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Research of Technology for Creating High-Temperature Textured Materials for Manufacturing Multilayer Piezo Transducer Elements

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Abstract—The most important stimulus for the study of piezoceramic materials is the increasing requirements for extending the operating temperature range, improving the measurement characteristics, and the stability to destabilizing factors of the devices created on their basis. However, along with a search for new promising materials and refinement of manufacturing technology to solve the above problems, the development of high-temperature textured materials for manufacturing multilayer piezoelectric transducer elements is becoming increasingly necessary. Research methods were chosen based on the possibility of obtaining the most complete information about the change in the structure and properties of the material after sintering and polarization of products. When carrying out research, X-ray structural, radiographic, metallographic, and electron microscopic analyses were used. The measurements of mechanical and electrical strength, fracture resistance, dielectric permittivity, piezoelectric, and segmented elastic characteristics of the products were carried out in the course of the work. The technology of multilayer piezo package production has been developed, the results of the technology of solid solution system piezoceramics production have been obtained, the structure, dielectric, and piezoelectric properties of ceramics in the temperature range 20–600°C have been studied. Experimental samples of multilayer piezoelements were made.

Keywords: piezosensitivity, piezoceramic element, piezoceramic elements, manufacturing technology, multilayer structure, piezoactuator, model, slip casting

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Piezoceramics are widely used in various fields of the national economy, as well as rocket and space and special technology [1–3]. Piezoceramic elements can be used in various acoustic devices, in sensors for measuring pressure, vibration, and acceleration, sensors for ultrasonic delay lines, in filter technology, ignition systems, gyroscopes, and piezoelectric transformers. They are used in telephones, microphones, sound pickups, ultrasonic devices designed to intensify technological processes, seismic receivers, medical diagnostic equipment, gyroscopes, and many other devices.

Piezoceramic elements in a multilayer structure are widely used to create sensitive elements of high-sensitivity sensors, variable-capacitance microcapacitors, microphase shifters, switches, piezoelectric actuators controlled by micromirrors for adaptive optics, and other micro- and nanoelectronic devices.

The production of multilayer piezoceramic elements consisting of alternating layers offers a number of advantages:

— Thin ceramic layers allow for large displacements at low excitation voltages (20–100 V) [4].

— High intensity of the electric field (up to 3000 V/mm) allows one to obtain a large amount of displacement per unit volume.

— Low power consumption.

— Reliable operation in harsh conditions thanks to the use of built-in electrodes.

The variety of applications of piezoceramics leads to a wide variety of requirements for its properties. For example: special piezoelectric sensors [5] require ceramics capable of operating in a wide temperature range; filter resonators require high stability of parameters in a wide temperature range and over a long period of time; hydroacoustic applications require piezoelectric ceramics capable of operating in strong electric fields and at high pressures; and hydroacoustics and seismic receivers require highly efficient piezoelectric ceramics (with large piezoelectric moduli values). The requirements for piezoceramics are constantly increasing. This makes it necessary to search for new piezoceramic materials and study their properties.

The following requirements are imposed on the piezoelectric materials sought in this work for their

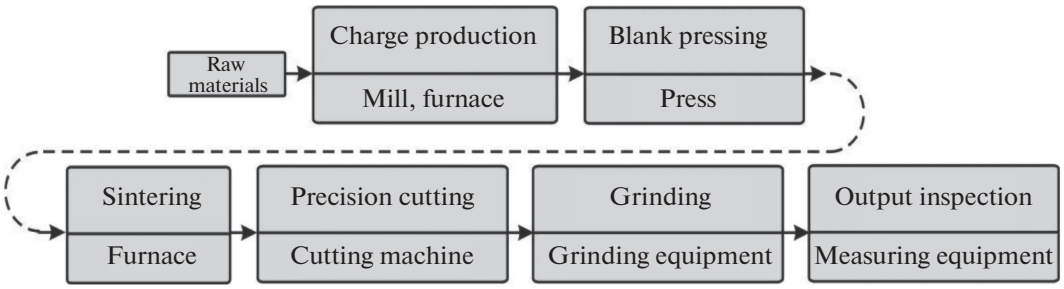

Fig. 1. Large-scale structural diagram of the technological process for the production of piezoceramic elements.

operation as a transducer in special piezoelectric sensors:

— Operability in the temperature range from –60 to +600°C.

