International Conference on Experimental Mechanics Experimental Analysis of Nano and Engineering Materials and Structures Alexandroupolis, Greece, July 1-6, 2007

ICEM13

Fracture in piezoelectric ceramics and PZT/electrode interfaces

H. Jelitto, F. Felten, G. A. Schneider,
C. Häusler*, H. Balke*

Hamburg University of Technology, Institute of Advanced Ceramics, Germany
*Technical University Dresden, Institut für Festkörpermechanik, Germany

(supported by the German Research Foundation, DFG)

TUHH
Technische Universität Hamburg-Harburg

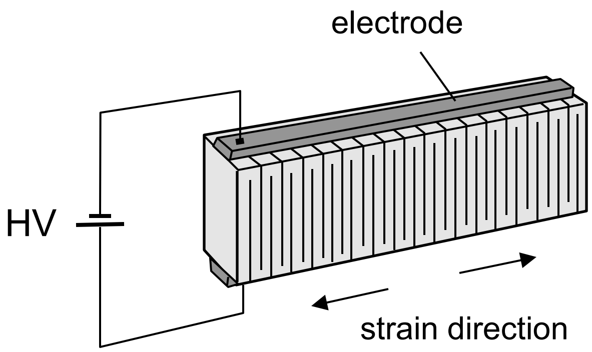
TK
TUHH Ceramics

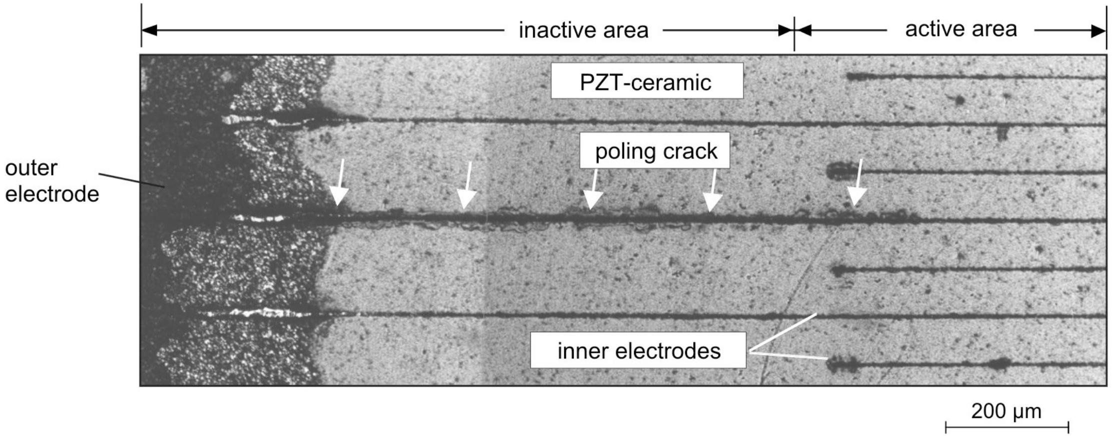
Outline

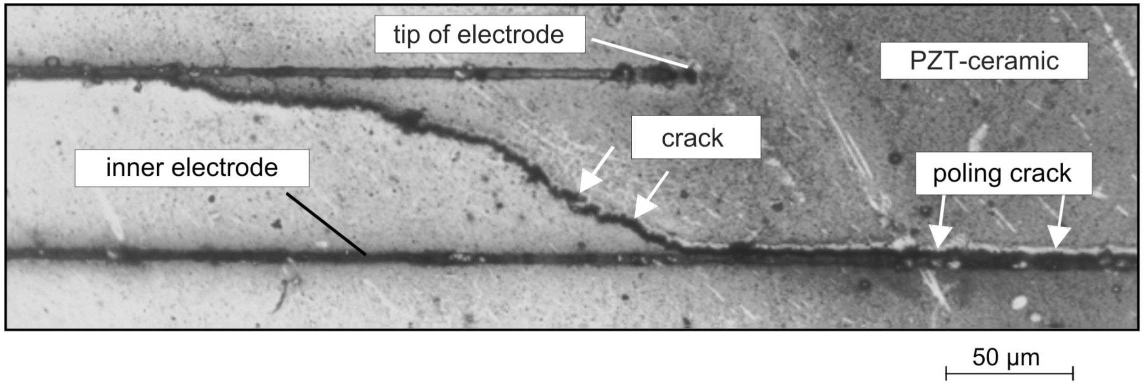
1. Introduction
2. Theoretical basis
3. Experimental set-up for stable crack growth with small signal modulation method
4. Results
   a) Insulating crack in PZT
   b) Conducting crack in PZT
   c) Interfacial crack
5. Summary and prospects

Practical motivation

Damage phenomena in actuators







Dependency of interfacial fracture toughness on:

a) the poling configuration
b) external electric fields

Photos by Holger Weitzing: „Schadensphänomene und bruchmechanische Characteri-sierung piezokeramischer Multilayeraktoren," dissertation, TUHH, Hamburg, 2000

Motivation concerning the theory

1. Fracture mechanics in the mechanical case basically understood.
   The crack grows, if $K_I \geq K_{IC}$ (fracture toughness) or $G_m \geq G_{mc}$.

2. Piezo- and ferroelectric materials are more complicated.
   a) piezoelectric coupling
   b) additional external electrical loads
   c) high permittivity (ε) $\rightarrow$ high electrical energy density
   d) fracture in metal-piezo-ceramic interfaces
   e) additional inelastic processes

3. What is the general valid fracture criterion? G_{tot}?

Theoretical basis

Critical stress intensity factor (K_{IC}) or fracture toughness as a function of the crack length → **R-curve**

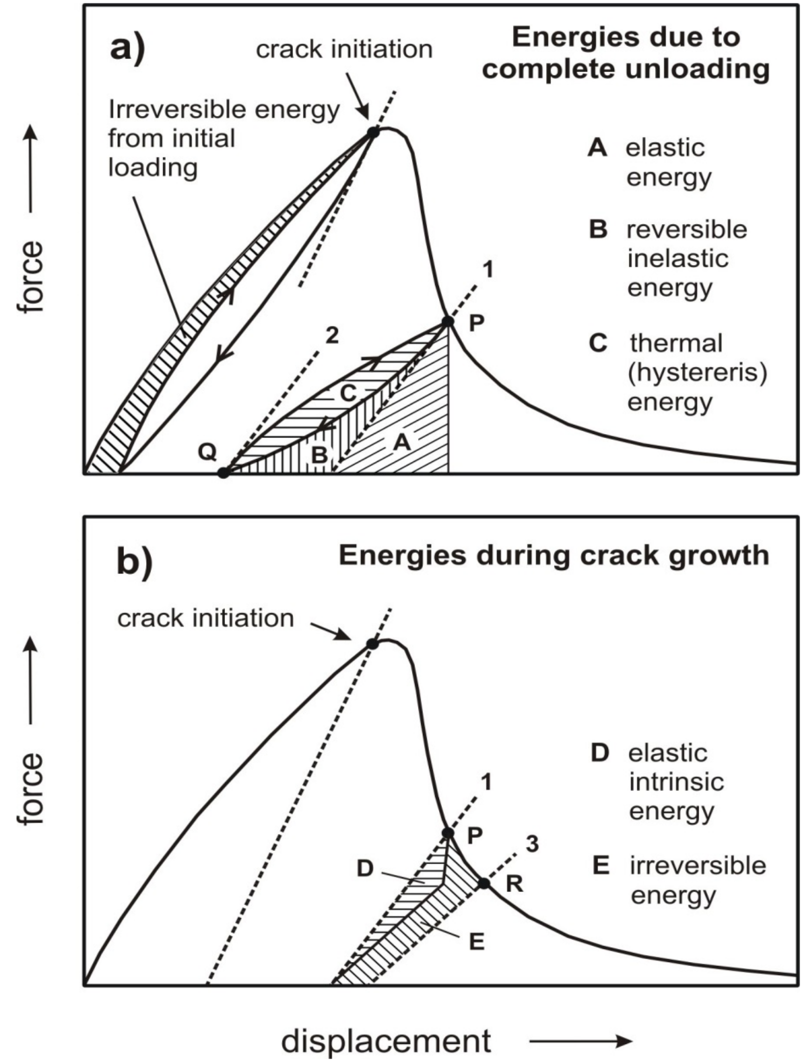
$$K_{IC} = \sqrt{a} \cdot \sigma \cdot Y\left(a/h\right)$$

→ Stable crack growth

The situation is complicated because of additional inelastic processes.

The (linear) elastic contribution can be separated

→ small signal modulation technique



Theoretical basis (linear elastic processes)

$$\longrightarrow \quad G_{tot} = -\left(\frac{\partial \Pi}{\partial A}\right) = \frac{F^2}{2}\frac{\partial C_m}{\partial A} + \frac{V^2}{2}\frac{\partial C_e}{\partial A} + F\,V\frac{\partial C_p}{\partial A}$$

(Z. Suo)

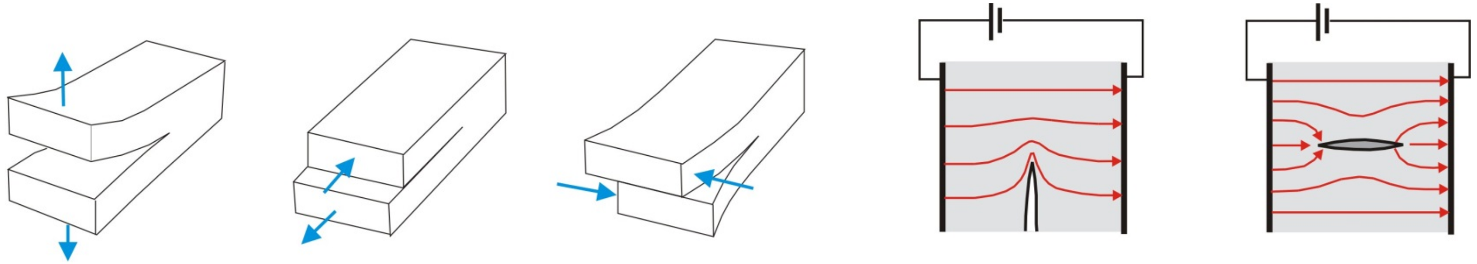
$$\text{with} \quad C_m = \frac{\partial \Delta}{\partial F}, \quad C_e = \frac{\partial Q}{\partial V}, \quad \text{and} \quad C_p = \frac{\partial Q}{\partial F} = \frac{\partial \Delta}{\partial V},$$

