

Temperature Dependence of Energy Conversion Efficiency in Piezoelectric Ceramics

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ABSTRACT: Energy conversion efficiency of PZT energy harvesters depends on that of the PZT materials. The electromechanical coupling factor of piezoelectric materials represents the energy conversion efficiency between electrical energy and mechanical energy. Temperature dependence of the energy conversion efficiency of harvesters using PZT materials may depend on the electromechanical coupling factor of the PZT materials. In this paper, the effects of poling strength and thermal aging on temperature dependence of electromechanical coupling factor, k_{31} of PZT ceramics were investigated. The PZT ceramic specimens with rhombohedral phase, morphotropic phase boundary (MPB) and tetragonal phase were fabricated. And the specimens were poled at the poling strengths, 1.5, 2.5, 3.5 [kV/mm] respectively. Electromechanical coupling factor of the specimens were successively measured after poling, after first thermal aging and after second thermal aging. Thermal aging decreased electromechanical coupling factor k_{31} due to depoling. The degree for the factor to decrease was significant in the specimens with the composition of MPB and was the least in the specimens with the composition of tetragonal phase. When measurement temperature increased from -20[°C] to 80[°C], electro-mechanical coupling factor k_{31} of PZT ceramics decreased only a little. PZT energy harvesters need not worry about decrease of energy conversion efficiency due to change of measurement temperature. And forced thermal aging in fabrication process improved the thermal resisting property of the energy conversion efficiency of PZT energy harvesters.

Keywords: energy harvester, electromechanical coupling factor, temperature dependence, PZT

1. Introduction

Piezoelectric energy harvesters usually use PZT ($\text{PbZrO}_3\text{-PbTiO}_3$) ceramics or PVDF polymer as energy conversion materials [1],

[2]. Energy conversion efficiency of PZT energy harvesters depends on that of the PZT materials. The electromechanical coupling factor of piezoelectric materials represents the energy conversion efficiency between

electrical energy and mechanical energy [3]. The factor can be easily obtained through measuring using a network analyzer and calculating. Temperature dependence of the energy conversion efficiency of harvesters using PZT materials may depend on that of the electromechanical coupling factor of the PZT materials.

Piezoelectric PZT ceramics have achieved wide usage in many applications involved energy harvesting part because of their superior energy conversion efficiency. The effects of additives in binary PZT system have been studied and various ternary PZT systems have been developed extensively [4], [5]. And the effects of Zr/Ti ratio and thermal aging in the binary PZT ceramics on temperature dependence of the resonance frequency were investigated [6].

In this paper effects of poling strength and thermal aging on temperature dependence of the electromechanical coupling factor of PZT ceramic substrates are investigated. Poling cause polarization toward the direction of the electric field in piezoelectric ceramics and thermal aging weakens the polarization. Stability of polarization depends on poling strength and thermal aging.

The PZT ceramic specimens with rhombohedral phase, morphotropic phase boundary (MPB) and tetragonal phase are prepared. And the specimens are poled in the three steps of the poling strengths, 1.5, 2.5 and 3.5 [kV/mm]. Piezoelectric properties of the specimens are measured, and then they are thermally aged and measured, and then they are once more thermally aged and measured. From these measurements we can check the effect of poling strength and thermal aging on temperature dependence of the energy conversion efficiency of PZT energy harvesters.

2. Experiment

The compositions in the vicinity of morphotropic phase boundary of binary PZT system were chosen. $\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$ ceramics with $x=0.50$ (Zr/Ti=50/50,

tetragonal), $x=0.53$ (Zr/Ti=53/47, MPB) and $x=0.56$ (Zr/Ti=56/44, rhombohedral) were fabricated.

The raw materials were oxides; PbO , ZrO_2 and TiO_2 . They were mixed in regulated molar ratio and calcined at 850 [°C] for 2 hours. The calcined powders were crushed and pressed into rectangular plates at a pressure of 700 [kg/cm²]. The plates were sintered in closed alumina crucibles. The sintered rectangular plates were lapped into the shape shown in Figure 1 in order to measure the length extensional vibration mode [7].

