SGL GROUP
THE CARBON COMPANY

Bruchmechanik grobkörniger Graphitkörper – Experimentelle Untersuchung und FEM Modellierung

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BROAD BASE. BEST SOLUTIONS.

Frühjahrstagung des Arbeitskreises „Kohlenstoffe“
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Outline

- Company Profile
- Motivation
- Materials & Methods
- Results
- Conclusion

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Company Profile

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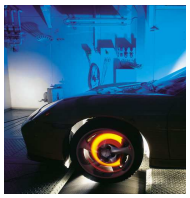
SGL Group
Company Profile








- **SGL Group is one of the world's largest manufacturers of carbon-based products**
- **Comprehensive portfolio ranging from carbon and graphite products to carbon fibers and composites**
- **46 production sites worldwide**
- **Service network covering more than 100 countries**
- **Sales of ~€ 1.5 bn in 2011**
- **Head office in Wiesbaden/Germany**
- **Approx. 6,500 employees worldwide**
- **Listed on MDAX**

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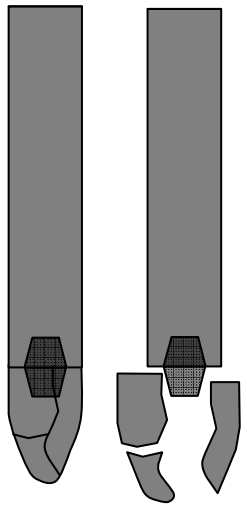
Motivation

Background:

- Graphite electrodes (GE) for electric arc furnaces (EAF)
  - ➔ Extreme conditions
    - 70 – 120 kA
    - T > 1800 ℃
    - mechanical load (strand weight > 3 t, vibrations)
  - ➔ Material failure
  - ➔ Increased electrode consumption

Target:

- Fracture mechanical characterization
  - ➔ material improvement
- FEM analysis
  - ➔ design for application



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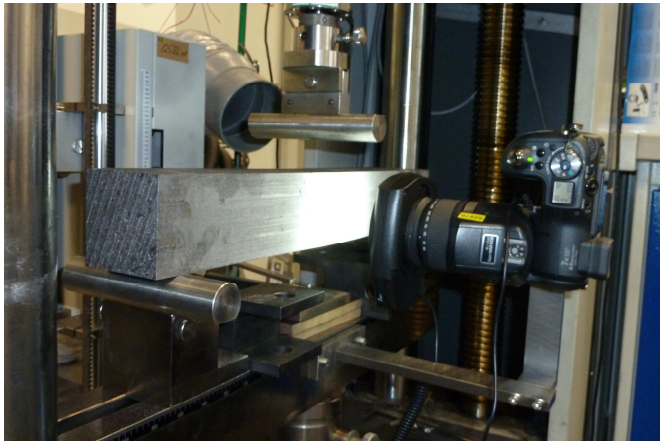
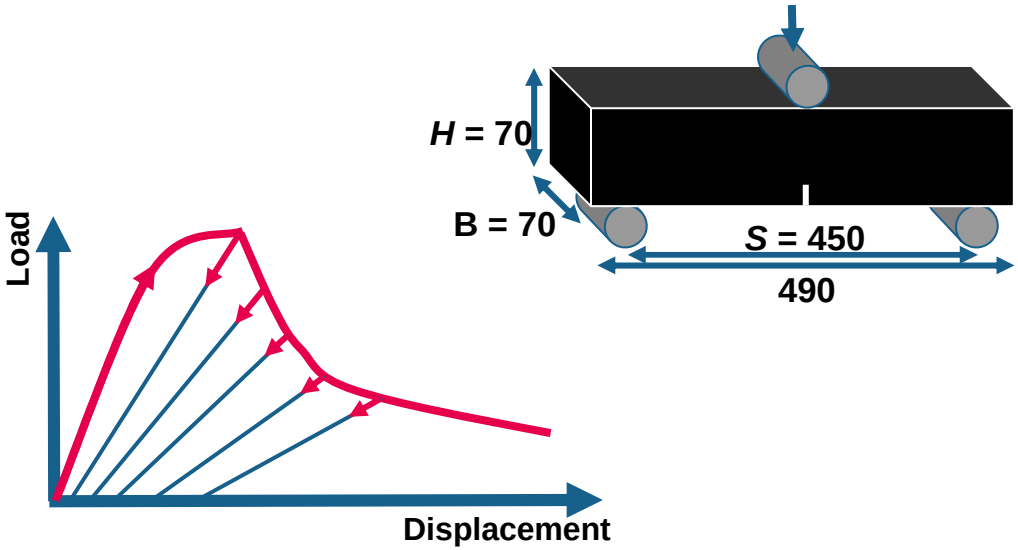
Materials & Methods
Determination of fracture mechanical properties - Setup