Π: potential energy, A: crack surface area, F: force, V: voltage, Δ: displacement,
Q: electric charge, C_m: mechanical compliance, C_e: capacitance, C_p: piezoelectric compliance

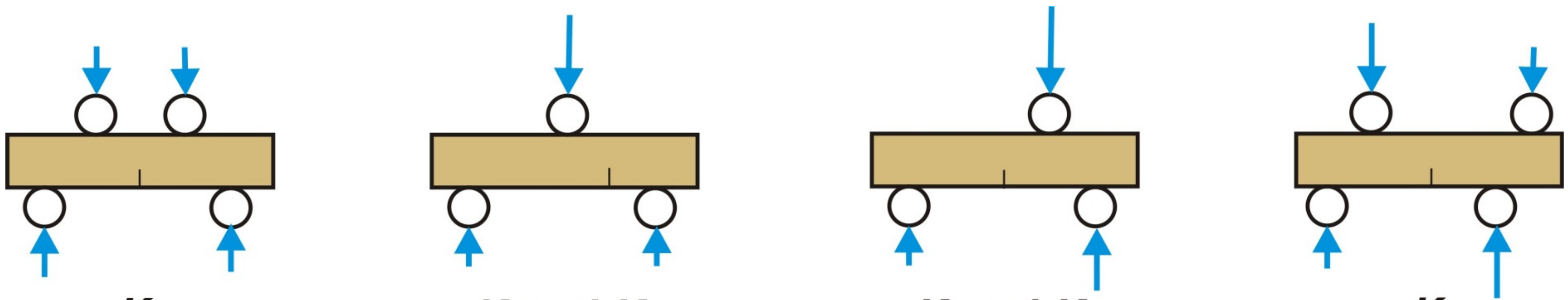
Aim of the experiment is the determination of the
total (linear) energy release rate: $G_{tot} = G_m + G_e + G_p$
in the metal piezo ceramic interface and mixed mode loading.

Equations by Z. Suo: „Mechanics Concepts for Failure in Ferroelectric Ceramics,“ AD-Vol. 24/ AMD-Vol.123, pp. 1–6, Smart Structures and Materials, ASME 1991

Different fracture modes



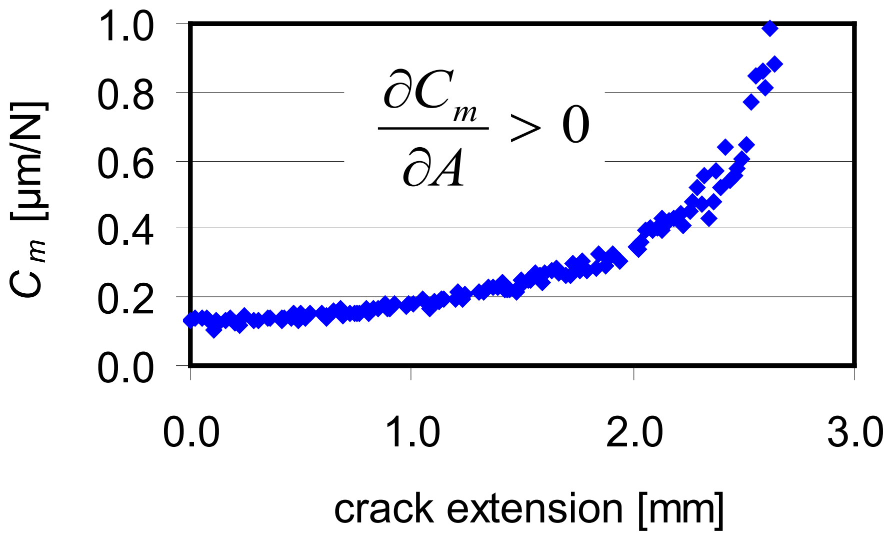
mode I | mode II | mode III | mode IV | mode E

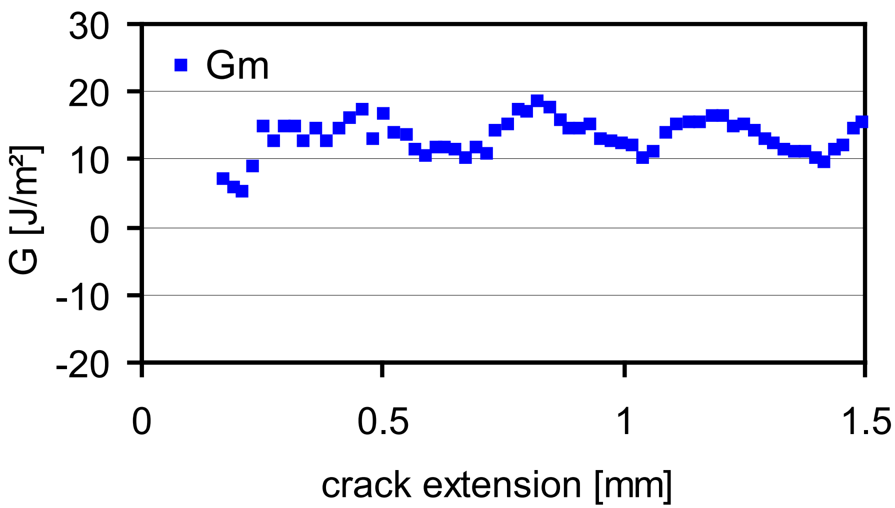


K_I | K_I and K_{II} | K_I and K_{II} | K_{II}

Measurement of single forces necessary

Calculation of the energy release rate

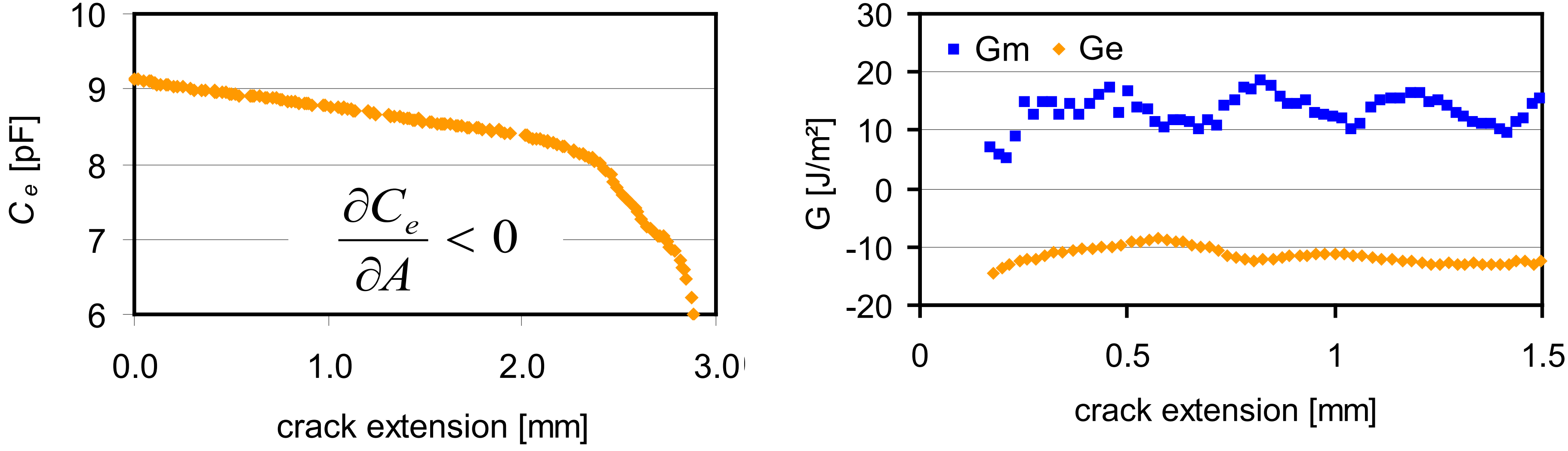




$$G_m = \frac{F^2}{2}\frac{\partial C_m}{\partial A}$$

Energy release rates for the growing crack in PZT at 500 V/mm (equations by Z. Suo, ASME 1991)

Calculation of the energy release rate



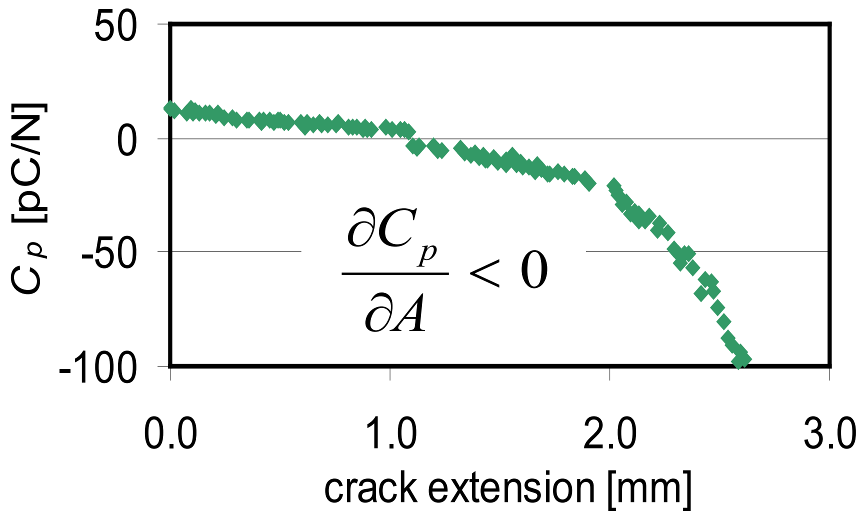
$$\frac{\partial C_e}{\partial A} < 0$$

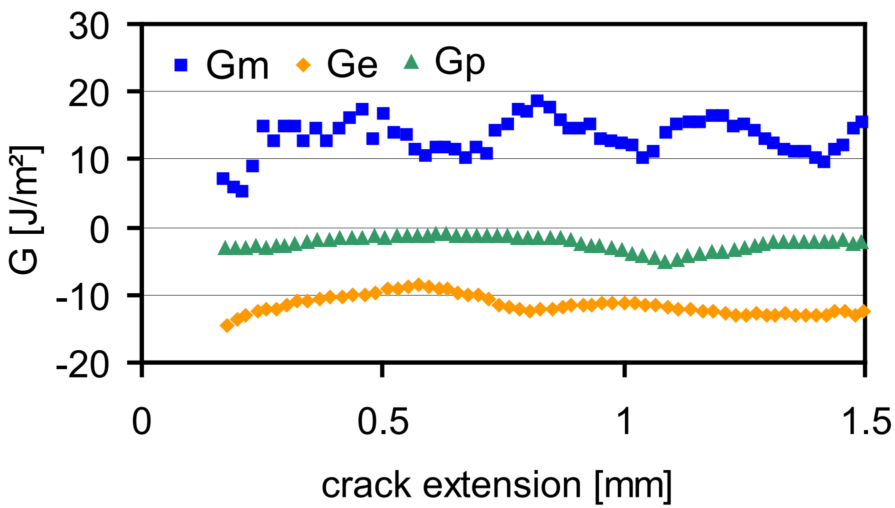
$$G_m = \frac{F^2}{2}\frac{\partial C_m}{\partial A}$$

$$G_e = \frac{V^2}{2}\frac{\partial C_e}{\partial A}$$

Energy release rates for the growing crack in PZT at 500 V/mm (equations by Z. Suo, ASME 1991)

