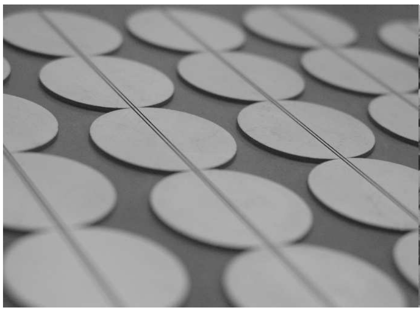
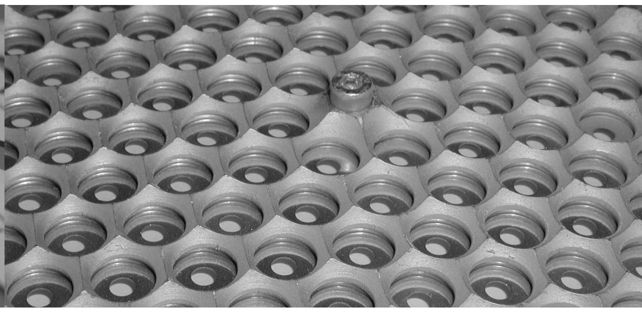
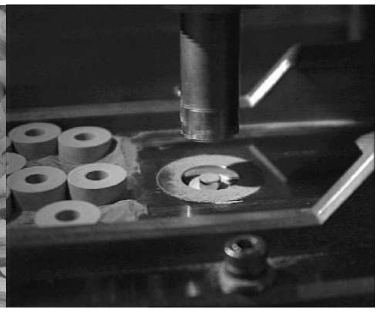

FERROPERM
PIEZOCERAMICS

HIGH QUALITY COMPONENTS AND MATERIALS FOR THE ELECTRONIC INDUSTRY

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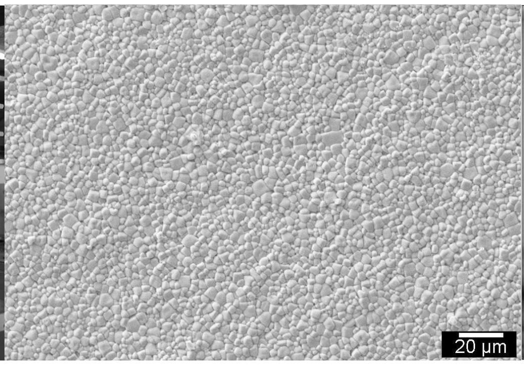


The Company

FERROPERM was registered in Denmark in May 1952 as a personal business to produce iron dust cores, ferrites and ceramic capacitors. In 1955, piezoelectric ceramics based on barium titanate were added to the product range.

The business was transferred to a limited company, ”Industriselskabet Ferroperm A/S” in 1957. This company steadily expanded its activities, and at a time also comprised production of capacitors and optical interference filters.

Since the formation of Ferroperm's Piezoelectric Division in 1958, its turnover has increased by approximately 15 % per year. In 1989 the Piezoelectric Division moved to modern premises to accommodate further expansion, and was turned into a separate limited company in 1998.

After a short period under American ownership in the year 2001, Ferroperm Piezoceramics A/S is now owned by a group of the senior managers in the company in partnership with a strong Danish investment group.

New products have been continuously developed and the Ferroperm product range today includes 6 types of lead zirconate-titanate, PZT, suitable for a variety of applications, a relaxor-based solid solution optimized for medical imaging, bismuth titanate, for use at elevated temperatures, modified lead titanate and lead metaniobate, with high anisotropy, and an electrostrictive material, lead magnesium niobate, PMN.

Finally, for special applications, "HIP Quality" very low porosity ceramics can be obtained in some of the above materials.

Research and Development

Ferroperm has a long standing commitment to R&D and currently spends approximately 20 % of its turnover on R&D projects. There is a close collaboration with leading universities throughout Europe. Ferroperm has continuously been involved in large European projects under Brite/Euram, Eureka, Cost, Esprit, FP5 etc.
Research topics include high-temperature piezo-electric ceramics, high sensitivity materials, lead-free materials, and thick-film technology.

Policy

More than 95 % of the products in Ferroperm Piezoceramics A/S are custom made to meet individual requirements of customers.

Our main focus throughout the entire production process is to provide materials and components with the highest possible reproducibility of properties and parameters, and to obtain the lowest ageing rates in the industry. This enables customers to optimize design and improve performance and production flow, thereby contributing to improved competitiveness on their markets.

May 2003

Table of Contents

Piezoelectric Materials

By definition, a piezoelectric material generates a charge when put under pressure, and will show a change in volume when an electrical field is applied. It can be used as a transducer material for transforming electrical energy into mechanical energy and vice versa. Furthermore, applying an A.C. voltage to the material will cause it to vibrate, and thus generate mechanical waves with the same frequency as the electrical voltage. Similarly, if a mechanical vibration is applied, then a charge of proportional size and same frequency will be generated.

History

Piezoelectric activity was first discovered in single crystals by J. and P. Curie in 1880. However, it was not until 1946 that scientists discovered that $BaTiO_3$ ceramics could be made piezoelectric by application of an electric field. This lead to the discovery of a number of piezoceramics and to the Lead Zirconate Titanate (PZT) family, in 1956. With its increased sensitivity and higher operating temperature, PZT soon replaced $BaTiO_3$ in many existing devices and are still the most widely used piezoceramics today.

The ceramic materials have several advantages over single crystals, including; higher sensitivity (up to several hundred times higher) and ease of fabrication into a variety of shapes and sizes. In contrast, single crystals must be cut along certain crystallographic directions, limiting the possible geometrical shapes.

Applications

Piezoelectric ceramics are used in a broad range of applications due to their excellent properties, such as high sensitivity, ease of manufacture and the possibility of poling the ceramic in any direction. A few applications are listed below:

- Accelerometers.
- Flow meters: Blood, industrial processes, waste water.
- Medical: Imaging, HIFU, IVUS, surgical knives, and cleaning of blood veins.
- Underwater acoustics: echosounders, sonar systems, fish-finders, seabed mapping.
- Industrial sensors based on ultrasound: Level control, detection, and identification.
- Hydrophones: Seismic, biologic, military, underwater communication.
- Inkjet printheads.
- Dental work: Removal of plaque.
- Alarm systems: Movement detectors, broken window sensors.
- NDT: Transducers for Non Destructive Testing.
- Musical instrument pickups.
- Acoustic emission transducers.
- Actuators.
- Micro positioning devices: Optics, scanning tunneling microscopes.
- Surface Acoustic Waves: Personal Computer touch screens, filters.
- Welding and drilling of metals and plastics.

Piezoceramics

Piezoelectric ceramics are, after firing, composed of small grains (crystallites), each containing domains in which the electric dipoles are aligned. These grains and domains are randomly oriented, so the net electric dipole is zero, i.e. the ceramics do not exhibit piezoelectric properties.

The application of a sufficiently strong DC. field will orient the domains in the field direction, as nearly as the orientation of the crystal axes allows. This ability to change the orientation of the domains and achieve a net polarization is called ferroelectricity.

A remanent polarization can be created in ferroelectric ceramics by polarization. After the poling process is complete, a voltage with the same polarity as the poling voltage causes expansion along the poling axis and contraction perpendicular to the poling axis. Compressive or tensile forces applied to the ceramic element will generate a voltage.

Definitions and Terminology

In piezoelectric ceramics, material characteristics depend on the direction of the applied field, displacement, stress and strain. Hence superscripts and subscripts indicating the direction are added to the symbols.

The direction of polarization is generally designated as the z-axis of an orthogonal crystallographic system. The axes x, y and z are respectively represented as 1, 2 and 3 directions and the shear about these axes are represented as 4, 5 and 6. This is shown schematically on page 4. The various piezoelectric material constants are generally expressed with subscripts using this notation. Some examples are shown in the table on next page. In addition to the above, planar modes are sometimes expressed with a subscript ´p´.

The first subscript gives the direction of the electrical field associated with the voltage applied or the charge produced. The second subscript gives the direction of mechanical stress or strain.

Superscripts indicate a constant mechanical or electrical boundary condition. The table below gives a general description of the superscripts.