3 point bending test

- Scientifically well established
- Crack propagation starts at notch ➔ well defined Mode I

Samples

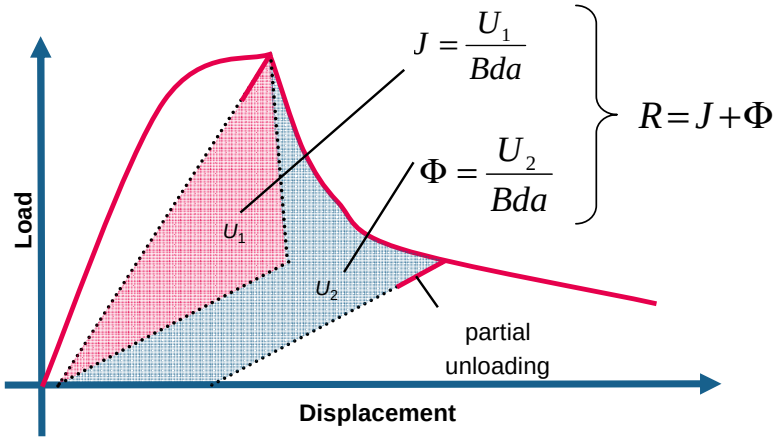
- Coarse grain graphite (< 2.5 cm)
- Notched (bandsaw)
- Dimensions are compromise btw. accuracy and material available

Partial unloading

- Compliance determination

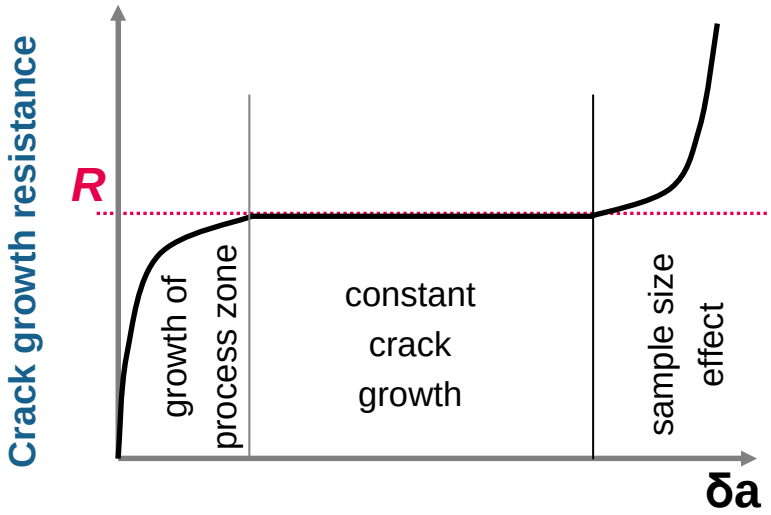
Crack growth resistance R:

$R = J + \Phi_P$ (elastic and plastic contribution)



➔ **Crack length measurement crucial for data evaluation**

Typical *R*-curve behavior in synthetic graphite:



Conditions for crack growth:

- G < R: δa = 0; no crack growth (stable)
- G = R: δa = 0; quasi-static crack growth
- G > R: δa = 0; dynamic crack growth (unstable)

Materials & Methods
Crack length measurement methods

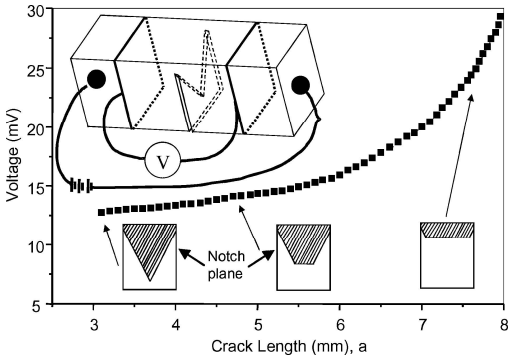
Means to measure the crack propagation in graphite:

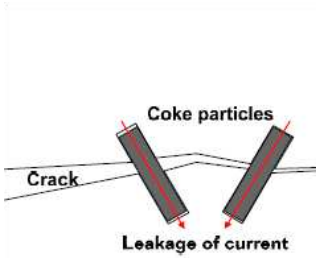
- **Potential drop method**
  - ⊕ Easy to measure
  - ⊖ Systematic errors due to crack bridging; needs calibration

