Available online at www.sciencedirect.com

SciVerse ScienceDirect

Ceramics International 38 (2012) 4445–4451

CERAMICS INTERNATIONAL

www.elsevier.com/locate/ceramint

A study of the effects of vibration on the electric power generation properties of lead zirconate titanate piezoelectric ceramic

Mitsuhiro Okayasu [a,*], Daisuke Sato [b], Yuki Sato [b], Masashi Konno [c], Tetsuro Shiraishi [a]

[a] Department of Materials Science and Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama, Ehime 079-8577, Japan
[b] Department of Machine Intelligence and Systems Engineering, Akita Prefectural University, 84-4 Aza Ebinokuchi, Tsuchiya, Yurihonjo, Akita 015-0055, Japan
[c] K-Engineering Co. Ltd., 4-11 Sanuki Arayamachi, Akita 010-1623, Japan

Received 24 January 2012; accepted 6 February 2012
Available online 15 February 2012

Abstract

To better understand how the electric power generated from PZT piezoelectric ceramics is affected by mechanical loading conditions the power generation was examined during cyclic loading under various loading conditions. The electric power generation was continuously examined using a monitoring system that we have recently developed. This system revealed that the electric power increased with increase of the applied load but then decreased when the applied load exceeded a certain level. In addition, greater electric power was generated with a simple beam configuration compared with a cantilevered beam. The change of electric power generation was directly related to the stress direction; high stress in the tetragonal structure parallel to the *c*-axis gave rise to high electric power generation. On the other hand, material failure, including domain switching and crack generation, caused a reduction of the electric power generated. Based upon our experimental data, suitable loading conditions to give high piezoelectric energy generation have been clarified.

Keywords: Piezoelectric ceramic; Lead zirconate titanate ceramic; Electric power generation; Failure mechanism

1. Introduction

The piezoelectric ceramic lead zirconate titanate (PZT) crystallizes with the perovskite structure. The PZT ceramic also possesses the unique property of exhibiting spontaneous polarization that is reversible in an applied electric field. This piezoelectric effect, which is generated by the application of stress to a piezoelectric material, has found application in several technologies, such as ignition systems, sensors and actuators. Electric power generation using piezoelectric elements is a technique that also utilizes the piezoelectric effect [1]. Electrical power generation from high vibration sources, e.g., automobile engines using piezoelectric materials, has received special attention in our industrial community. In addition to electrical energy generation, the removal of mechanical energy from a vibrating engine by the harvesting of piezoelectric energy provides vibration suppression or damping [2]. The harvested energy is, however, limited to a few milliwatts; thus, power management and saving are a crucial consideration [3]. The ability of piezoelectric materials to generate electric power has given rise to significant interest for use in numerous microelectronic elements [4]. Piezoelectric materials have also been studied with the aim of creating electricity from pressure variations in micro-hydraulic systems [5]. Although several researchers have reported on electric power generation using the vibration of piezoelectric materials, the details have not been investigated. In particular, there appears to be little data concerning the effects of loading condition on the electric power generation, important information for the design of a high efficiency energy harvesting system. The aim of this study is therefore to examine electric power generation from the vibration of lead zirconate titanate piezoelectric ceramics under various loading conditions. Furthermore, the influence of material damage on the electric power generation has been systematically investigated.

2. Experimental procedures

Fig. 1 shows a photograph of the commercial soft PZT ceramic ($PbZrTiO_3$) used in this work. The PZT ceramic

* Corresponding author. Tel.: +81 89 927 9811; fax: +81 89 927 9811.
E-mail address: okayasu.mitsuhiro.mj@ehime-u.ac.jp (M. Okayasu).

0272-8842/$36.00 © 2012 Elsevier Ltd and Techna Group S.r.l. All rights reserved.
doi:10.1016/j.ceramint.2012.02.018

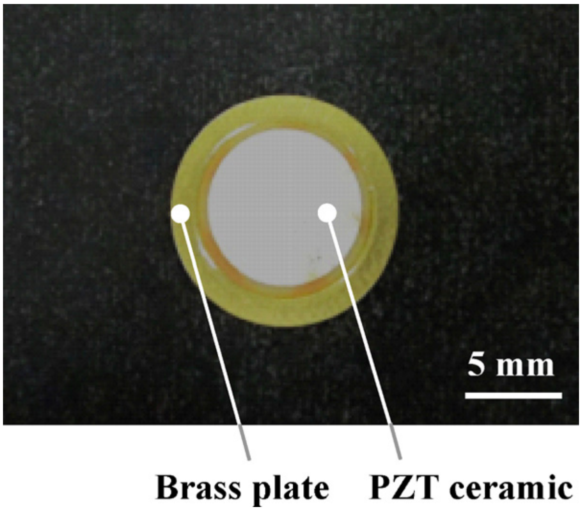

Fig. 1. Photograph of test specimen of lead zirconate titanate ceramic.