Calculation of the energy release rate





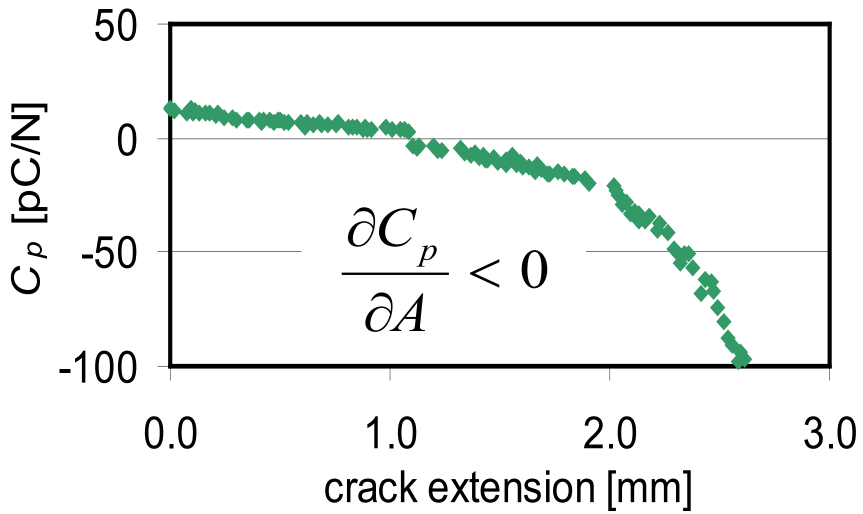
$$G_m = \frac{F^2}{2}\frac{\partial C_m}{\partial A}$$

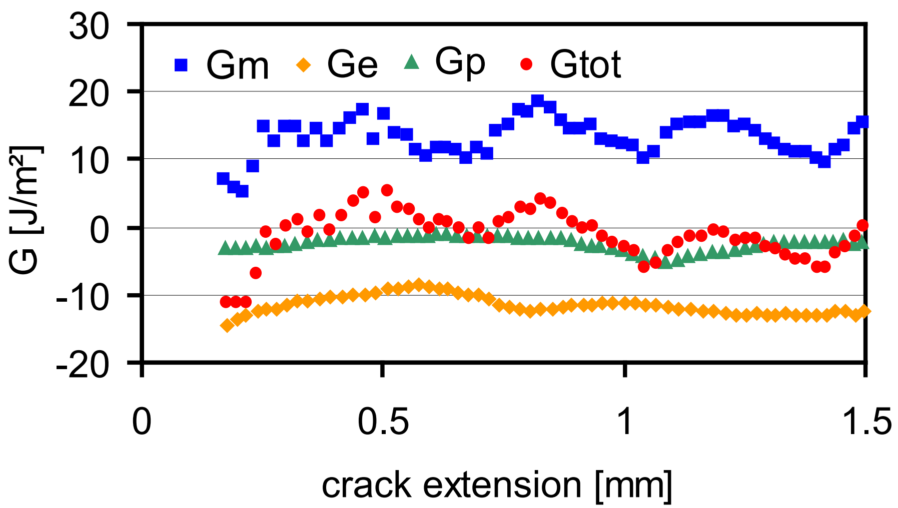
$$G_e = \frac{V^2}{2}\frac{\partial C_e}{\partial A}$$

$$G_p = FV\frac{\partial C_p}{\partial A}$$

Energy release rates for the growing crack in PZT
at 500 V/mm (equations by Z. Suo, ASME 1991)

Calculation of the energy release rate





$$G_m = \frac{F^2}{2}\frac{\partial C_m}{\partial A}$$

$$G_e = \frac{V^2}{2}\frac{\partial C_e}{\partial A}$$

$$G_p = FV\frac{\partial C_p}{\partial A}$$

$$G_{tot} = G_m + G_e + G_p$$

Energy release rates for the growing crack in PZT
at 500 V/mm (equations by Z. Suo, ASME 1991)

Principle set-up

measured:

