PI

Reliability of Multilayer Piezoelectric Actuators in Precise Positioning Applications

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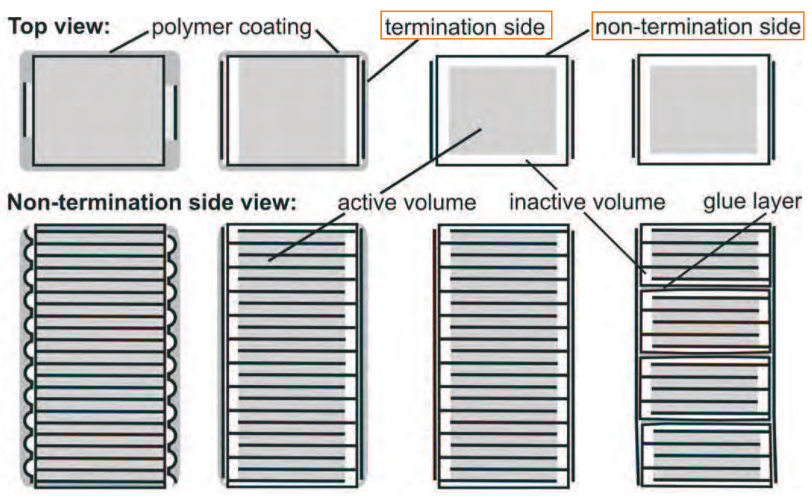
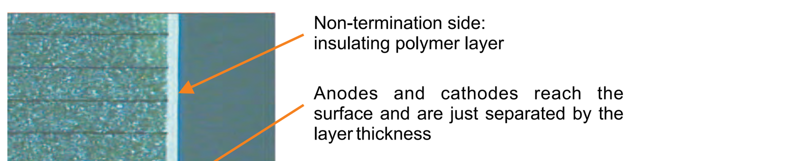
The piezoelectric multilayer actuator technology is an essential tool in ultra-precise nano-positioning. For the further spreading into new applications it is very important to exactly know and specify the operating limits of these actuators. This work presents a DC-signal-lifetime calculation tool for PICMA® co-fired multilayer actuators as a result of an extensive study at different temperature and humidity conditions. Furthermore, AC-results for several driving signals, pre-stress, and temperature conditions are shown.

Conventional multilayer actuator technology

Conventional designs

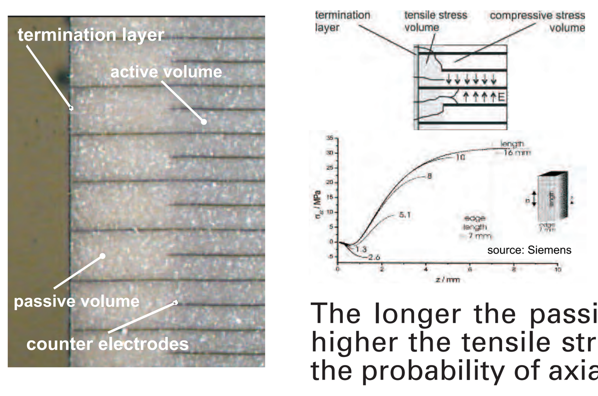


Polymer insulation



Polymer layers are not sealed for humidity! DC-signal degradation will happen in humid environments (see mechanisms below).

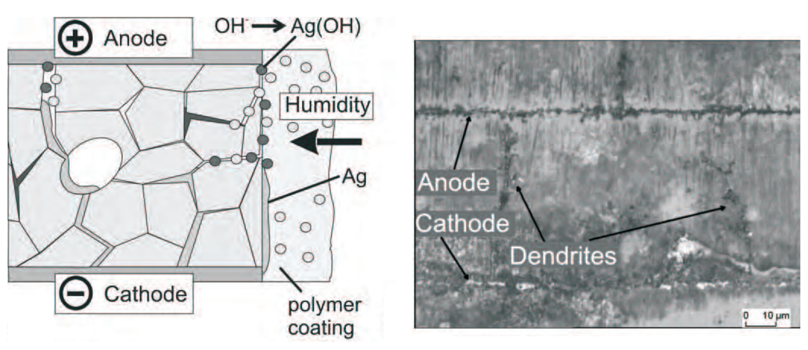
Stress accumulation



The longer the passive volume the higher the tensile stress, the higher the probability of axial cracks.