(ϕ 9.0 mm (d) × 0.12 mm (t)) was attached to a brass plate (ϕ 12.0 mm × 0.10 mm). A silver-based electroplated layer was applied to the PZT ceramic surface by a firing process in atmosphere. The PZT ceramics adopt a tetragonal structure with an aspect ratio $c/a = 1.014$ ($a = b = 0.4046$ nm and $c = 0.4103$ nm). The material properties of the PZT ceramics after polarization measured using an impedance analyzer (Agilent Technologies, 4294A) were: (i) effective elastic constant (C^E_{33}) 82 GPa, (ii) electromechanical coupling coefficient (k_{33}) 0.39, (iii) piezoelectric constant (d_{33}) 164 pm/V and (iv) permittivity (ε_{33}) 14.3 nF/m (or dielectric constant ($\varepsilon_{33}/\varepsilon_0$) 1619). The electric power generation (voltage and current) was measured using a novel testing system designed in our laboratory. Fig. 2 shows photograph and schematic illustration of the test apparatus, consisting of the loading machine and the monitoring system. With this loading machine, cyclic loading can be carried out over the range 0.1–50 V and 0.1–2.0 Hz with square or triangle waveforms. The electric power generation was measured with a monitoring system designed as in the block diagram shown in Fig. 3. In this monitoring system alternating electric power arising from the PZT ceramic during cyclic loading is compared with the DC power using a rectification circuit at Stage I (Fig. 3). The electric power data is then collected accurately and continuously by a programmable unit in Stage II. The adjustment of the current value using a variable resistor is carried out in Stage III. The current and

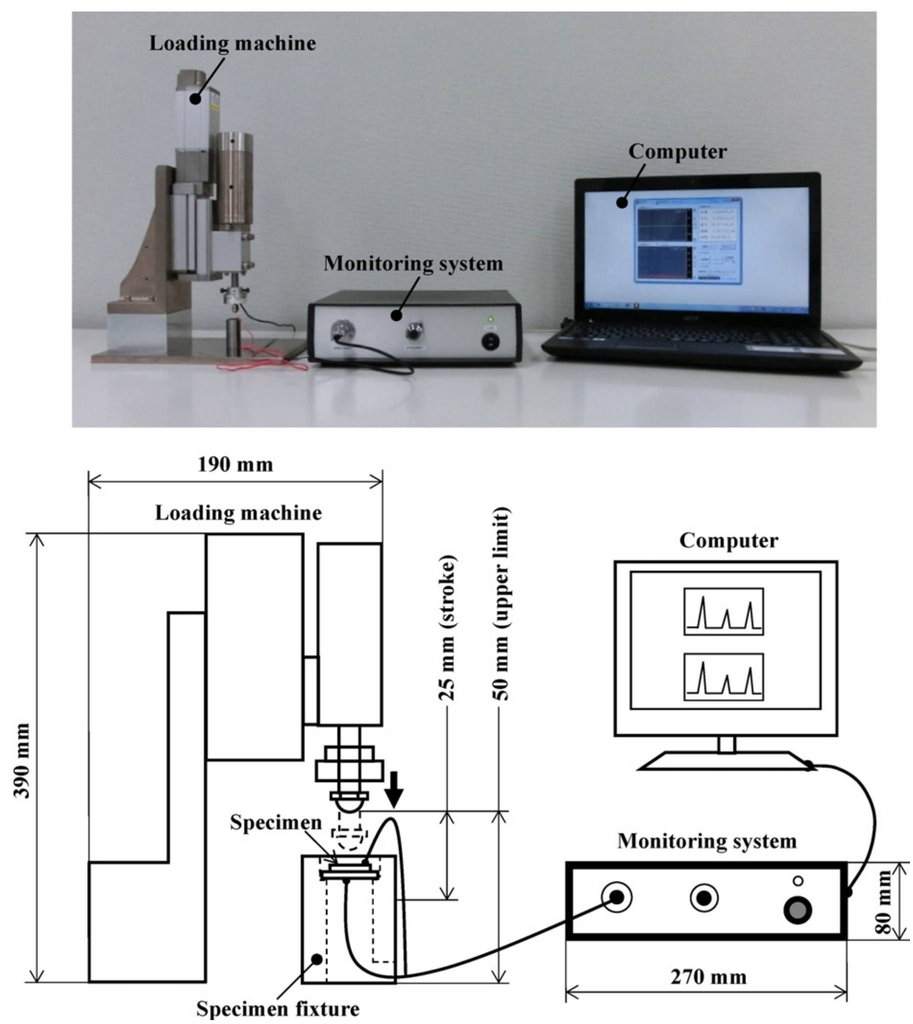

Fig. 2. Photograph and schematic illustration of the loading machine, and monitoring system for the electric power generation properties.

