Piezomechanik GmbH

Use of cofired monolithic piezo-ceramic stacks and chips

Overview

Contents

1. Selecting a proper piezo actuator system

Guideline:
The main pre-requisite for selecting suitable piezo components is the precise definition of the needed operation profile by the user.
Any supplier of piezo-mechanical components will highly appreciate precise specifications of the requested components.
Putting definite numbers on the needed piezo-parameters is helpful to avoid over-sizing and mismatch. Poorly selected system components are ineffective and therefore expensive.

Please try to analyze the needs for operating your mechanics successfully according to the following:

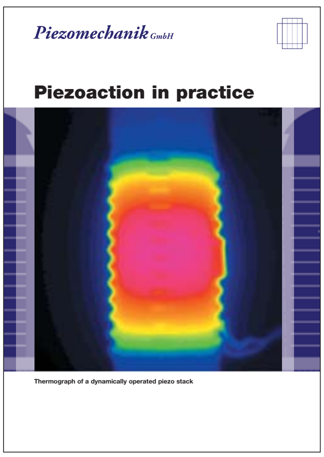
A, what shift/stroke shall be achieved?
B, what force variation shall be generated by the piezo action?
C, what static preload is acting on the actuator from the beginning?

D, what is the desired maximum operation frequency?
E, what is the desired stroke at maximum frequency (D)?
F, what is the desired max. frequency at maximum stroke (see A)?
G, shortest achievable rise-/fall-time?
H, what external masses shall be attached to the actuator?

A, to C, allow an actuator selection for low dynamic operation
D, to H, aims for the best match for the designated dynamic operation.

Selecting the amplifier
The above selection process results in a piezo-actuator of distinct voltage range and electrical capacitance. Only amplifiers with a matched voltage range should be considered for use.
Do not use amplifiers providing higher voltage!

The dynamic operation profile D, to H, defines the needed current levels (I_{peak} and $I_{average}$).
When the power consumption of the actuator exceeds the Watt-range, self-heating of the piezo-ceramics can occur.
See brochure: First Steps towards Piezoaction



For details see brochure:
“Piezoaction in practice”

Selecting power supplies

1. Rule of thumb: Use only power supplies with voltage ranges matched to the actuator ratings.

Power consumption, current levels:
Piezo-stacks behave like capacitors in the subresonant frequency range.
Therefore, a current flows only during a voltage variation for altering the position and/or force status of an actuator.

2. Rule of thumb: Define precisely the electrical current or power level to get the required dynamics of your actuating system (rise-/falltimes, see brochure "electronics").
Do not oversize significantly the max. current and power ratings of the used amplifier to avoid annecessary stress in the piezosystem.

$f \sim I$
$1/\Delta T \sim I$

resonance frequency:
For precise positioning and short settling time: Stay well below "resonance frequency".

Do not misinterpret catalogue data: Not all operating specifications can be realized at the same time due to simple physical facts.

- Maximum displacement/shift/stroke and maximum force generation /max. blocking force cannot be generated at the same time, only either-or.

- The maximum actuator shifts (strokes) shown in data sheet are only valid under constant load conditions (no force variation!).

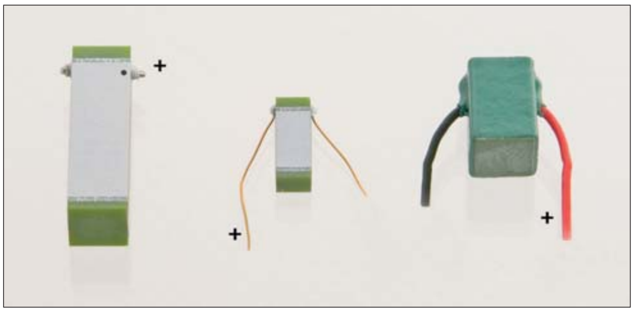
- Two values for stroke are stated in the data sheet
A, for unipolar activation 0V/+U_{max}
B, for semibipolar operation -U/+U_{max}
The semi-bipolar operation increases the open-loop stroke of a stack by 20 – 30%.

