to orthorhombic phase transition for BT single crystals [9], antiferroelectric to ferroelectric and ferroelectric to paraelectric phase transitions for PNZT and PLZT ceramics [10,11]; temperature-induced phase transitions, rhombohedral to tetragonal phase transition for PZN-PT single crystals [12], ferroelectric to antiferroelectric phase transition for NBT-BT ceramics [13] and ferroelectric to paraelectric phase transition; stress- induced phase transitions, tetragonal to rhombohedral phase transition for PZT ceramics [14], rhombohedral to orthorhombic phase transition for PZN-PT ceramics [15] and antiferroelectric to ferroelectric phase transition for PZNT ceramics [16]. It was found that phase transitions play important roles in the influence of test conditions on S-E behavior.

In this work, the electric field-induced strain of single PZT piezoelectric fibers were measured directly via a micro-displacement sensor. The field-induced strains of a single fiber under different applied electric amplitude and frequency, temperature and uniaxial compressive stress were studied. The influence of these factors on the depoling fields of single-fibers derived from S-E loops was also investigated.

2. Experimental procedure

Lead zirconate titanate (PZT) fibers were produced using a viscous plastic process (VPP) method. PZT ceramic powders were prepared using a conventional solid-state synthesis process。 The reagent grade metal oxides or carbonate powders were mixed and ball-milled to obtain uniform particle sizes and high dispersibility. Then, PZT powders were mixed with polyvinyl alcohol (PVA) solution, deionized water and some plasticizers under lofty shear force utilizing a twin roll mill to produce viscous plastic dough. The VPP paste was aged for 2 to 4 days, and then extruded under a pressure of 20 MPa to acquire green fibers with diameters of approximately 200 μm to 400 μm. After dried at 80 °C for 24 hrs, the green fibers were heat-treated at 850 °C to remove organic matters, and then sintered at 1180 °C to 1280 °C for 4 hrs in a PbO-enriched atmosphere to prevent the lead loss during sintering.

The sintered PZT fibers were cut into 1 mm to 3 mm in length. Both sides of the sample were polished and coated with silver electrodes. Dimethyl silicone fluid with dielectric strength of 16 kV/mm was utilized to prevent dielectric breakdown of the sample under high electric field. All tests for a single PZT fiber were performed at room temperature (RT) except the temperature dependence tests of S-E behavior. No pre-polarization was conducted before the S-E behaviors were tested. The electric field dependence tests of S-E behavior in the sample were carried out under an applied electric field with the amplitude range of 2 kV/mm to 5 kV/mm and the frequency range of 0.2 Hz to 200 Hz, respectively. Temperature dependence tests of S-E behavior were conducted in the temperature range from RT to 160 °C. The single PZT fiber was put into dimethyl silicone fluid at the desired temperature for 5 min to achieve a uniform temperature field. Stress dependence tests of S-E behavior were carried out in the compressive stress in a range of 2 MPa to 5 MPa. A ferroelectric tester (Precision Workstation, Radiant Technologies, Inc., America) combined with a fiber-optic measurement system (MTI 2000, MTI Instruments Inc., America) was employed to perform the S-E behavior tests. Two waveform formats referred to the S-E tests, bipolar and unipolar, were used. The bipolar waveform is a typical triangular wave signal that applied in the hysteresis task. The unipolar format is similar to the standard bipolar except that the triangle waveform is applied only from zero to E_{max} (the amplitude of the applied electric field), then back to zero. The symmetric triangle to negative E_{max} that is applied in the bipolar waveform is not evident in the standard unipolar. The depoling field is defined as a value of the reversed field at which depolarization of the sample occurs. The schematic diagram of the experimental setup for S-E behavior test is illustrated in Fig. 1.