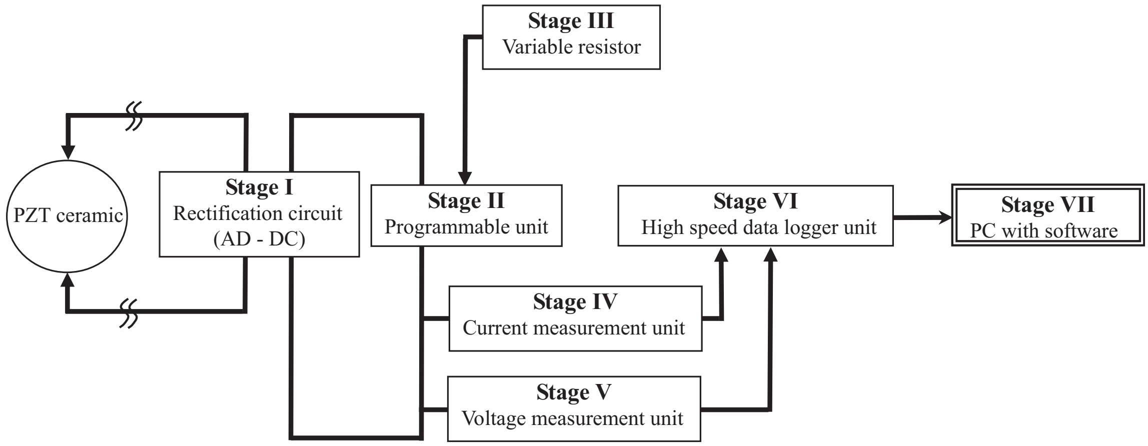

Fig. 3. Block diagram of the monitoring system in Fig. 2.

voltage levels are measured in Stages IV and V, respectively. The electrical data are transferred to a personal computer using a high speed data logger unit in Stage VI. The electric power generated is calculated and displayed using original software. These data are obtained simultaneously during the cyclic loading taking place in Stage VII. Fig. 4 displays the variation of electric voltage and current value arising from the PZT ceramics during cyclic loading under the simple beam configuration. Based upon the wave profiles shown in Fig. 4, the electric power generation properties could be continuously assessed. Using this approach, cyclic loading was applied with a square waveform at $R = 0.05$ using load control. The cyclic loading was carried out for 300 cycles, and the mean value of electric power generated (voltage and current) was obtained. To examine the influence of loading conditions on electric power generation, cyclic loading was carried out using a range of different loading conditions: (i) load level (0.2–20 N), (ii) frequency level (0.2–2.0 Hz), (iii) tensile stress and compressive stress and (iv) cantilever beam and simple beam. Fig. 5 shows a photograph and schematic diagram of the specimen fixtures for the simple beam and cantilever beam configurations for tensile and compressive stress.

