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Piezoelectric Ceramics: Operation and properties

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INTRODUCTION

At any frequency range or power, the active element and the core of most ultrasonic transducers is a piezoelectric and can be classified into the following groups [1]:

- piezoelectric ceramics,
- quartz crystals,
- piezoelectric composites,
- water-soluble crystals,
- piezoelectric single crystals,
- piezoelectric semiconductors, and
- piezoelectric polymers;

All this makes the knowledge of the properties and the electro-mechanical behavior of these materials essential for any enterprise and professional who works with ultrasound. Of these groups, the piezo ceramics are the more flexible in format and properties, being largely used in the manufacture of power ultrasonic equipment, non-destructive testing devices and actuators. The piezoelectric materials are also used in impact detonators, sparks generators (magic clicks), nebulizers, actuators, positioners, transformers, and in many applications where the piezoelectric effect is useful.

The purpose of this application note is to provide an overview of the piezoelectric materials, in particular, of the piezoelectric ceramics, in order to facilitate to our customer's use of these materials with the understanding of its properties and characteristics.

HISTORY

The piezoelectric effect was discovered by the Curie brothers in 1880 and used in a practical application for the first time by Paul Langevin in the development of sonars during the First World War. Langevin used quartz crystal coupled to metallic masses (inventing the Langevin type transducer) for generating ultrasound in the range of a few dozen of kHz. After the First World War, due to the difficulty of excite quartz crystals transducers and their demand for high voltage generators, the development of synthetic piezoelectric materials began. These efforts led to the discovery and improvement, in the 40's and 50's, of the piezoelectric ceramics of Barium Titanate by the USSR and Japan, and the piezoelectric ceramics of Lead Zirconate Titanate (PZT's) by the U.S. [2, 3].

The development of piezoelectric ceramics was revolutionary. In addition to providing better properties than the crystals after being polarized, they also offered flexible geometries and dimensions because they were manufactured by the sintering of ceramics and shaping through pressing or extrusion. Currently, the PZT piezoelectric ceramics, in its many variations, are predominant in the ceramics market. Also, other materials can be found, for example, PT (PbTiO3) and PMN (Pb (Mg1/3Nb2/3) O3) used in devices that require very specific and special properties, such as high temperature transducers.

WHAT THEY ARE AND HOW THEY WORK

The piezoelectric ceramics are massive bodies similar to those used in electrical insulators, see Figure 1, they are composed of numerous microscopic ferroelectric crystals, being even named polycrystalline.

Figure 1 – Examples of piezoelectric ceramics. From left to right: disk for physiotherapy ultrasonic equipment, tube for sonar and ring for ultrasonic welding machines.

Particularly in the PZT type ceramics, these small crystals have a Perovskite type crystal structure, which presents tetragonal symmetry, rhombohedral or simple cubic, depending on the temperature at which the material is, see Fig 2. Falling below a certain critical temperature, known as the Curie temperature, the Perovskite structure has a tetragonal symmetry where the center of symmetry of the positive electrical charges does not coincide with the center of symmetry of the negative charges, resulting in an electric dipole, as illustrated in item 1 of the Figure 2.

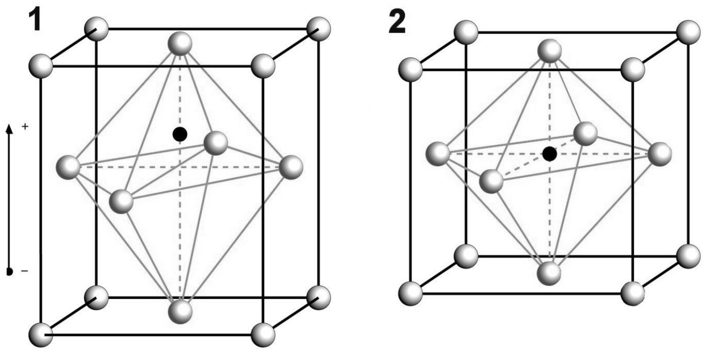

Figure 2 - Perovskite structure of the PZT type piezoelectric ceramics: 1) Below the Curie temperature. 2) Above the Curie temperature.

The existence of the dipole causes the deformation of the crystalline structure in the presence of an electric field and generates an electric displacement when subjected to a mechanical deformation, which characterizes the direct and inverse piezoelectric effect, respectively. The mechanical deformation or the variation of the electrical dipole of the crystalline structure of ceramics does not necessarily imply macroscopic effects, as the dipoles are arranged in domains, which in turn are randomly distributed in the polycrystalline material. For macroscopic behavior to occur, a preferred orientation of these domains known as polarization is required. Even this polarization fades with time and usage, disabling the material for transforming electrical energy into mechanical energy [4, 5].