3. Results and discussion

3.1 Effect of applied electric field and frequency on S-E behavior

Fig. 2 shows the unipolar S-E loops of PZT single fiber measured in the range of 2 kV/mm to 5 kV/mm. The inset of Fig. 2 shows that the maximum value of strain (S_{max}) increases from 0.445% to 0.775% when the applied electric field increases from 2 kV/cm to 5 kV/cm. Fig. 3 shows bipolar S-E loops of the sample with the identical test conditions. The S_{max} of bipolar S-E curves shows a similar tendency to the unipolar ones, which is consistent with the literature reported [17]. The sample exhibits a strong S-E behavior. This may be due to the increase in domain switching as the motion of domain walls becomes easier with elevated applied electric field. The rate of domain switching is increased with the increase of the applied electric field, which may cause the strain to increase rapidly. The S_{max} and the depoling field, which were derived from bipolar S-E loops, as functions of the applied electric field amplitudes are shown in Fig. 4. It shows that S_{max} increases from 0.418% to 0.973% and depoling field increases from 0.878 kV/mm to 0.955 kV/mm with the increase of applied electric field, respectively. At a fixed frequency of 1 Hz, the loading rates increase with the increase of the applied electric field. This may be attributed to the faster electric field loading rates, which will be discussed in more details below.

Fig. 5 shows the unipolar S-E loops of the sample measured at 200 Hz, 20 Hz, 2 Hz and 0.2 Hz. Strong frequency dependence is evident, both in the maximum strain (S_{max}) and remnant strain (S_{rem}) of the response. The inset of Fig. 5 shows that the S_{max} increases from 0.556% to 0.634% with the increase of the frequency from 0.2 Hz to 200 Hz, and becomes stable when frequency is over 20 Hz. The frequency dependence of S_{max} for the sample may be mainly caused by the space charge effect. There are a lot of space charges on the surface and the interior of the sample formed during the preparation process, which cause a space charge polarization. Generally, space charge polarization occurs under a lower frequency, and the polarizability of such polarization decreases with the increase of the frequency. This type of polarization follows in the opposite direction to the applied electric field, and which will weaken the total polarization. The space charge polarization weakens with the increasing of temperature. As a result, the polarization process becomes even easier along the axial direction of the fiber, resulting in larger strains at higher frequencies. When the frequency is over 20 Hz, the space charge effect becomes invalid. The impact of space charge on the total polarization disappears at much higher frequencies. In the meanwhile, the S_{rem} values increase from 0.039% to 0.176% with increasing frequency from 0.2 Hz to 200 Hz, which are owing to the rate mismatch between the strain response and applied electric field loading. At a higher frequency, the recovery rate of strain is slower than the unloading rate of the applied electric field which decreases from the amplitude value to zero.

3.2 Effect of temperature on S-E behavior

Fig. 6 shows the S-E loops of PZT single fiber measured in the temperature range from RT to 160 ˚C, at both 10 Hz and 20 Hz. S-E loops tested at a frequency of 10 Hz are shown in Fig. 6a, where the curve tested at RT shows a nonlinear relationship between strain values and applied electric field intensity. The strain reaches an inflection point at the applied electric field of about 1.75 kV/mm. The curve demonstrates an ideal linear relationship before and after the inflection point. The inflection point decreases from 1.75 kV/mm to 0.50 kV/mm with the increasing of the temperature. Furthermore, the inflection points at 20 Hz follow the same trend to those at 10 Hz.

Fig. 7 shows the recoverable strain (S_{max}-S_{rem}) as a function of temperature at 10 Hz and 20 Hz, respectively. The recoverable strain is defined as the difference between S_{max} and S_{rem}. It can be seen that the recoverable strains increase sharply with increasing temperatures, and then reach the maximum values of 0.742% at 10 Hz and 0.821% at 20 Hz at 140 ˚C, respectively. The recoverable strains tested at both frequencies follow a similar trend with increasing temperature in the range from RT to 160 ˚C. Moreover, the recoverable strains measured at 20 Hz are higher than those tested at 10 Hz, which matches well with the results shown in Fig. 5.

The influence of temperature on the strain lies in the following two respects mainly: the strain from the piezoelectric effect [18] and the strain from domain switching [19]. At room temperature, high rhombohedral phase content with low lattice distortion limits domain switching, and therefore the strain. Moreover, a high poling texture leaves only a few domains available for switching [20]. Therefore, at room temperature, the strain caused by domain switching is low. With increasing temperature, significant parts of the rhombohedral phase transform into the tetragonal phase. The rise of temperature tends to increase the average lattice distortion [21] and to reduce the poling texture. Both effects promote the strain obtained from 90° domain switching. Therefore, the strain both from the piezoelectric effect and domain switching, contributes to a strong increase in field-induced strain with further increase of temperature, and this also may cause the reduction of the electric field intensity at the inflection points mentioned above.