Parameter	Symbol	Condition
Stress	*T*	Mechanically free
Field	*E*	Electrical short circuit
Diel. displacement	*D*	Electrical open circuit
Strain	*S*	Mechanically clamped

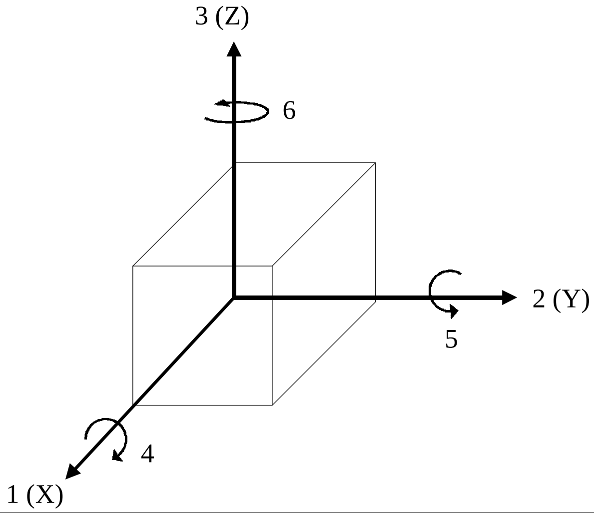
Curie Temperature

The crystal structure of a material changes at the Curie temperature, T_c, from piezoelectric (non-symmetrical) to a non-piezoelectric (symmetrical) form. This phase change is accompanied by a peak in the dielectric constant and a complete loss of all piezoelectric properties.

Table of Symbols

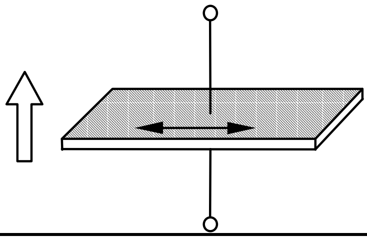
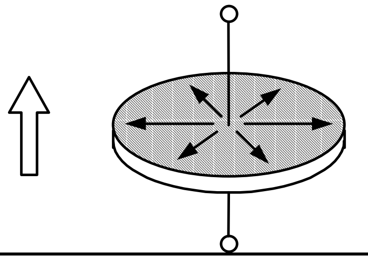
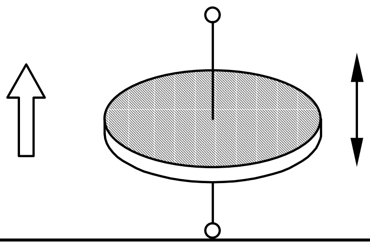
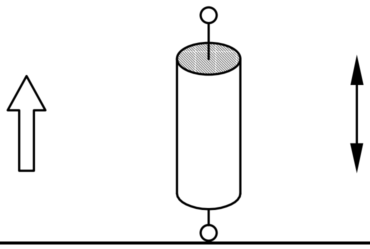
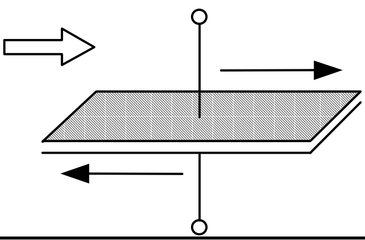
A	surface area (m^2)
c	stiffness coefficient (N/m^2)
C	capacitance (F)
d	piezoelectric charge coefficient (C/N)
D	diameter (m)
f_1, f_2	-3dB points from the resonance frequency f_r
f_a	anti-resonance frequency (Hz)
f_r	resonance frequency (Hz)
g	piezoelectric voltage coefficient (Vm/N)
k	coupling factor
K	relative dielectric constant
L	length (m)
N	frequency constant (Hz·m)
Q_m	mechanical quality factor
s	elastic compliance (m^2/N)
Th	thickness (m)
T_C	Curie temperature (°C)
W	width (m)
Y	Young's modulus (N/m^2)
Z_m	minimum impedance at f_r (ohm)
$\tan\delta$	dielectric dissipation factor
ε_0	permittivity of free space (8.854x10^{-12} F/m)
ε^T	Permittivity at constant stress (F/m)
v	sonic velocity (m/s)
ρ	density (kg/m^3)
σ^E	Poisson's ratio

Symbols And Terminology



K_3^S	All strains in the material are constant or mechanical deformation is blocked in any direction. Electrodes are perpendicular to 3 axis. Relative dielectric constant ($\varepsilon_3^S/\varepsilon_0$).	K_1^T	All stresses on material are constant or no external forces. Electrodes are perpendicular to 1 axis. Relative dielectric constant ($\varepsilon_1^T/\varepsilon_0$).
k_p	Stress or strain is equal in all directions perpendicular to 3 axis. Used only for ceramics. Electrodes are perpendicular to 3 axis. Electromechanical coupling factor.	k_{15}	Stress or strain is in shear form around 2 axis. Electrodes are perpendicular to 1 axis. Electromechanical coupling factor.
d_h	Hydrostatic stress or stress is applied equally in all directions. Electrodes are perpendicular to 3 axis (Ceramics). Piezoelectric charge coefficient.	d_{33}	Applied stress, or piezoelectrically induced strain is in 3 direction. Electrodes are perpendicular to 3 axis. Piezoelectric charge coefficient.
g_{15}	Applied stress, or the piezoelectrically induced strain is in shear form around 2 axis. Electrodes are perpendicular to 1 axis. Piezoelectric voltage coefficient.	g_{31}	Applied stress, or the piezoelectrically induced strain is in 1 direction. Electrodes are perpendicular to 3 axis. Piezoelectric voltage coefficient.
s_{36}^E	Compliance is measured with closed circuit. Stress or strain is shear around 3 direction. Strain or stress is in 3 direction. Elastic compliance.	s_{11}^D	Compliance is measured with open circuit. Stress or strain is in 1 direction. Strain or stress is in 1 direction. Elastic compliance.

Note: All stresses, other than the stress involved in second subscript, are constant except in the case of s where all stresses other than the stress involved in one subscript are constant.

Piezoelectric Modes Of Vibration				
Vibration Mode	Dimensions L - Length W - Width T - Thickness D - Diameter		Constants To Be Calculated Piezoelectric	Mechanical
Transverse Length Mode		$Th, W < L/5$	$k_{31}, d_{31}, g_{31}, \varepsilon_{33}^{T}$	$s_{11}^{D}, s_{11}^{E}, Q_{31}$
Radial Mode		$D > 10Th$	$k_{p}, \varepsilon_{33}^{S}, \varepsilon_{33}^{T}$	$\sigma^{E}, s_{12}^{E}, Q_{p}$
Thickness Extension Mode		$D > 10Th$	$k_{t}, \varepsilon_{33}^{S}$	$c_{33}^{D}, c_{33}^{E}, s_{13}^{E}, Q_{t}$
Longitudinal Length Mode		$D < L/2.5$	$k_{33}, d_{33}, g_{33}, \varepsilon_{33}^{T}$	$s_{33}^{D}, s_{33}^{E}, Q_{33}$
Thickness Shear Mode		$L > 3.5(Th,W)$	$k_{15}, d_{15}, g_{15}, \varepsilon_{11}^{T}, \varepsilon_{11}^{S}$	$c_{55}^{D}, s_{55}^{D}, s_{55}^{E}, Q_{15}$

Polarisation direction ⇧ Direction of displacement, ⟶

Dielectric Constant

The relative dielectric constant is defined as the ratio of the permittivity of the material to the permittivity of free space. This is generally measured well below the mechanical resonance. The dielectric constant is derived from the static capacitance measurements at 1 kHz using a standard impedance bridge.

$$K^T = \frac{\varepsilon^T}{\varepsilon_0} = \frac{C^T T}{\varepsilon_0 A}$$

Dielectric Loss Factor

The dielectric loss factor is defined as the tangent of the loss angle (tan δ). The loss factor represents the ratio of conductance to susceptance of a parallel equivalent circuit of the ceramic element. The loss factor can be measured directly using an impedance bridge.

Mechanical Quality Factor

The mechanical quality factor is the ratio of the reactance to the resistance in the series equivalent circuit representing the piezoelectric resonator. The Q_m factor is also related to the sharpness of the resonance frequency.

$$Q_m = \frac{f_a^{\,2}}{2\pi f_r Z_m C^T (f_a^{\,2} - f_r^{\,2})}$$

Alternatively the Q_m factor can also be determined using the equation:

$$Q_m = \frac{f_r}{f_1 - f_2}$$

Frequency Constants

The frequency constant, N, is the product of the resonance frequency and the linear dimension governing the resonance. N is also equal to half the sound velocity in the same direction. The various modes of resonance are shown schematically on page 5.