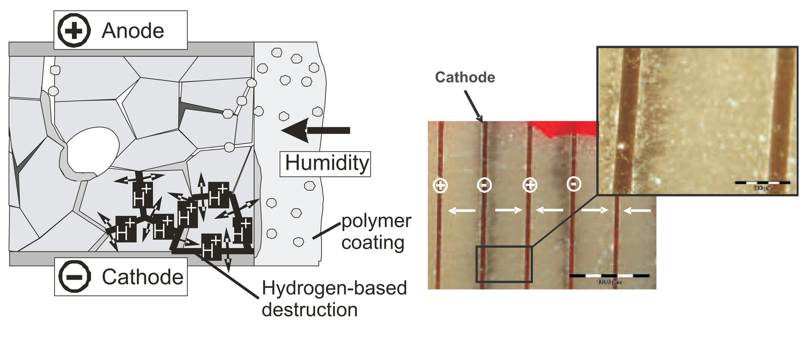
DC-signal degradation

Metal migration



Humidity, which penetrates the polymer coating and high electric field yield in electrolysis of water -> ionic transport of metal can happen on non protected surfaces and internal ceramic failures -> dendrites will grow.

Hydrogen degradation



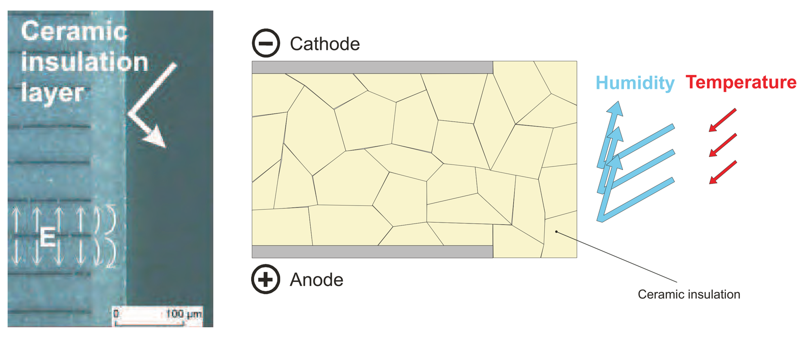
Humidity, which penetrates the polymer coating, and high electric field yield in electrolysis of water -> hydrogen will lower the fracture toughness by orders of magnitude -> internal stresses will separate the ceramic grains -> insulations resistance is lowered. This is the dominating, humidity-driven, DC-degradation process!

PICMA® actuator technology

PICMA® design

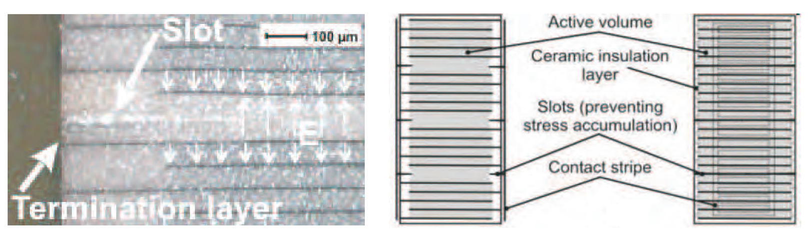
Ceramic insulation

- application of a ceramic foil of a defined thickness to the non-termination surface before sintering
- **inorganic layer is dense for humidity – humidity degradation is prevented!**
- insulation layer is penetrated by the scattering electric field of the internal electrodes, undefined cracks are minimized and distance between these cracks is increased



Slot design

- artificial cracks ("slots") separate the passive volume into 2 mm segments, **stress accumulation is prevented!**
- depth: 0.3 ... 0.4 mm
- layer is active but with double layer thickness
- cracks are bypassed by the outer contact stripe (see below)