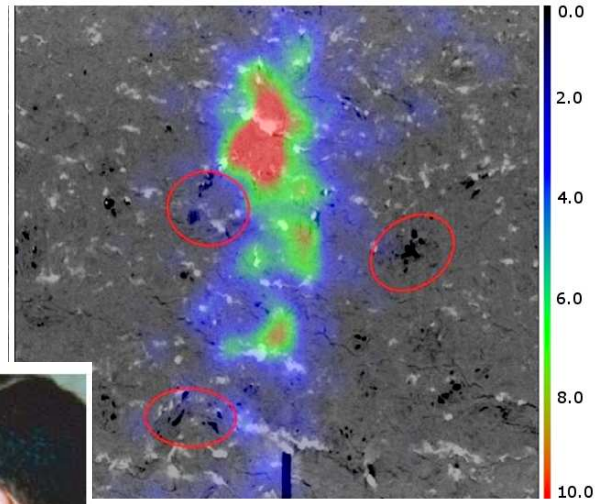
- **Acoustic Emission**
  - ⊕ Volume analysis of crack position; additional information about areas of increased plastic energy dissipation
  - ⊖ Spatial resolution (?); hard to implement in standard lab test

- **Compliance crack length**
  - ⊕ No additional measurement necessary
  - ⊖ Significant systematic deviations

- **Optical**
  - Microscopy method (travelling, long distance)
    - ⊖ Hard to introduce into standard lab method
  - Digital Image Correlation

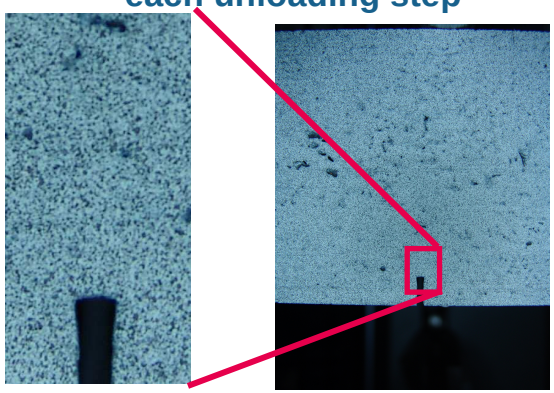




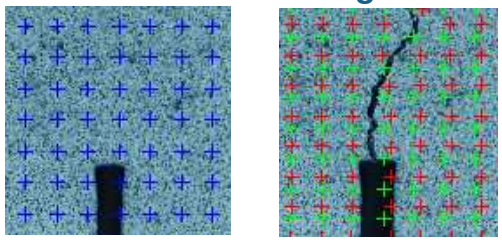


Materials & Methods
Crack length measurement with Digital Image Correlation (DIC)

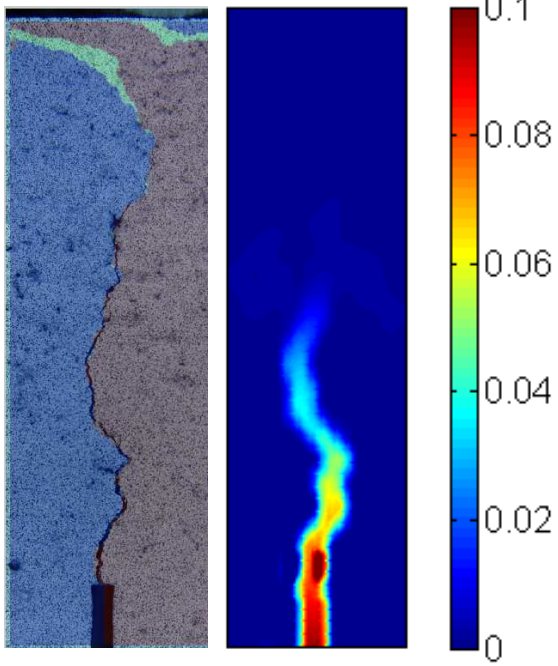
1. Application of statistical pattern; Pictures taken after each unloading step



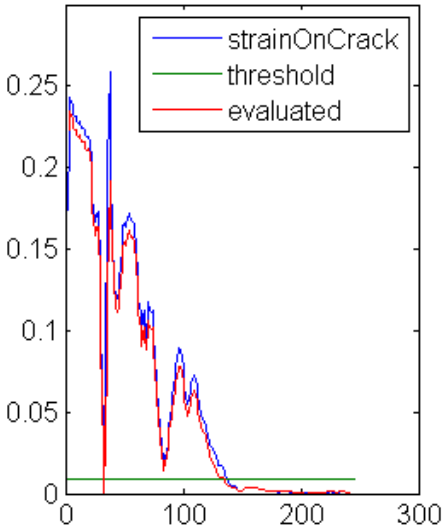
2. Define grid, use digital image correlation to observe change in material