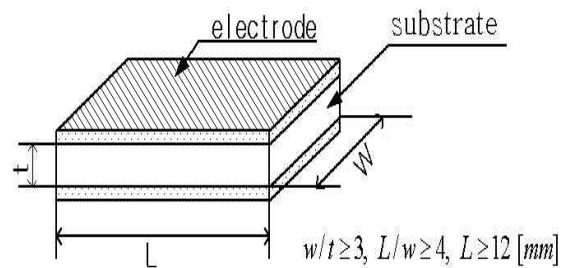


Figure 1: The aspect of the standard piezoelectric ceramic specimen for the length extensional vibration mode

The both sides electrodes of specimens were deposited by painting and firing silver paste. The specimens were poled in silicon oil of 80[°C] by applying a DC field of 1.5, 2.5, 3.5 [kV/mm] respectively for an hour, but poling electric field were removed after the oil temperature became room temperature [8].

The first and the second thermal aging processes were carried out by heating the poled specimen at 200[°C] for 1 hour with both electrodes shorted. Poled or thermal aged specimens were measured after 24 hours. Temperature dependence of the electromechanical coupling k_{31} of the specimens was measured by using a thermostat and a network analyzer. The measurement of k_{31} was carried out at intervals of 10[°C] from -20[°C] to 80[°C] with the temperature rising and falling speeds, 2~3 [°C/min].

3. Results and Discussion

Poling strengths were planned in three steps, 1.5, 2.5 and 3.5 [kV/mm], and so three specimens with the same composition were prepared. Thermal aging was carried out twice for the poled specimens and so measurement was carried out three times, after poling, after first thermal aging and after second thermal aging.

3.1 Effects of thermal aging and poling strength on electromechanical coupling factor k_{31}

Experiment results are shown in Fig. 2. Specimens with composition Zr/Ti=50/50, 53/47 and 56/44 has tetragonal phase, MPB and rhombohedral phase respectively. After first thermal aging, k_{31} of all specimens decreased due to depoling except the specimen with tetragonal phase poled at 1.5[kV/mm]. k_{31} decrease is significant in MPB specimens but small in tetragonal phase specimens. Second thermal aging also decreased k_{31} except the specimens with tetragonal phase and rhombohedral phase poled at 1.5[kV/mm]. Influence of second thermal aging, in comparison with first thermal aging, on decrease of k_{31} is insignificant, and so we can expect the improvement of thermal resisting property for k_{31} through 1st thermal aging. And the improvement of thermal resisting property for k_{31} is more significant in the case of the specimens poled in low electric strength.

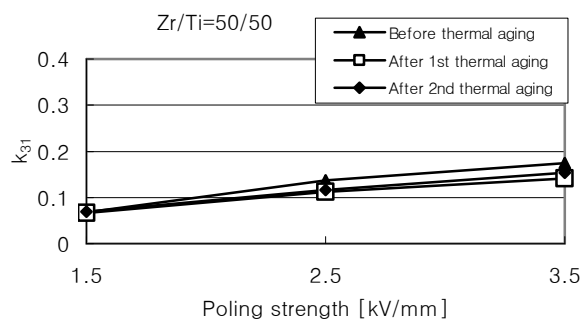


Fig 2. (a): Zr/Ti=50/50

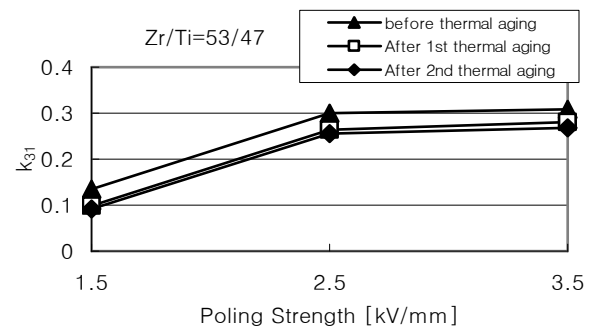


Fig 2. (b): Zr/Ti=53/47

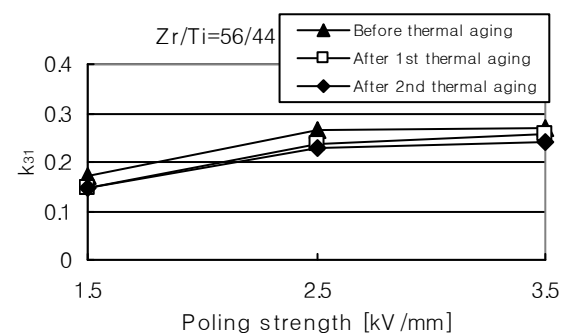


Fig. 2 (c): Zr/Ti=56/44. Changes of electro-mechanical coupling factor k_{31} according to the poling strength, and 1st and 2nd thermal aging.

