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Smart Energy Materials of PZT Ceramics

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***Abstract*— To better understand the material properties of lead zirconate titanate (PZT) ceramics, the domain-switching characteristics and electric power generation characteristics have been investigated during loading and unloading by using various experimental techniques. Furthermore, the influence of oscillation condition on the electrical power generation properties of lead zirconate titanate (PZT) piezoelectric ceramics has been investigated. It is found that the power generation is directly attributed to the applied load and wave mode. The voltage rises instantly to the maximum level under square-wave mode, although the voltage increases gradually under triangular-wave mode. After this initial increase, there is a rapid fall to zero, followed by generation of increasingly negative voltage as the applied load is removed for all wave modes. Variation of the electric voltage is reflected by the cyclic loading at higher loading frequencies. On the basis of the obtained experimental results for the wave modes, the electrical power generation characteristics of PZT ceramics are proposed, and the voltages generated during loading and unloading are accurately estimated. The electric generation value is decrease with increasing the cyclic number due to the material failure, e.g., domain switching and crack. The influence of domain switching on the mechanical properties PZT piezoelectric ceramics is clarified, and 90 degree domain switching occurs after the load is applied to the PZT ceramic directly. Note that, in this paper, our experimental results obtained in our previous works were introduced [1,2].**

***Index Terms*— piezoelectric ceramic; domain switching; harvesting energy; PZT; applied loading; electric generation**

I. INTRODUCTION

Since piezoelectric ceramics were developed in the 20th century, their material properties have been studied widely by a great number of scientists around the world. Recently, one of the popular piezoelectric ceramics is lead zirconate titanate (PZT), consisting of a perovskite structure. This ceramic could provide the ability to transform mechanical strain energy into electrical charge (piezoelectric effect) or applied electrical energy into mechanical strain (inverse piezoelectric effect). Using the piezoelectric effect, electric power generation has been employed as a clean energy system, namely harvesting of energy [3]. Piezoelectric energy harvester basically consists of mechanically applied vibrating system, which could convert mechanical energy into electrical energy [4]. Such clean energy system has received special attention in our society. In these energy harvesting systems, a number of PZT ceramic plates are setting in parallel under a floor. In recent years, associated trial tests have been conducted using the energy harvesting systems in society. Although this clean energy system is suitable, that system has not been employed widely in our society, as the extent of the electric power generation of the energy harvesting systems is not sufficient. It is therefore an improvement of the energy harvesting system is required. In order to improve the efficiency of electric power generation, piezoelectric energy harvesting devices has been designed and material properties have been investigated experimentally and theoretically. The influence of mechanical loading conditions on the electric power generation characteristics has been studied using commercial PZT ceramic plates under various cyclic loading conditions. In the study by Shu and Lien [5], it is reported that the harvested power is dependent on the input vibration characteristics (frequency and acceleration), the mass of the generator, the electrical load, the natural frequency, the mechanical damping ratio and the electromechanical coupling coefficient. Furthermore, they have proposed several design guidelines for devices with large coupling coefficient and quality factor [5]. With piezoelectric and electromagnetic systems, portable generators with human mechanical energy harvesting systems have been proposed [6], and Sudevalayam and Kulkarni have surveyed various aspects of energy harvesting sensor system architecture, energy sources and storage technologies and examples of harvesting-based modes and applications [7]. Although there are several experimental works involving development of energy harvesting systems, there is apparently a lack of information to achieve high-efficiency energy harvesting power generation, where determination of suitable loading conditions would be required. This is especially true, as electric power generation from a piezoelectric ceramic can come with low current. The aim of this work is therefore an attempt was made to examine the relationship between the loading conditions and material properties (domain characteristics and the electric power generation).

II. EXPERIMETNAL PROCEDURE

In the present study, a commercial soft PZT ceramic, lead zirconate titanate ($PbZrTiO_3$) with various shapes was used, see Fig. 1(a); a thin plate and rectangular rod specimens. A silver-based electroplated layer was made on the surface of the PZT ceramic. This PZT ceramic has been utilized widely for

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buzzers and ultrasonic sensors. The nominal grain size of this PZT is about 1 µm and that ceramic adopted a tetragonal structure at room temperature with an aspect ratio of 1.014. The electric power generation was examined during the cyclic loading, which was monitored using an 8846A digital multimeter (Fluke) [1].

Fig. 1(b) shows the test apparatus and the main testing methods. In this study, domain switching characteristics were investigated first [2]. Moreover, the effects of (i) number of PZT ceramic plates and (ii) stress conditions on electric voltage generation were examined during cyclic loading. Fig. 2 displays our devices to detect the voltage and current generated from the PZT ceramic. With the electric generation, a LED light could work.