- crack length a
- force F
- displacement Δ
- electr. charge Q

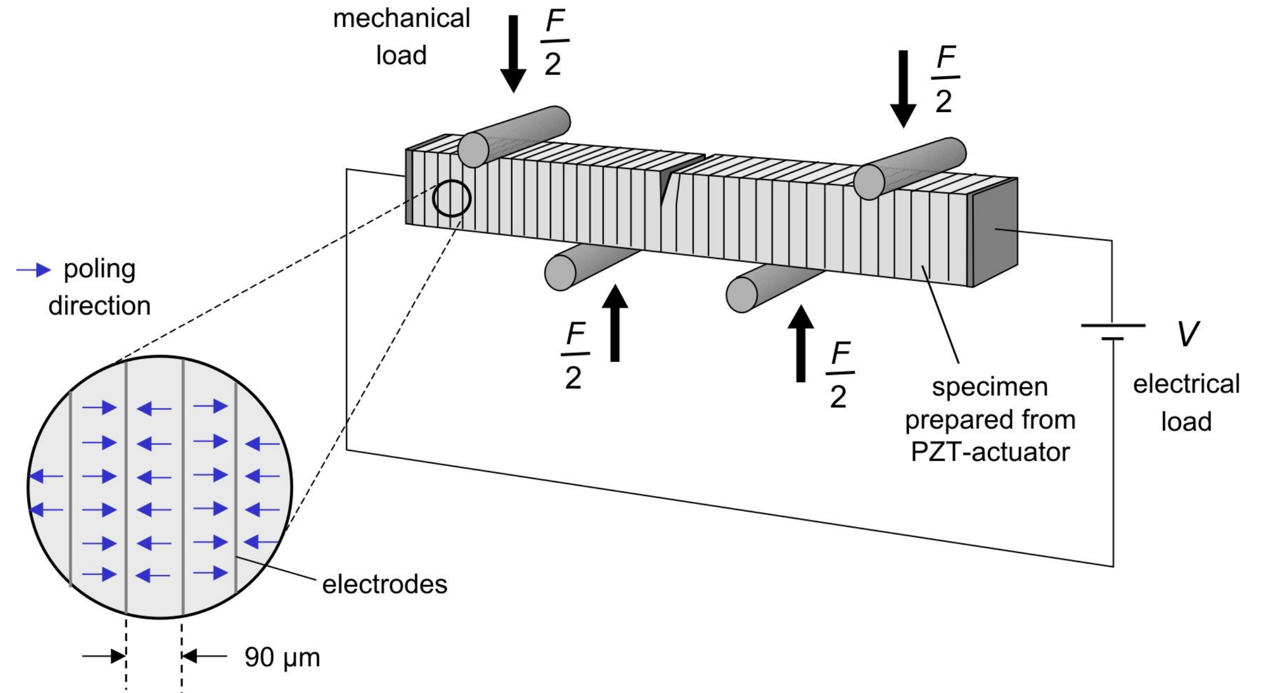
$$C_e^F = \frac{dQ}{dV}$$

$$C_m^V = \frac{d\Delta}{dF}$$

$$C_p^V = \frac{dQ^*}{dF}$$

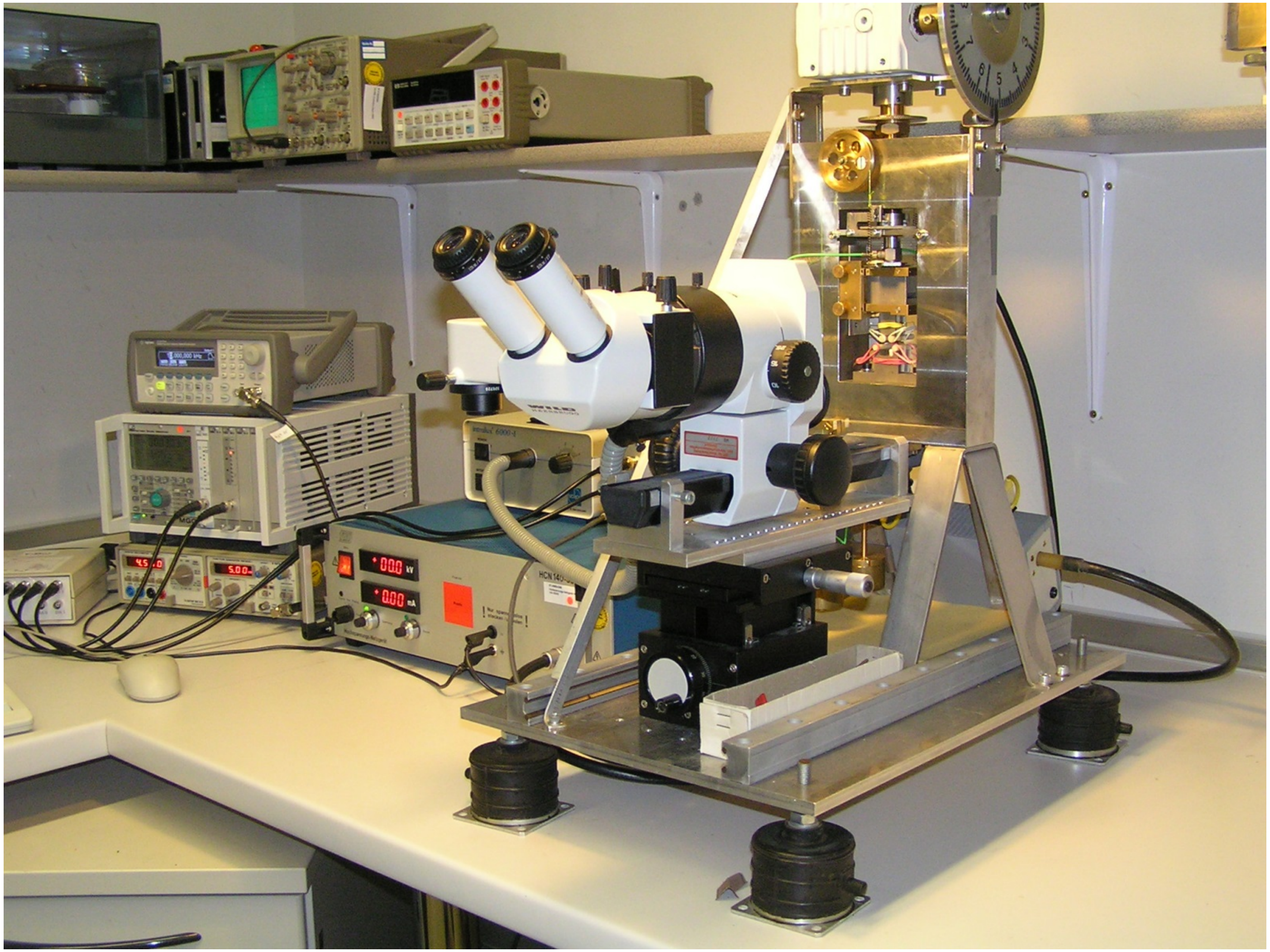
10 kHz modulation of *V*

5 Hz modulation of *Δ*

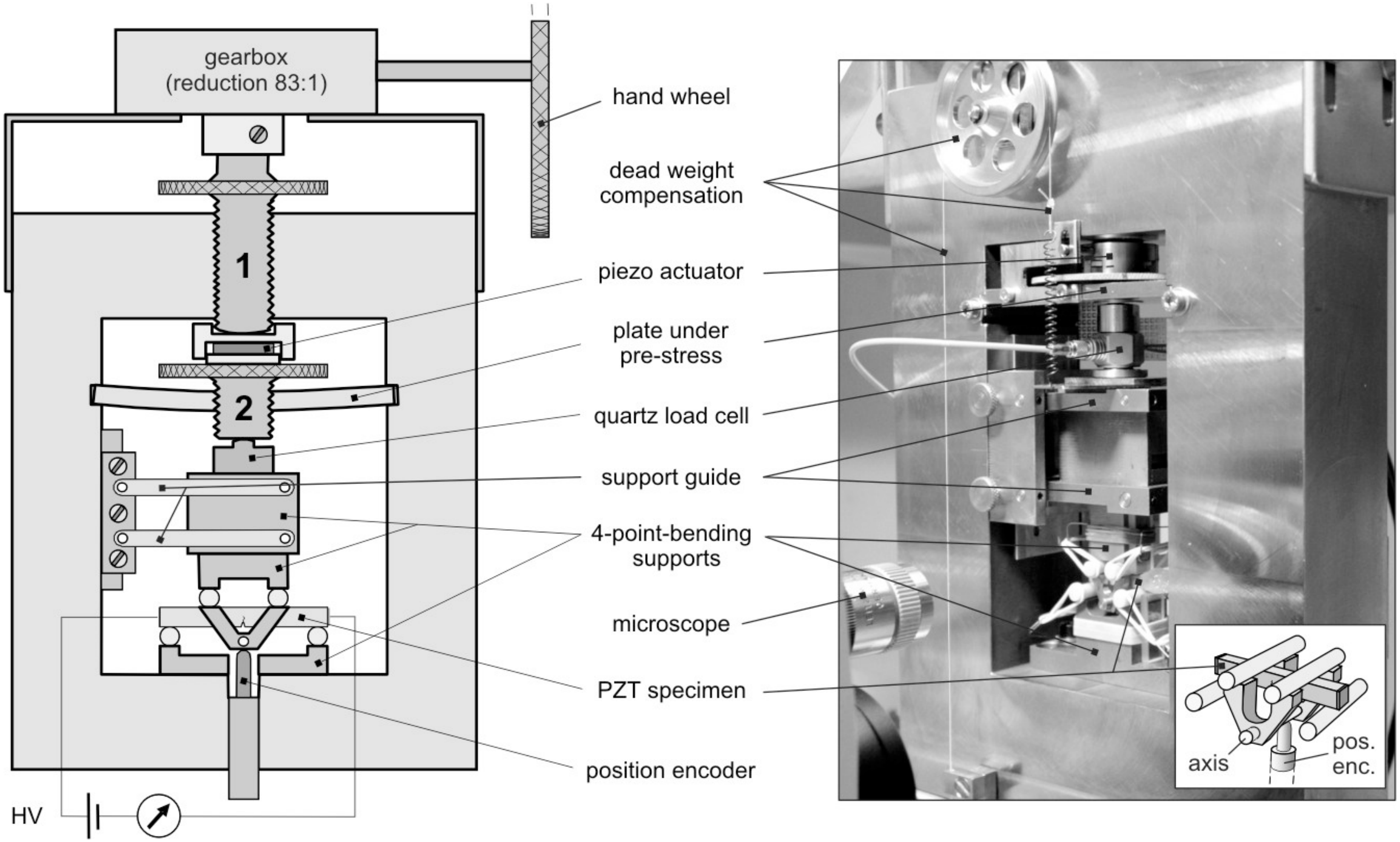


Controlled crack growth in 4-point-bending under high electric fields up to 500 V/mm