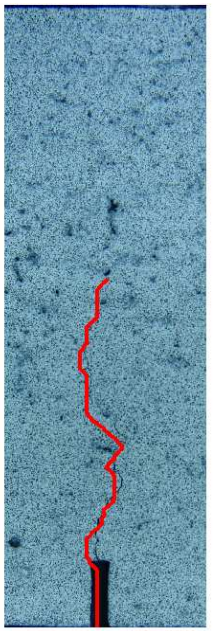


3. Compute displacement and raw strain



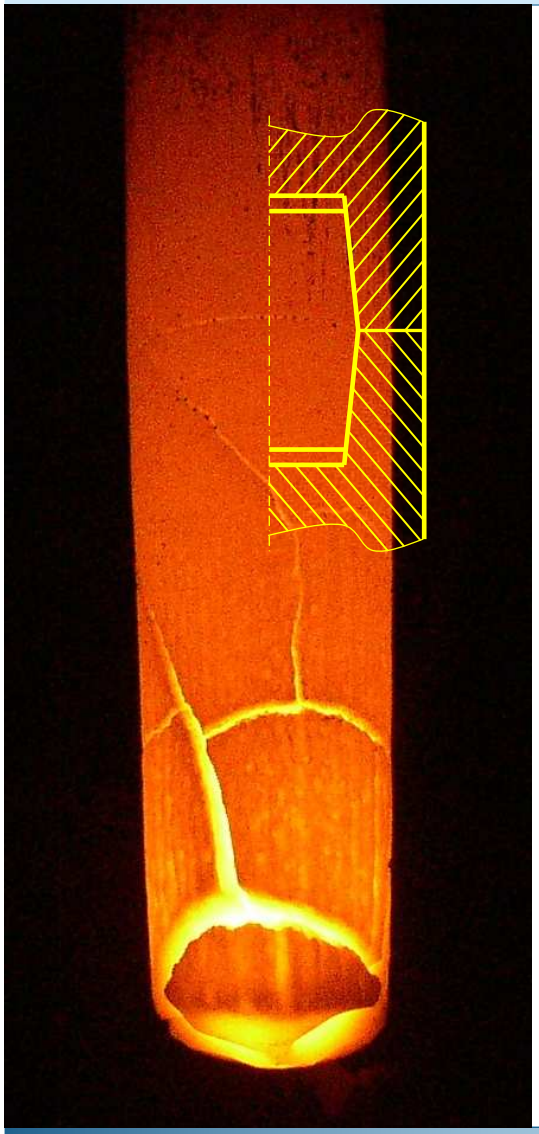
4. Define threshold for strain to assume crack propagation

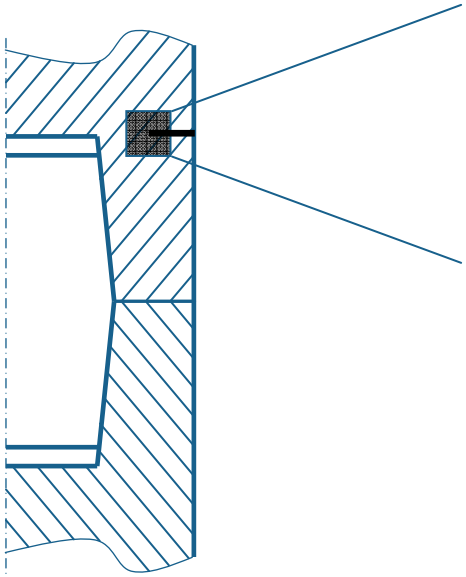


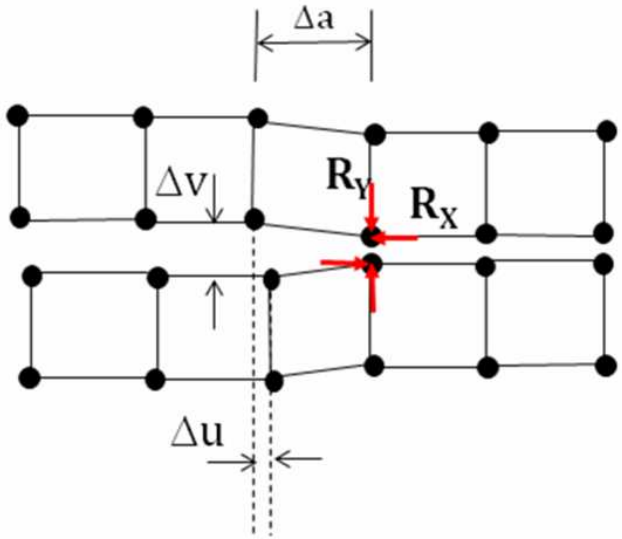


- Direct measurement of displacement
- Sufficient spatial resolution
- Can be implemented in standard lab setups
- Only surface information

Materials & Methods
FEM Approach







- Transversal crack near to socket bottom assumed
- Electric-Thermal-Structural simulations conducted
- Energy release rate calculated with help of the Virtual Crack Closure Technique