Compression loading was applied directly to the PZT ceramics using the rectangular rod specimens. In this examination, a screw driven type universal testing machine with 10 kN capacity was used. The loading speed for the compression tests was 1 mm/min, where the loading was conducted via insulation ceramic blocks. During the compression tests, the stress was monitored by a data acquisition system in conjunction with a computer though the load cell. In this test, the mechanical loads were applied along the long axis specimen.

The electric voltage generation was investigated by cyclic loading with the following conditions: loading value (1–20 N) and number of PZT ceramic plates (1–5). Also two different wave formations were selected (triangular and square wave mode). The electric voltage was continuously monitored for 10 cycles using a digital multimeter. It should be noted that the 10 cycles used for this examination was selected due to a reduction in the sample damage, e.g., domain switching [2].

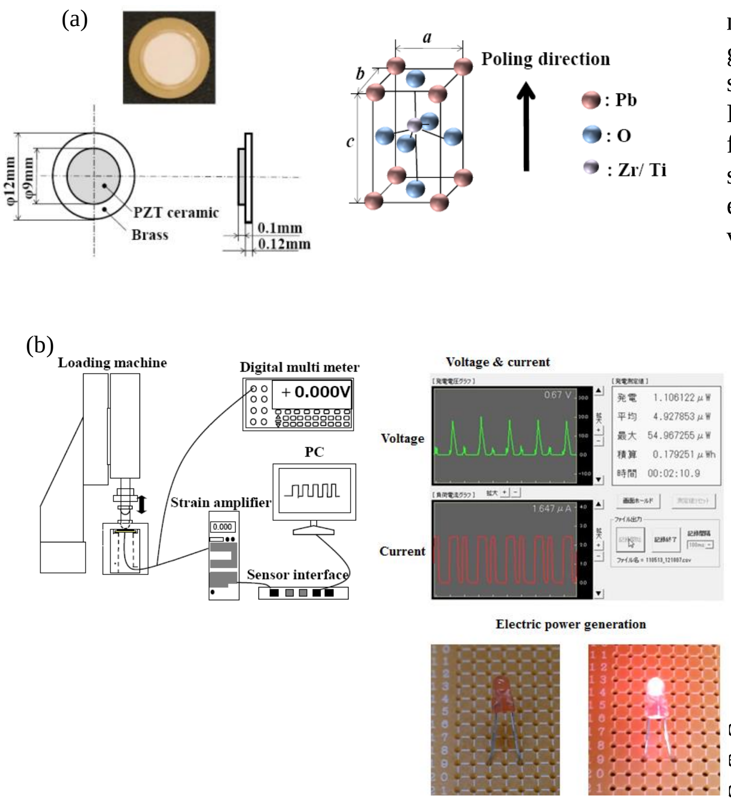

Fig. 1 PZT ceramic and experimental setup and testing methods for electric power generation tests.

III. RESULTS

A. Effect of the number of PZT ceramic plates [2]

Fig. 2 displays the relationship between the applied load and the maximum electric voltages, obtained by the triangular wave formation. It is seen that the electric voltage value increases with increasing loading value. Moreover, the electric voltage value increases with increasing frequency. A higher electric voltage value is obtained for a larger number of PZT ceramic plates, in which the peak electric voltage is detected for three PZT plates. For five PZT ceramic plates, the maximum electric voltage seems to decrease slightly compared to the four-plate case.

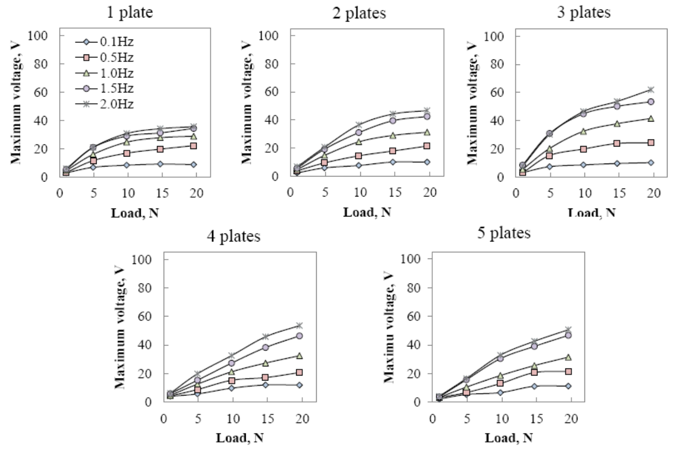

Fig. 2 Variation of the mean maximum electric voltage as a function of the stress intensity on the PZT ceramic plate.