Experimental set-up



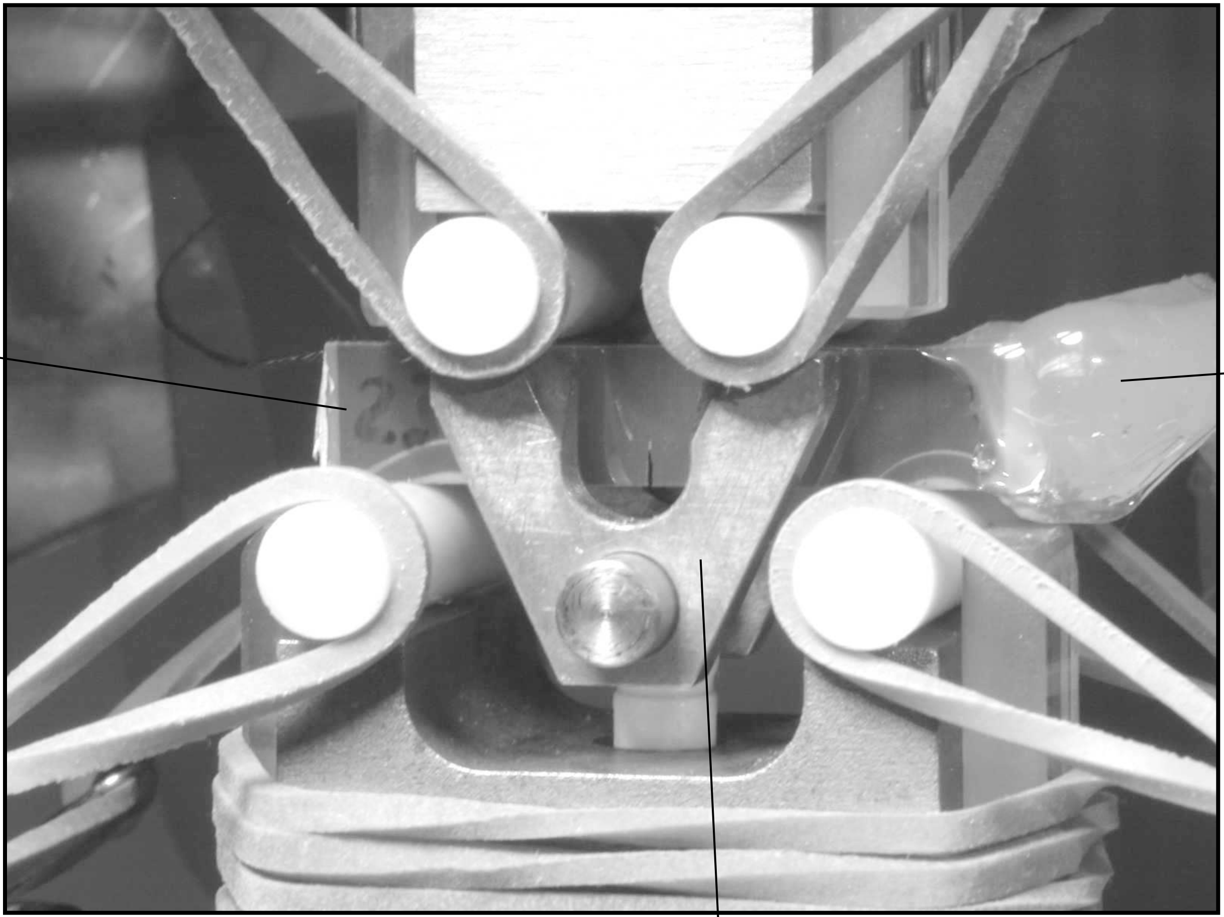
Mechanical set-up



4-point bending device

Experimental set-up

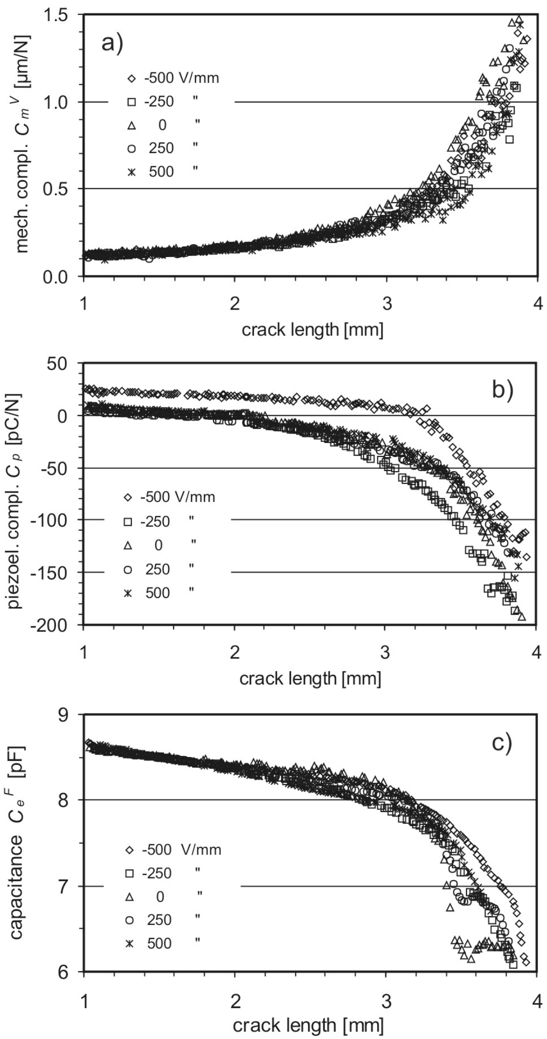
specimen

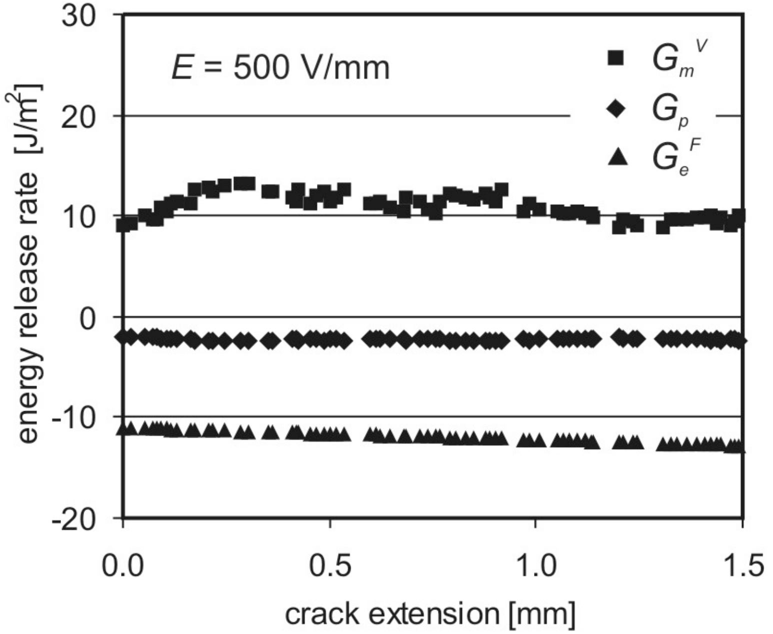


thermo-
plastics

Support rollers with small *construct* for transferring the displacement to the position encoder

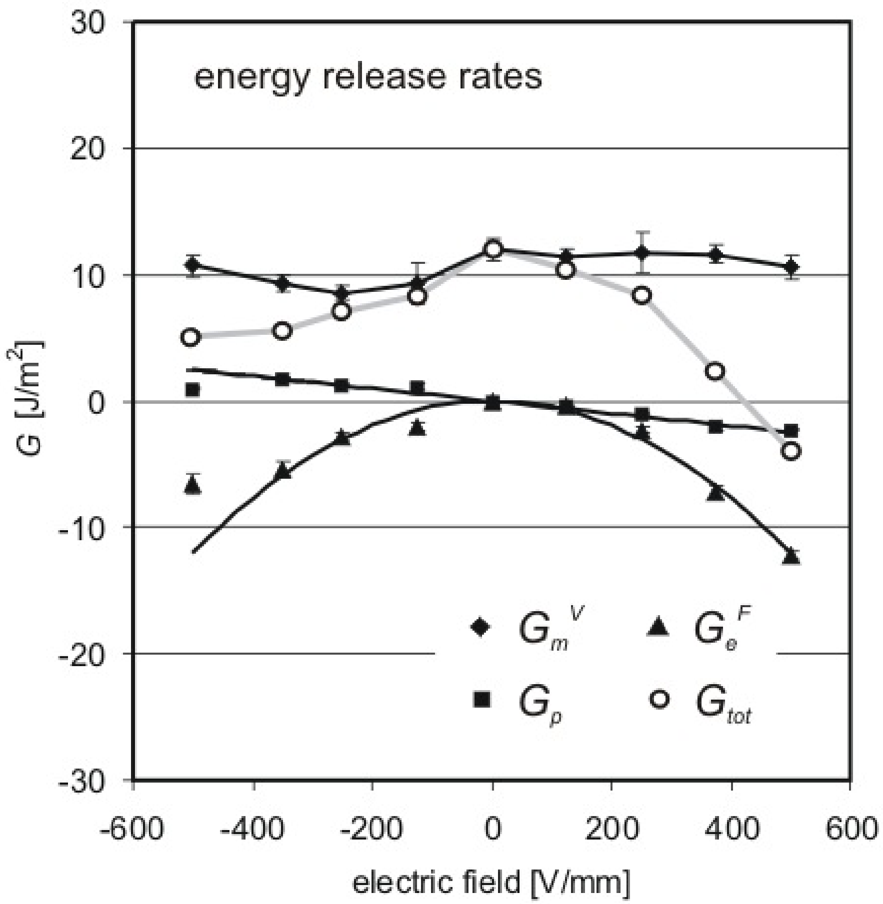
Insulating crack: experimental results





The total (linear) energy release rate G_{tot} at 500 V/mm becomes negative.

Insulating crack: experimental results



The total (linear) energy release rate G_{tot} is not a good fracture criterion , but more likely the mechanical part of it, which is G_m or $G_m + G_p$.

Possible reasons:

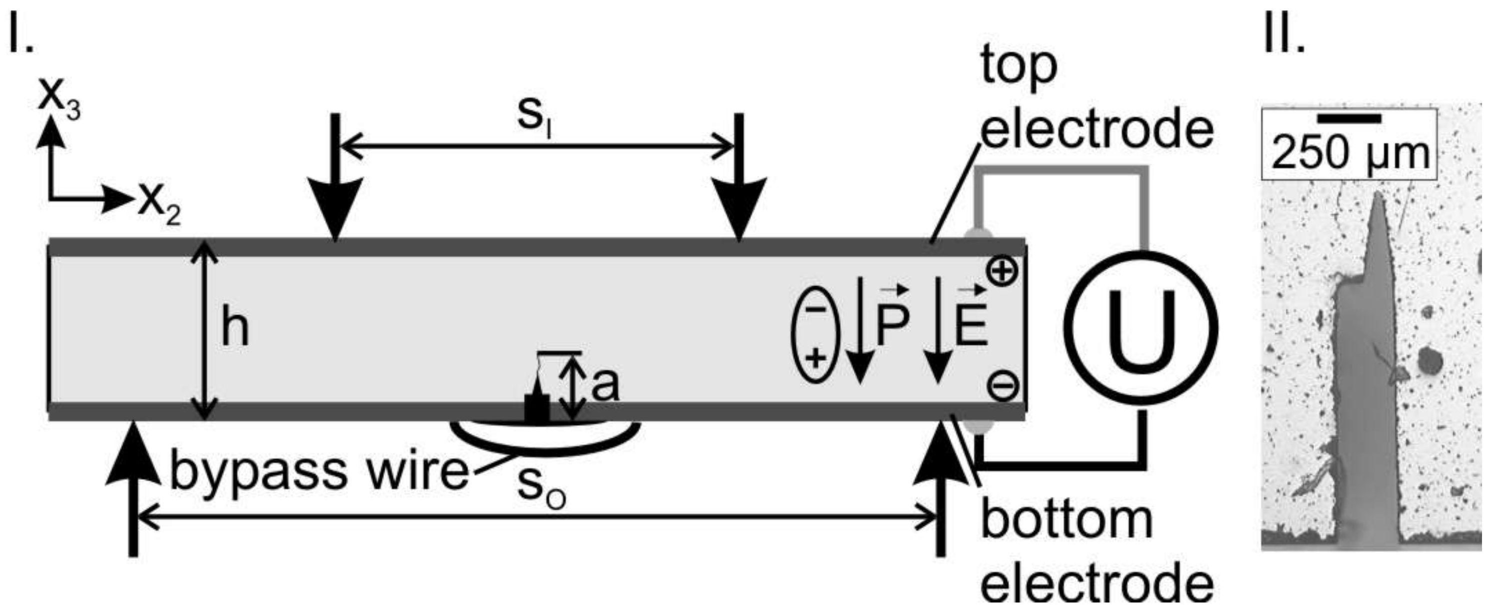
The electric energy contribution is reduced by

1. Screening of remanent charges on the crack faces by free charges.
2. Electric break down effect, when the electric field inside the crack reaches the break down level.

Effect of electric field is about 10 to 20 %.

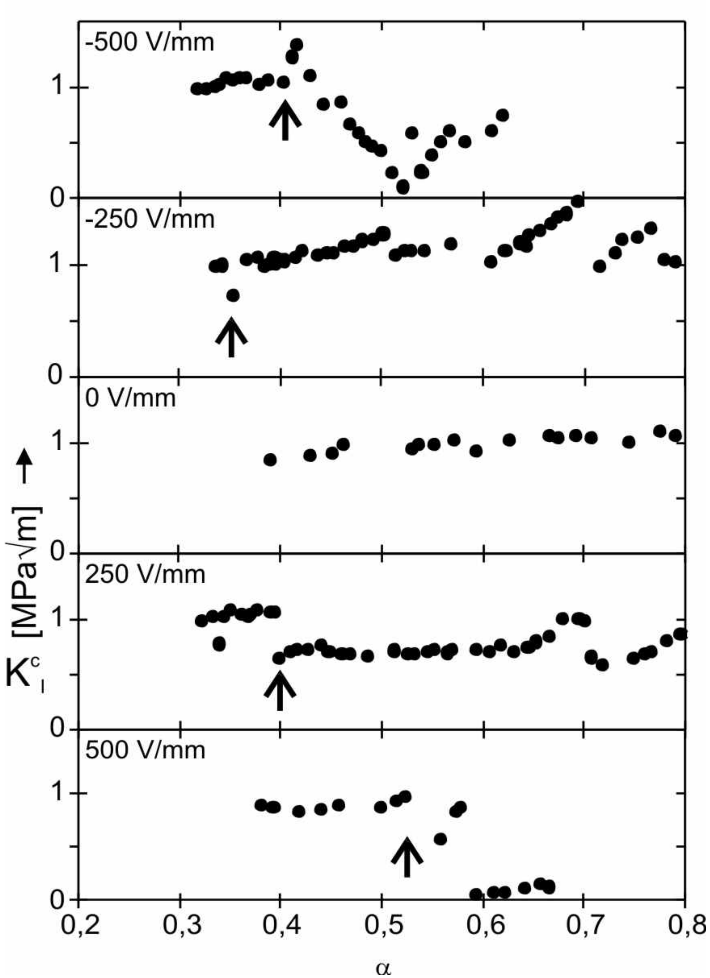
Negative fields facilitate crack growth.