— High sensitivity.

— Minimal change in sensitivity due to time, temperature, and pressure.

— Minimum temperature hysteresis of sensitivity.

— High strength of piezoceramics.

The creation of ferro-piezoelectric materials with optimal properties for various applications is an important task in materials science. The parameters of piezoelectric elements are largely determined by the composition of the piezoceramic material from which they are made.

To date, three main groups of piezoceramic materials have found practical application. These include barium titanate and its derivative materials based on lead titanate and niobate materials. These materials have been most thoroughly studied and it is for them that the characteristics that determine the possibility of using them as piezoelectric transducers are known in the literature. It is known that the use of barium titanate ceramics in piezoelectric sensors is limited to temperatures of about 70–80°C.

Introduction of additives Sa and Pb increases operating temperatures to 110–130°C, but reduces sensitivity by half. Introduction of cobalt into a solid solution of barium-calcium titanate $(BaCa)TiO_3$ increases the composition's resistance to exposure to strong electric fields and high mechanical stresses. Low upper operating temperature limits and low-temperature phase transitions limit the use of barium titanate-based ceramics over a wide temperature range.

In order to expand the range of operating temperatures, piezoelectric sensors with ceramics $(PbBa)Nb_2O_6$ were developed. These piezoelectric sensors operate on shear, their sensitivity is characterized by piezoelectric module d_{15}, with an upper limit of operating temperatures up to 200°C.

Solid solution-based piezoelectric ceramics $(PbBa)Nb_2O_6$, according to a number of indicators, is more effective than barium titanate systems, however, it is not yet possible to determine the conditions for obtaining stable compositions.

Currently, piezoelectric sensors are being evaluated using piezoceramic materials of the lead zirconate titanate (PTZ) system. The family of PZT have Curie temperatures of up to 350–400°C, operating temperatures of about 250°C, good piezoelectric sensitivity, but require careful research taking into account the requirements [6].

In recent years, new piezoceramic materials have been intensively developed. Compositions are now known that retain relatively good piezoelectric properties up to 400°C. These materials are based on lead titanate, lead metaniobate, and sodium and potassium metaniobates.

The following tasks were solved during the research:

— Search and research of new piezoceramic materials that operate in the operating temperature range from –60 to +600°C.

— Study of the possibility of increasing the temperature stability of piezoceramics.

— Search for ways to increase the piezosensitivity of piezoelectric materials.

— Development of theoretical foundations for the influence of structural defects on the stability of the operating parameters of piezoelectric materials.

— Obtaining and studying dielectric properties and stability of operating parameters when exposed to destabilizing factors, including exposure to elevated temperatures.

— Implementation of the developed technology for the production of high-temperature textured materials for piezoelectric elements in the manufacturing of piezoelectric drives based on piezoelectric plates obtained by cold semi-dry pressing for structural monitoring systems for the performance of special equipment. A comprehensive structural diagram of the technological process for the production of piezoceramic elements using the cold semi-dry pressing method is shown in Fig. 1.

In conducting the research, currently known ferroelectrics and solid solutions based on them, which are promising for producing piezoceramics, were considered. A review of the crystal chemical principles of searching for new compositions operating in the temperature range from –60 to +600°C was conducted, experimental data regarding the possibility of con-

Table 1. Technical characteristics of experimental samples of multilayer piezoelectric elements

No. s/n	Name of the characteristic	Value
1	Length a, mm	From 5 to 50
2	Width b, mm	From 5 to 50
3	Thickness H, mm	From 1 to 10
4	Layer thickness h, μm	From 30 to 50
5	Number of layers n, pcs.	Is determined by the thickness of one layer and the thickness of the piezoelectric element
6	Piezo sensitivity d_{33}, not less than, pKl/N	250
7	Curie temperature, °C, not less than	260
8	* Maximum voltage, V	200
9	Maximum deformation, %	0.1
10	** Electric capacitance, μF	At least 1
11	Maximum electric field, kV/mm	2

trolling the electrophysical properties of the material were analyzed, and the possibilities of increasing piezoelectric activity were analyzed.