In cleaning and welding ultrasonic systems, for example, the converse piezoelectric effect is explored by applying an alternating electric field in an appropriately polarized piezoelectric ceramic, transduction occurs from a considerable amount of the electrical energy in mechanical energy, by means of the deformation of the ceramic and the consequent generation of ultrasound, see the example of the inverse piezoelectric effect in Figure 3.

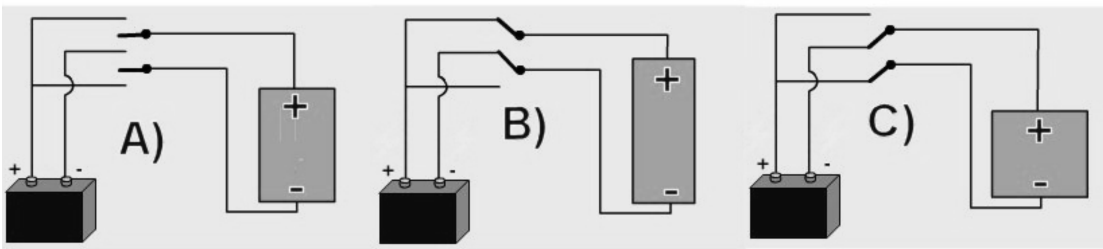

Figure 3 - Inverse piezoelectric effect in a piezoelectric ceramic rod polarized on the length: An electric field applied in accordance with the field used in the polarization causes it to stretch, and a field with reversed polarity, to contract.

MAIN CONSTANTS

In ordinary solids, the electric displacement can be considered an exclusive function of the electric field vector (E) and of the dielectric constant (ε)), and the mechanical deformation (S), a unique function of strain (T) and elastic constants (s) as shown by the following equations in matrix notation:

$$\begin{aligned} D_m &= \varepsilon_{mk}^{S} E_k \\ S_i &= s_{ij}{}^{E} T_j \end{aligned} \quad (1).$$

The coupling of the mechanical and electric variables takes place in the piezoelectric material: At the same time that the deformation depends on the mechanical stresses, it also depends on the electric field, and at the same time that the electric shift depends on the field, it also depends on the mechanical deformation. We can better visualize this coupling in the following equation (also written in matrix notation [6]):

$$D_m = e_{mi} S_i + \varepsilon_{mk}^{S} E_k$$
$$S_i = s_{ij}{}^{E} T_j + d_{mi} E_m \qquad (2).$$

There exists a set of coefficients (e and d) which are used to characterize the piezoelectric materials, particularly in cases of recurrent interest, the piezoelectric ceramics. Using these coefficients and constants, we can get an idea of the piezoelectric performance and we can choose the most appropriate material for each application [7].

Coupling coefficients, k

Coupling coefficients can be defined and calculated in several ways, the coupling coefficients k can be interpreted as the efficiency of the material in absorbing the electrical energy supplied by the excitation source.

Piezoelectric constant, *d*

The piezoelectric constants, d, establish a proportionality between the charge generation and the applied mechanical stress (direct piezoelectric effect), and between the deformation and the applied electric field (inverse piezoelectric effect). In Equations 3a and 3b, we have a differential definition of d for fixed temperature and electric field values. We can compare the piezoelectric character of different materials through d constants, which are particularly relevant in the design of actuators and positioners.

$$d_{nij}{}^{\theta} = \left[\frac{\partial D_n}{\partial T_{ij}}\right]_{E,\theta} \text{ (C/N)} \qquad \text{(3-A)},$$

$$d_{nij}{}^{\theta} = \left[\frac{\partial S_{ij}}{\partial E_n}\right]_{T,\theta} \text{ (m/V)(3-B).}$$

Dielectric constants, *K*

The dielectric constants establish proportionality between the electric displacement and the applied electric field. In equation 4, we have the differential definition of the dielectric permittivity ε at constant temperature and electric field values, being $K=\varepsilon/\varepsilon_0$.

$$\varepsilon_{nm}{}^{T,\theta} = \left[\frac{\partial D_n}{\partial E_m}\right]_{T,\theta} \text{ (C}^2\text{/Nm}^2\text{)} \qquad (4).$$

The dielectric constants are important because they determine the capacitance of the piezoelectric ceramic, which in turn is the determining factor of the design and calculation of impedance matching circuits.

Piezoelectric constant, *g*

Defined as the ratio between the constants *d* and *ε*, correlating the voltage response of the material to an applied mechanical stress (has dimension of Vm/N), and is particularly relevant in the design of sensors.