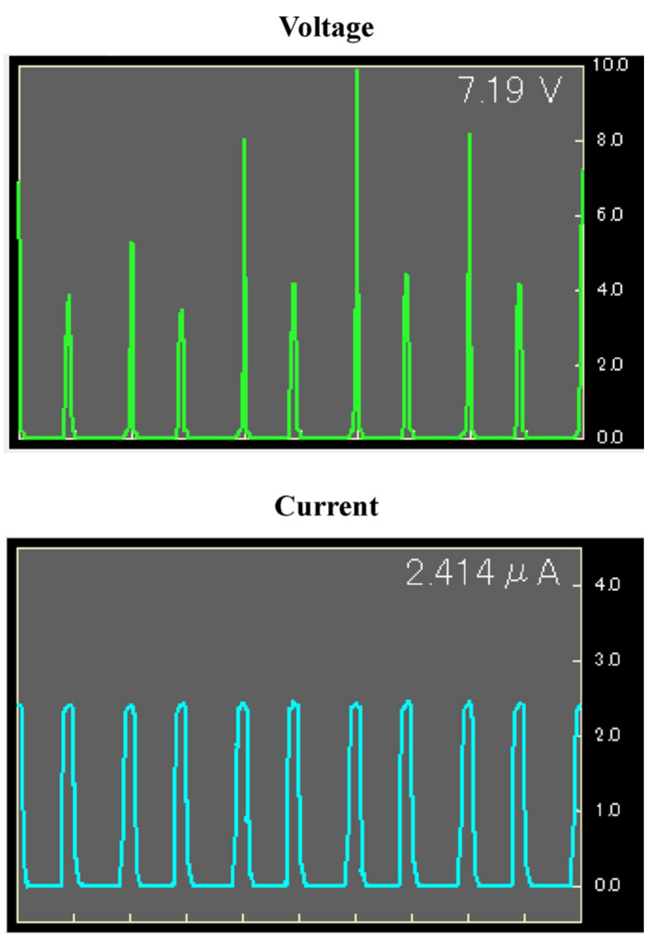

Fig. 4. Wave profiles of voltage and current values generated from PZT ceramic during the cyclic loading.

3. Results and discussion

Fig. 6 shows the variation of the mean voltage and the mean current value for 300 cycles as a function of the applied load level. It can be seen that the overall electric power properties under compressive stress are higher than that for tensile stress. The reason for this might simply be that the stress is greater for the generation of electric power under the compressive loading. Fig. 7 displays a schematic diagram showing the stress distribution in the samples. With compressive loading, high stress can be obtained in the tetragonal structure parallel to the *c*-axis, resulting in high electric power generation. On the other hand, the tensile stress causes a separation of the jointed tetragonal structures, leading to low electric power. It is also clear in Fig. 6 that the electric power generated increases with increasing applied stress although it then decreases rapidly with more than 3.6 N and 11.8 N tensile loading and compressive loading, respectively. The reason for the reduction in electric power generation is the material damage caused to the PZT ceramic.

To examine the material damage in PZT ceramics, the domain orientations were investigated using X-ray diffraction measurements of the proportion of *c*- and *a*-oriented domains parallel to a given sample direction. Fig. 8 displays the XRD spectra obtained after the loading process at the points *A* and *B* shown in Fig. 6. In this case, the diffraction peaks from the PZT