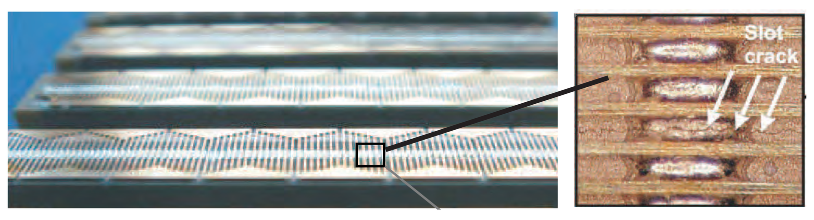


PICMA® variants

Dynamic driving

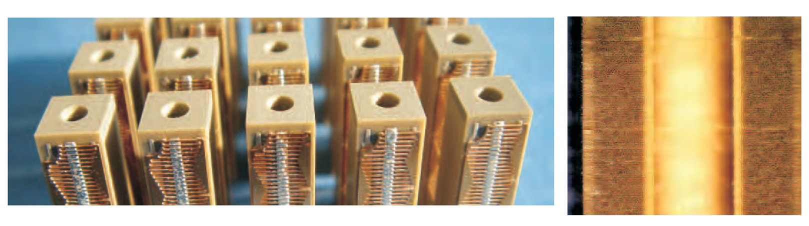
New meandric contact stripe design:

- basic functions same as with standard version: axially soft and bypassing the artificial slot cracks
- high peak currents (20A)
- allows for fast movements (50 µs slew rate)



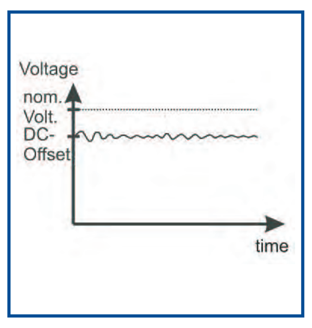
PICMA® with hole

- PICMA® 5 x 5 x 18 mm³ / ID2 mm
- PICMA® 5 x 5 x 9 mm³ / ID2 mm
- complete ceramic insulation
- slots inside and outside

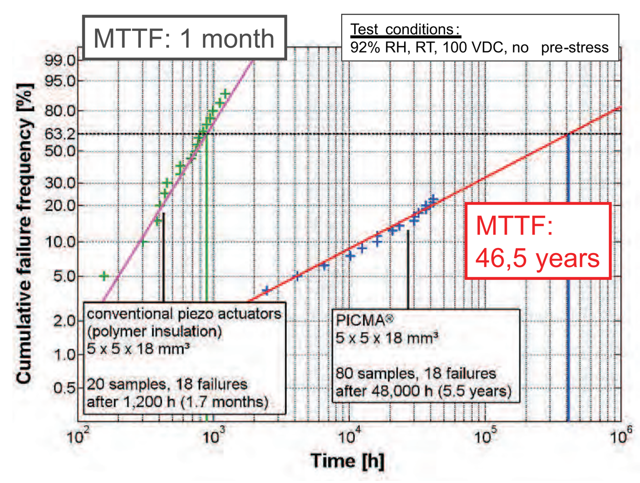


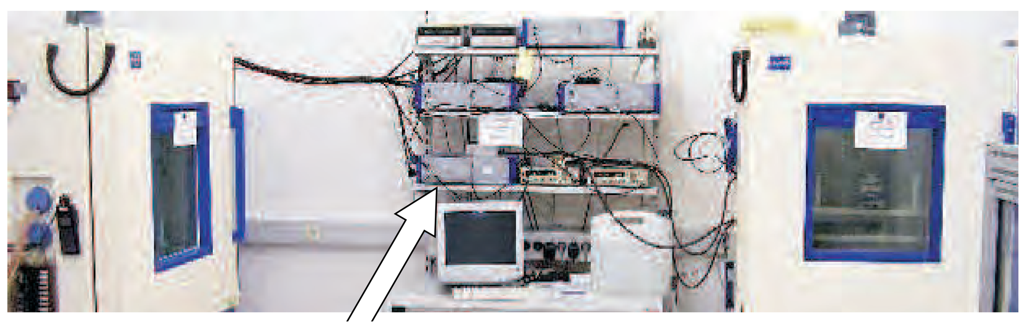
Reliable PI-nanopositioning systems with PICMA®