2. Overview: main operating parameters

Piezoactuators
PSt 150, HPSt 150, PCh 150, HPCh 150

Max. Voltage ranges: -30V thru +150V

Typical operating schemes:
Unipolar range: 0V/+150V
for high power applications
Semi-bipolar range: -30V thru +150V
for quasistatic low power applications with enhanced stroke/blocking force



Actuator's poling

Piezo-actuators are poled components from factory
Usually, *the* ***positive*** pole is indicated e.g. by
red *insulation wires , dots , longer wire*

Strokes A/B
Max. ratings shown in data sheet
A, for max. semi bipolar
B, for max. unipolar activation
Example:
Max. stroke: PSt 150/7/20 VS12
A/B = 27µm/20µm

Stiffness
Inverse compliance,
– measured for open loop voltage control operation
– measured with a static preload of at least of 10% of actuator's maximum load.

Blocking force/max force generation
Means maximum force generation of an actuator.
Depends on the applied voltage variation.
Stated values refer to maximum semi-bipolar operation.
Maximum uni-polar operation gives about 30% lower values

Resonant frequency
– Refers to axial mode
– Defined for one side fixed piezo-element (other modes like planar diameter not taken into)

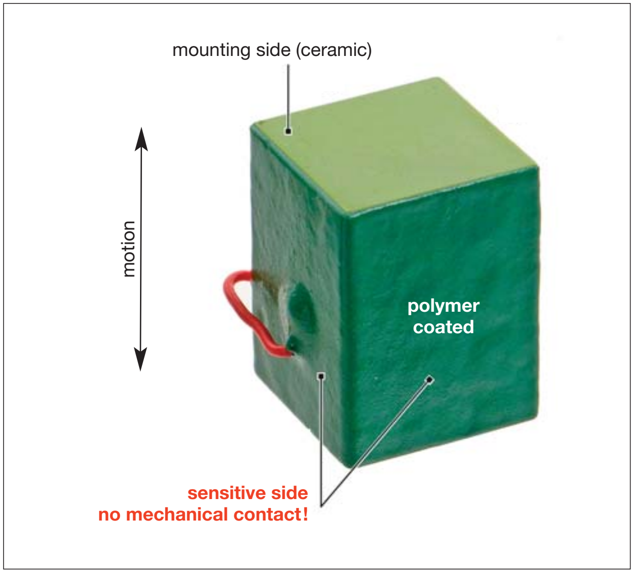
Capacitances
– Measured at low field excitation at room temperature
– Manufacturing tolerances up to +/- 20%
– Capacitance can depend on high field excitation and temperature

3. Ceramic piezo actuators

The handling of piezo-actuators during mounting and operation is ruled by the specific mechanical properties of ceramics like brittleness, low tensile stress damage threshold on one side and its sensitive electrical structure on the other side.

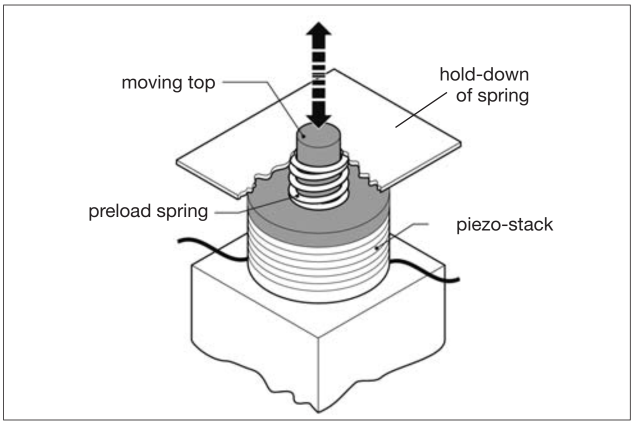
Stack type actuators are mechanically coupled only via the end faces e.g. by clamping, glueing or other methods. The end-faces are electrically insulated.
No mechanical contact/**impact** shall be applied **to the side faces**.
The side faces bear the supply-electrodes to contact electrically the internal layer electrodes of the capacitor structure. The supply electrodes are wired by pig-tails near the actuator socket. Standard actuators PSt 150 are finally coated with a high quality polymer and are therefore more resistant to mechanical and other influences than bare ceramic components.

Piezo-stacks can bear high compressive load forces, but they are very sensitive to bending-, torsion-, shear-forces and especially to tensile forces. Attention has to be paid to this fact not only during the final operation of such stacks, but during all handling and mounting steps in advance to operation.
The design of any attached mechanics shall aim for pure axial loading of the actuators without any compromise. Imperfect solutions can lead to strongly reduced performance and reliability.
Pay attention not only to the static force balances, but also to dynamic influences (acceleration forces resulting in bending motion or torque).