N_{31}	=	$f_r \cdot L$	Transverse mode, thin bar
N_p	=	$f_r \cdot D$	Radial mode, disc
N_t	=	$f_r \cdot T$	Thickness mode, disc
N_{33}	=	$f_r \cdot L$	Length mode, cylinder
N_{15}	=	$f_r \cdot T$	Shear mode, plate

Piezoelectric Coupling Coefficient

The coupling coefficient (electromechanical coupling coefficient) is defined as the ratio of the mechanical energy accumulated in response to an electrical input or vice versa.

$$k = \sqrt{\frac{\text{Mechanical energy stored}}{\text{Electrical energy applied}}}$$

$$k = \sqrt{\frac{\text{Electrical energy stored}}{\text{Mechanical energy applied}}}$$

The coupling coefficients can be calculated for the various modes of vibration:

$$k_{31} = \sqrt{\frac{\pi}{2}\frac{f_a}{f_r}\frac{1}{\frac{\pi}{2}\frac{f_a}{f_r} - \tan\left(\frac{\pi}{2}\frac{f_a}{f_r}\right)}}$$

$$k_p \cong \sqrt{2.51\frac{f_a - f_r}{f_a} - \left(\frac{f_a - f_r}{f_a}\right)^2}$$

$$k_t = \sqrt{\frac{\pi}{2}\frac{f_r}{f_a}\cot\left(\frac{\pi}{2}\frac{f_r}{f_a}\right)}$$

k_{33} and k_{15} can be calculated similar to k_t by using the appropriate resonance frequencies.

Another parameter, k_{eff}, is frequently used to express the effective coupling coefficient of an arbitrary resonator, either at fundamental resonance or at any overtone and is expressed as follows:

$$k_{eff} = \sqrt{\frac{f_a^{\,2} - f_r^{\,2}}{f_r^{\,2}}}$$

Piezoelectric Charge Coefficients

The piezoelectric charge coefficient is the ratio of electric charge generated per unit area to an applied force (C/N or m/V).

$$d = \frac{\text{Strain developed}}{\text{Applied field}} = \frac{\text{Charge density}}{\text{Applied stress}}$$

The d constants are calculated from the equation:

$$d = k\sqrt{\varepsilon^T s^E}\ \text{(C/N)}$$

$$d_{31} = k_{31}\sqrt{\varepsilon_{33}{}^T s_{11}{}^E}$$

$$d_{33} = k_{33}\sqrt{\varepsilon_{33}{}^T s_{33}{}^E}$$

$$d_{15} = k_{15}\sqrt{\varepsilon_{11}{}^T s_{55}{}^E}$$

Piezoelectric Voltage Coefficient

The piezoelectric voltage coefficient is the ratio of the electric field produced to the mechanical stress applied (V m/N).

$$g = \frac{\text{Strain developed}}{\text{Applied charge density}}$$

$$= \frac{\text{Field developed}}{\text{Applied mechanical stress}}$$

The g constants are calculated from the equation:

$$g = \frac{d}{\varepsilon^T}\ \text{(V m/N)}$$

$$g_{31} = \frac{d_{31}}{\varepsilon_{33}{}^T}$$

$$g_{33} = \frac{d_{33}}{\varepsilon_{33}{}^T}$$

$$g_{15} = \frac{d_{15}}{\varepsilon_{11}{}^T}$$

Elastic Compliances

Young's modulus describes the mechanical stiffness properties and is expressed as the ratio of stress to strain. In a piezoelectric material, mechanical stress produces an electrical response, which opposes the resultant strain. The value of the Young's modulus depends on the direction of stress and strain and the electrical conditions. The inverse of Young's modulus, Y, is the elastic compliance, s, which can be calculates as follows (see relevant geometries on page 5):

$$s = \frac{1}{Y} = \frac{\text{Strain}}{\text{Stress}} = \frac{1}{\rho v^2}\left(\frac{\text{m}^2}{\text{N}}\right)$$

$$s_{33}{}^D = \frac{1}{4\rho f_a{}^2 L^2}$$

$$s_{33}{}^E = \frac{s_{33}{}^D}{1 - k_{33}{}^2}$$

$$s_{11}{}^E = \frac{1}{4\rho f_r{}^2 L^2}$$

$$s_{11}{}^D = s_{11}{}^E\left(1 - k_{31}{}^2\right)$$

$$s_{55}{}^D = \frac{1}{4\rho f_a{}^2 Th^2}$$

$$s_{55}{}^E = \frac{s_{55}{}^D}{1 - k_{15}{}^2}$$

Ageing Rate

The ageing rate of a piezoelectric ceramic is an index of the change of certain material parameters with time:

$$\text{Ageing Rate} = \frac{1}{(\log t_2 - \log t_1)}\left(\frac{P_2 - P_1}{P_1}\right)$$

Where
t_1, t_2 are number of days after polarization
P_1, P_2 are measured corresponding values

Standards

- American National Standard on Piezoelectricity. ANSI/IEEE Std. 176, 1987.
- Military Standard. DOD-STD-1376A(SH), 1984. Piezoelectric Ceramic for Sonar Transducers. (Hydrophones and Projectors).
- CENELEC, EN 50324-1, Piezoelectric properties of ceramic materials and components, Part 1: Terms and definitions.
- CENELEC, EN 50324-2, Piezoelectric properties of ceramic materials and components, Part 2: Methods of measurement - Low power.
- CENELEC, EN 50324-3, Piezoelectric properties of ceramic materials and components, Part 3: Methods of measurement - High power.
- International Electrotechnical Commission. IEC Standard 483, 1976. Guide to Dynamic Measurements of Piezoelectric Ceramics With High Electromechanical Coupling.

Recommended literature

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- Moulson, A.J., Herbert, J.M. ***Electroceramics.*** Chapman and Hall, 1990. ISBN: 0412294907.
- Setter, N (Ed). ***Piezoelectric Materials in Devices.*** EPFL-LC, 2002. ISBN: 2-9700346-0-3.
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- Levassort, F., Tran-Huu-Hue, L.P., Lethiecq, M., Bove, T. & Wolny,W.W. ***New Piezoceramic Films for High-Resolution Medical Imaging Applications.*** Proceedings Of IEEE UFFC, October 2000.
- Bove, T., Wolny, W.W., Ringgaard, E., Pedersen, A. ***New Piezoceramic PZT-PNN Material for Medical Diagnostic Applications.*** Proceedings of Electroceramics 2000.

- Damjanovic, D., Wolny, W.W., Engan, H., Lethiecq, M. & Pardo, L. ***Properties and Applications of Modified Lead Titanate Ceramics.*** Proc. of the 1998 IEEE International Frequency Control Symposium. (IEEE 98CH36165) 770-778.

- Gómez, T.E., Montero de Espinosa, F., Levassort, F., Lethiecq, M., James, A., Ringgaard, E., Millar, C.E. & Hawkins, P. ***Ceramic Powder--Polymer Piezocomposites for Electroacoustic Transduction: Modeling and Design.*** Ultrasonics, 36 907-923.

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- Pardo, L., Durán-Martín, P., Mercurio, J.P., Nibou, L. & Jiménez, B. ***Temperature Behaviour of Structural, Dielectric and Piezoelectric Properties of Sol-Gel Processed Ceramics of the System*** $LiNbO_3$***-***$NaNbO_3$***.*** J.Phys.Chem. Solids, 58 [9] 1335-1339.

- González, A.M. & Alemany, C. ***Determination of the Frequency Dependence of Characteristic Constants in Lossy Piezoelectric Materials.*** J.Phys.D: Appl.Phys., 29, 2476-2482.

- Lethiecq, M., Levassort, F., James, A.S., Wolny, W.W. & Mercurio, J.P. ***High Permittivity Ceramics for Medical Ultrasonic Transducers: a Study on the Optimisation of Processing Parameters.*** Kulwicki, B.M., Amin, A. & Safari, A. (eds.): Proc. 10th IEEE International Symp. on Applications of Ferroelectrics (ISAF '96) . (IEEE 96CH35948) 287-290.

- Levassort, F., Lethiecq, M., Gomez, T., Montero de Espinosa, F., James, A.S., Ringgaard, E., Hawkins, P., Millar, C.E. ***Modeling the Effective Properties of Highly Loaded 0-3 Piezocomposites.*** Levy, M., Schneider, S.C. & McAvoy, B.R (eds.): 1996 IEEE Ultrasonics Symposium Proc. (IEEE) 463-466.