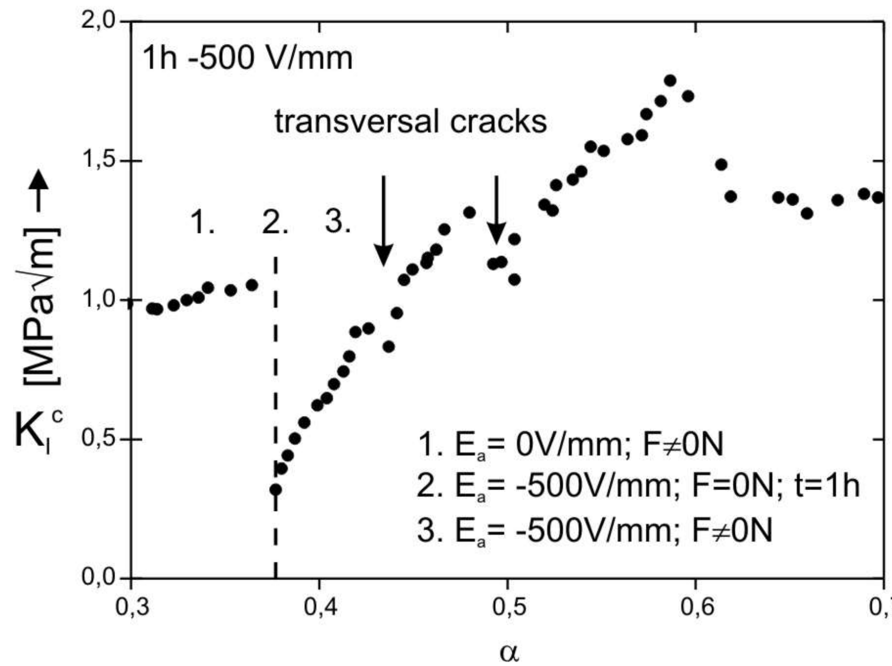
Conducting crack: experimental results



Drawing by Florian Gehrig: „Bruchmechanische Untersuchung am leitenden Riss in PZT," diploma thesis, TUHH, Hamburg, 2004

Conducting crack: experimental results





(Here, *E* negative means *E* parallel to poling direction.)

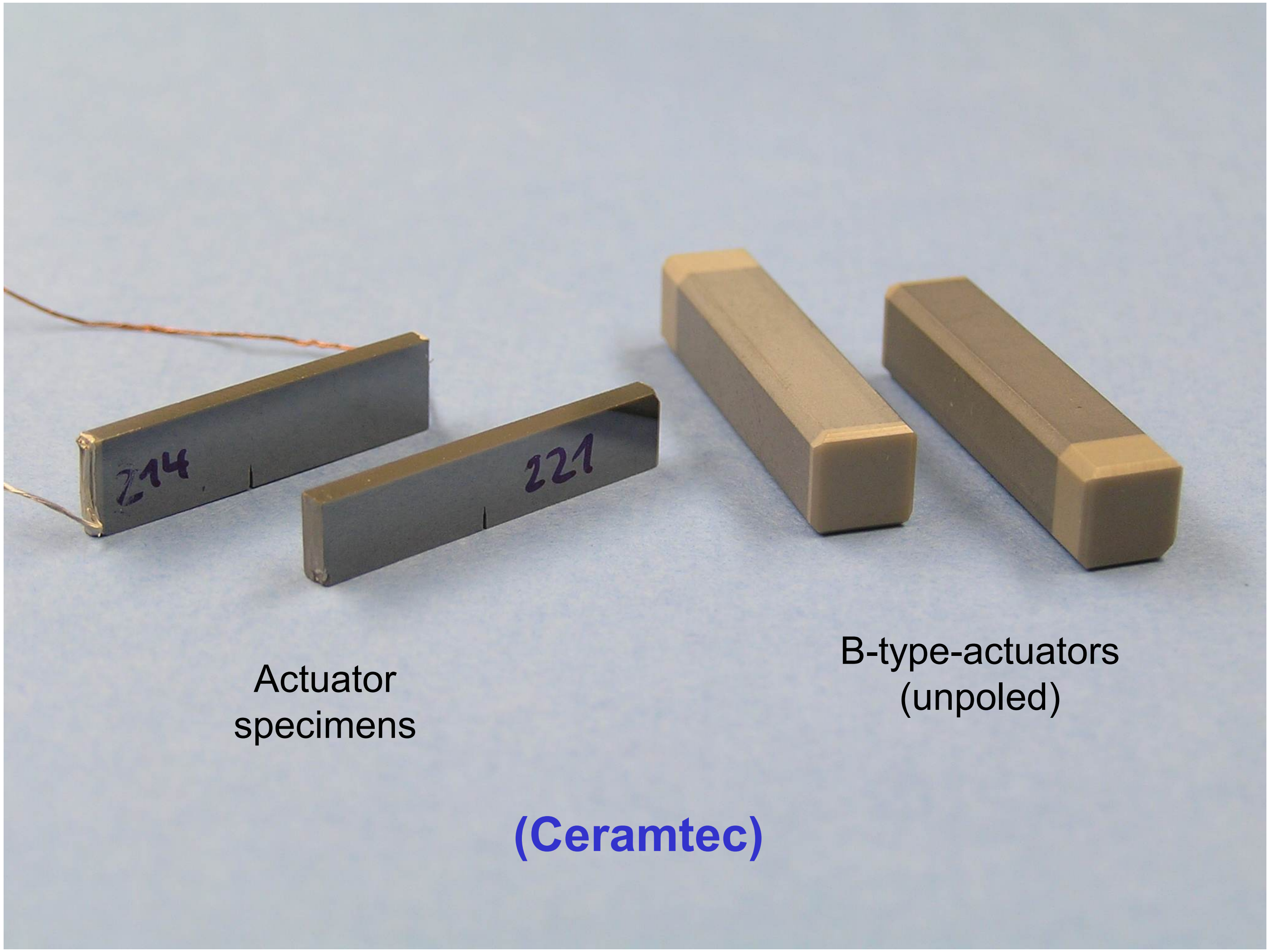
E parallel: K_{IC} is continuously increasing.

E antiparallel: K_{IC} immediately decreases.

Effect of electric field is up to 100 %.

Measurements by Florian Gehrig: „Bruchmechanische Untersuchung am leitenden Riss in PZT," diploma thesis, TUHH, Hamburg, 2004

Actuator specimens

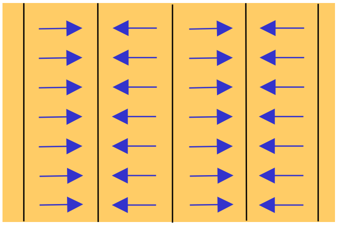


Bending tests in multilayer actuators

Two types of actuators with different piezo ceramics

1. A-type actuator

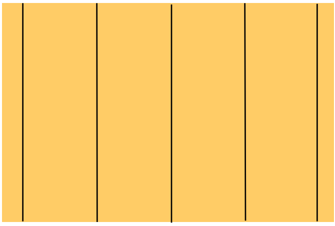
alternating polarization



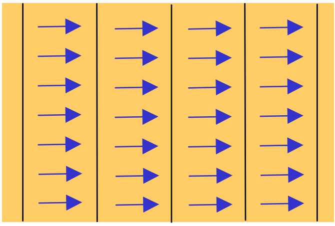
(all parameters known)