The issues of piezoceramics production technology and the influence of individual technological factors on its electrophysical and mechanical properties are considered. Heat treatment and polarization modes were studied, and X-ray structural analysis was carried out.

Dependences were obtained showing the influence of impurity atoms on the stability of the piezoelectric properties of piezoceramics. An analysis of the main mechanisms associated with the diffusion of impurities to domain boundaries was carried out, the characteristic times of such processes were determined, and recommendations for improving the stability of the operating parameters of piezoelectric materials were proposed. The results of the development of the technology for producing piezoceramics of a solid solution system $(1 - x)PbTiO_3 + xBi(Zn_{0.5}Zr_{0.5})O_3$ have been obtained. The structure, dielectric, and piezoelectric properties of this ceramic were studied in the temperature range of 20–600°C, stability of piezoelectric properties with cyclic temperature changes from 20 to 600°C. Experimental samples of multilayer piezoelectric elements with technical characteristics given in Table 1 were manufactured.

The external appearance of one of the manufactured prototypes of a multilayer piezo actuator is shown in Fig. 2.

As a result of studying the issues of manufacturing piezoelectric packages, a technology for manufacturing multilayer piezoelectric packages with a linear

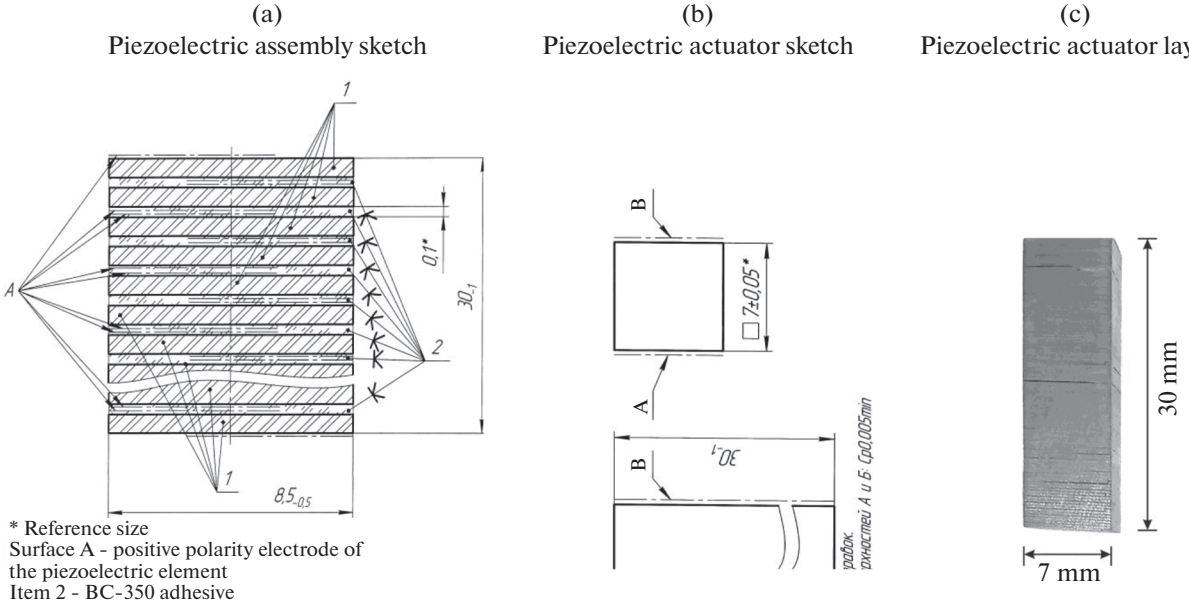

Fig. 2. External appearance of the multilayer piezo actuator model.

deformation of up to 15 μm with a piezoelectric package height of 30 mm and a control voltage of 200 V was developed and tested [7].

CONCLUSIONS

Further improvement of technical characteristics (increase in linear deformation at a given control voltage) is possible by developing the technology of connecting (gluing) piezoelectric elements in a piezoelectric package. In particular:

— When developing the possibility of manufacturing piezoceramic elements with a thickness of less than 100 microns.

— When choosing an adhesive with low viscosity, ensuring the minimum possible thickness of the adhesive layer.

To meet technical requirements, it is necessary to use the technology of manufacturing monolithic multilayer piezoelectric elements using slip casting technology.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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