Elastic constants, *s*

The elastic constants, ***s***, establish a proportionality between the deformation and the applied voltage. They are the "spring constants" of the material. From the elastic constants, defined in differential form as shown in equation 5, we can calculate the velocity of propagation of acoustic waves on the piezoelectric material in any direction and polarity, and estimate dimensional changes due to static pressures.

$$s_{ijkl}{}^{E,\theta} = \left[\frac{\partial S_{ij}}{\partial T_{kl}}\right]_{E\theta} \qquad (5).$$

Frequency constants, *N*

In geometries where we have an uncoupled vibration mode, the frequency constant is defined as the product of the resonance frequency by the dimension in question, and this may be a length, diameter or thickness. From the constant frequency we can estimate the resonant frequency for the same geometry with different dimensions.

The frequency constants are very useful in the design of ultrasonic transducers to estimate the operation frequency. We can also estimate the speed of sound propagation through the material with those constants, doubling them.

Mechanical quality factor Q_m and Dielectric dissipation factor tanδ

The mechanical quality factor and the dielectric dissipation factor are some of the most important in defining the potential dynamic applications of the material. Those factors determine the energy losses of the transduction process, from them you can know if, for example, the material in question is suitable for power applications, such as ultrasonic cleaning systems.

Curie temperature

Curie temperature is the critical temperature where the crystalline structure of the material undergoes the phase transition from tetragonal symmetry to cubic. A polycrystalline ceramic which is subjected to temperatures above or equal to the Curie temperature, when cooled recovers its piezoelectric microscopic characteristics, but not the macroscopic ones by the losing the preferred orientation of the domains due to the polarization process, this allows the practical use of the material as electro-mechanical transducer.

Dynamic transition limit

This is the maximum traction to which the material can be subjected dynamically without breakage. This limit must be taken into consideration especially in the design of power transducers, where the piezoelectric ceramics are subjected to high electric fields which promote both the contraction (compression) and expansion (traction) of the material.

Aging rate

This is the rate at which the piezoelectric properties of the material change with time as the orientation of the domains of the dipoles, carried out by the polarization process, fades.

COMERCIAL MATERIALS AND APPLICATIONS

The main commercial piezoelectric materials and their properties are listed in Table 1 (Shown on the next page).

The PZT-4 is commonly used in ultrasonic cleaning systems and in physiotherapy, the PZT-8 in ultrasonic welding systems, the PZT-5A in sensors and transducers for nondestructive testing, the PZT-5H and 5J in spark generators by impact (detonators and magic clicks) and positioners respectively.

Table I – Main commercial piezoelectric materials and their constant.

Material	**PZT-4**	**PZT-8**	**PZT-5A**	**PZT-5J**	**PZT-5H**
k_p	0,60	0,50	0,61	0,60	0,63
k_{33}	0.68	0,63	0,70	0,71	0,73
d_{33} (10^{-12} C/N)	300	215	400	460	550
d_{31} (10^{-12} C/N)	-11.5	- 9.5	- 170	- 210	- 265
g_{33} (x10^{-3} Vm/N)	26	25	25	22	19
g_{31} (x10^{-3} Vm/N)	- 11	- 11	- 11	- 9	- 9
K^T_3 (low signal) C. dielectric	1250	1000	1750	2450	3100
Dissipation factor tan δ (low field)	0,004	0,004	0,020	0,020	0,020
Density (kg/m^3)	7600	7600	7650	7500	7500
Curie Temp. (^{o}C)	325	330	360	260	190
Quality factor Q_m	500	1000	75	70	65
s^E11 (x10^{-12} m^2/N)	12	11	19	23	21
s^E33 (x10^{-12} m^2/N)	16	14	16	16	15
N_p (Hz-m) (planar mode)	2200	2270	1950	2000	1950
N_t (Hz-m) (Thickness mode)	1905	2032	1800	1950	2000

REFERENCES

[1] GALLEGO, J.; Piezoelectric ceramics and ultrasonic transducers, J. Phys. E: Sci. Instrum., 22 804-816 1989
[2] SUSLICK, K.S.; The Chemical Effects of Ultrasound, Scientific American February 1989.
[3] CADY, W. G.; Piezoelectricity: An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals, Dover Press, 1964.
[4] JAFFE, B.; Piezoelectric Ceramics, Academic Press, 1971.
[5] Piezoelectric ceramics: Properties and Applications, Morgan Electro Ceramics Inc. technical publication.
[6] NYE, J.F.; Physical Properties of Crystals, Clarendon Press, 1985.
[7] IKEDA, T.; Fundamental of Piezoelectricity, Oxford University Press, 1990.

Note: i) The contents of this application note were adapted from the dissertation "DEVELOPMENT AND CHARACTERIZATION OF BI-FREQUENTIAL POWER ULTRASONIC TRANSDUCERS FOR ULTRASONIC CLEANING SYSTEMS", by the same author presented in 2005 by UFSCar PPGCEM and web sites relevant to the subject in question. ii) The ATCP Physical Engineering is not responsible for use of the information contained herein and any associated damages.

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