DC-signal lifetime



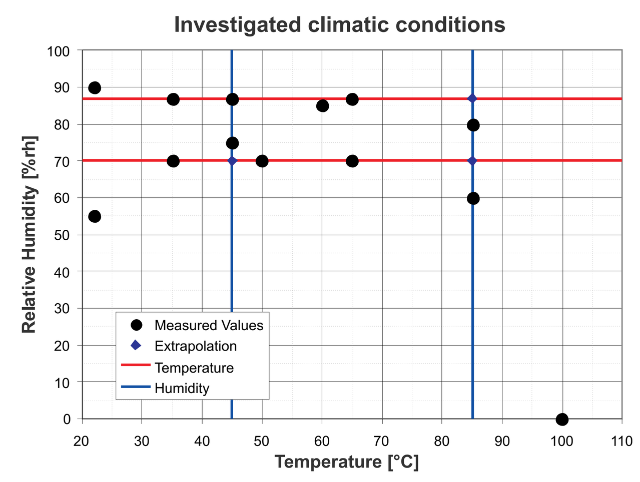
- first singular tests demonstrated the **superior DC-lifetime behavior of PICMA® actuators compared to conventional polymer insulated designs**
- but there was a strong customer request for the prediction of the PICMA®-lifetime for variable environmental conditions as well as variable driving voltages
- therefore a comprehensive study was started to get a DC-signal lifetime calculation tool for PICMA® actuators



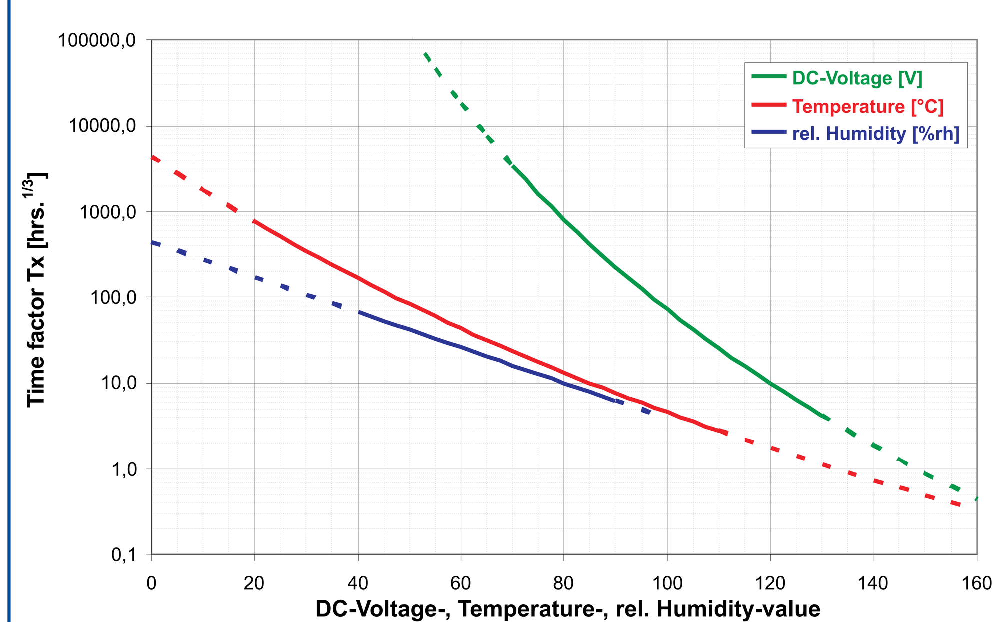


DC-signal-lifetime study:

- run for 2 years; 4 climatic chambers in parallel; grid of tested environmental conditions (temperature + humidity)
- more than 1.000 PICMA®-samples, 8 samples at every DC voltage, 5 DC voltages at every climatic condition, samples from different production batches, precycled
- interpolation, averaging and iteration sequence to extract the lifetime relationship
- use a power law for the voltage-, an Arrhenius function for the temperature- and an exponential function for the humidity-relation
- present the results not as a (difficult) equation but as a graphical tool

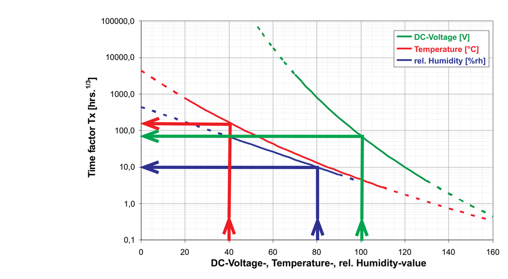


PICMA® DC-signal lifetime calculation tool



How to use the tool?