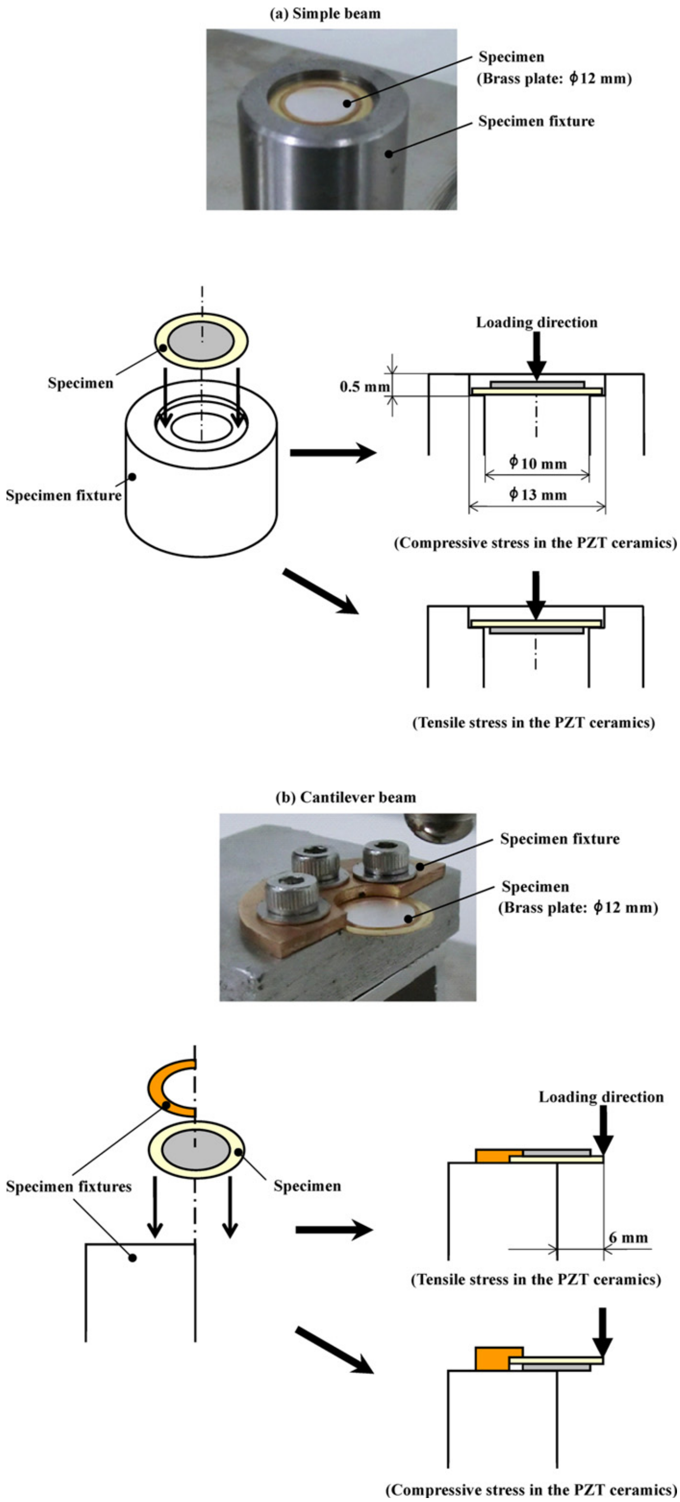

Fig. 5. Photograph and schematic diagram of specimen holder for (a) simple beam and (b) cantilever beam criterion.

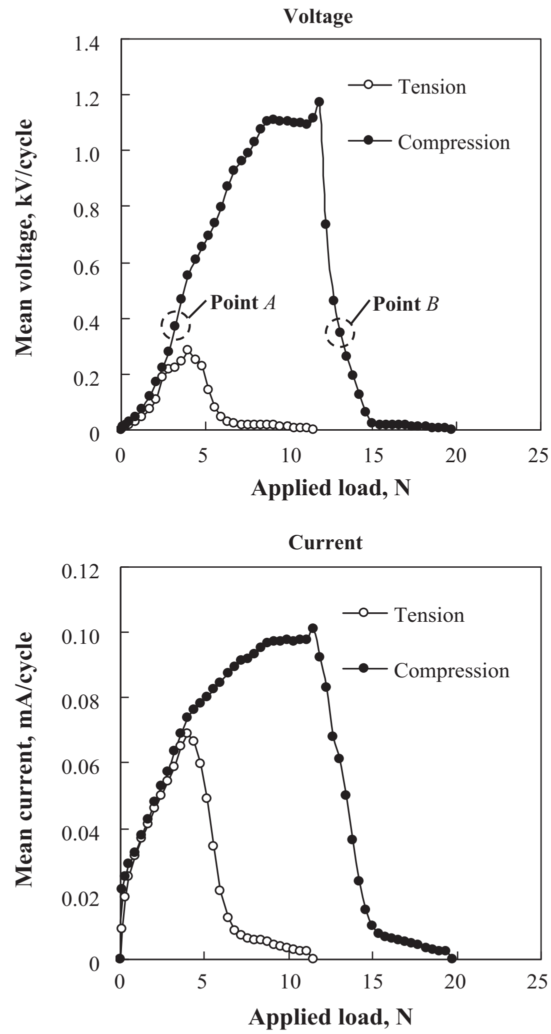

Fig. 6. Variation of mean voltage and the mean current value as a function of the applied cyclic loading under simple beam condition (compressive and tensile stress for 300 cycles).

samples at 2θ =43.6° and 44.9° correspond to the *c*-axis (0 0 2) and *a*-axis (2 0 0) planes of the tetragonal phase, respectively. As seen in Fig. 8, a strong (2 0 0) peak and weak (0 0 2) peak are detected at point *A*, a result similar to that before the loading process. The relative intensity of the (0 0 2) peak and (2 0 0) peak is altered after the loading is applied to point *B*, since the (2 0 0) peak decreases and the (0 0 2) peak increases. The XRD profile at point *B* is caused by different crystal orientation arising from the 90° domain switching [6]. Thus, one of the reasons for the reduction in electric power generation seen in Fig. 6 can be the 90° domain switching.

Fig. 9 shows the variation of the mean voltage and the mean current as a function of the fatigue frequency for the PZT ceramics. In this case, cyclic loading was carried out using compressive stress and the simple beam configuration. Unlike the results of Fig. 6, no clear change of electric power generation was obtained. The reason for this might be the use of the square waveform. This is because the loading speed to maximum load with the square waveform has the same value even if the frequency is altered. In previous work, a related approach was carried out, in which the cyclic loading was applied using a sinusoidal waveform [7]. Because of the sinusoidal waveform, the electric power level increases with increasing fatigue frequency.

