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Ceramics International 40 (2014) 341–345

CERAMICS INTERNATIONAL

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Power generation characteristics of PZT piezoelectric ceramics using drop weight impact techniques: Effect of dimensional size

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Received 25 April 2013; received in revised form 30 April 2013; accepted 8 June 2013
Available online 19 June 2013

Abstract

In this study the relation between the generated open circuit output voltages and the generated electrical energy of PZT piezoelectric ceramic body with applied impact mechanical energy are studied. The output voltages and the generated electrical energy of PZT piezoelectric ceramic body are increased with the increasing of the applied mechanical energy. Under the same impact mechanical energy, the output voltages and the generated electrical energy of the PZT piezoelectric ceramic body are depending on both the dimensional size and properties of the samples. The PZT piezoelectric ceramic body with greater (t/D^2) can produce a higher output voltage and higher generated electrical energy. With the same piezoelectric ceramic body size, under the same impact mechanical energy, the output voltage and the generated energy of soft type piezoelectric ceramic body is higher than that of hard type piezoelectric ceramic body, which is because the g_{33} and ε_{33}^{T} value of soft type piezoelectric ceramic body is higher than that of hard type piezoelectric ceramic body.

Keywords: Piezoelectric ceramics; Power generation; Energy harvesting

1. Introduction

Piezoelectric ceramics are able to interchange electrical energy and mechanical motion or force. The power transfer phenomenon of PZT piezoelectric ceramics had been studied by many researchers. Umeda et al. [1] used a free-falling ball to impact a piezoelectric ceramic wafer attached to its underside, and developed an electrical equivalent model of the PZT transforming mechanical impact energy to electrical power. They also investigated the energy storage characteristics of the PZT with a bridge rectifier and a capacitor. Starner [2] examines the energy available from leg motion of a human being and surveys other human motion sources of mechanical energy including blood pressure. Goldfarb et al. [3] presented a linearized model of a PZT stack and analyzed the efficiency of it as a power generation device. It was shown that the maximum efficiency occurs in a low frequency region much lower than the structural resonance of the stack. The efficiency is also related to the amplitude of the input force due to hysteresis of the PZT. In addition to the force applied in the poling direction (d_{33} mode), Clark and Ramsay [4] have investigated and compared it with the transverse force (d_{31} mode) for a PZT generator. There work showed that the d_{31} mode has a mechanical advantage in converting applied pressure to working stress for power generation. They concluded that a 1 cm^2 piezoelectric ceramic wafer can power MEMS device in the microwatt range. Kasyap et al. [5] formulated a lumped element model to represent the dynamic behavior of PZT in multiple energy domains using an equivalent circuit.

In this paper a comparison of two types of piezoelectric ceramics were experimentally investigated for use as energy transducers. The two types tested were the hard type PZT and the soft type PZT piezoelectric ceramic. The effect of

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http://dx.doi.org/10.1016/j.ceramint.2013.06.007

Table 1
The dimension and capacitance of the samples used in this study.

Sample	1 (QB)	2 (KA)	3 (QB)	4 (QB)	5 (QB)	6 (QB)
Diameter (mm)	15	15	25	25	20	15
Thickness (mm)	0.9	0.9	1.24	2.07	1.24	2.07
D/t	16.67	16.67	20.16	12.08	16.13	7.25
t/D^2	0.004	0.004	0.001984	0.003312	0.0031	0.0092
Capacitance (nF)	2.628	3.564	5.402	3.196	3.402	1.047

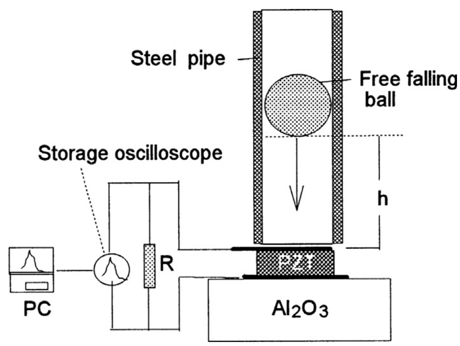

Fig. 1. Schematic drawing of the impact testing.

dimensional size on the output electrical characteristics of PZT piezoelectric ceramics using drop weight impact techniques was studied in this paper.