Mounting scheme of piezo-actuators

Mechanical preloading:
Preloading is achieved in most cases by using an elastic spring for resetting the moving part of an actuator.
Mechanical preloading of piezo ceramics is necessary to allow a push-pull-operation of an actuator. This is to handle externally applied tensile forces caused by static or dynamic driving conditions.
A properly designed mechanical preloading of actuators reduces further microscopic tilting of the actuator end-faces. Coherent optical arrangements like tuneable etalons/resonator structures do not need then additional guiding mechanism for shifts in the micro-meter range.



Schematic of a preload spring mechanism

Preload forces can be high as 50% of the load capability of actuators or even more, to handle extreme driving conditions (e.g. pulsed operation or symmetrical push-pull arrangements).
The "golden rule" of preloading:
Use preload springs of lowest possible stiffness (large compliance).
A good attempt is to select for a spring's stiffness in the % range of actuator's stiffness.
Then, no loss of stroke will occur even when high preload forces are applied (details: See "force generation" in main cata logue).

Operating stack actuators with reduced strain
A beginner in piezo actuation usually seeks for an actuator type, what's maximum rating stroke covers rather exactly the needed range. This implies consequently, that the actuator is operated then up to maximum voltage, maximum electrical field strength, maximum strain and thereby for dynamic applications with maximum power consumption and power losses.
The use of an "oversized" longer actuator can have a lot of advantages compared to the above mentioned "maximum ratings" operation:

- The long-term reliability is improved by the use of reduced electrical field strength (driving voltage << max. voltage rating).
- The reduced mechanical strain results in a lower power consumption and self-heating.
Vice versa higher oscillation frequencies can be achieved by applying the same power as with the maximum rating type actuators.
- Power supplies with reduced output voltages can be used, providing higher currents (=> higher actuator oscillation frequency) and lower costs.

This reduced strain strategy finds its limits, when higher resonance frequencies, stiffness are a must or the stack length is restricted by space limitation.

The achievable performance and reliability of an actuator must be seen always in context with the interaction with the operated mechanical system and the electrical driving characteristics.

Poorly designed mechanics like low stiffness coupling to the actuator, friction, wrong preloading, wrong force coupling, misalignment of coupling faces from actuator to mechanics reduce significantly usable stroke, accuracy, force generation and make the use of piezo actuator more or less worthless. Poor designing impact further actuator's long-term reliability.
Fig. A shows the consequences of inhomogeneous high force loading: A stack with excessive edge squeezing/pressure of the ceramic-stack by an improper force coupling (Fig. C and D). Cracks are generated within the active ceramic section resulting in electrical break down and arcing.

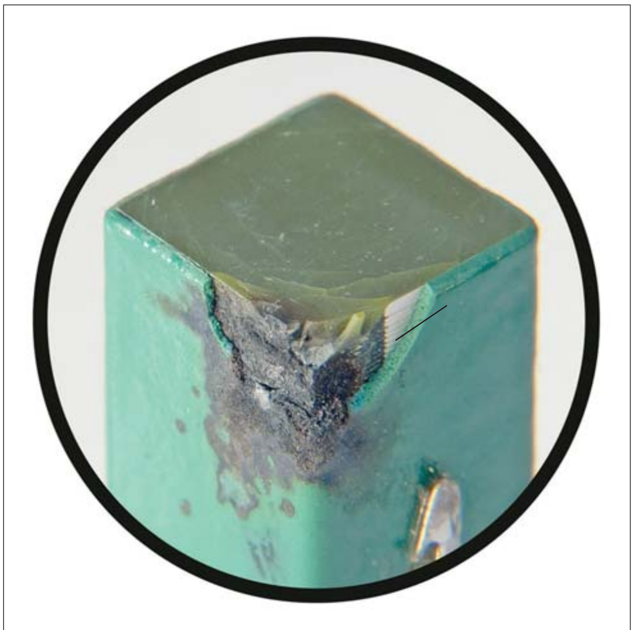


Fig. A: Failed actuator stack, caused by a wrong coupling to the actuated mechanics. Local edge pressure exceeded ceramic's stability with subsequent electrical break down after approx. 800 hours.