Fig. 10 shows the variation of the mean voltage and mean current as a function of the compressive cyclic loading. In this

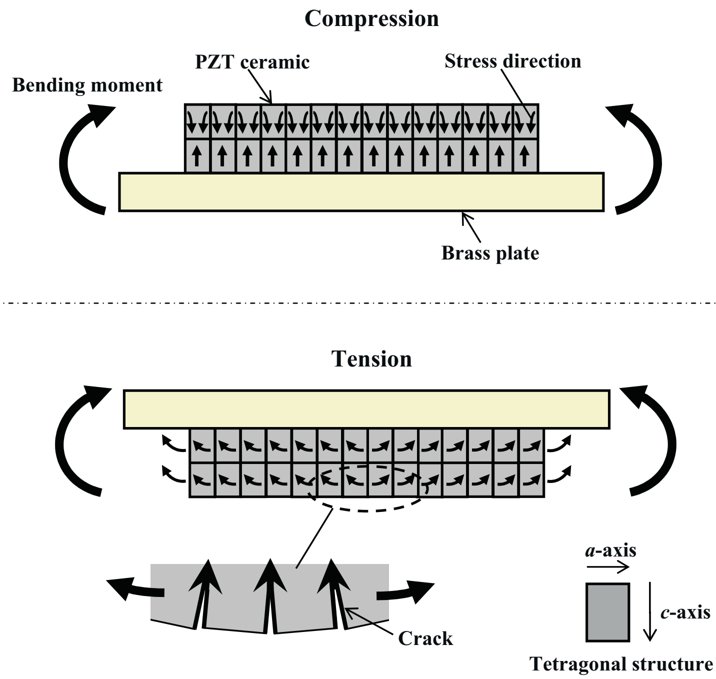

Fig. 7. Schematic illustration of the PZT ceramics showing the stress distribution in the tetragonal structures during the cyclic loading under the compressive and tensile stress.

case, the cyclic loading was performed with the cantilever beam configuration. It should be noted first that the equivalent data obtained with the simple beam configuration (Fig. 6) is also indicated in Fig. 10. Moreover, the data of tensile cyclic loading obtained with cantilever beam configuration is not indicated in Fig. 10 due to the similar trend to the simple beam one. Both simple beam and cantilever configurations produce increasing electric voltage and current with increasing applied load. However, the peak value for the cantilever beam is much lower than that for the simple beam. The reason for this may be attributed to the more severe material damage in the PZT ceramics, where high stress concentration would occur, especially adjacent to the specimen fixture. To confirm this, the specimen surface was observed directly by a scanning

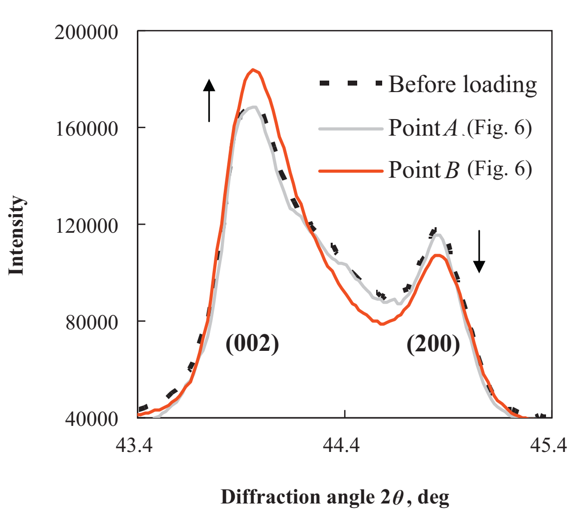

Fig. 8. X-ray diffraction profiles of the PZT ceramics before and after cyclic loading process.

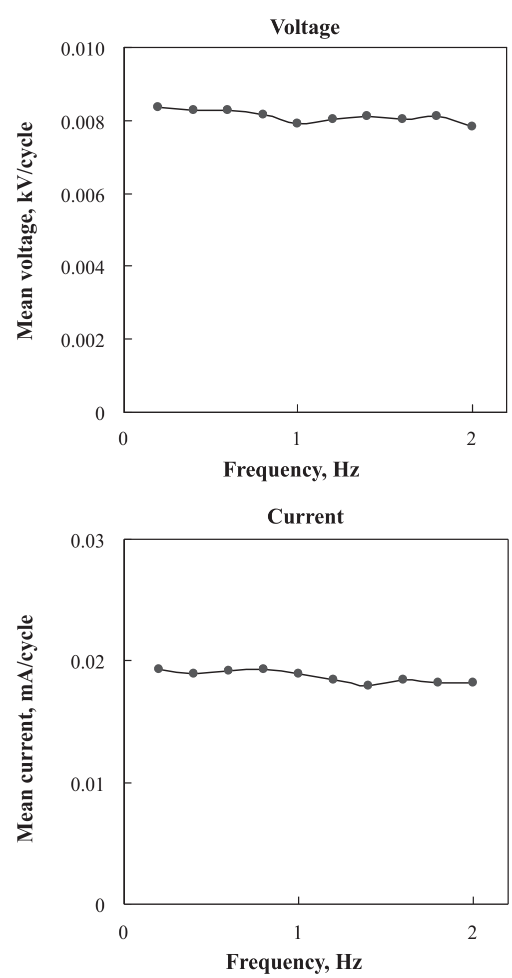

Fig. 9. Variation of the mean voltage and the mean current value as a function of the fatigue frequency under the simple beam condition (compressive stress for 300 cycles).