2. Experimental processes

The PZT piezoelectric ceramics used in this study were supplied by Eleceram Technology Co., Ltd., Taiwan. Two kinds of ceramics body were used in this study, one was hard type with the coded QB, and the other was soft type with the coded KA. The compositions of both types were in the vicinity of the MPB of PZT system in the tetragonal range. The hard QB was doped with MnO_2 and Sb_2O_3, and it presented a free dielectric constant ε_{33}^T (1 kHz)=1140, a dielectric dissipation factor D (1 kHz)=0.3%, a piezoelectric voltage constant $g_{33}=19.8\times10^{-3}$ Vm/N, a planar electromechanical coupling factor $k_p=0.65$, a thickness electromechanical coupling factor $k_{33}=0.69$, a mechanical quality factor $Q_m=1650$, a Curie temperature $T_C=315$ °C and a bulk density $\rho=7.95$ g/cm^3. The soft KA was doped with Nb_2O_5 and Sb_2O_3, and it presented a free dielectric constant ε_{33}^T(1 kHz)=2100, a dielectric dissipation factor D (1 kHz)=1.5%, a piezoelectric voltage constant $g_{33}=24\times10^{-3}$ Vm/N, a planar electromechanical coupling factor $k_p=0.70$, a thickness electromechanical coupling factor $k_{33}=0.72$, a mechanical quality factor $Q_m=65$, a Curie temperature $T_C=325$ °C and a bulk density $\rho=7.90$ g/cm^3. The disc-shaped samples with different diameter and thickness were used in this study, as shown in Table 1.

The electrical output performance of PZT specimens during applying mechanical compressive stress was measured using drop weight impact techniques, in a way as shown in Fig. 1. A steel ball (38.6 mm in diameter, 16.5 g in weight) was dropped from a height from 5 to 50 mm, through a steel guide pipe, thereby applying an impact to the test PZT specimen. The electrical response of PZT specimens to applied stress was displayed on a digital storage memory oscilloscope (Agilent MSO-X 3054A) with an input resistance R of 10^7 Ω, which was connected to a personal computer (PC) for data acquisition and analysis.

3. Results and discussions

The relation between applied mechanical stress and the generated open circuit output voltage of PZT piezoelectric ceramic can be expressed as[6]

$$V=g_{33}tT_3=\frac{g_{33}tF_3}{A}=\frac{4g_{33}tF_3}{\pi D^2}=\frac{4g_{33}F_3}{\pi}\left(\frac{t}{D^2}\right) \quad (1)$$

in which g_{33} is the piezoelectric voltage constant of the PZT piezoelectric ceramics, A is the surface area of the sample, t is the thickness of the sample, D is the diameter of the sample, F_3 is the applied mechanical force and T_3 is the applied mechanical stress.

The piezoelectric ceramic body also is the dielectric, with the generated open circuit voltage and measured capacitance, the generated electrical energy E_E stored in the piezoelectric ceramic can be calculated using a simple equation as

$$E_E=CV^2 \quad (2)$$

when substituted capacitance C with

$$C=\varepsilon_o\varepsilon_{33}^T\frac{A}{t}=\varepsilon_o\varepsilon_{33}^T\frac{\pi D^2}{4t} \quad (3)$$

and generated open circuit output voltage V with Eq. (1), the Eq. (2) can be rewritten as

$$E_E=\varepsilon_o\varepsilon_{33}^T g_{33}^2F_3^2\left(\frac{4t}{\pi D^2}\right) \quad (4)$$

From Eqs. (1) and (4), it is found when the piezoelectric ceramics material and the applied mechanical stress or applied mechanical energy is the same, the generated open circuit output voltage and the generated electrical energy were dependent on the (t/D^2) ratio of the piezoelectric ceramic body, the piezoelectric ceramics body with higher (t/D^2) ratio can produce larger generated open circuit output voltage and larger generated electrical energy.

Fig. 2 shows the relation between applied mechanical energy and the generated open circuit output voltage of the

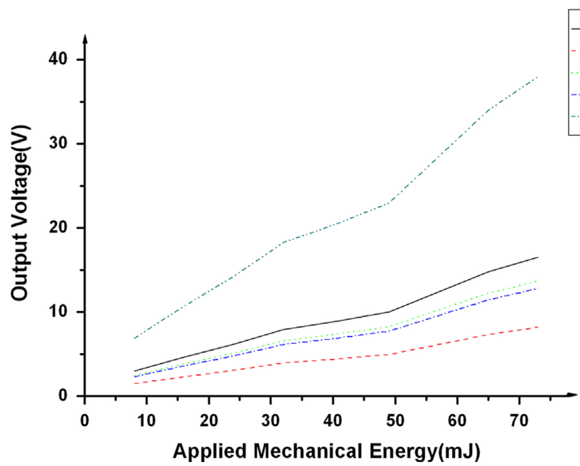

Fig. 2. The relation between applied mechanical energy and output voltage of the QB series.