2. B-type actuator

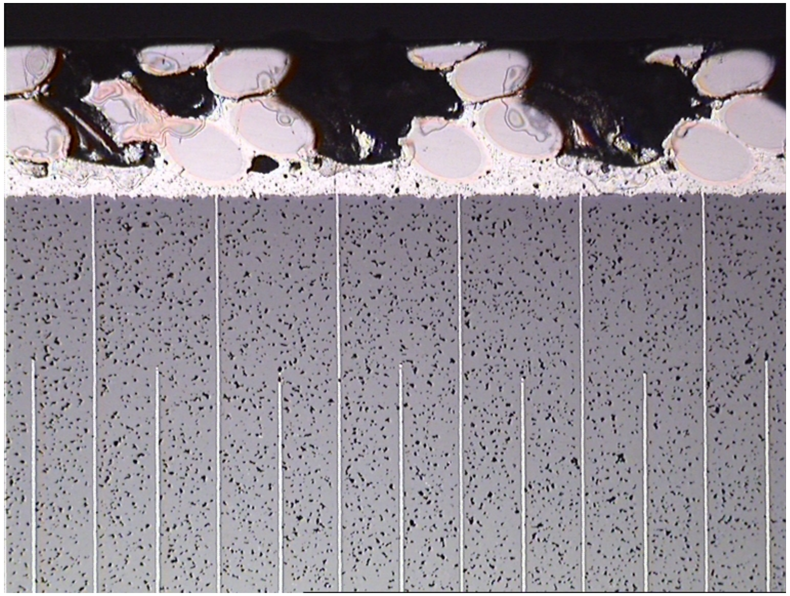
not poled

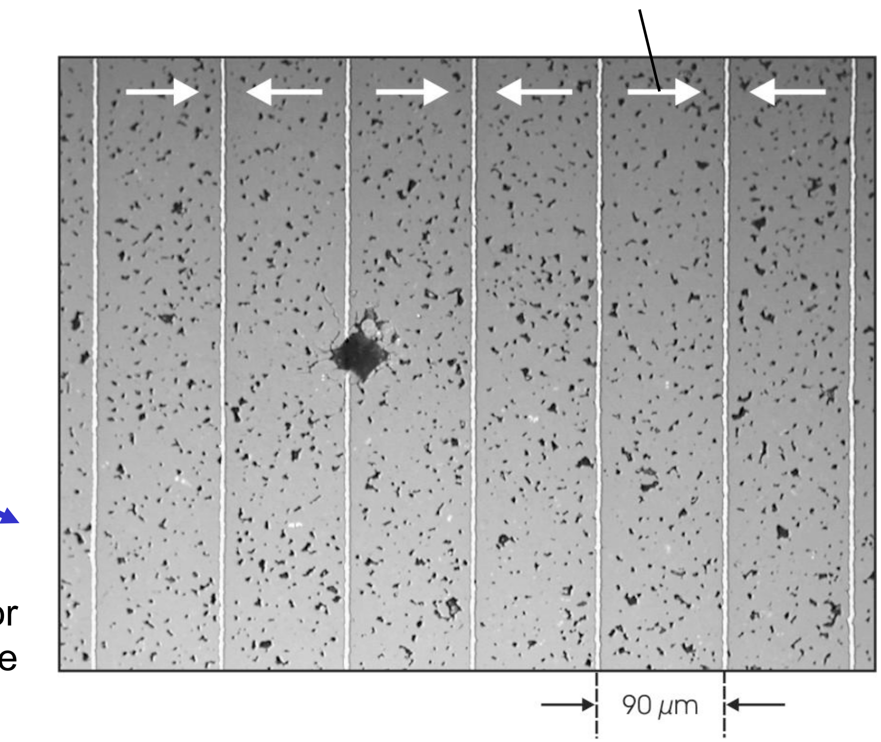


unidirectional polarization



Experimental set-up





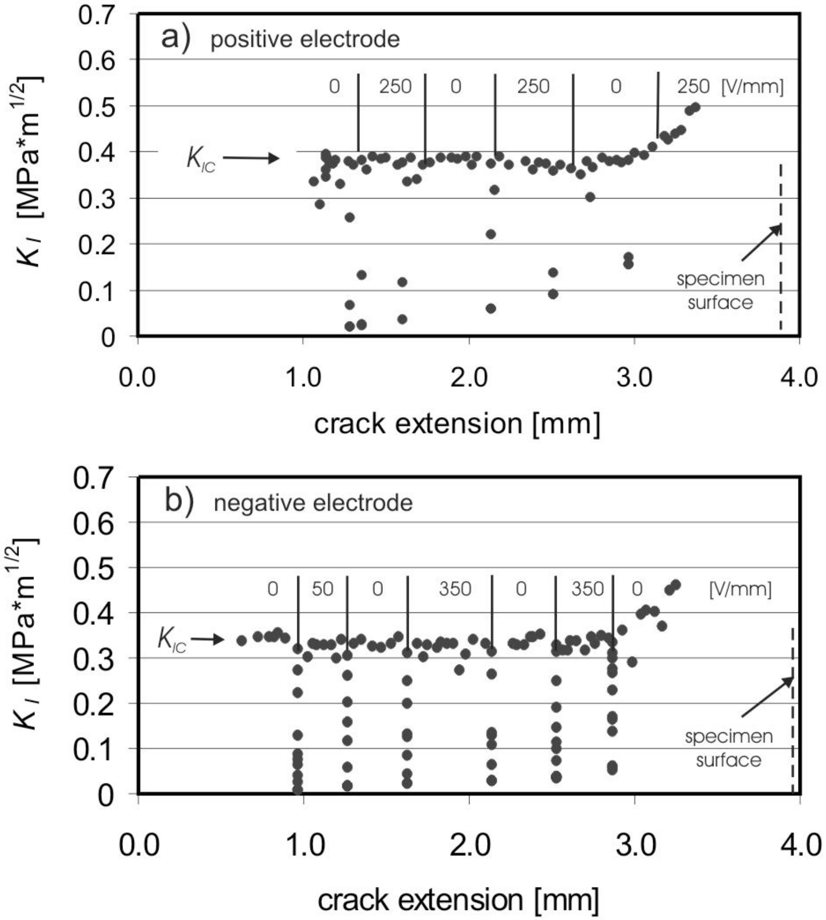
How can the crack electrode be identified as plus or minus electrode?

Vickers indent at electrode with known polarity for subsequent identification of the crack electrode

Experimental results

Influence of an electric field on the fracture toughness

(A-type-actuators, alternating polarisation)



1. K_{IC} and G_m larger for positive electrode than for negative electrode
2. The electric field has no influence

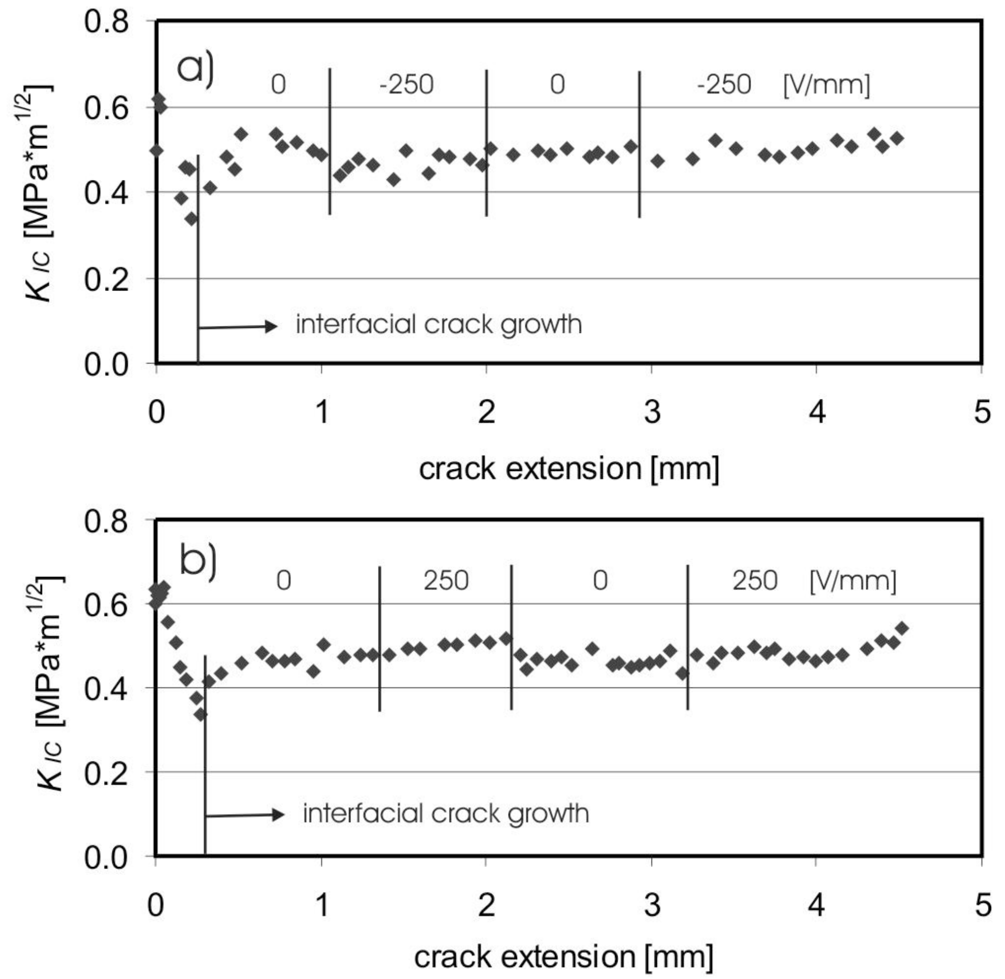
Experimental results

Influence of an electric field on the fracture toughness

(B-type actuators unidir. poled)

Negative electric field

Positive electric field



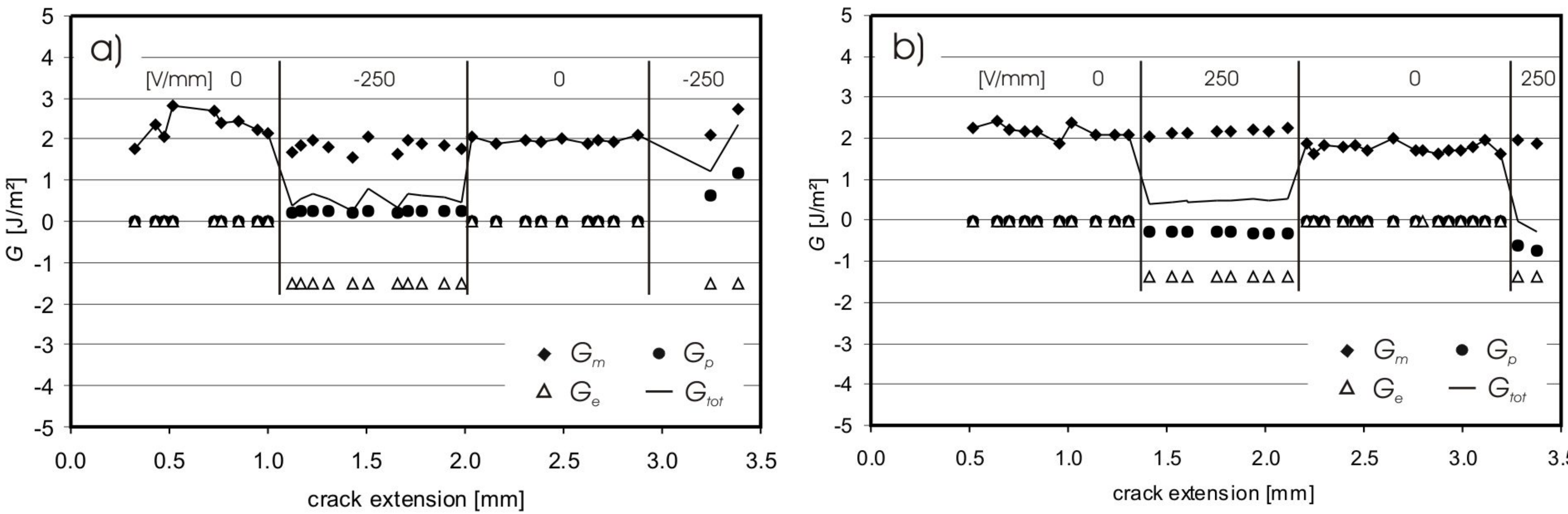
An electric field seems to have a very tiny, if any effect at all.

Experimental results

The total energy release rate

The same measurement (B-type, unidir. poled)

G_{tot} is not a good fracture criterion, but more likely G_m.