- Pardo, L., Durán-Martín, P., Millar, C.E., Wolny, W.W. & Jiménez, B. ***High Temperature Electromechanical Behaviour of Sodium Substituted Lithium Niobate Ceramics.*** Ferroelectrics, 186 281-285

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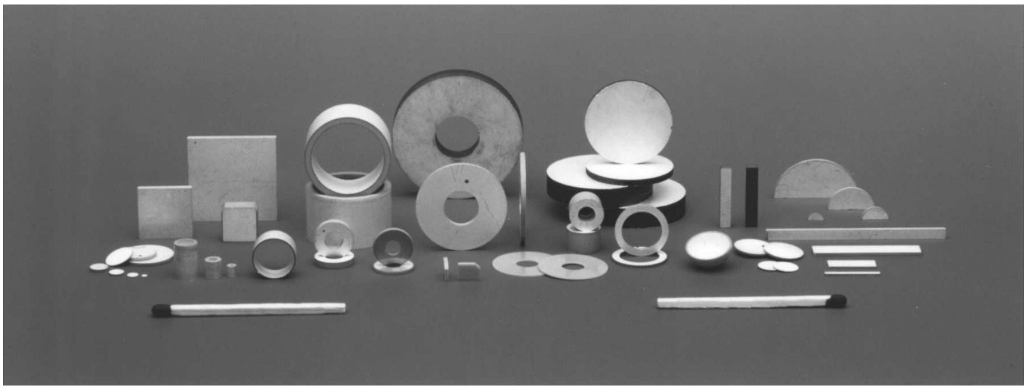
- C. E. Millar, B. Andersen, E. Ringgaard, W.W. Wolny, J. Ricote, L. Pardo. ***Fabrication of High Density, Fine-Grained PZT Ceramics Using a Post Sinter HIP Treatment.*** ISAF ´ 94, Aug. 7-10, 1994, Pennsylvania, USA.

Ferroperm manufactures piezoelectric ceramics in 5 material groups, traditional lead zirconate titanate (hard and soft PZT), relaxor-based solid solutions, modified lead titanate, lead metaniobate and bismuth titanate. A brief description of the materials is given below and material data can be found on pages 12 to 16.



Lead zirconate titanate (Soft).
Type Pz23 and **Pz27**. These materials are characterized by relatively high Curie temperatures (> 350°C), low mechanical Q_M factor and high electrical resistivity at elevated temperatures. **Pz27** has a high dielectric constant, high charge coefficients and high electromechanical coupling coefficients.
Type Pz29 has a lower Curie temperatures, but high dielectric constants, and high coupling coefficients.

Ceramics from these compositions are particularly useful in for a wide spectrum of applications ranging from combined resonant transducers for medical and flow measurements to accelerometers, pressure sensors, and NDT.

Lead zirconate titanate (Hard).
Type Pz24, **Pz26** and **Pz28**. These materials are characterized by high coercive field, high mechanical Q_M factor and low dielectric loss. **Pz24** has a very low dielectric constant. **Pz26** and **Pz28** are both high power and low loss materials.

Typical applications include underwater applications, high voltage generators, high power ultrasonics, e.g. cleaning, welding and drilling devices.

Relaxor-based solid solution
Type Pz21. This material is characterized by a very high dielectric constant, high charge coefficient and high electromechanical coupling coefficients.

Used primarily for medical imaging systems, i.e. phased arrays and composites.

Modified lead titanate. **Type Pz34** has large electromechanical anisotropy, low dielectric constant and properties and have extremely low grain size. It is very stable over time, temperature and frequency.

Recommended for single element high frequency medical transducers and applications where interference from radial modes is a significant problem.

Lead metaniobate. **Type Pz35** is anisotropic, has a low Q_M factor, low acoustic impedance, and low dielectric constant.

Primarily used in NDT systems where low Q_M factor and clean impulse response are required.

Bismuth titanate. **Type Pz46** has a very high Curie temperature (> 600°C) and working temperatures of up to 550°C.

Used in high temperature applications, i.e. accelerometers, flow-meters and pressure sensors.

Material Applications

Application	Material Suggestion									
	Pz21	Pz23	Pz24	Pz26	Pz27	Pz28	Pz29	Pz34	Pz35	Pz46
Underwater										
• Transmitters				●		●				
• Receivers	●			●	●	●	●			
• Hydrophones	●			●	●	●	●			
Transducers/Sensors										
• Level			●	●	●	●	●	●	●	
• Flow			●	●	●	●	●	●	●	
• NDT	●	●	●	●	●	●		●	●	
• Accelerometers	●	●	●	●	●					
• Pressure	●	●			●		●			
• Acoustic Emission	●	●			●		●			
• High Temperature										●
• Shock		●			●					●
Medical										
• Diagnostic	●		●	●	●		●	●		
• Therapeutic			●	●		●				
• Combined / Doppler	●			●	●		●			
Industrial										
• High Voltage				●		●				
• High Power				●		●				
• Automation	●				●		●			
• Actuators	●			●	●		●			
• Motors				●						

Material Data For Standard Test Specimens

Data are measured at 25°C and 24 hours after poling.

	Symbol	Dimension	Pz21	Pz23	Pz24	Pz26	Pz27
Electrical Properties							
Relative dielectric const. at 1 kHz	K_{33}^{T}	1	3800	1500	400	1300	1800
Diel. dissipation factor at 1 kHz	tan δ	10^{-3}	18	13	2	3	17
Curie temperature	T_c >	°C	205	350	330	330	350
Recommended working range	<	°C	130	250	230	230	250
Electromechanical Properties							
Coupling factors	k_p	1	0.60	0.52	0.50	0.57	0.59
	k_t	1	0.47	0.45	0.52	0.47	0.47
	k_{31}	1	0.33	0.29	0.29	0.33	0.33
	k_{33}	1	0.70	0.65	0.67	0.68	0.70
Piezoelectric charge coefficients	$-d_{31}$	10^{-12} C/N	250	130	55	130	170
	d_{33}	10^{-12} C/N	600	330	190	330	425
	d_{15}	10^{-12} C/N	650	335	150	400	500
Piezoelectric voltage coefficients	$-g_{31}$	10^{-3} Vm/N	7	10	16	11	11
	g_{33}	10^{-3} Vm/N	18	25	54	28	27
Frequency constants	N_p	Hz·m	2030	2160	2400	2230	2010
	N_t	Hz·m	1970	2030	2100	2040	1950
	N_{31}	Hz·m	1375	1480	1670	1500	1400
	N_{33}	Hz·m	1325	1600	1600	1800	1500
Mechanical Properties							
Density	ρ	10^3 kg/m^3	7.80	7.70	7.70	7.70	7.70
Elastic compliances	s_{11}^{E}	10^{-12} m^2/N	18	15	10	13	17
	s_{33}^{E}	10^{-12} m^2/N	18	19	23	20	23
	s_{11}^{D}	10^{-12} m^2/N	16	14	10	12	15
	s_{33}^{D}	10^{-12} m^2/N	9	11	13	11	12
Poisson's ratio	σ^{E}	1	0.40	0.39	0.29	0.33	0.39
Mechanical quality factor	Q_m	1	65	100	>1000	>1000	80

Standard tolerances:

Electrical Properties	± 10 %
Electromechanical Properties	± 5 %
Mechanical Properties	± 2.5 % (Except for σ^{E} and Q_m)

Material Data For Standard Test Specimens

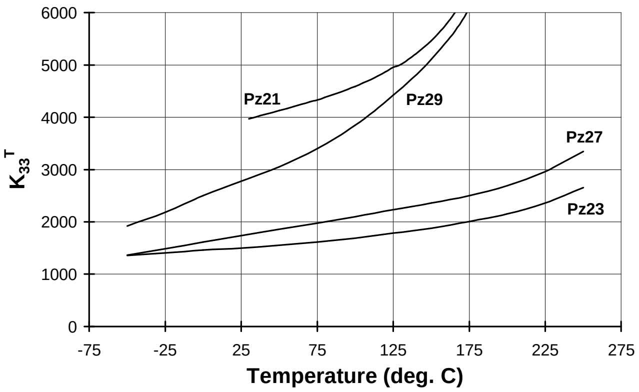
Data are measured at 25°C and 24 hours after poling (Pz28 10 days after poling)