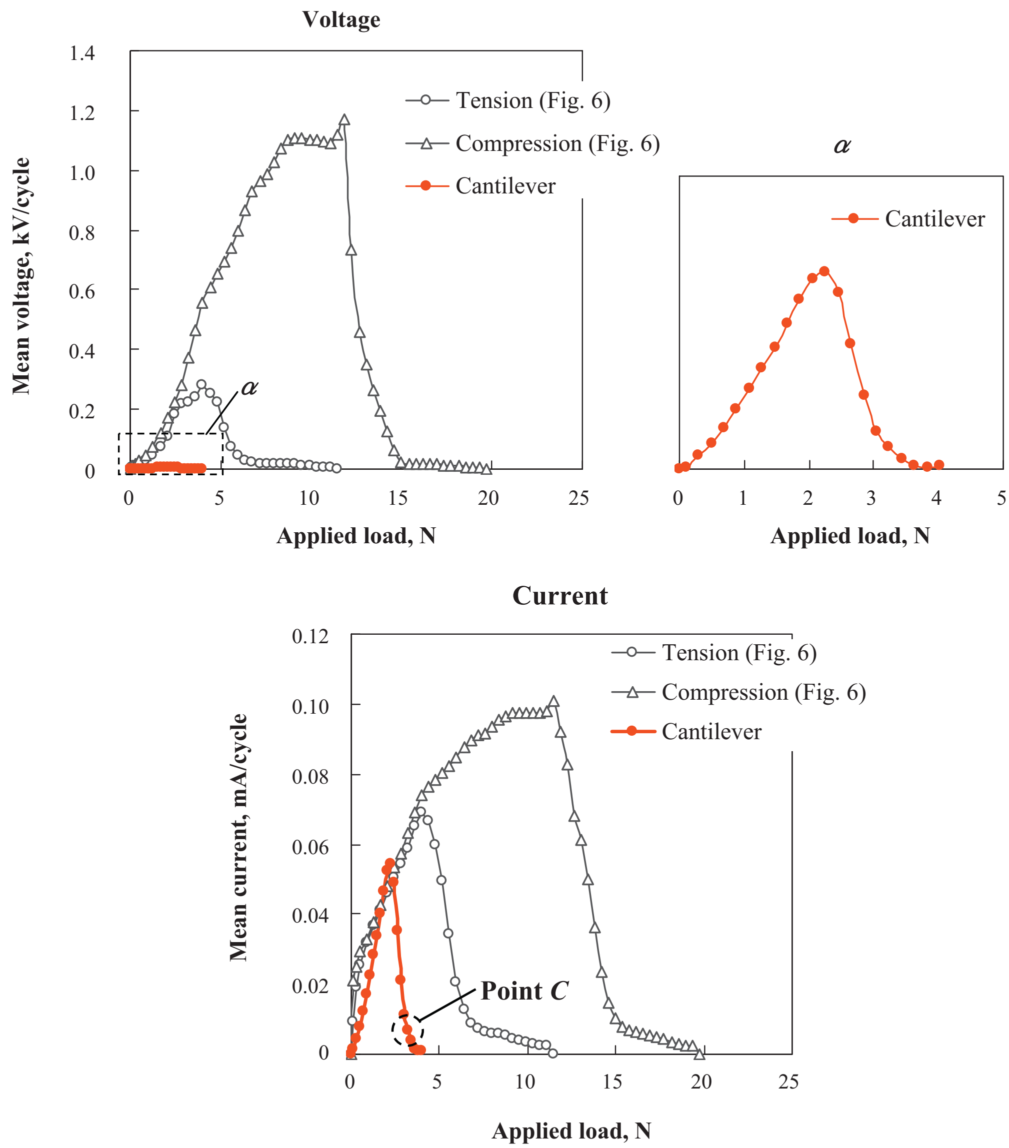

Fig. 10. Variation of the mean voltage and the mean current value as a function of the applied cyclic loading under cantilever beam condition (compressive stress for 300 cycles).

