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High-Temperature Piezoelectric Materials for Elements of Linear Piezo Motors

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Abstract. This paper discusses technological and construction ways to achieve a high working temperature with a high displacement in linear piezo motors. The first part reviews the results of the piezoelectric material development, its temperature stability testing and basic parameters for piezo motors. The second part focuses on the multilayer structure of piezoelectric elements, which are based on high-temperature piezoelectric materials (HTPM). Also analyzed are working temperatures of multilayer piezoelectric elements (MPE) and their hysteresis. Finally, the third part shows a comparison of three recent prototypes of high-temperature MPEs that were in our lab using different materials.

INTRODUCTION

Today, motors and drives for high-precision positioning are widely used in various fields of science and technology, among which special attention should be given to areas with extremely high working temperatures such as space, aviation industry, etc., which complicates the use of electromagnetic units (EMU). The current alternative to the EMU are piezo motors, the use of which allows us to significantly increase the working temperature of positioning systems.

The working temperature of the piezoelectric element can reach 750°C, but an increase of temperature decreases its displacement, making it unsuitable for using in linear piezo motors. Due to the fact that the main characteristics of any piezo motors primarily depend on the properties of the piezoceramic material and design of the piezoelectric element (actuator), it becomes relevant to research new piezoceramic compositions and structures of the actuator.

HIGH-TEMPERATURE PIEZOCERAMIC MATERIALS

High-temperature piezoelectric materials are commonly characterized by the Curie temperature (T_C), which should be at least 350°C and the working temperature (T_w) is not less than 250°C. In the course of this work, we analyzed HTPM compositions of Russian and foreign companies. As follows from the previous work [1], with a rise of T_C the piezoelectric charge coefficient (d_{33}) is reduced: when T_C is higher than 450°C ($T_w \geq 350$°C), d_{33} does not exceed 100 C/N and, when $T_C \geq 750$°C ($T_w \geq 600$°C), values of d_{33} generally below 20 C/N.

PRODUCTION TECHNOLOGY OF HTPMS

Using the methodological process of solid-phase synthesis [2], the Elpa Research Institute obtained HTPMs. Subsequently, attestation specimens with the dimension $10\times10\times1$ were produced by hot pressing. Surfaces 10×10 were covered by a conductive layer of Ag and their electrical properties were measured. The measurements were carried out according to the IRE Standards on Piezoelectric Crystals [3]. The results are presented in Table 1.

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TABLE 1. Compositions of high-temperature piezoceramic obtained by the ELPA Institute

Piezoceramic	T_C, °C	T_w, °C	ρ, g/cm^3	$\varepsilon^T_{33}/\varepsilon_0$	tanδ, %	$\lvert d_{31}\rvert$, 10^{-12} C/H	d_{33}, 10^{-12} C/H	g_{33}, 10^{-3} Vm/H
$BiScO_3$–$PbTiO_3$ (BSPT-1) [4]	420	330	7.4	1800 ± 150	≤0.3	≥135	340 ± 15%	21.3
$Na_{0.5}Bi_{4.5}Ti_4O_{15}$ [5]	630	450	6.6	130 ± 25	≤0.8	–	18 ± 15%	19.1
$BiTiNbO_9$ [6]	900	750	8.0	120 ± 20	≤0.2	–	16.9 ± 15%	14.1

Then the dependences of the piezoelectric charge coefficient on the temperature were carried out on specimens from BSPT-1, $Na_{0.5}Bi_{4.5}Ti_4O_{15}$, and $BiTiNbO_9$; the results are shown in Fig. 1.

ACTUATORS FOR LINEAR PIEZO MOTORS

The operation principle and design of linear piezo drive systems (piezo motor) is extensively described elsewhere [7–11] by the example of the linear piezo actuator microdevice of the peripheral spacecraft reflector of the pull cord. The most important characteristic of the high-temperature actuator is displacement, which is calculated for single-layer $(\Delta l_1, \mu\text{m})$ and multilayer $(\Delta l_n, \mu\text{m})$ structures by the formula [12]