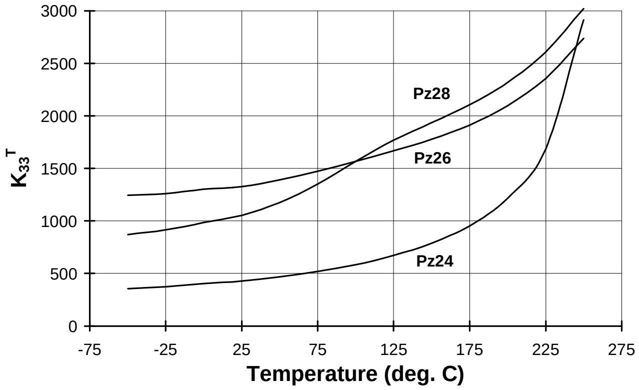
	Symbol	Dimension	Pz28	Pz29	Pz34	Pz35	Pz46
Electrical Properties							
Relative dielectric const. at 1 kHz	K_{33}^{T}	1	1000	2900	210	220	120
Diel. dissipation factor at 1 kHz	$\tan \delta$	10^{-3}	4	19	14	6	4
Curie temperature	$T_c >$	°C	330	235	400	500	650
Recommended working range	<	°C	230	150	150	200	550
Electromechanical Properties							
Coupling factors	k_p	1	0.58	0.64	0.07		0.03
	k_t	1	0.47	0.52	0.40	0.34	0.20
	k_{31}	1	0.34	0.37	0.05		0.02
	k_{33}	1	0.69	0.75	0.40		0.09
Piezoelectric charge coefficients	$-d_{31}$	10^{-12} C/N	120	240	5		2
	d_{33}	10^{-12} C/N	320	575	50	100	18
	d_{15}	10^{-12} C/N	375	650	40	50	16
Piezoelectric voltage coefficients	$-g_{31}$	10^{-3} Vm/N	13	10	3		2
	g_{33}	10^{-3} Vm/N	34	23	25	43	17
Frequency constants	N_p	Hz·m	2180	1970	2770		2470
	N_t	Hz·m	2010	1960	2200	1550	2000
	N_{31}	Hz·m		1410			
	N_{33}	Hz·m		1500			
Mechanical Properties							
Density	ρ	10^3 kg/m^3	7.70	7.45	7.55	5.60	6.55
Elastic compliances	s_{11}^{E}	10^{-12} m^2/N	13	17	7		11
	s_{33}^{E}	10^{-12} m^2/N	23	23	7		44
	s_{11}^{D}	10^{-12} m^2/N	11	15	7		11
	s_{33}^{D}	10^{-12} m^2/N	12	10	6		44
Poisson's ratio	σ^{E}	1	0.31	0.34	0.22		0.21
Mechanical Quality factor	Q_m	1	>1000	90	> 500	15 - 25	> 600

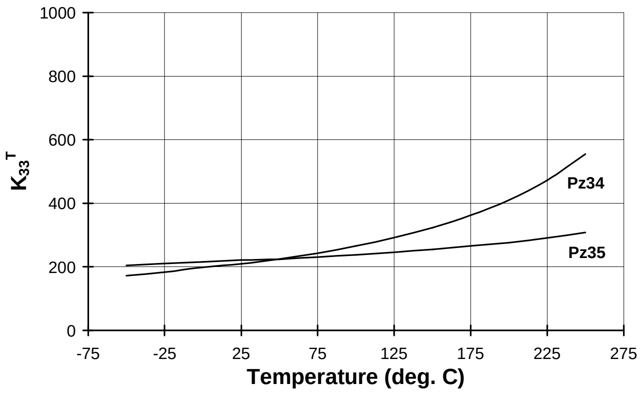
Standard tolerances:

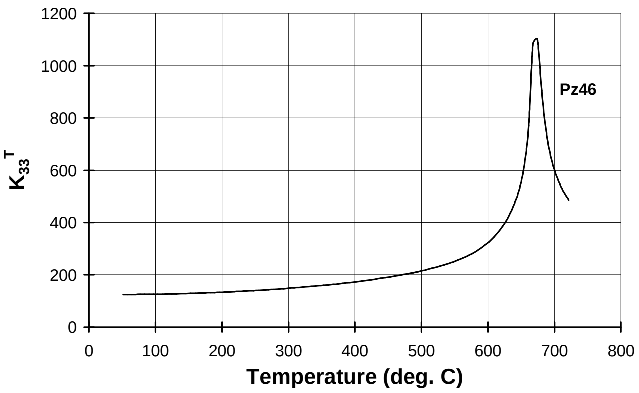
	Electrical Properties	± 10 %
	Electromechanical Properties	± 5 %
	Mechanical Properties	± 2.5 % (Except for σ^{E} and Q_m)

Relative Dielectric Constant vs. Temperature

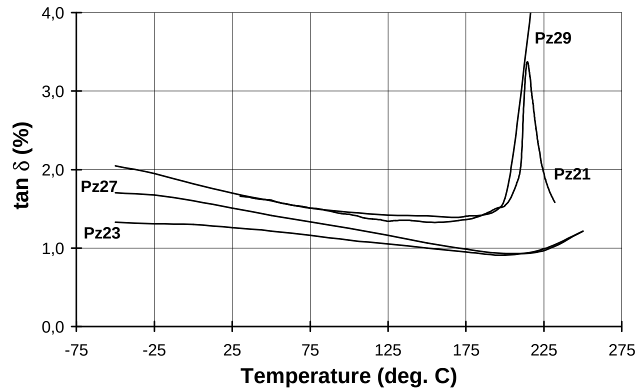


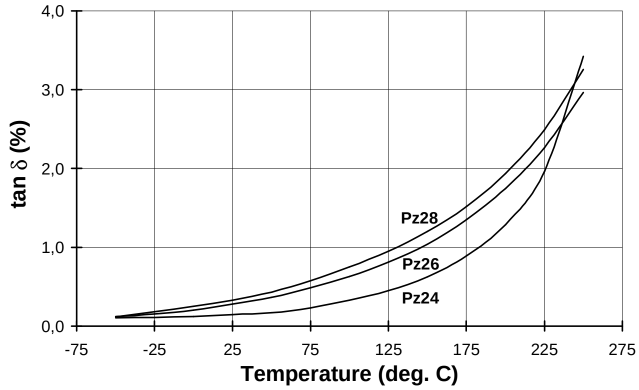


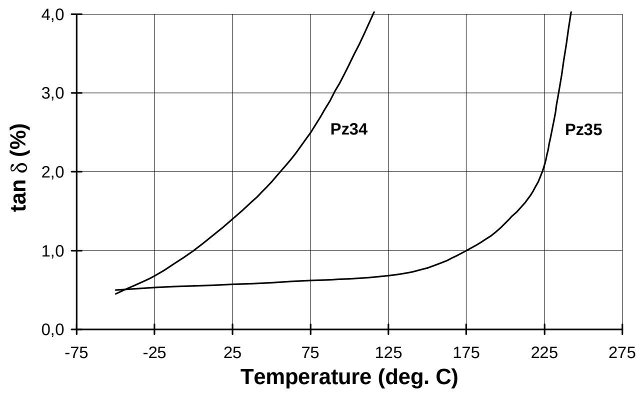




Dielectric Loss vs. Temperature

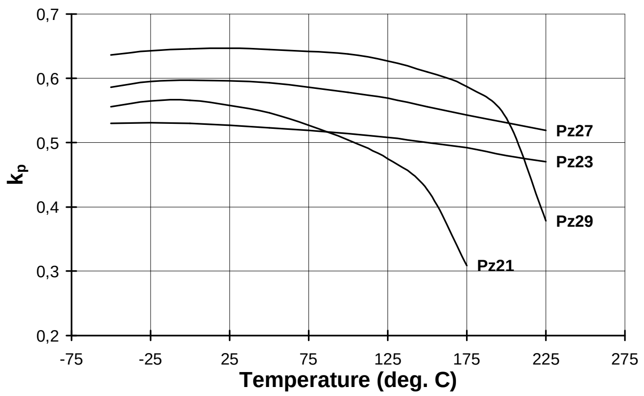




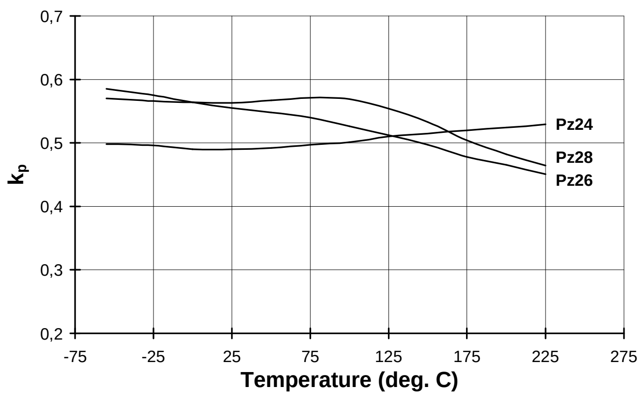


Pz46 measurements were made at “Laboratory of Ceramics, EPFL” Switzerland.