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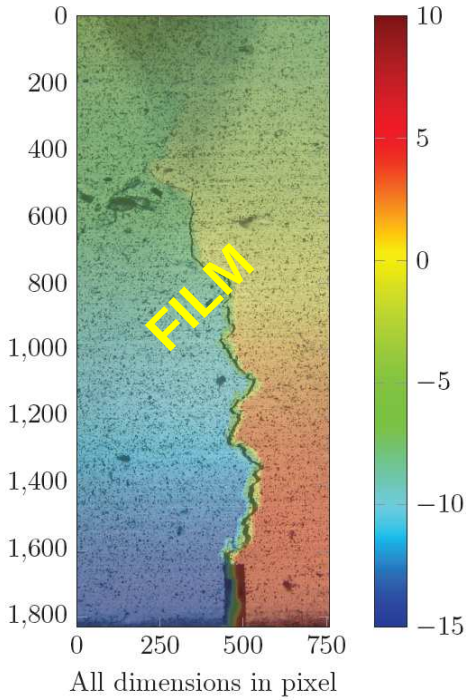
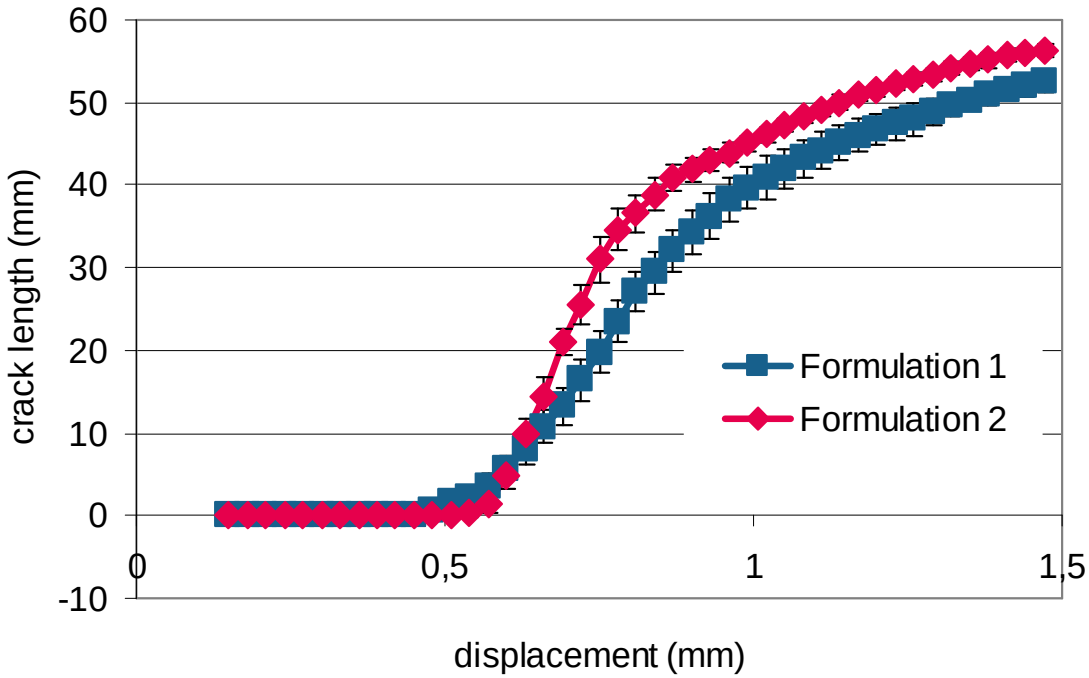
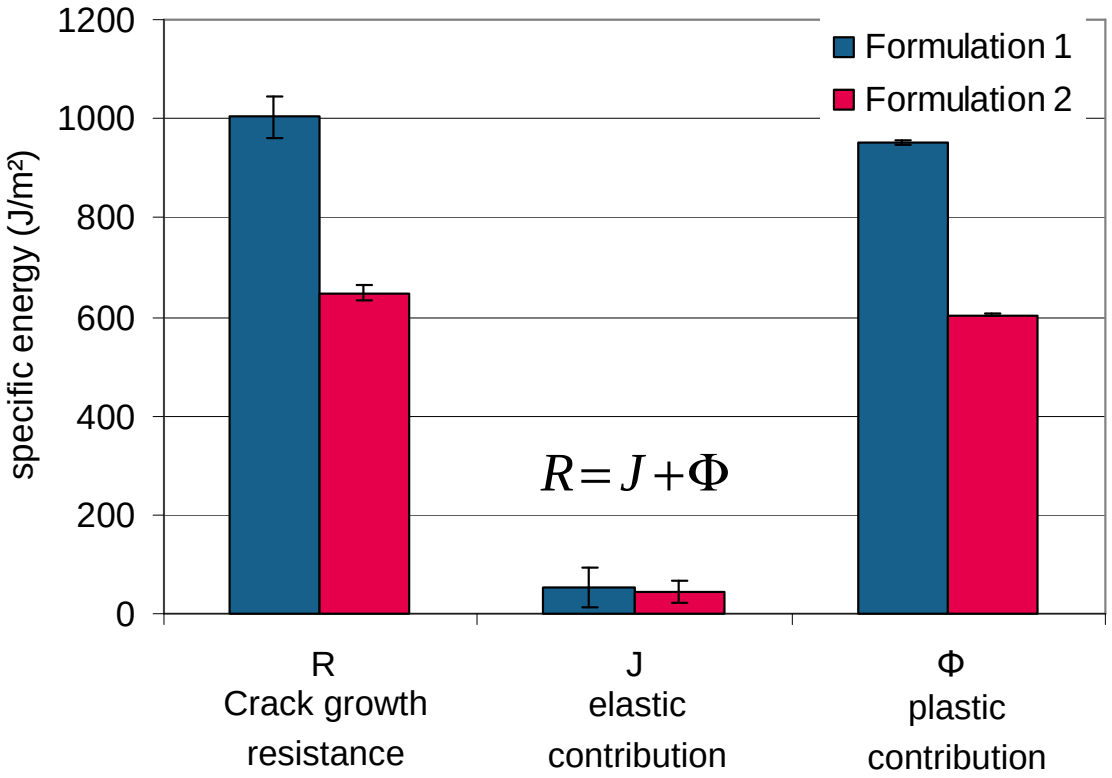
Results
Crack length detection for different graphite recipes