Coupling of actuator and mechanics
Optimum actuation performance is achieved by following a few simple rules

- The coupling face of the mechanics shall cover completely actuator's end faces to achieve maximum force transfer (Fig. B). The contact force shall be homogeneously distributed over the contact area.
- When a high load pressure is applied, the coupling faces of actuator and mechanics faces shall be absolutely plain (eg. by grinding) to avoid local overload of the ceramic front face.
- The resulting load force vector shall coincide with actuator's axis. Within a virtual cylinder of +/- 10% of actuator's cross-section (Fig. A) to avoid excessive bending and shear stress. Force misalignment tolerance becomes more critical for increased ratios actuator length / diameter. For high dynamic operation, actuator's axis shall further hit the centre of mass of the attached mechanics to avoid dynamic torque.

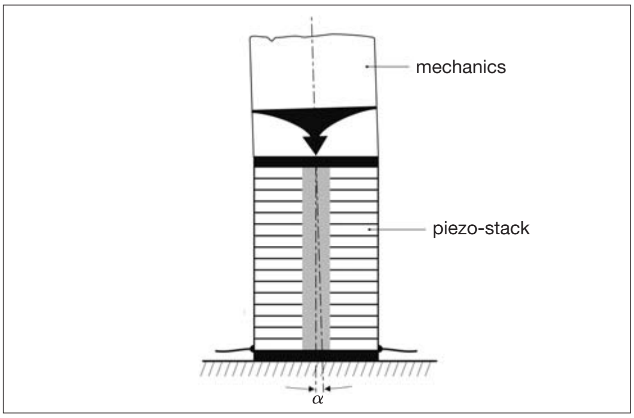


Fig. B: Perfect plain-plain coupling of piezo-stack and attached mechanics by floating axis orientation of the mechanics. Acceptable tolerance α: See above

- When the mechanical partner can read just itself by a free suspension (floating axis) according actuator's plane face, no problems will occur.

- Coupling of piezo actuators to guided mechanisms (axis orientation not floating). One of most widespread design mistake is coupling a plain-faced actuator directly to a plainfaced guided mechanism (Fig. C) Even the slightest misalignment between the orientations of both plains leads immediately to edge squeezing with very high local spot pressures and subsequent ceramic damaging.

In a similar way, the plain-plain coupling of an axially acting stack with a rotating lever arrangement will lead to a fundamental edge squeezing situation in any case (Fig. D).
Do not try this!

In the above cases, it is a must to decouple the axis orientations by using spherical/plain coupling or flex hinges or other means!

- The above requirements are valid at any time and any state of the system during set up and operation.

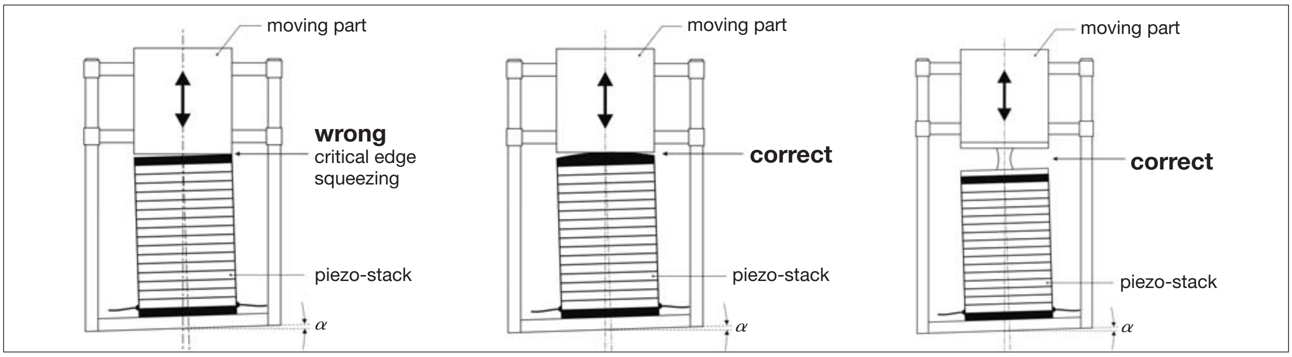


***Fig. C:** Perfect plain-plain coupling of piezo-stack and attached mechanics by floating axis orientation of the mechanics. Acceptable tolerance α: See above*