3.3 Effect of uniaxial compressive stress on S-E behavior

Fig. 8 shows the S-E curves of a PZT single fiber measured at a stress range from 2 MPa to 5 MPa. The S_{max} and depoling field, which derived from the S-E curves, as functions of compressive stress, are shown in Fig. 9. The S_{max} of the sample increases with the increase of compressive stress, and attains a maximum value of 0.400% at 3 MPa. Then the S_{max} reduces to 0.290% rapidly with further increase of compressive stress from 3 to 5 MPa. In the meantime, the presence of an axial compressive stress causes the change of the depoling field. The depoling field increases from 0.675 kV/mm to 0.742 kV/mm with the increase of compressive stress levels from 2 MPa to 3 MPa, and then reduces to 0.583 kV/mm with further increasing compressive stress.

The contribution of the applied electric field to strain is switching ferroelastic 90° or 180° domains towards the polarization direction. The 90° domain switching plays a leading role in the electric field-induced strain. However, compressive stress makes ferroelastic 90° domain switching away from the polarization direction, which prevents domains switching. A preset loop with a triangular wave applied electric field has been performed before the measurement of a bipolar S-E curve. The pre-measurement signals, which are applied to the sample, may result in the negative polarization state. This means that the actual measurement will cause the domain switching of the sample. With a small stress (below 3 MPa) applied on the single fiber, the stress will reduce the negative remnant polarization ($-P_r$), which is due to the decrease of the dipole moment along the axial direction of fiber. With increasing stress level, the P_r is even lower. In the actual measurement process, the domain switching of the sample changes much easier with the increase of the compressive stress. The S_{max} increases with the increase of stress level from 2 MPa to 3 MPa and reaches the maximum value under a proper preload compressive stress as shown in Fig. 9. Greater applied compressive stress (over 3 MPa)will induce mechanical depolarization. In contrast to the trivial stress condition (the single fiber sample should be fixed under a suitable champing force), more domains are aligned perpendicular to the applied load. The following high electric field will reorient most of the domains parallel to the polarization direction again. Apparently, under a slight stress preload, more 90° domain switching is repeated during the cyclic field loading process, which results in a larger strain output. However, with the further increase of compressive stress over 3 MPa, mechanical depolarization predominates. Most of the domains are aligned perpendicular to the applied load and constrained by the high compressive stress. Subsequently applied electric field of 2 kV/mm in this measurement is insufficient to overcome the compressive stress. Consequently, fewer domains can be reoriented to contribute to strain output. The resultant piezoelectric responses become negligible, and the corresponding S-E curves display a quite slight hysteresis. The depoling fields decrease rapidly with further increasing compressive stress levels. The magnitude of the depoling field under a greater compressive stress preload is smaller than that of a slight stress state. This may benefit from the factors that fewer domains participate in polarization reversal. Compressive stress destabilizes the polarized state and results in part of the first 90° domains switching during the electric field unloading from 2 to 0 kV/mm. The first 90° domain switching process is a result of the combined action of the applied electric field and uniaxial compressive stress.

4. Conclusions

S-E behavior of a single PZT fiber depended on the applied electric field amplitude and frequency, temperature and compressive stress. Within the examined electric field range of 2 kV/mm to 5 kV/mm, both the S_{max} and depoling field increase with the increase of electric field. As frequency increases from 0.2 Hz to 200 Hz, both the S_{max} and the S_{rem} increase with increasing frequency. Then, the S_{max} tends to be stable when the frequency exceeds 20 Hz and the S_{rem} increases with the further increase of frequency. For the same electric field magnitude, the recoverable strains increases with increasing temperature at 10 Hz and 20 Hz, and reached the maximum values at 140°C. While the recoverable strains measured at 20 Hz are high compared with those tested at 10 Hz. Within the examined stress level range from 2 MPa to 5 MPa, both S_{max} and depoling field increase initially, reach maximum values at 3 MPa, and start decreasing rapidly with increasing compressive stress.

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