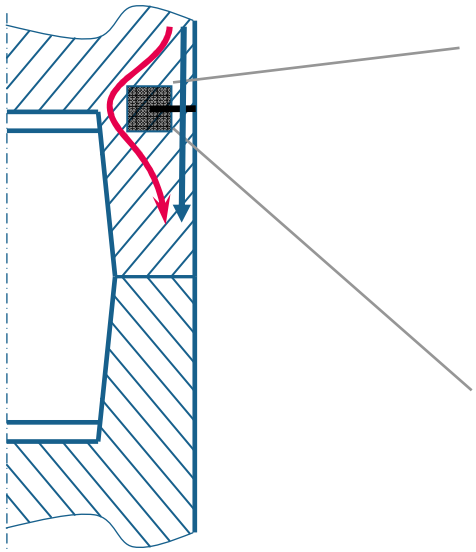
➔ **Crack development during deformation can be changed by material formulation and processing regarding onset and speed**

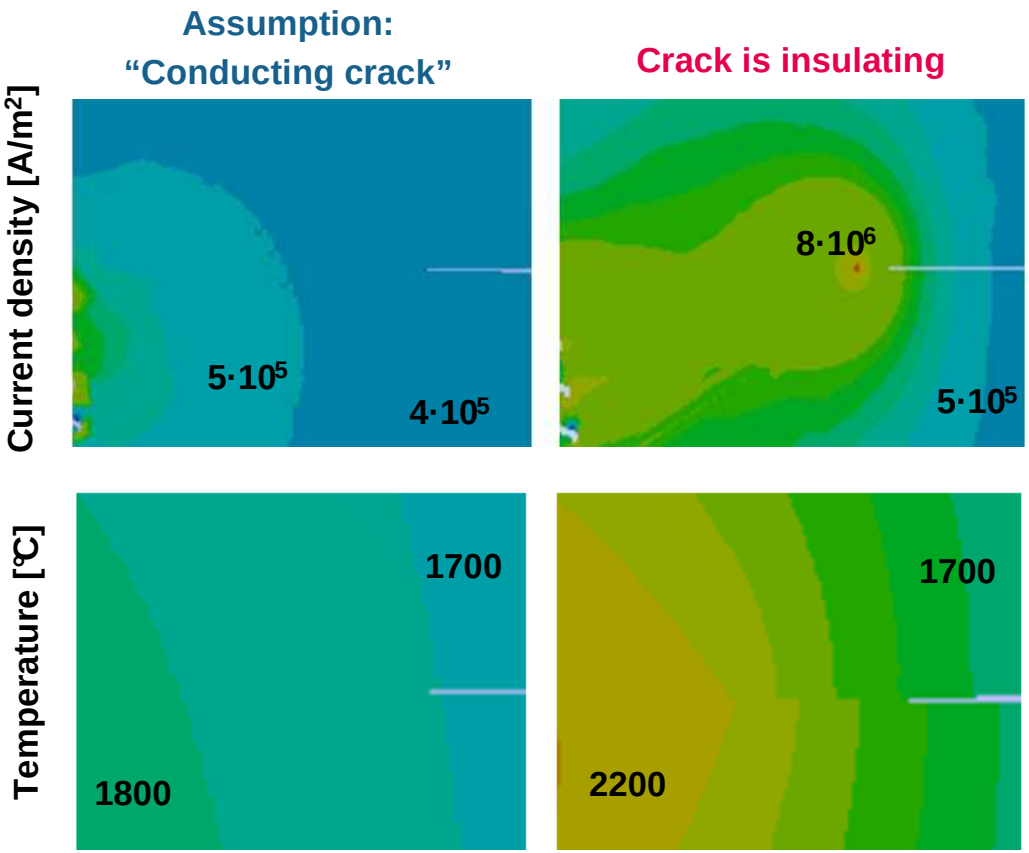
Results
Crack growth resistance



➔ **Reduced crack propagation of formulation 1 is reflected by a higher crack growth resistance, mainly based on increased plastic energy dissipation**