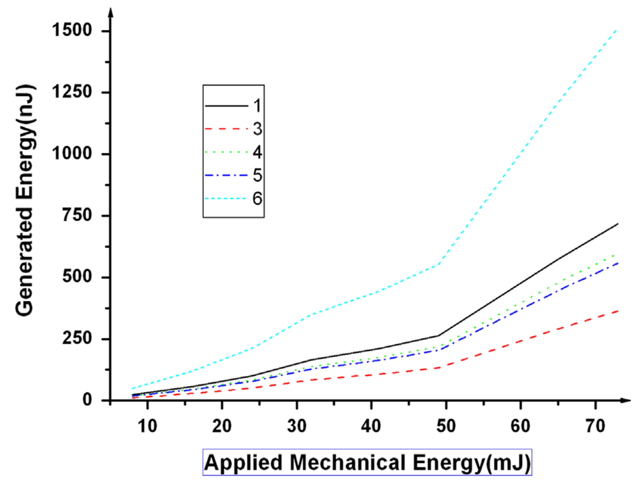

Fig. 3. The relation between applied mechanical energy and generated energy of the hard type QB series.

hard type QB series. From the results of Fig. 2, it is found that the generated open circuit output voltage of each sample is increased with the increasing of applied mechanical energy. With the same applied mechanical energy, the generated open circuit output voltage is largest for no. 6 sample, and then is no. 1 sample, no. 4 sample, no. 5 sample and no. 3 sample. From the data of Table 1, it is found that no. 6 sample had highest (t/D^2) ratio, and then is no. 1 sample, no. 4 sample, no. 5 sample and no. 3 sample, so the results are the same as that predicted by Eq. (1).

In this study, the relation between applied mechanical energy and the generated open circuit output voltage of QB series piezoelectric ceramics can be fit by the second order polynomial, as follows:

$$V_1 = 2.17716 + 0.13579(E_M) + 8.26018 \times 10^{-4}(E_M)^2 \tag{5}$$

$$V_3 = 1.08231 + 0.06742(E_M) + 4.09873 \times 10^{-4}(E_M)^2 \tag{6}$$

$$V_4 = 1.79949 + 0.11252(E_M) + 6.81974 \times 10^{-4}(E_M)^2 \tag{7}$$

$$V_5 = 1.69919 + 0.10452(E_M) + 6.47682 \times 10^{-4}(E_M)^2 \tag{8}$$

$$V_6 = 5.01662 + 0.31135(E_M) + 0.00191(E_M)^2 \tag{9}$$

where V_1, V_3, V_4, V_5 and V_6 corresponding to the generated open circuit output voltage of sample no. 1, no. 3, no. 4, no. 5 and no. 6, respectively. E_M is the applied mechanical energy.

Fig. 3 shows the relation between applied mechanical energy and generated electrical energy of the hard type QB series. The generated electrical energy from impact stress is in the nJ order, the conversion ratio of energy thus derived is on the order of 10^{-6} for impact stress, the results are the same as that of Xu et al. [7]. In QB series, the variation of generated electrical energy is the same as that of generated open circuit output voltage, the largest is no. 6 sample, and then is no. 4 sample, no. 1 sample, no. 5 sample and no. 3 sample, as that predicted by Eq. (4).

In this study, the relation between applied mechanical energy and the generated electrical energy of QB series piezoelectric ceramics can be fit by the second order polynomial, as follows:

$$E_{E1} = 50.87592 - 2.42103(E_M) + 0.1577(E_M)^2 \tag{10}$$

$$E_{E3} = 25.78505 - 1.22705(E_M) + 0.07993(E_M)^2 \tag{11}$$

$$E_{E4} = 42.37317 - 2.01645(E_M) + 0.13135(E_M)^2 \tag{12}$$

$$E_{E5} = 39.51691 - 1.8804(E_M) + 0.12252(E_M)^2 \tag{13}$$

$$E_{E6} = 107.11009 - 5.0971(E_M) + 0.33203(E_M)^2 \tag{14}$$

where E_{E1}, E_{E3}, E_{E4}, E_{E5} and E_{E6} corresponding to the generated electrical energy of sample no. 1, no. 3, no. 4, no. 5 and no. 6, respectively. E_M is the applied mechanical energy.