$$\Delta l_1 = d_{33} E l_3, \tag{1}$$

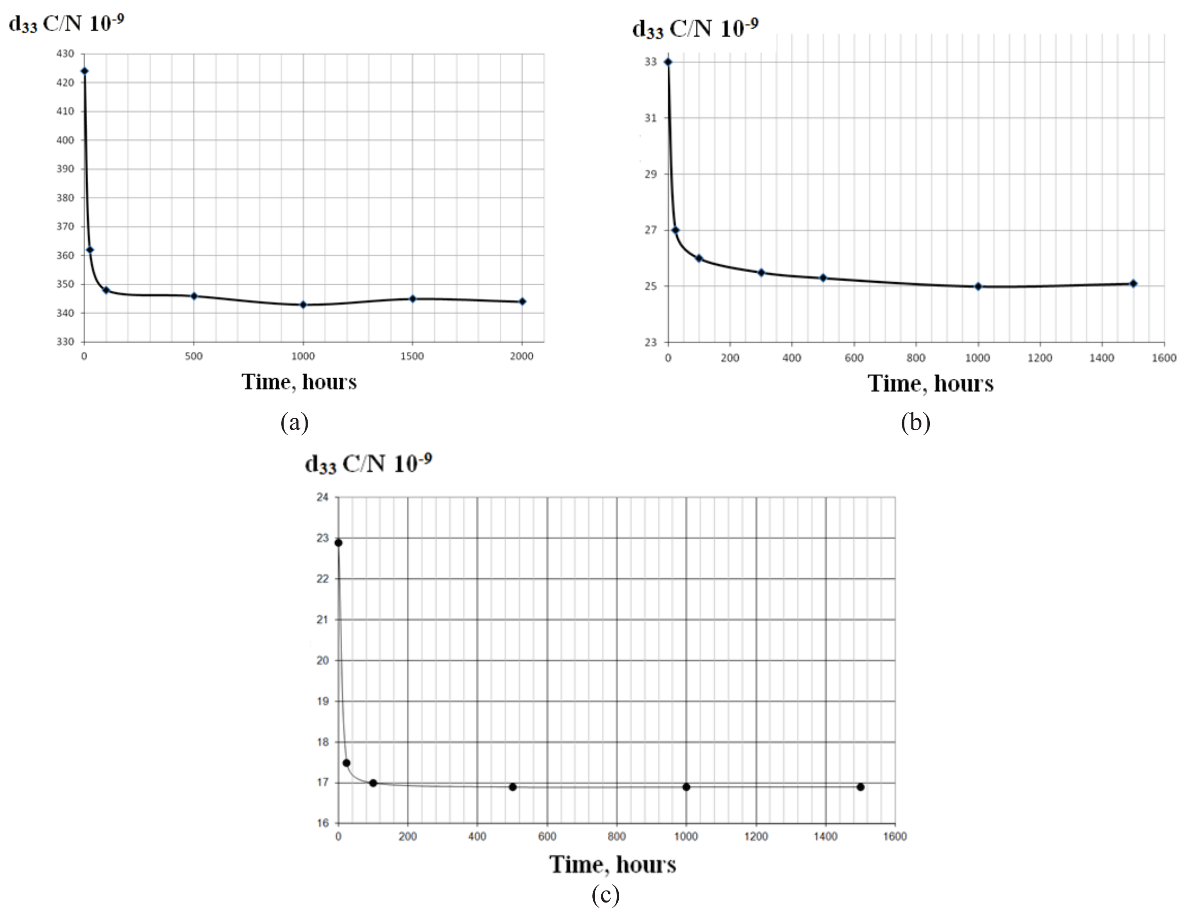

FIGURE 1. Dependence of d_{33} of HTPMs on time during heating. (a) BSPT-1 heated to $T = 330$°C; (b) $Na_{0.5}Bi_{4.5}Ti_4O_{15}$ heated to $T = 500$°C; (c) $BiTiNbO_9$ heated to $T = 750$°C