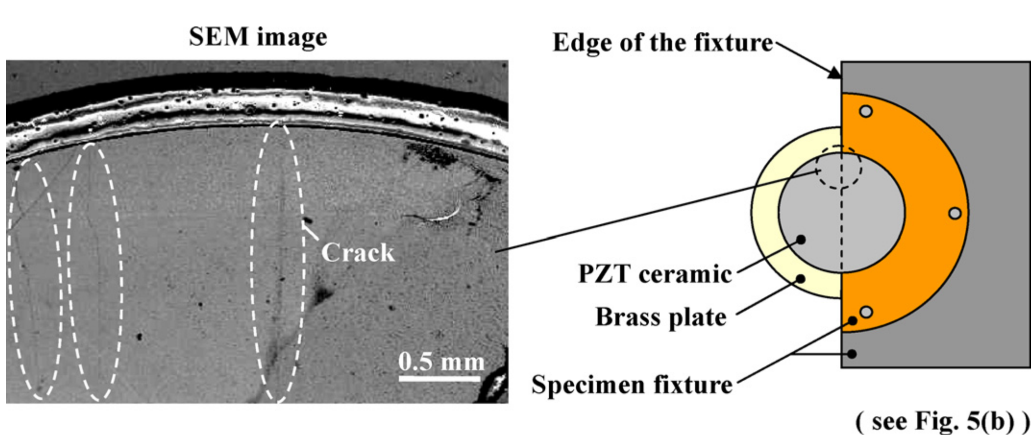

Fig. 11. SEM micrograph of the surface of the PZT ceramic showing the cracks created by the cyclic loading.

electron microscope. Fig. 11 presents the SEM image of the surface of the PZT ceramic after cyclic loading at 3.5 N for 300 cycles (point C in Fig. 10). It is clear that several cracks were created in the specimen parallel to the edge of the specimen fixture (see Fig. 11). Such material failure could reduce the electric power generated. It should be noted that, in this case, 90° domain switching may have also influenced the reduction of electric power, as the domain switching generally occurs before crack generation. From the above experiments, a suitable loading condition for high electric power generation would use high compressive stress (11.8 N) with the simple beam configuration.

4. Conclusions

The electric power generation properties of PZT ceramics have been examined experimentally with various loading conditions. For this investigation, a new monitoring system was developed, and the electric power generation properties were assessed from the values of mean voltage and mean current during cyclic loading for 300 cycles. The electric power generation properties increased with increasing values of applied load, but then decreased due to material failure in the PZT ceramics (domain switching and crack generation). Higher values for generated electric power were obtained under compressive loading compared with tensile loading. In addition, the electric power generation was greater using the simple beam configuration compared with the cantilever beam.

Acknowledgements

The authors would like to express the appreciation to Dr. Noriko Muto at Akita Prefectural University for her technical supports on the manuscript.

References

[1] D. Koyama, K. Nakamura, Electric power generation using vibration of a polyurea piezoelectric thin film, Appl. Acoust. 71 (2010) 439–445.
[2] H.W. Kim, S. Priya, K. Uchino, R.E. Newnham, Piezoelectric energy harvesting under high pre-stressed cyclic vibrations, J. Electroceram. 15 (2005) 27–34.
[3] M. Lallart, D. Guyomar, Y. Jayet, L. Petit, E. Lefeuvre, T. Monnier, P. Guy, C. Richard, Synchronized switch harvesting applied to self-powered smart systems: piezoactive microgenerators for autonomous wireless receivers, Sensors Actuat. A 147 (2008) 263–272.
[4] F. Mohammadi, A. Khan, R.B. Cass, Power generation from piezoelectric lead zirconate titanate fiber composites, Mater. Res. Soc. Proc. 736 (2003) D5.5.1–D5.5.3.
[5] S.R. Platt, S. Farritor, H. Haider, On low-frequency electric power generation with PZT ceramics, IEEE/ASME Trans. Mech. 10 (2005) 240–252.
[6] M. Okayasu, N. Odagiri, M. Mizuno, Damage characteristics of lead zirconate titanate piezoelectric ceramic during cyclic loading, Int. J. Fatigue 31 (2009) 1434–1441.
[7] N. Sekine, T. Kitahara, M. Ichiki, S. Fujimoto, Study on power generation technique using structure vibration (vibration test of piezoelectric type power generation device), in: The 14th Conference of Jpn. Foundry Eng. Soc. (Kanto Shibu Sokai), Japan, 2008, pp. 507–508 (in Japanese).