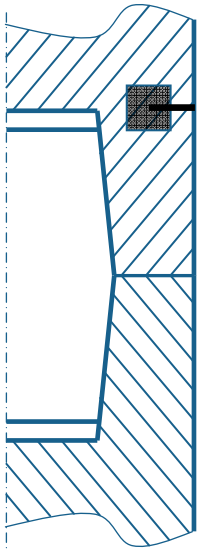
Results
Effect of the transversal crack on the electric and thermal fields

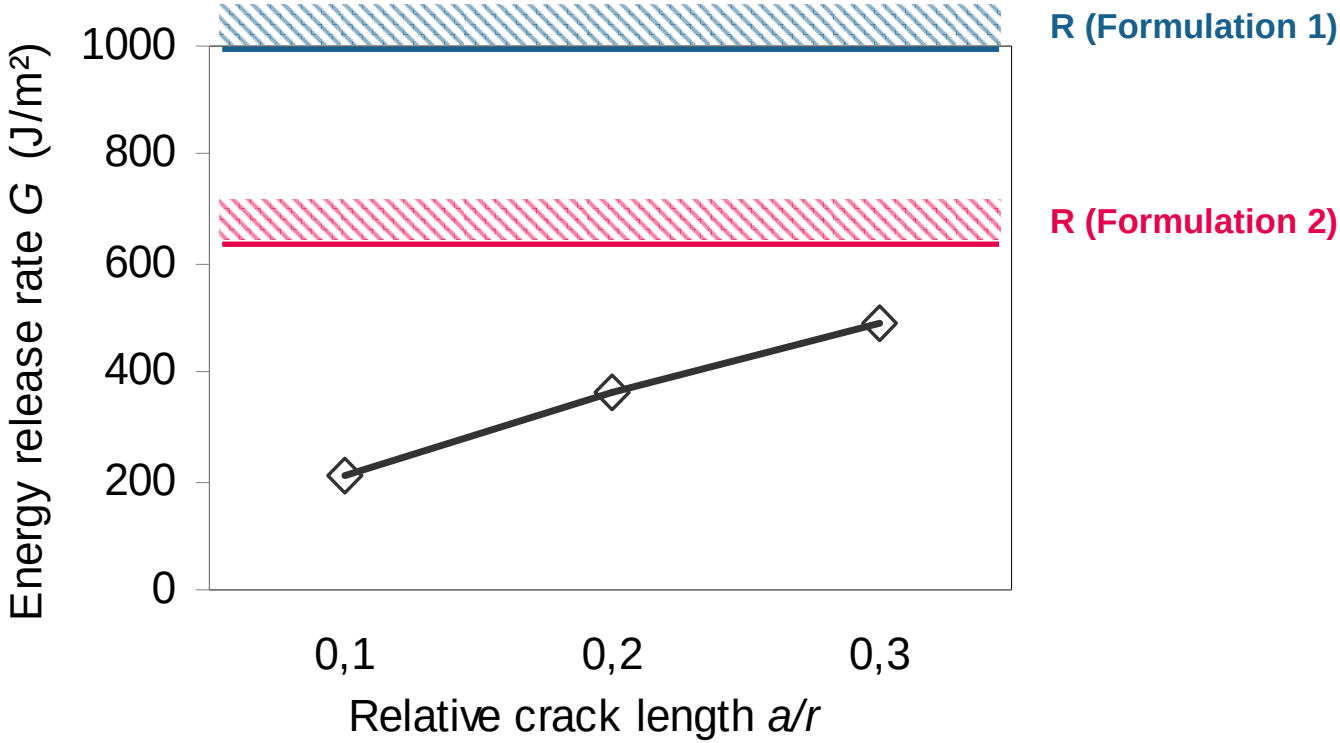




- ➔ **crack increases current density by factor > 10**
- ➔ **significantly increased temperature gradients**