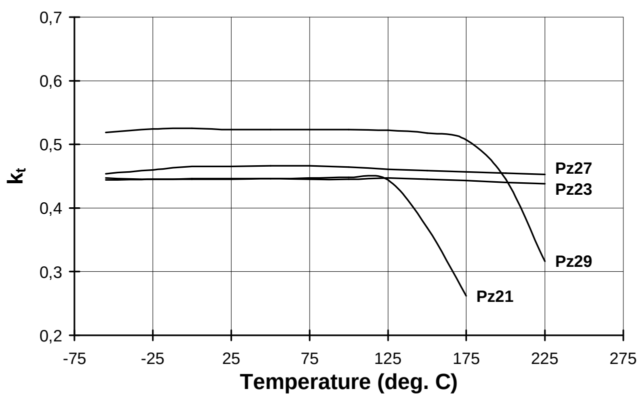
Planar Coupling Factor vs. Temperature



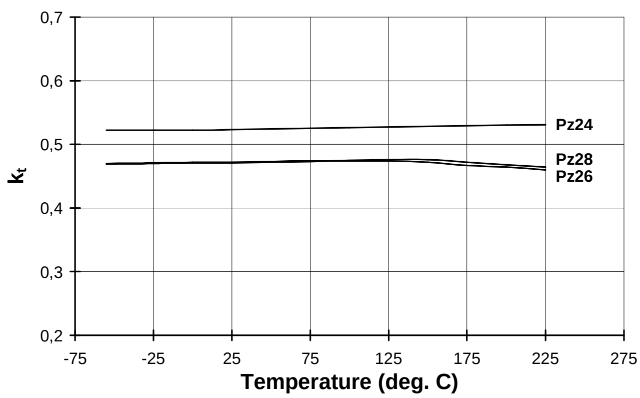
Planar Coupling Factor vs. Temperature



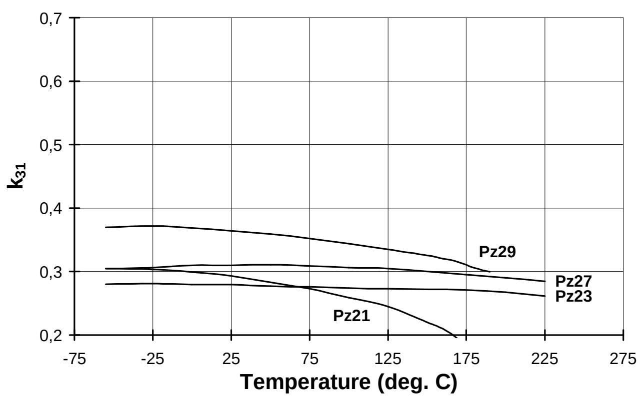
Thickness Coupling Factor vs. Temperature



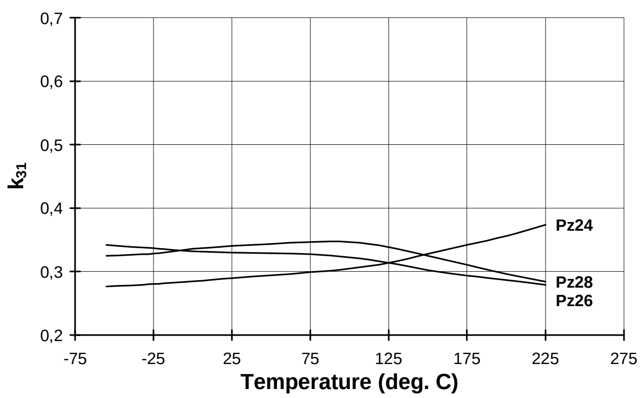
Thickness Coupling Factor vs. Temperature