Fig. 3 shows variations of the electric voltage and strain value obtained from the PZT ceramic plates with different number [2]. To examine the strain value, a commercial strain gauge was employed attached on the PZT ceramic plate. As seen, the electric voltage increases with increasing number of PZT plates, and the highest maximum voltages are obtained for four PZT plates under the square waveforms. The ending strain decreases with increasing number of PZT nonlinearly, e.g., about 0.25% for three PZT plates. The different strain value may cause a change of the electric voltage generation.

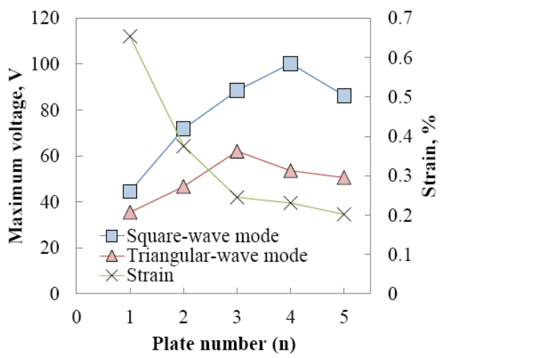

Fig. 3 Variation of the mean maximum electric voltage as a function of the applied load value.

Fig. 4 indicates representative compressive stress vs. strain curves obtained from the un-poled and poled specimens. The elastic modulus (E) in the early stage of the stress vs. strain curves is different; the E value for the un-poled ceramic is slightly higher than that for the poled one. In this case, the

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different modulus is caused by the severity of domain switching. Fig. 4 also shows the different compressive strength of the PZT ceramics. As can be seen, the compressive strength for the poled samples is about 10% higher than the un-poled samples. The reason for the high strength of the poled sample is related to the material strain due to domain switching, i.e., piezoelectric strain. Fig. 5 displays a schematic illustration showing the work hardening mechanism, in which a randomly oriented domain structure can produce a high material strength. Moreover, the domain switching may affect the low elastic modulus shown in Fig. 4. This is because that the longitudinal (*c*-axis) tetragonal structure, formed to the parallel direction against the loading direction, is tilted to 90˚, resulting in an acceleration of the macroscopic strain attained during mechanical loading.

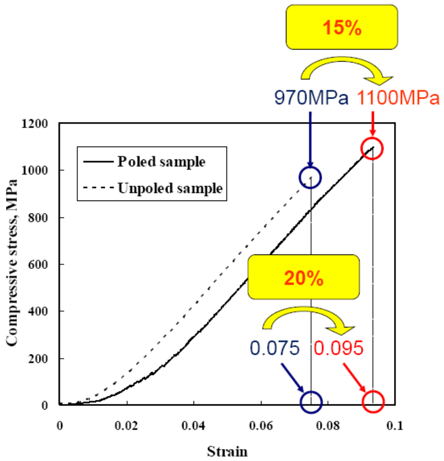

Fig. 4 Relationship between the compressive stress and strain of PZT ceramics.

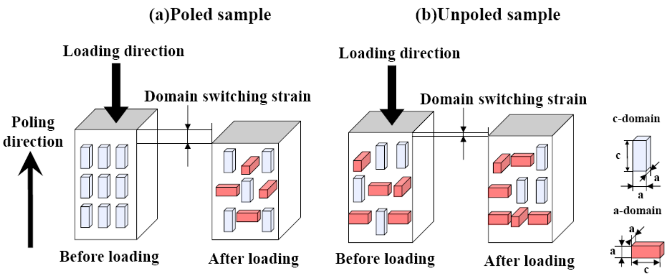

Fig. 5 Schematic illustration of domain switching characteristics for un- poled samples.

B. Domain structures [1]

To understand clearly the domain switching characteristics after the loading process, x-ray and EBSD analysis were carried out. Because the direction of the tetragonal long axis can be altered to the parallel to any of the three <001> directions, diffraction is used to evaluate the proportion of *c*- and *a*-oriented domains parallel to a given sample direction. The reorientation of a domain by 90˚ domain switching from the *c*- and *a*-direction can be revealed by a change of the diffraction intensity ratio. It should be noted that the MRD can be 1 as a random domain orientation is obtained. On the other hand, the MRD is equaled to 3 when *c*-domains are all oriented parallel to the poling direction. The MRD measurement was carried out using x-ray diffraction. In this approach, the (002) and (200) peaks are related to the angle around 2θ = 45˚. Fig. 6 displays the representative x-ray diffraction patterns obtained from the PZT samples. The (002) peak decreases and the (200) peak increases with increase of the compressive load level. As the peak levels alter, the MRD value is assessed by the equation as follows:

$$\mathrm{MRD} = \frac{(I_{002}/I_{002}^{R})}{(I_{002}/I_{002}^{R}) + 2\times(I_{200}/I_{200}^{R})} \tag{1}$$

where I_{002} and I_{200} are the integrated intensities of the (002) and (200) peaks after mechanical loading. Fig. 7 shows the MRD variation as a function of the applied compressive load. For the polled sample, the MRD level increases with increase of the applied load from about 1.4 to 1.7. On the contrary, the MRD value for the un-poled sample is closed to 1.0 without any applied load, and increases with increase of the load level to about 1.4.