With the same diameter, the output voltage will depend on the thickness of the piezoelectric ceramic body; the piezoelectric ceramic body with larger thickness can produced higher output voltage. Fig. 4 shows the relation between applied mechanical energy and output voltage for samples with same diameter, but different thicknesses. Sample no. 1 and no. 6 had the same diameter $D=15$ mm, but different thicknesses, the thickness of sample no. 6 ($t=2.07$ mm) is larger than that of sample no. 1 ($t=0.09$ mm), so the output voltage of sample no. 6 is higher than that of sample no. 1. The same phenomena also existed for sample no. 3 and no. 4, they had the same diameter $D=25$ mm, but the thickness of sample no. 4 ($t=2.07$ mm) is larger than that of sample no. 3 ($t=1.24$ mm), so the output voltage of sample no. 4 is higher than that of sample no. 3.

With the same thickness, the output voltage will depend on the diameter of the piezoelectric ceramic body; the piezoelectric ceramic body with smaller diameter can produced higher output voltage. Fig. 5 shows the relation between applied mechanical energy and output voltage for samples with same thickness but different diameters. Sample no. 4 and no. 6 had the same thickness $t=2.07$ mm, but the diameter no. 6 ($d=15$ mm) is smaller than that of sample no. 4 ($d=25$ mm), so the output voltage of sample no. 6 is higher than that

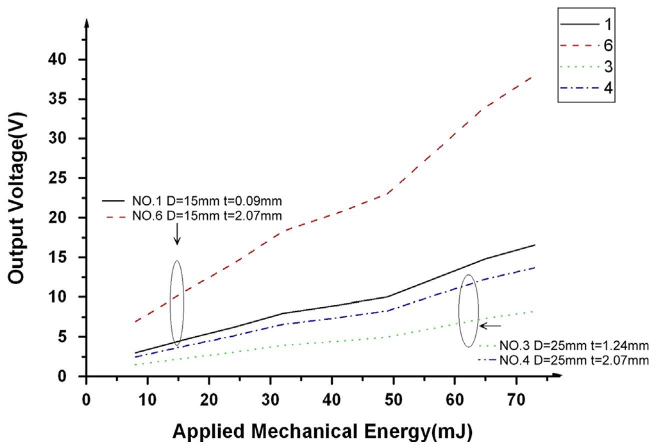

Fig. 4. The relation between applied mechanical energy and output voltage for samples with same diameter but different thicknesses.

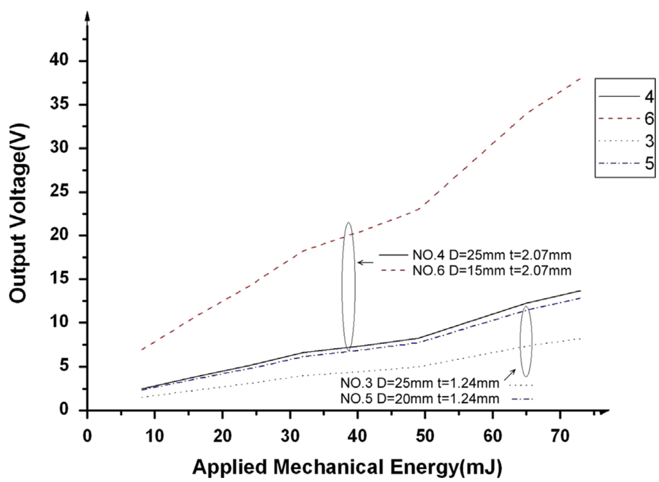

Fig. 5. The relation between applied mechanical energy and output voltage for samples with same thickness but different diameters.

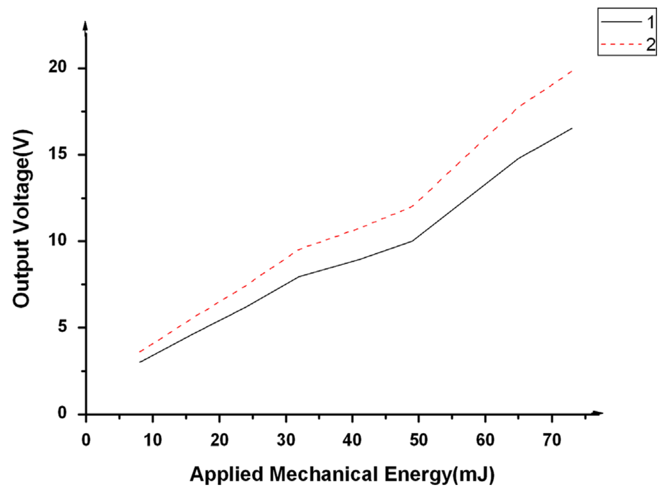

Fig. 6. The relation between applied mechanical energy and output voltage for QB and KA series.