3.2 Effects of thermal aging on temperature dependence of electromechanical coupling factor k_{31}

Experimental results are shown in Fig. 3. The specimens were poled in electric field 2.5[kV/mm]. As measurement temperature increases, k_{31} decreases slowly in the specimens with the compositions Zr/Ti=50/50 and 53/47. It is very interesting that decrease of k_{31} of the specimens with rhombohedral phase according to increase of temperature is not greater than decrease of k_{31} of the specimens with MPB and rhombohedral phase, which have higher Curie temperature than specimens with rhombohedral phase. We can estimate that k_{31} of the specimens with lower Curie temperature will decrease greater according to increase of temperature than that of the specimen with high Curie temperature. But above results show that the specimen with

rhombohedral phase has the least decrease in k_{31} .

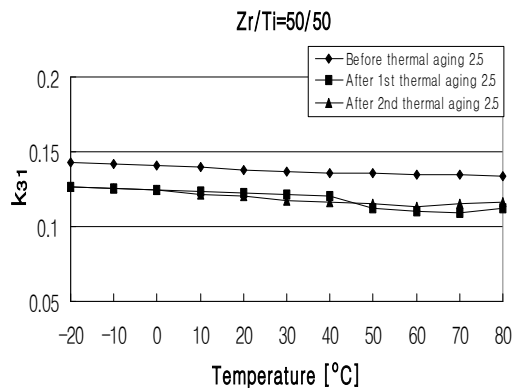


Figure 3 (a): Zr/Ti=50/50.

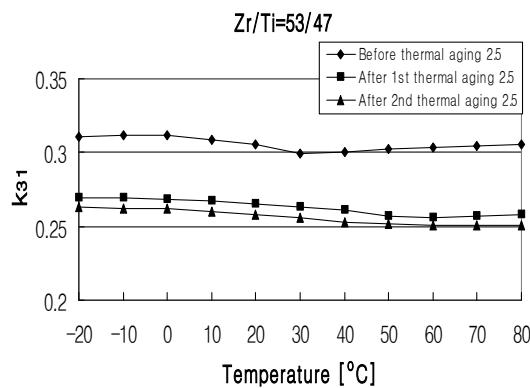


Figure 3 (b): Zr/Ti=53/47.

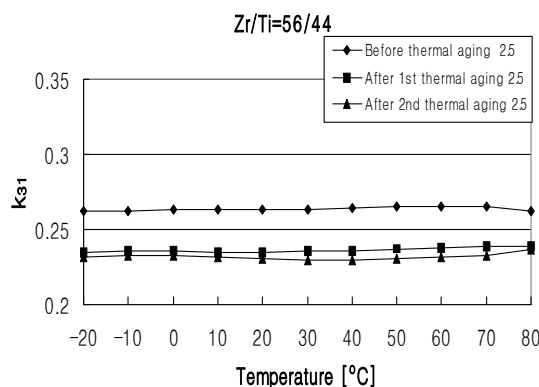


Figure 3 (c): Zr/Ti=56/44. Temperature dependence of electromechanical coupling factor.

Figure 3 shows that as temperature increases from $-20[^\circ\text{C}]$ to $80[^\circ\text{C}]$ electromechanical coupling factor k_{31} of all specimens decreased only a little. We conclude PZT energy harvesters need not

worry about decrease of energy conversion efficiency due to change of temperature.

And we can assume the first thermal aging as unwanted thermal shock. The thermal shock may decrease the energy conversion efficiency of PZT energy harvesters. We can intentionally thermal-age the specimen in fabrication process. The forced thermal aging may improve thermal resisting property of k_{31} of PZT ceramics and the energy conversion efficiency of PZT energy harvesters

4. Conclusion

Thermal aging decreased electro-mechanical coupling factor k_{31} due to depoling. The degree for the factor to decrease was significant in the specimens with the composition of MPB and was least in the specimens with the composition of tetragonal phase. As measurement temperature increased from $-20[^\circ\text{C}]$ to $80[^\circ\text{C}]$, electromechanical coupling factor k_{31} of PZT ceramics decreased only a little. PZT energy harvesters need not worry about decrease of energy conversion efficiency due to change of temperature. And forced thermal aging in fabrication process improved the thermal resisting property of the energy conversion efficiency of PZT energy harvesters.

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