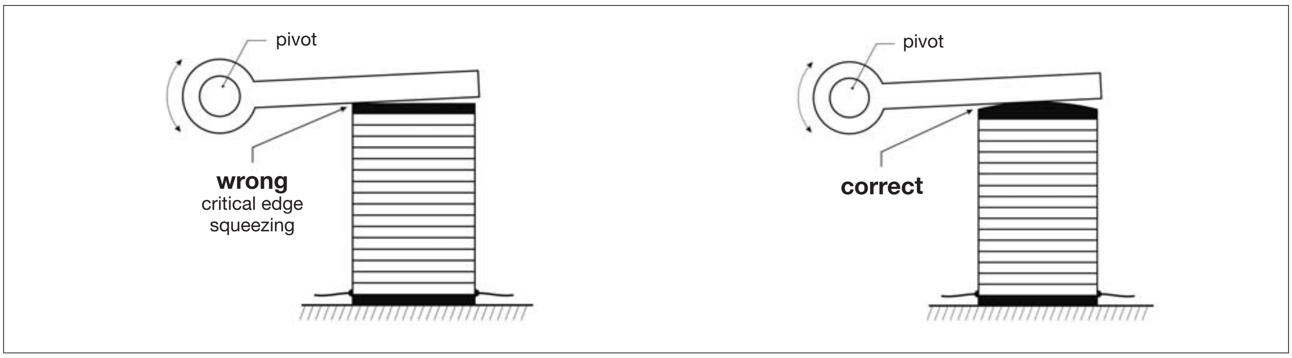


***Fig. D:** Perfect plain-plain coupling of piezo-stack and attached mechanics by floating axis orientation of the mechanics. Acceptable tolerance α: See above*

Bonding of piezo stacks and chips to mechanical parts:
Piezoceramic elements are often bonded to mechanical counterparts by glueing.
The quality of the glue-line is important both for the motion transfer quality and reliability of the piezo-mechanical system.
"Quality" means in this context, that the glue-line must not be "too hard" or "too soft".
Especially too hard glue line may result in rather high in-plane tensile stress within the brittle piezo-ceramic components

A, due to the in-plane d_{31} piezo-contraction of a PZT-layer coupled with the axial (out of plane) d_{33}-mode mostly used for piezo-chip and stack applications.

B, by varying temperatures as a consequence of potentially different thermal expansion coefficients of the couples materials.
The planar CTE of poled piezo-ceramics is about 5 ppm/°C.

For applications within a range of -20 °C/+60 °C, any good quality standard epoxy can be used. The cure temperature shall be held rather low to avoid thermally induced stress, when the CTEs of the joined parts is remarkably different. The thickness of the glue lines shall be held rather thin (< 50 µm) to avoid a "softening" of the coupling quality.
For "exotic" driving conditions like very low or very high temperature, vacuum application etc. special adhesive formulations and glueing techniques are recommended.
Ask PIEZOMECHANIK for support.

Piezo-chips
Too hard and too thin glue-lines increase the "d_{31}-clamping" effect, what can hinder or block the axial motion especially of piezo-chips (Fig. B,C).

For coherent optical applications, unwanted tilting of mounted optical element will then occur. Further, thin optical elements can be distorted by a hard coupling to a piezo-chip (bending structure).

Only when the d_{31}-planar contraction is not hindered, a thin piezo-chip will show the maximum axial d_{33}-expansion and planar displacement.