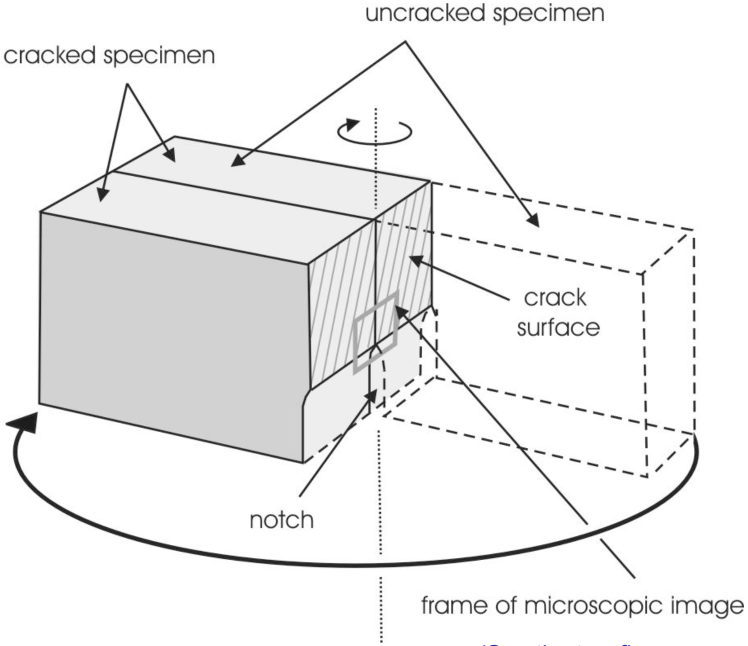


(negative electric field)

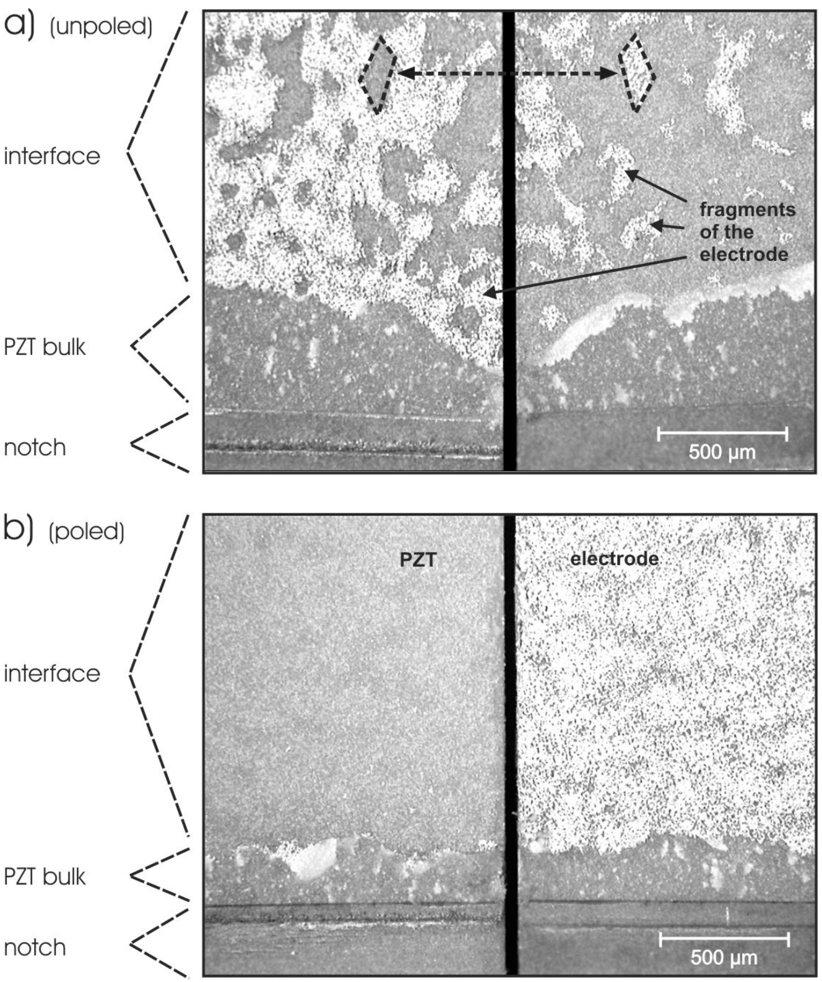
(positive electric field)

Experimental results

Crack morphology (actuator B)



(See the two figures on the right.)

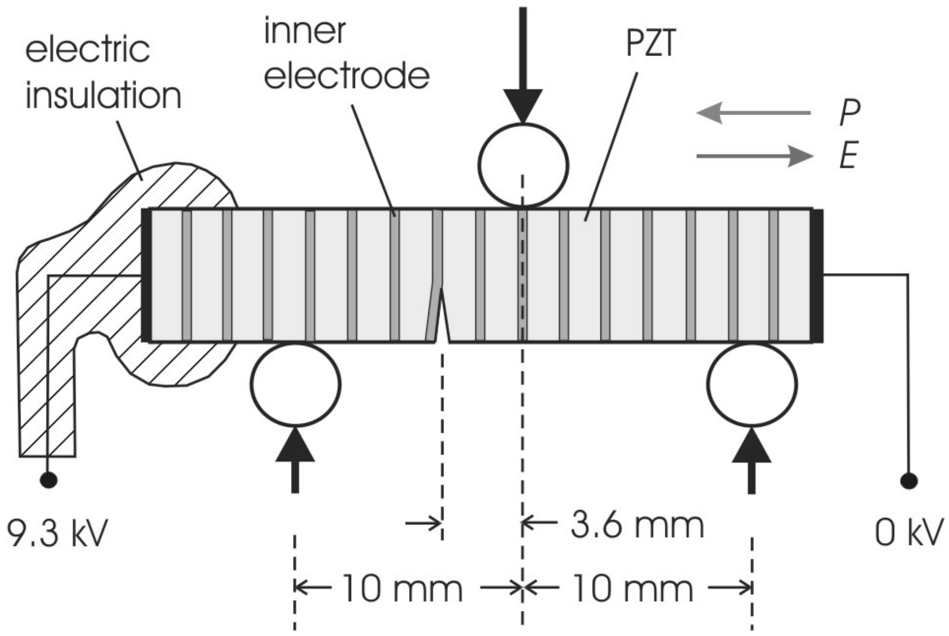


Experimental results for K_I-mode

specimen type	A1 (pos. electr.)	A2 (neg. electr.)	B1/ B2 (unpoled)	B3/ B4 (poled unidir.)
K_{IC} [MPa·m$^{1/2}$] (PZT bulk)	0.7	0.7	0.83	> 0.65
K_{IC} [MPa·m$^{1/2}$] (interface)	0.38	0.33	0.80	0.48
G_m [J/m^2] (interface, theory)	1.7	1.7	—	—
G_{ms} [J/m^2] (interface, exp.)	1.5	1.4	3.3	2.0
C_m [µm/N] (bending, theory)	0.066		—	
C_{ms} [µm/N] (bending, exp.)	0.055		—	

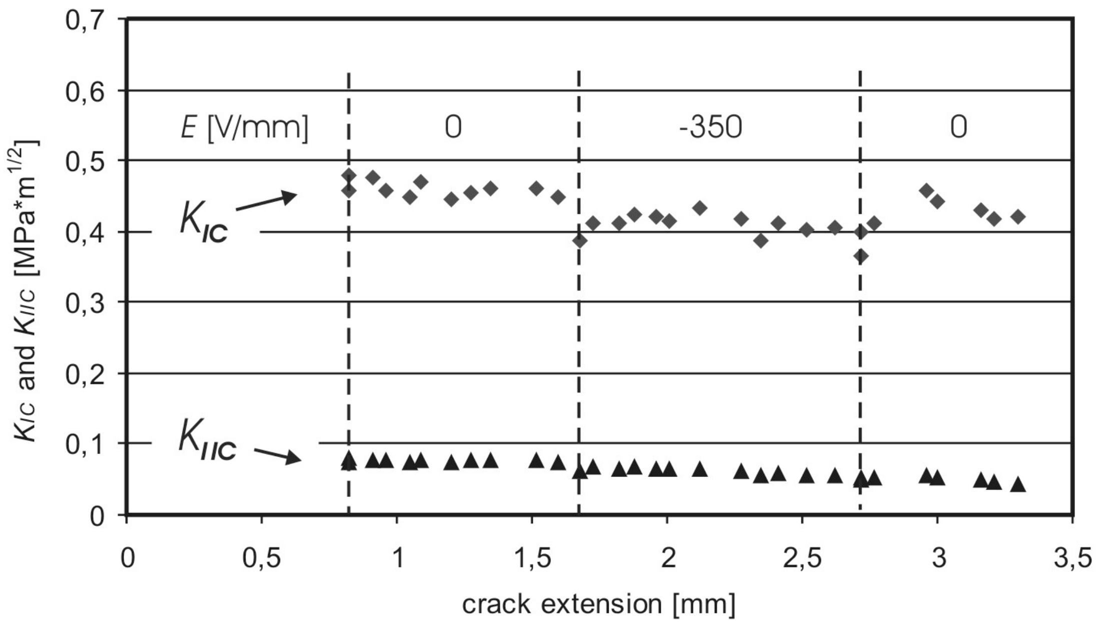
K_I-K_{II} mixed mode

Actuator B, poled unidirectional



The E-field of -350 V/mm was switched on and off during stable crack growth.

Experimental results for K_I-K_{II} mixed mode



Results:

1. In our first K_{II}-experiment stable crack growth is achieved.
2. The crack does not bend off and stays at the metal electrode.
3. The stress intensity factor(s) are dependent on the external electric load. The negative E-Field slightly facilitates crack growth.

Summary

PZT bulk material

- Insulating crack: K_{IC} is slightly dependent on E-field. Thus, the crack is nearly permeable to electric fields.

  a) E-field parallel to polarization: K_{IC} slightly increased.
  b) E-field antiparallel to polarization: K_{IC} is slightly decreased.

- Conducting crack: K_{IC} is highly dependent on E-field.

  a) E-field parallel to polarization: K_{IC} is slowly increasing to a high value.
  b) E-field antiparallel to polarization: K_{IC} is immediately decreasing (down to zero).
  c) Zero electric field: K_{IC} is unaffected.

- Electric field; insulating crack: 10%-effect, conducting crack: 100%-effect.

- All components of the (linear) total energy release rate can be measured under combined electromechanical loading (insulating crack).

- Elastic and inelastic contributions can be separated.

- Total (linear elastic) energy release rate is not a good fracture criterion, but more likely the mechanical part of it. (Similar results e. g. by Park and Sun)

*Detailed information: „Measurement of the Total Energy Release Rate for cracks in PZT under Combined Mechanical and Electrical Loading," accepted by **J. Appl. Mech.***

Summary

Metal ceramic interfaces in multilayer actuators

- Fracture toughness dependent on poling state and slightly on E-field.

  a) E-field parallel to polarization: K_{IC} slightly increased.
  b) E-field antiparallel to polarization: K_{IC} is slightly decreased.

- Unidirectional poling: Crack electrode remains on one crack face.
  Unpoled: Electrode is disrupted and remains on both crack faces.

- Fracture toughness dependent on poling direction (towards or away from electrode) → explanation on molecular level

- Additional K_{II}-loading also allows stable crack growth.

Detailed information: „Interfacial fracture of piezoelectric multilayer actuators under electromechanical loading," to be submitted to ***J. Am. Ceram. Soc.***

Future prospect

Automatic R-curve measurement

- The sensitivity is much better, because electronics reacts faster than a person.
- Measurements with pure K_{II}-loads are possible. Manually, the crack cannot be seen early enough.
- R-curve measurements with very brittle materials are much easier.
- The experimental effort is less than before.