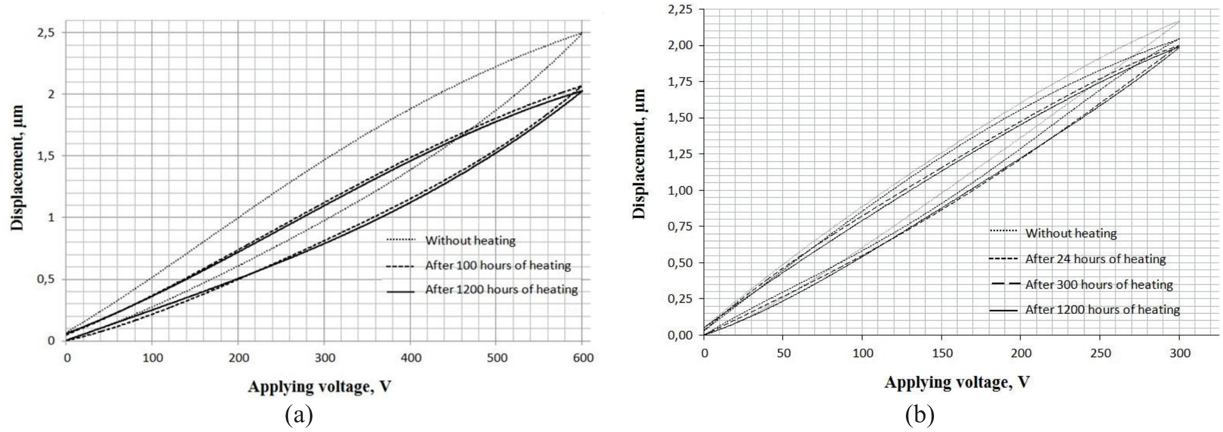

FIGURE 2. MPA displacement under the influence of voltage before and after heating up to $T = 330$ and 500°C: (a) BSPT-1 ($T = 330$°C) and (b) $Na_{0.5}Bi_{4.5}Ti_4O_{15}$ ($T = 500$°C)

$$\Delta l_n = d_{33}^{*} E l_3 = N d_{33} E l_3, \quad (2)$$

where E is the electric field intensity in V/m, l_3 is the thickness of the piezoceramic element or layer (if it is a multilayer structure) in µm, d_{33} is the piezoelectric charge coefficient in C/H, d_{33}^{*} is the effective piezoelectric charge coefficient in C/H, and N is the number of layers.

From this it follows that the most important characteristic of piezoelectric materials for linear piezo motors is d_{33}. On the basis of the previous calculations [9, 10, 13], the displacement of the actuator should be more than 12 µm, which is measured in the static mode at the 100 V voltage on specimens with the thickness about 20 mm. As follows from Table 1, d_{33} of HTPMs is insufficient for using in actuators with single-layer structures. It is necessary to use multilayer piezoelectric elements. For creating a multilayer structure, a tape-casing technology was commonly used [14–16]. This technology allows us to obtain a monolithic multilayer piezo actuators (MPA) with a high displacement.

For this study, MPAs from BSPT-1 were fabricated using the tape-casting technology. The number of active piezoceramic layers is $N = 16$, and its thickness is $t = 100$ µm. Further thermal resistance tests of the obtained specimens are shown in Fig. 2, which presents graphs of the MPA displacement under the influences of voltage before and after heating up to $T = 330$°C. From the graph in Fig. 2, it can be concluded that the working temperature of the MPA is equal to the working temperature of the BSPT-1 material and the effective piezoelectric charge coefficient d_{33}^{*} is 16 times higher than d_{33} (5300 pC/N), which indicates a directly proportional dependence of the number of layers in the actuator structure (N) on its d_{33}^{*}. Therefore, for application of high-temperature materials with low d_{33} you need more layers. A similar dependence can be observed for MPA specimens of $Na_{0.5}Bi_{4.5}Ti_4O_{15}$ with a 150-layered structure and $t = 50$ µm, as shown in Fig. 2. The graph shows that the MPA working temperature is identical to the element without internal layers ($T_w = 500$°C) wherein the set of layers allows us to increase d_{33}^{*} of the actuator.

The $BiTiNbO_9$ MPA specimens were made by a similar technology and had the same structure with $Na_{0.5}Bi_{4.5}Ti_4O_{15}$ MPA. But the displacement values do not exceed 0.14 µm. This happened due to "negative" texturing of anisometric particles occurring during tape casting. This process and its influence on the parameters of piezoelectric ceramics are described elsewhere [17, 18].

Thus, we failed to increase d_{33}^{*} of the MPA relative to d_{33} of specimens without the multilayer structure. Moreover, the values of d_{33} measured in attestation specimens are higher than d_{33} of the material. This is due to its technology (uniaxial hot pressing) and the polarization vector which is perpendicular to the vector of pressure during sintering [18].

CONCLUSIONS

The results of this work are the development and verification of high-temperature piezoceramic materials with T_w = 330, 450, and 750°C, but with a rather low value of d_{33}. The developed materials are used to produce attestation specimens of multilayer piezoelectric elements.

Constructive ways are proposed and tested to increase its displacement. Based on the experiments and measurements, we can conclude that the tape-casting technology for the production of MPAs is the way to create actuators for linear piezo motors with the extremely high working temperature. However, for the application of textured ceramic ($BiTiNbO_9$), it is necessary to change the tape-casting technology or to search for other solutions to increase the piezoelectric charge coefficient.

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