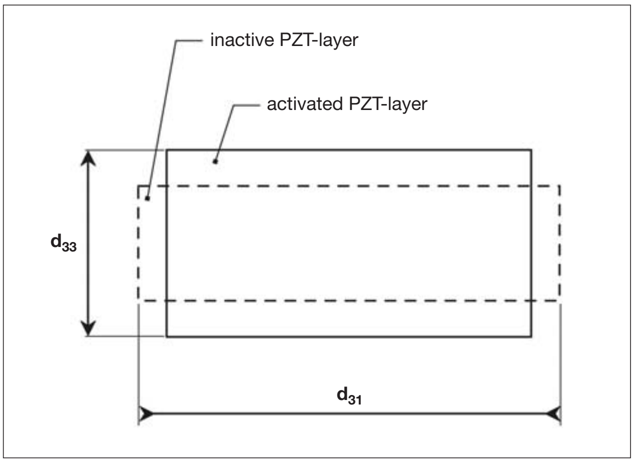


Fig. A: *Action of a free PZT-layer*

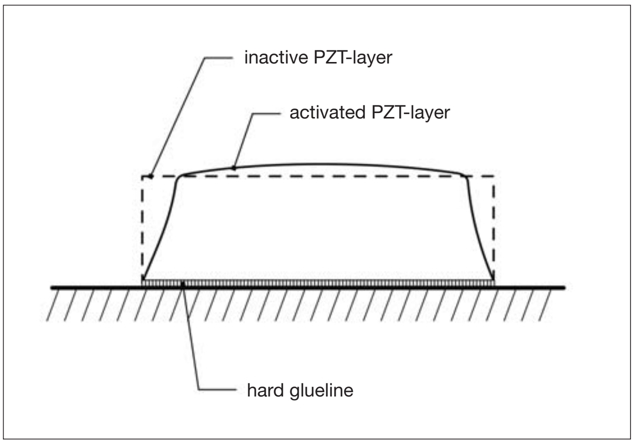


Fig. B: *Hindered expansion of a PZT-layer by clamping by a hard glue line together with a rigid substrate*

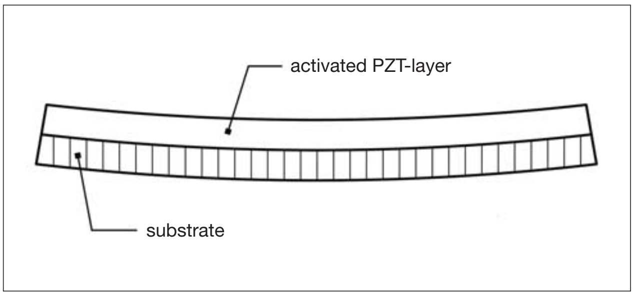


Fig. C: *Bending structure by gluing a PZT-layer onto a thin substrate.*

Contamination: Piezo stacks are electrically highly active elements with high electrical fields at stack's surface.

For mounting stacks into metal constructions, ensure sufficiently large insulation gaps between stack's side-faces and the surrounding mechanics. A PZT-stack-structure is rather sensitive to any contamination by conductive species like electrolytes. Leakage currents will set on, leading to electro corrosion and subsequent short circuiting of the actuator.
Contact to aqueous liquids shall be avoided.

On the other hand stacks with polymer coating can be operated within non-aqueous fluids (e.g. Diesel fuel, transformer oil, silicon oil), what can be used for high efficient cooling of dynamically operated stacks.
Do not touch bare stacks with bare fingers.
Cleaning of coated and uncoated stacks shall be done only with 100% iso-propanole.
Never use acetone!

4. LV-Piezostacking technologies (osi)

Piezo stacks are electrically highly active elements with high electrical fields at stack's surface. Among the spectrum of low voltage multilayer actuators, the osi-based elements have found the widest applications. The patent for this technology has expired since a few years. The main step is to use a fine glass filament fused onto the PZT-ceramic stack, where the internal layer electrode comes to surface and shall be separated electrically from the counter-polar supply electrode. The glass filaments are well separated from each other and do not form a dense (inflexible) glass layer (Fig. A)

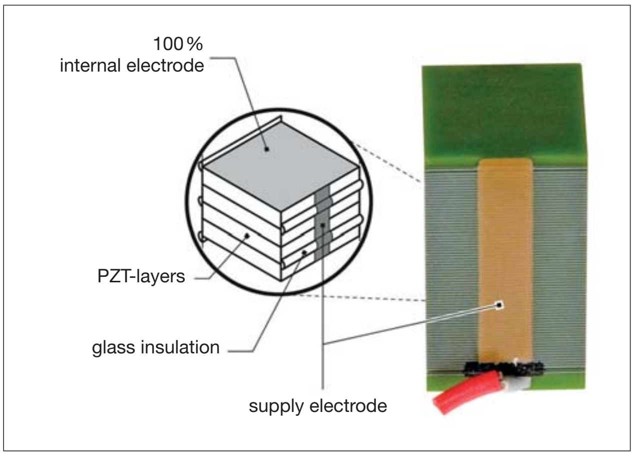


Fig. A: *Schematic of the osi-technique using fused-on glass fibers to terminate internal electrodes on stack's surface*

The main highlights of the osi-technique are

- 100% active PZT-ceramic cross-section and stack volume for maximum stroke and force generation (blocking force).
- Homogeneous strain within the PZT-volume, no intrinsic mechanical tensile stress by active/inactive PZT-boundaries resulting in ceramic cracking and electrical break down.
- The absence if intrinsic inhomogeneous stress results in low tilting of the actuator endfaces (useful for coherent-optical arrangements of ring-actuators).
- High electrical reliability:
  Osi-actuators show a dense PZT-ceramic surface without side cuts or slots as the isi-technique does. No risk of rupturing the supply electrodes at slots/cuts within the side-faces of the stack.
- Due to the absence of structure borne tensile stress within the ceramics, the osi-stacks can be operated with high strain rates without mechanical preload (as long as no external tensile forces are present).