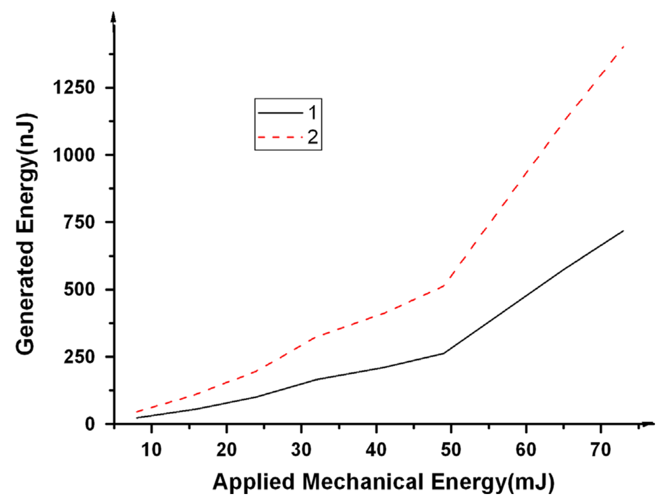

Fig. 7. The relation between applied mechanical energy and generated energy for QB and KA series.

of sample no. 4. The same phenomena also existed for sample no. 3 and no. 5, they had the same thickness 1.24 mm, but the diameter of sample no. 5 ($t=20$ mm) is smaller than that of sample no. 3 ($d=25$ mm), so the output voltage of sample no. 5 is higher than that of sample no. 4.

When the sample size is the same, the generated open circuit output voltage will depend on the properties of piezoelectric ceramics. Fig. 6 shows the relation between the applied mechanical energy and the generated open circuit output voltage for no. 1 and no. 2 sample, in which no. 1 sample is hard type QB series, and no. 2 sample is soft type KA series. From the results of Fig. 6, it is found that the generated open circuit output voltage of the soft type KA is larger than that of hard type QB that is because the piezoelectric voltage constant g_{33} of soft type KA is higher than that of hard type QB.

Fig. 7 shows the relation between the applied mechanical energy and the generated electrical energy for no. 1 and no. 2 sample. From the results of Fig. 7, it is found that the generated electrical energy of soft type KA is nearly double to that of hard type QB. From Eq. (4), when the sample size was the same, the ratio between the generated electrical energy of soft type KA and hard type QB can be expressed as

$$\frac{(E_E)_{\mathrm{KA}}}{(E_E)_{\mathrm{QB}}} = \frac{(\varepsilon_{33}^T)_{\mathrm{KA}}(g_{33})_{\mathrm{KA}}^2}{(\varepsilon_{33}^T)_{\mathrm{QB}}(g_{33})_{\mathrm{QB}}^2} = \frac{(2100)(24\times10^{-3})^2}{(1650)(19.8\times10^{-3})^2} = 1.87 \tag{15}$$

So, the experiment result is matched to that theoretical prediction.

4. Conclusions

Open circuit output voltage and generated electrical energy of piezoelectric ceramic body increased with the increasing of the applied mechanical energy. With the same impact mechanical energy, the piezoelectric ceramic body with greater (t/D^2) can produce a higher open circuit output voltage and higher generated electrical energy. With the same diameter, the open circuit output voltage and generated electrical energy will depend on the thickness of the piezoelectric ceramic body; the piezoelectric ceramic body with larger thickness can produced higher open circuit output voltage and higher generated electrical energy. With the same thickness, the open circuit output voltage and generated electrical energy will depend on the diameter of the piezoelectric ceramic body; the piezoelectric ceramic body with smaller diameter can produced higher open circuit output voltage and higher generated electrical energy. With the same piezoelectric ceramic body size, under the same impact mechanical energy, the open circuit output voltage and generated electrical energy of soft type piezoelectric ceramic body is higher than that of hard type piezoelectric ceramic body, which is because the g_{33} and ε_{33}^{T} value of soft type piezoelectric ceramic body are higher than that of hard type piezoelectric ceramic body. In this study, the generated electrical energy of soft type piezoelectric ceramic body is nearly double to that of hard type piezoelectric ceramic body.

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