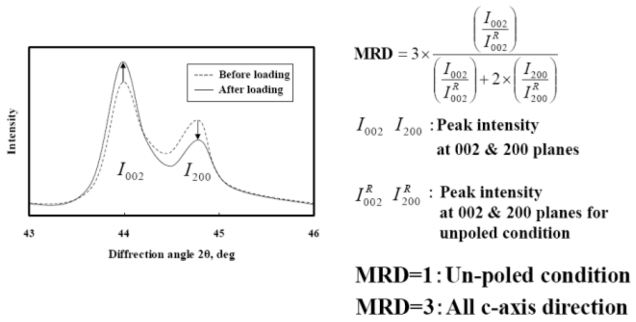

Fig. 6 X-ray diffraction patterns for the poled PZT ceramic.

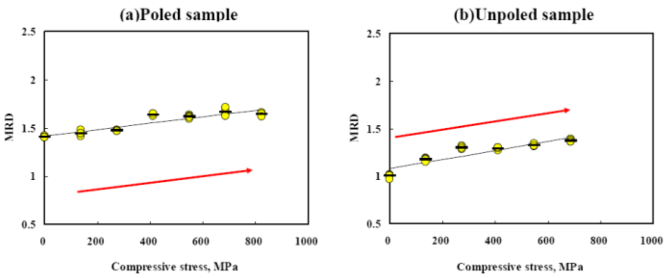

Fig. 7 Variation of MRD values as a function of the compressive stress for (a) poled sample and (b) un-poled sample.

To understand domain switching characteristic in detail, the crystal orientation in the PZT ceramics was examined. The crystal orientation was measured on the surface of the PZT specimen after a compressive load was applied. Fig. 8 shows crystal orientation maps. The color level of each pixel in the crystal orientation map is defined according to the deviation of the measured orientation with respect to the ND direction. From this analysis, the crystal orientation depends on the grain. It is clear that the crystal orientation in some grains alters after the loading process, where about 90˚ domain switching occurs throughout. In this instance, the domain orientation in grain is

(210) before loading, but is tilted to (102) following the loading process.

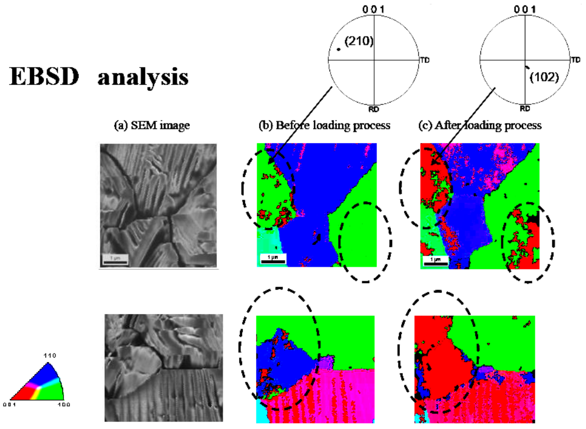

Fig. 8 Crystal orientation characteristics for PZT ceramics before and after loading.

IV. CONCLUSIONS

1) The mechanical properties of the PZT ceramic are attributed to domain switching. Because of domain switching, the higher mechanical properties were obtained for the poled PZT ceramics, where a work hardening-like occurred due to the complicated lattice structures.
2) With both x-ray diffraction and electron back scatter diffraction analysis, various types of 90˚ domain switching were clearly revealed. In addition, the amount of domain switching increases linearly with increasing applied load.
3) With increasing the number of the PZT ceramic plate, the electric voltage increases and the highest electric voltage is obtained for the sample with the four PZT ceramic plates putting together; however, the maximum electric voltage becomes almost stable for the PZT ceramic plates with more than four. This is attributed to the low strain and the complicated strain characteristic (compressive and tensile strain).
4) The electric voltage increases linearly with increasing the applied stress area on the PZT ceramic. The electric voltage is generated to the positive direction as the compressive stress is applied to the PZT ceramic.

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