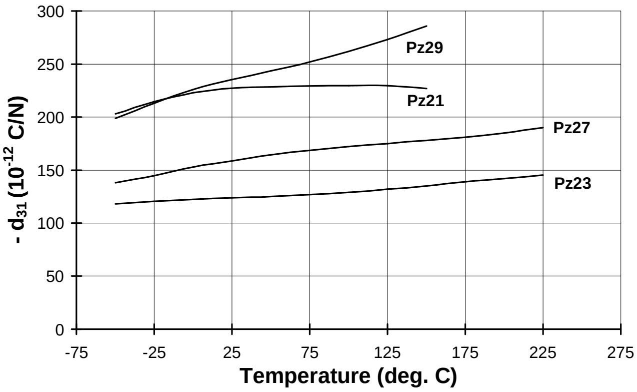
k_{31} Factor vs. Temperature



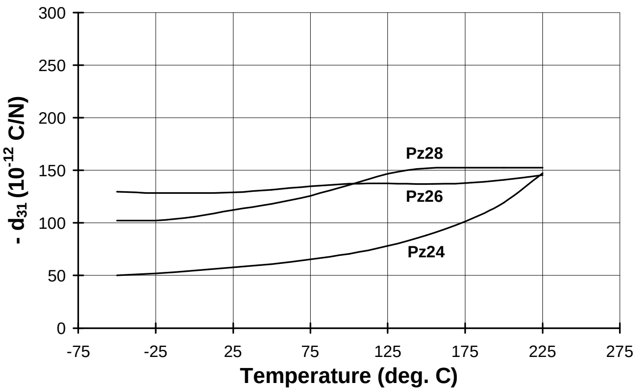
k_{31} Factor vs. Temperature



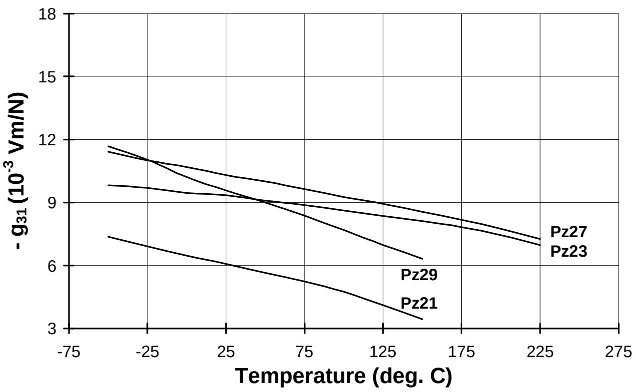
d_{31} Coefficient vs. Temperature



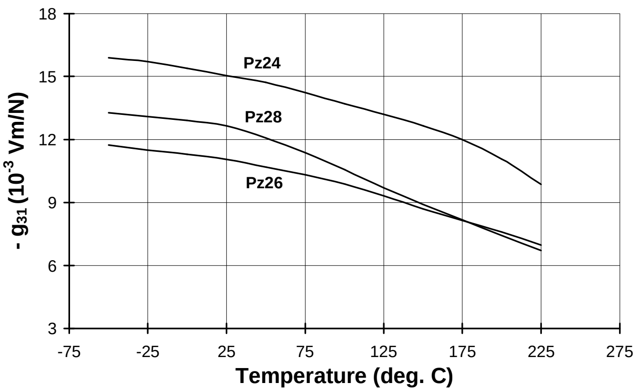
d_{31} Coefficient vs. Temperature



g_{31} Coefficient vs. Temperature



g_{31} Coefficient vs. Temperature

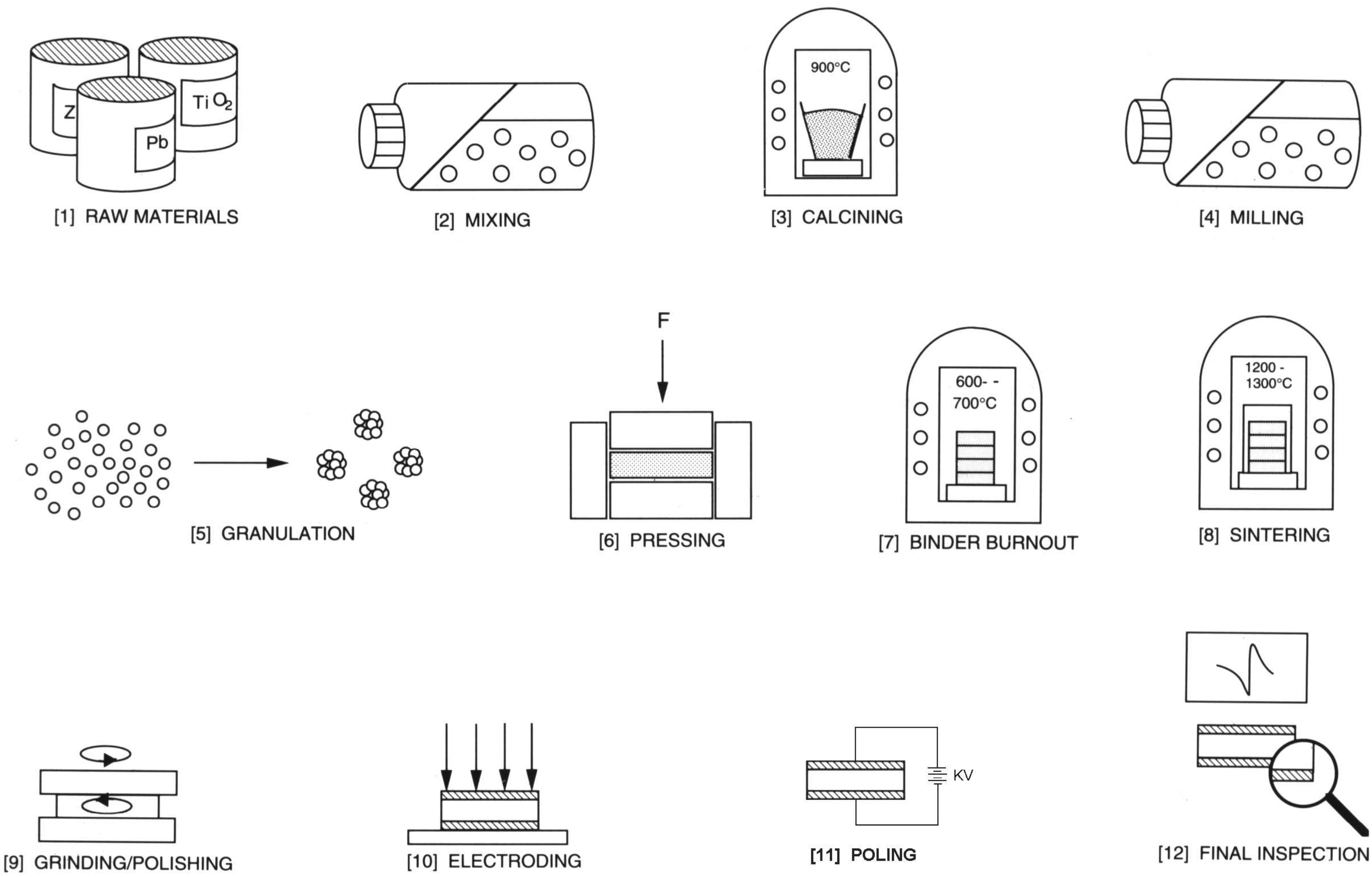


The manufacturing process involves a number of stages shown schematically in figures 1 to 12. The first step is to weigh, dry mix and ball mill [2] the raw materials. The uniform mixture is then heat treated (calcined) [3], during which the components react to form the polycrystalline phase. The calcined powder is ball milled [4] to increase it' s reactivity, and granulated [5], with the addition of a binder, to improve its pressing properties.

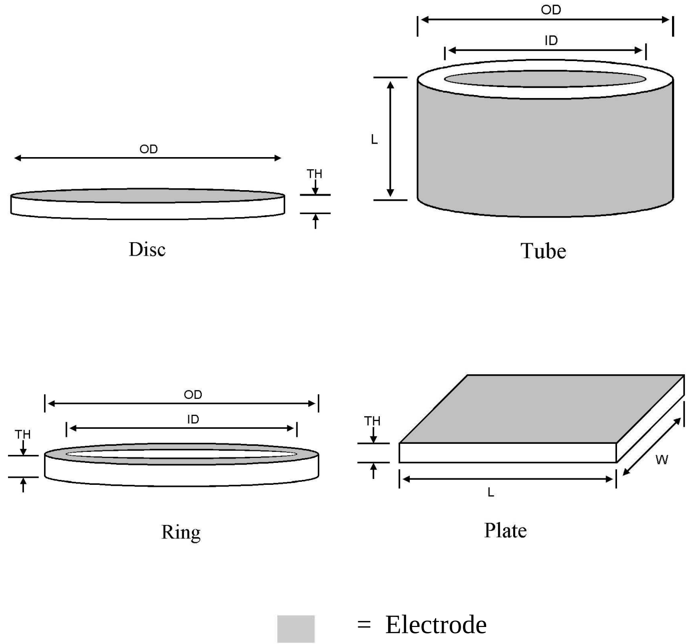
After shaping by dry-pressing [6], the binder is burnt out [7] by slowly heating the green ceramics to around 700°C. The parts are transferred to another furnace, where they are sintered [8] between 1200 and 1300°C. The dimensional tolerance of fired parts (± 3 %) is improved by cutting, grinding, lapping etc. [9].

Electrodes are applied either by screen printing or by vacuum deposition [10]. Poling then is carried out by heating in an oil bath at 130-220°C, and applying an electrical field of 2-8 kV/mm to align the domains in the material [11]. The oil bath is used as a heat source and to prevent flash over.

Final inspection [12] is performed 24 hours later, and includes testing of electrode-ceramic bonding as well as measurement of dimensional tolerances, di-electric and piezoelectric properties.



Certain commonly requested parts: discs, rings, tubes and square plates in Pz26 and Pz27, are carried in stock for prompt delivery.



Pz26 And Pz27 Discs

Electrodes on flat surfaces

OD (mm)	*Th* (mm)	Part Number Pz26	Pz27
5.00	0.5	26000	27000
	1.0	26001	27001
	2.0	26002	27002
6.35	0.5	26010	27010
	1.0	26011	27011
	2.0	26022	27012
10.00	0.5	26020	27020
	1.0	26021	27021
	2.0	26022	27022
12.70	0.5	26030	27030
	1.0	26031	27031
	2.0	26032	27032
16.00	0.5	26040	27040
	1.0	26041	27041
	2.0	26042	27042
20.00	0.5	26050	27050
	1.0	26051	27051
	2.0	26052	27052
25.00	0.5	26060	27060
	1.0	26061	27061
	2.0	26062	27062
30.00	0.5	26070	27070
	1.0	26071	27071
	2.0	26072	27072
38.00	0.5	26080	27080
	1.0	26081	27081
	2.0	26082	27082
50.00	0.5	26090	27090
	1.0	26091	27091

Pz26 And Pz27 Tubes

Electrodes on curved surfaces

OD (mm)	*ID* (mm)	*Th* (mm)	Part Number Pz26	Pz27
6.35	5.20	3.20	26201	27201
6.35	5.20	6.35	26202	27202
12.70	11.10	3.20	26203	27203
24.00	20.00	15.00	26204	27204
32.00	28.00	14.00	26205	27205

Pz26 And Pz27 Rings

Electrodes on flat surfaces

OD (mm)	*ID* (mm)	*Th* (mm)	Part Number Pz26	Pz27
5.00	2.30	1.00	26101	27101
5.00	2.30	2.00	26102	27102
6.35	2.40	1.00	26111	27111
6.35	2.40	2.00	26112	27112
10.00	5.00	1.00	26121	27121
10.00	5.00	2.00	26122	27122
20.00	3.80	1.00	26131	27131
20.00	3.80	2.00	26132	27132

Pz26 And Pz27 Plates

Electrodes on flat surfaces

L (mm)	*W* (mm)	*Th* (mm)	Part Number Pz26	Pz27
6.35	6.35	1.00	26301	27301
12.70	12.70	1.00	26302	27302
30.00	30.00	1.00	26303	27303
50.00	50.00	1.00	26304	27304

Materials

In addition to the standard compositions shown in the previous sections, Ferroperm offers a HIP quality (Hot Isostatic Pressed) of most PZT ceramics. The advantage of HIP quality is very low porosity and improved mechanical and piezoelectric properties.

Special formulations and fine-grained materials can be manufactured on request.

Electrodes and special designs

Fired screen-printed silver electrodes are available as standard electrode materials on conventional parts. Other electrode materials include:

- Screen-printed gold-palladium
- Evaporated chromium-silver
- Evaporated chromium-gold
- Evaporated chromium-silver with gold-flash on one side
- Chemically deposited nickel-gold

Polished or fine-grinded surfaces are available on request.

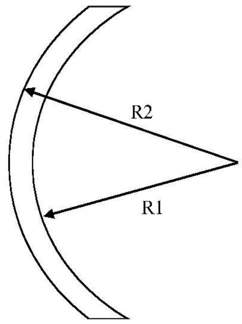
Wrap around electrodes and side connections are made on request, and electrode configurations can be varied to accommodate polarization patterns and acoustic designs.

Custom Products

By far the largest proportion of the production in Ferroperm is made according to customer specification. The ceramics can be produced in many shapes i.e. discs, plates, tubes, rings, hemispheres and focusing bowls. Shear plates, shear tubes and shear rings are available in most compositions. For special requirements, please contact Ferroperm Piezoceramics A/S directly.

Focusing Bowls

Focusing bowls are available in all standard compositions. Special non-standard diameters, resonant frequencies, focal lengths (R_1) and closer tolerances can be made on request.