Surface protection

The sidefaces of standard osi-stacks are coated by polymers.

The coating protects the brittle ceramics against "less skillful handling", mechanical attack or chemical contamination.

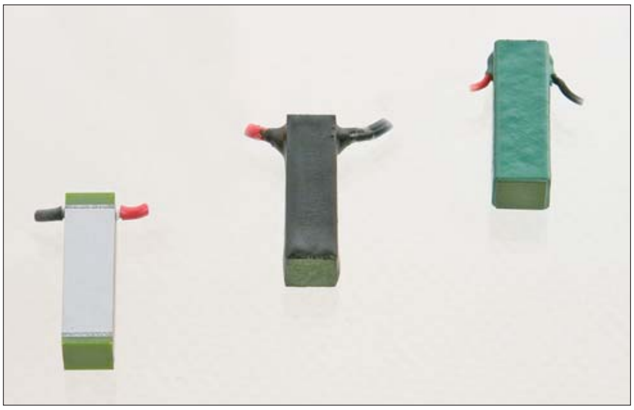


Fig. B: *Different kinds of stack coatings*

Special coatings are available to handle exotic driving conditions like cryogenic temperatures, vacuum / UHV, immersion in (non-aqueous) liquids. Polymers are much more flexible than PZT-ceramics and do therefore not affect adversely the piezoaction.

On the contrary: A thicker coating acts as a kind of reinforcement and "ruggedizing", making the stacks less sensitive to bending or tilting forces than an uncoated ceramic stack (Fig.).

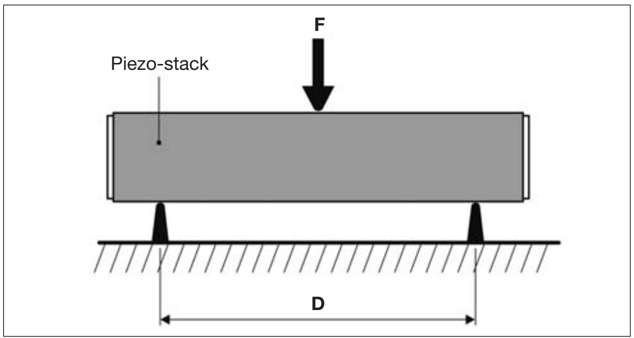


Fig.: *Schematic of a bending experiment*

A piezo-stack PSt 150/2x3/20 with a ceramic cross-section of 2 x 3 mm has been bended by a force F (distance D of the supporting points: 15 mm, bended stack's dimension: 2 mm).

Ruggedizing
The coated ceramic stack withstands a force F of **80 Newtons** before breaking, whereas the uncoated stack can bear only **38 Newtons!**

Thick coated stacks show a better resistance to a robust handling or sub-optimum mechanical designs. Bending oscillations of longer stacks with a critical ratio of length/cross-section are damped away.

Osi-Technology is used by PIEZMECHANIK for PSt 150/HPSt 150 actuators.

Cofired multilayer piezo-ceramic technologies: In-Stack-Insulation (isi)

The isi-piezo-stack design is a more simple insulating strategy, well-known since the early days of low voltage actuation in the 70ies of the past century.
The necessary electrical insulation step is done inside the stack: The PZT-layers are not completely metallized. A small insulation gap ensures the electrical separation between the internal electrode and the external supply electrode (Fig. A).