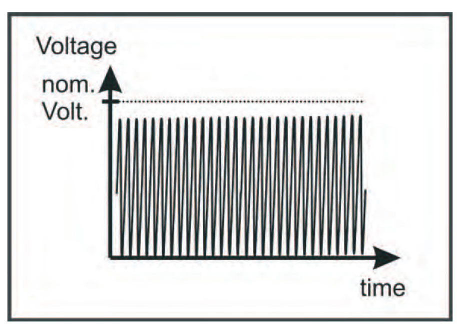
- take the numbers of the driving conditions:
  - voltage in volt
  - environmental temperature in °C
  - relative humidity next to the PICMA® in %
- determine the three factors T_x from the relevant curves (see example below)
- calculate the lifetime MTTF in hours just by multiplying the three factors
- when comparing the curves, especially the voltage shows a steep slope, hence the voltage impact on the lifetime is very pronounced (please consider that the curve is extended above the nominal voltage range of 120 V)

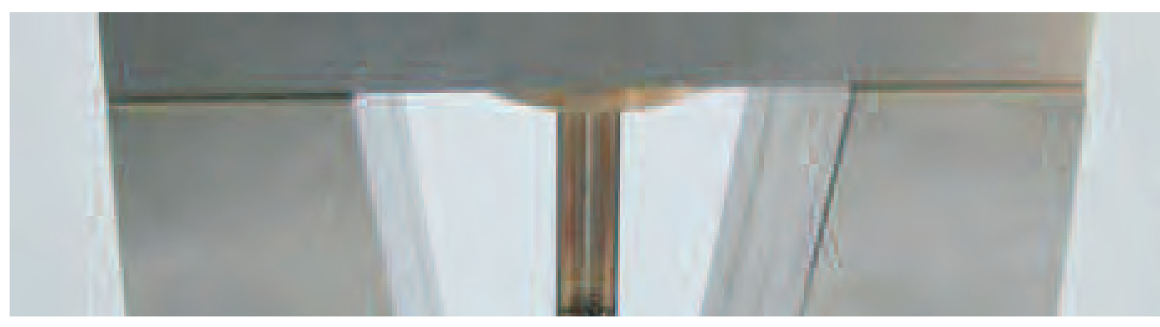


Conditions: 100 VDC, 80% RH, 40°C

MTTF = 70 x 10 x 130 hrs. = 91,000 hrs. (10 years)

AC-signal lifetime





Goal: High testing frequency to get many cycles within short time.

- high current version PICMA 5 x 5 x 36 mm³ (see left), 5 samples
- forced air cooling (to counteract self heating), 300 N pre-stress
- 0...120 V, sine wave, 1.2 kHz (10^8 large signal cycles per day!)
- **10^{10} cycles within 100 days -> successful**

Further tests (extreme voltage signals above the nominal voltage of 120 V):

- 3 samples PICMA® 7 x 7 x 36 mm³, 0...150 V, unipolar, 800 N pre-stress, rectangular signal with 80 µs slew rate and 50µm displacement at 150°C to 5 x 10 cycles
- 10 samples PICMA® 2 x 3 x 18 mm³ at 0...200 V unipolar, triangular signal, 464 Hz, -30°C silicone oil, no pre-stress, $1x10^9$ cycles
- All tests were successful. No actuator lost > 10% of its initial displacement.

Conclusions

- DC-degradation: humidity is important; electrolysis -> migration, hydrogen embrittlement; distinct voltage dependency
- AC-degradation: tensional stresses in passive volume -> axial cracks
- PICMA® -> 3 patented design elements: 1) ceramic insulation layer, 2) slot design, 3) crack bypassing contact stripe
- DC-lifetime: superior lifetime of PICMA® actuators, 2.5 magnitudes better than conventional quality; graphical calculation tool
- AC-signal: 10^{10} full range cycles at 1.2 kHz

References: [1] Pertsch, P.; Broich, B.; Block, R.; Richter, S.; Hennig; E.: DC- and AC-signal reliability of piezoelectric multilayer actuators. Conference proceedings ACTUATOR2010, Bremen, June 2010, pp. 55-58. [2] PatentsDE102 34787C1 and US7,449,077 [3] Patents DE 10 2005 015 405 and DE10 2007 011652