Resonant frequency range available:
- 100 kHz to 10 MHz

Diameter range available:
- 5 mm to 65 mm

Shear plates

Shear plates are offered based on customer specification. Plates can be specified with- our without centre holes.
Electrodes are chemically plated nickel-gold or evaporated silver or gold.

Shear Tubes

Shear tubes are offered based on customer specification. These can be specified with special cuts, slots, or chamfering to aid assembly, and have multiple output signals.
The electrode material is typically chemically plated nickel-gold.

Shear Rings

Shear rings (opposite polarisation/electrode configuration to shear tubes) are offered based on customer specification. These can be specified with special cuts, slots, or chamfering to aid assembly, and have multiple output signals.
Electrodes are chemically plated nickel-gold or evaporated silver or gold.

Soldering Procedure

Clean the area to be soldered thoroughly. Pre-tin the electrode area and the lead. A low melting point Sn/Pb solder containing 2 - 4 % silver is recommended (Multicore LMP, FLUX 362).

Place the lead in the middle of the pre-tinned area, applying a firm pressure, see figure 1 and 2. Heat the lead a little above the ceramic surface. When the solder on the lead melts, move the soldering iron down the lead to ensure the melting of the solder on the silver electrode. Withdraw the soldering iron as soon as the solder has melted (5 - 7 seconds).
Soldering temperature should be approximately 270 - 300°C. Using too low a temperature will increase soldering time. The right temperature is when the solder melts readily. Care should be taken to use a short soldering time as excessive heat could locally depolarise the ceramic, or reduce the piezoelectric properties.

Remove flux according to the recommendations of the solder manufacturer. The electrodes will withstand ordinary ultrasonic cleaning processes.

Tolerances

A set of standard tolerances is used, if nothing else is specified by the customer. This set is separated into several different categories. For most of these categories the customer however have the opportunity to specify other tolerances for the specific parameters, which are most critical for that certain application. Changes in inspection level should however always be discussed with Ferroperm and incorporated into the quotation and ordering as soon as possible in the dialog.

The first step in approval of a new production is the material itself, where a list of tolerances must be fulfilled in order to qualify as one of the 10 materials in the programme. A set of tolerances has therefore been defined. These tolerances are also used to verify any new material batches before it is released for regular production.

Dielectric Properties	
Relative dielectric constant Dielectric loss factor	± 10 %
Electromechanical Properties	
Coupling factors Charge coefficients Voltage coefficients Frequency constants	± 5 %
Mechanical Properties	
Density Elastic compliances	± 2,5 %

Note:
Catalogue values are based on measurements on standard geometries fulfilling recommended geometrical conditions.

For the specific production there will be a list of parameters regarding the size, geometrical parameters and electric behaviour, which have to be fulfilled. The standard tolerances on these are:

	Standard tolerance	**Minimum tolerance**
Diameter of Rings and Discs		
OD ≤ 10 mm	± 0,3 mm	0,01 mm
OD > 10 mm	± 3 %	0,01 mm
Length and width of Plates	± 0,3 mm	0,01 mm
Thickness of Rings, Discs and Plates		
Th ≤ 1 mm	± 0,03 mm	0,01 mm
Th > 1 mm	± 3 %	0,01 mm
Focussing Bowls		
Radius of curvature (R1 and R2)	± 3 % or ±3 mm whichever is largest	1 mm (dependent on total size)
Diameter	± 3 % or ±3 mm whichever is largest	0,01 mm
Thickness uniformity	Max variation 2,5% or 0,025 mm whichever is largest	0,05 mm (dependent on total size)
Resonance frequency		
Resonance ≤ 4MHz	± 5%	± 0,5%
Resonance > 4MHz	± 10%	± 1%
Capacitance		1 pF

Finally other more subjective parameters will be measured and documented when relevant. Among these parameters are for example, internal cracks, solderability, electrode adherence, surface roughness, and edge resistance in wrap-around electrodes.

Quality Assurance and Standards

The quality system in Ferroperm ensures full traceability for all productions and all operations carried out on an order.

The starting point in the system is that all productions are performed *material-batch-specific* rather than based on generic material data. This means, that before any material is released for regular production, a pilot production has been completed, and all relevant parameters have been measured and approved. The data for a specific batch is saved in a database, which is used by the production manager to optimise the production parameters for each new production.

The material batch number is therefore an important parameter for every new production, and will be clearly marked on both the production- and final inspection sheets.

As shown in previous sections, each production have a number of different processes, which must be performed before a certain part is completed. After each of these operations the responsible operator will record and register the time spent and the quantity of defects generated.

The quality system differentiate between more than 120 different types of defects ranging from simple errors on dimension to more complicated types, such as discrepancies in certain piezoelectric parameters. By operating this highly differential system, a more systematic approach to corrective actions can be taken.

After a completed production, all parts are passed through the final inspection unit. This department is a staff function under the managing director of Ferroperm Piezoceramics. Here qualified and well trained personnel uses modern and periodically calibrated equipment to verify that productions fulfil the internal standards to the materials and the tolerances given by the customer.

Most control operations are based on the statistical sampling described in Military Standard MIL-STD-1050 (ISO 2602-1973). The acceptable quality limit, AQL, is 0.65 - Sample plan 2. By operating this system, it is secured that maximum 0,65% defect parts can be sent to a customer without seeing any problems during inspection.

In some cases customers have one or more critical parameters, where defects cannot be tolerated in spite of an increased cost of the parts. In such cases Ferroperm offer a 100% inspection on these parameters.

Certificates of conformance and/or copies of the final inspection sheets are supplied on request from the customer.

Ordering Information

Submitting the following information when inquiring for quotations will be helpful:

- Type of material
- Geometric shape, dimensions and tolerances
- Electrode material, pattern and polarization
- Quantities required
- Specification of the part if available
- Requested delivery date
- If part-deliveries from stock are required

Packaging and Shipping

Ferroperm uses packaging and shipping methods that ensure safe delivery of products to the customer. These methods are based on our experience in shipping such materials. The shipping method is usually chosen based on the most economical method available. Special packaging and shipping services are available on request.
Shipping damage must be reported to the transport carrier immediately. Returns, if necessary, must be arranged with Ferroperm to obtain return authorisation and re-entry documentation.

Distributors

Direct Contact and Technical Discussion

Development, design and production of devices and products incorporating piezoelectric elements usually require a high degree of technical knowledge and experience.
As an active partner in this process, Ferroperm Piezoceramics is dedicated to assist at the designing stage with a choice of the best material for the application, guide customers through the definition phase in order to obtain the best quality vs. price ratio, be flexible and supportive at the sample-manufacturing stage, and finally supply consistent high quality reliable products at fair and competitive prices.

Existing or potential customers are therefore always welcome to contact Ferroperm directly in order to discuss problems and possibilities for future orders, and to solve technical and commercial details as quickly and flexible as possible.

Local Distributors

Below you will find a list of Ferroperm's sales distributors in Germany, United Kingdom, France and Brazil.

Main Office and Production Facilities
Ferroperm Piezoceramics A/S Hejreskovvej 18A DK-3490 Kvistgård Tel.: (+45) 49 12 71 00 Fax: (+45) 49 13 81 88 E-mail: pz@ferroperm-piezo.com Website: www.ferroperm-piezo.com

Germany	United Kingdom
Amroh Electronics GmbH Jakob-Kaiser-Straße 2 D-47877 Willich Germany Tel: (+49) 2154 945030 Fax: (+49) 2154 428421 E-mail: amroh@t-online.de, Website: www.amroh.via.t-online.de/piezo.htm	**E.P Electronic Components Ltd.** Unit 22, Station Road Ind. Est. Southwater, West Sussex RH13 7UD United Kingdom Tel: (+44) 1403 733030, Fax: (+44) 1403 733909 E-mail: info@epelectronics.co.uk Website: www.epelectronics.co.uk
France	**Brazil**
Hybrico International ZAE les Glaises 2 bis, Rue Léon Blum F-91120 Palaiseau France Tel: (+33) 1 69 19 13 07 Fax: (+33) 1 69 19 13 09	**Engecer Projetos e Produtos Cerémicos** R.N. Sra. Auxiliedore, 1141 Sta. Felicia - CEP 13560-970 São Carlos - SP Brazil Tel: (+55) 0162 72-6716 Fax: (+55) 0162 72-1125
Poland	
Sonomed ltd. Sliska52, PL00-826 Warszawa, Poland Tel: (+48) 22 65 41 506 Fax: (+48) 22 65 41 507 E-mail: biuro@sonomed.com.pl Website: www.sonomed.com.pl	