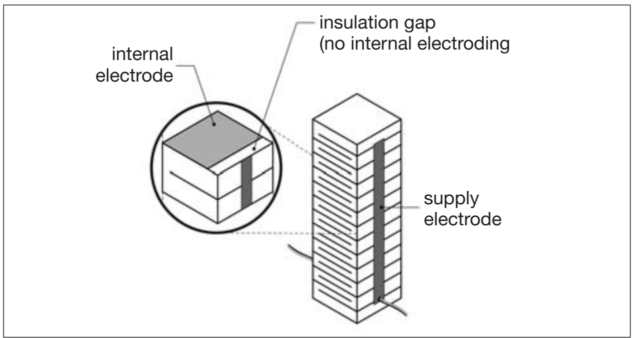


Fig. A: *In stack insulation scheme.*

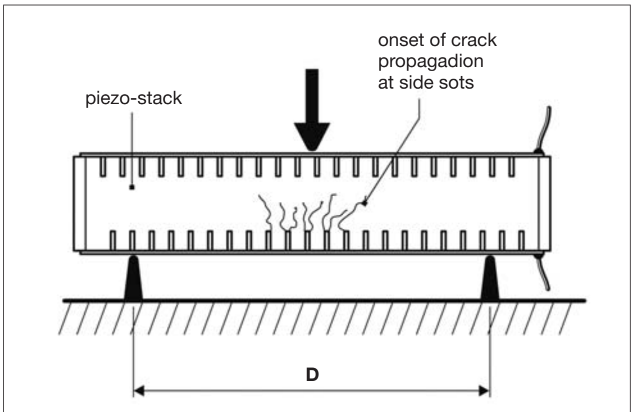


Fig. B: *Bending-induced ceramic cracking of isi-stacks with side slots*

It is easily seen, that the PZT-ceramic of the stack is only partially active and a steep transition from active to inactive PZT-ceramic is created:
A pronounced mechanical tensile stress at the active/inactive boundary region occurs, when the PZT-stack is activated and expanding.

This leads potentially to mechanical cracking of the ceramic and electrical break down of the stack during long-term action, when potential crack propagation is not compensated for by special techniques.

Further:
The isi-structure with inside slots is more sensitive to bending forces, because the notches act as starting point of ceramic cracking (Fig. B).

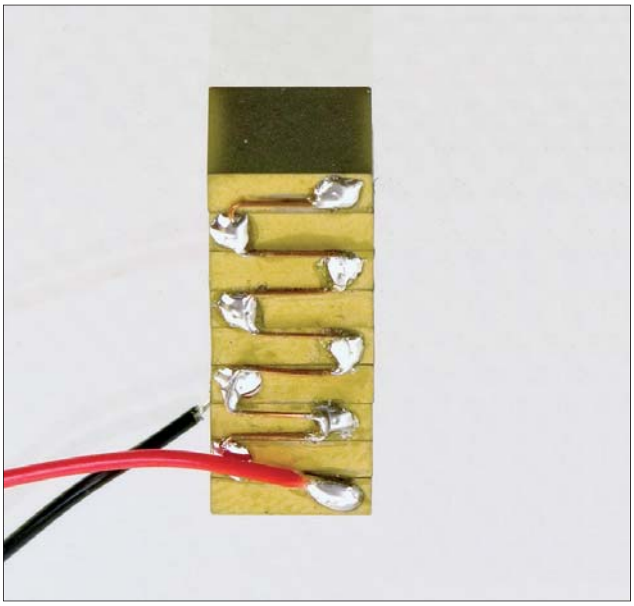
The designs of any coupled mechanics has to be optimized for strict axial loading of isi-stacks. Attention should be paid to any mechanical influences resulting in bending modes especially of stacks with large ratio of length/diameter.

Mechanical preloading
In addition to the above-mentioned techniques, the internal stress-problem of isi-actuators is usually handled by the application of a large axial preload or prestress even for static or low dynamic applications.

Supply electrodes
The supply electrodes of isi-structures bridge the side slots/cuts in the stack structure. For simple arrangements, the side electrodes tend to rupture in the vicinity of the side slots, when the stacks are operated with high strain and dynamics. The actuator will be deactivated then.
The optimum of highly reliable side electrodes is achieved by using metal mesh.
(The osi-techniques does not need such strategies simply due to the absence of the side cuts/slots).

6. LV quasi monolithic isi piezostacks

No cracking of the ceramic occurs for rather thin elements. This means: When the axial thickness of the multi-layer element is held within 2-3 mm (“Piezo-chips”).
Longer stacks are manufactured by glueing such monolithic piezo-chips. The gluelines between the chips provide stress relaxation.
The mechanical properties of such longer stacks depend to some extent on the quality of the glue-joints.



Chip-based quasi-monolithic-stack

PIEZOMECHANIK is a globally recognized supplier of first-class piezo systems.

**Our actuator specialists are excellent connoisseurs of the current actuator scene.
This allows you to point out certain intricacies of the topic, which you will not find in the usual company scripts.**

PIEZOMECHANIK successfully provides advice and development contributions even for unorthodox piezoaktorian applications, some of which go far beyond the classical approaches.

We get for you from actuators what is really in it.

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