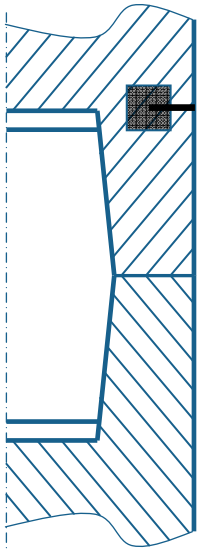
Results
Effect of the crack length

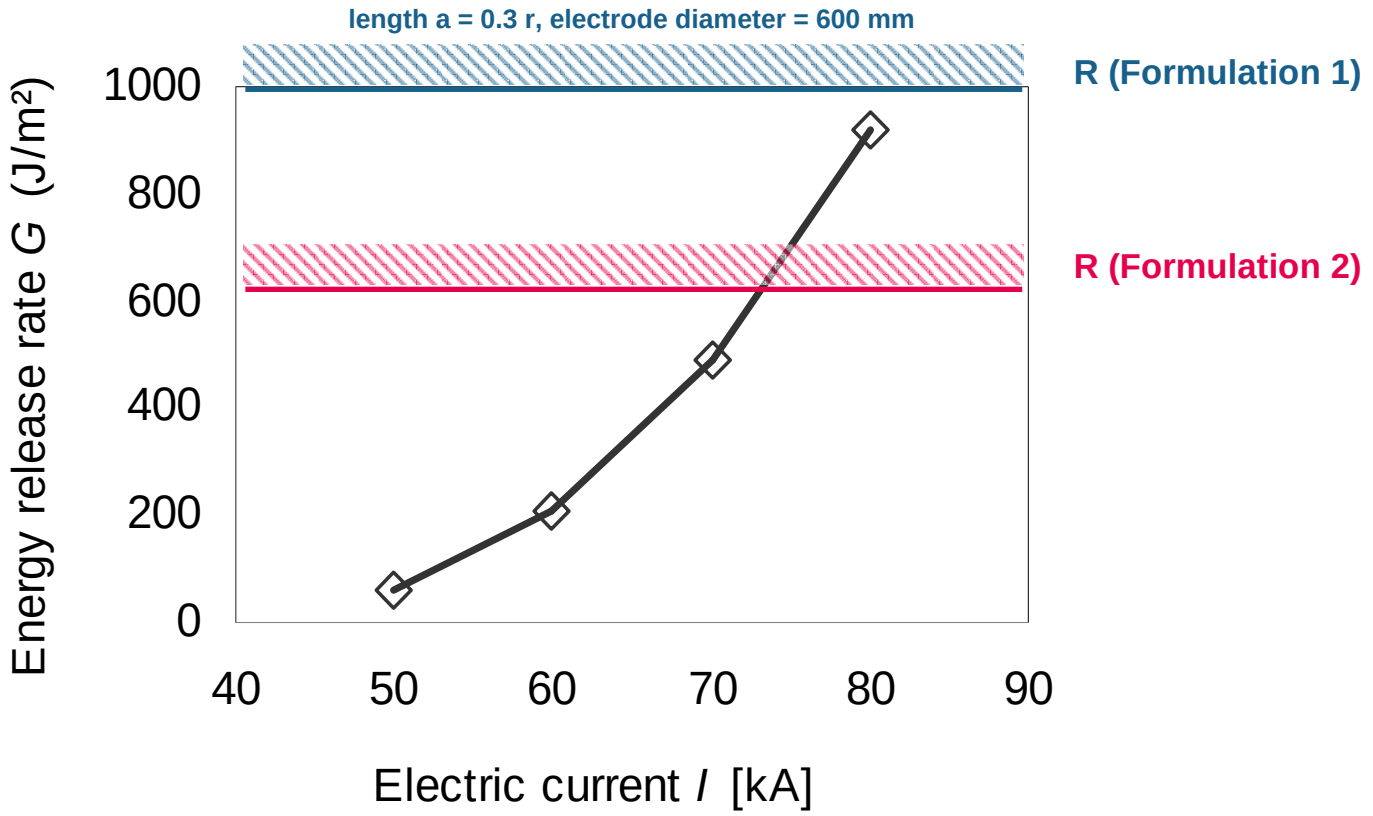




- **A stable growing crack turns into unstable growth when a certain crack length is passed**
- **Discontinuous material consumption can be reduced by improved crack growth resistance**

Results
Effect of the applied current





- ➔ **On furnaces operated at higher electric currents unstable crack propagation may take place**
- ➔ **Higher productivity possible by improved crack growth resistance**

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Fracture mechanical analysis of coarse grain graphite
Conclusions

- **Fracture mechanical analysis method developed**
  - 3PB on notched samples + compliance method
  - Crucial: crack length determination
  - Digital Image Correlation is a valuable tool for crack length measurement

➔ Graphite grade development can directly aim at materials with improved crack growth resistance

- **FEM modeling** to simulate complex electrical and thermal conditions on furnace
  - ➔ Improved crack growth resistance reduces discontinuous consumption
  - ➔ and enables the steel shop to increase total current ➔ higher productivity

➔ **Enhanced performance of graphite electrodes on EAF by on purpose improved fracture mechanical properties possible**