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The effect of anisotropy on crack propagation in pearlitic rail steel

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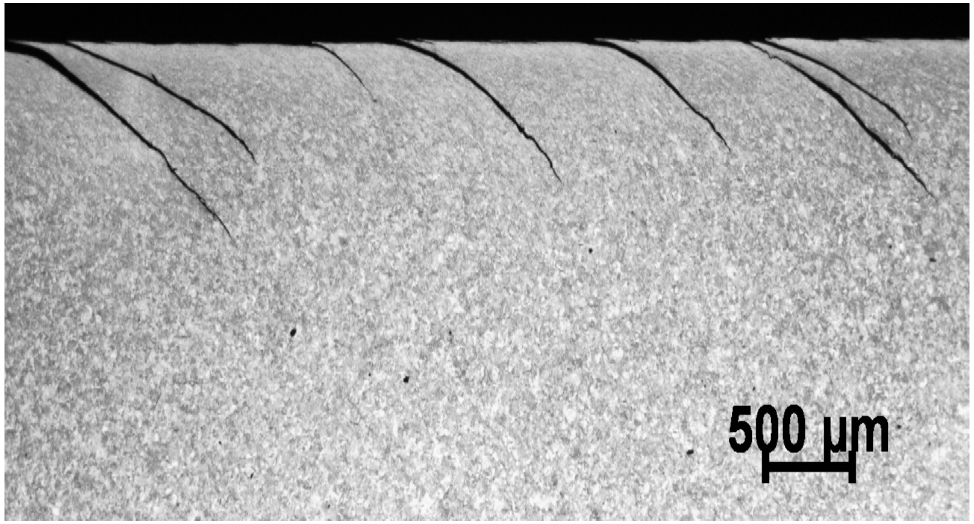
Material anisotropy and rolling contact fatigue of rails and switches



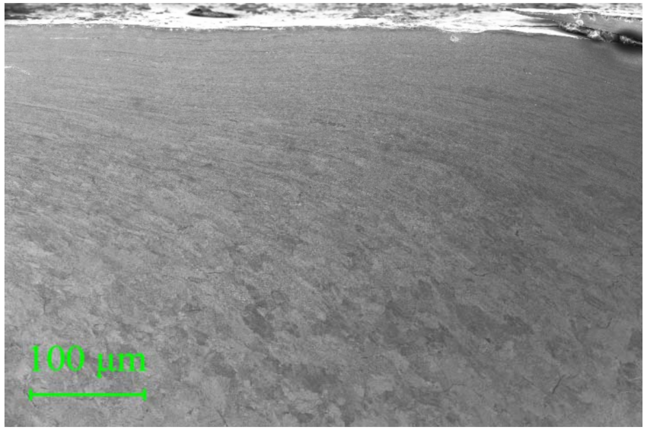
Supporting organizations:

Charmec, Trafikverket, SL Technology, voestalpine Schienen

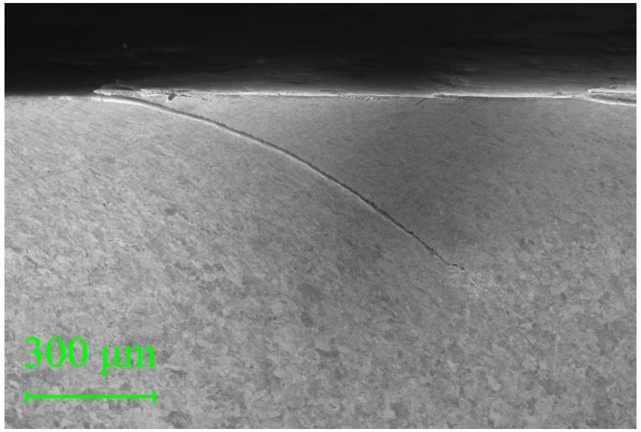
Outline

- Introduction and motivation of work
- Microstructural investigations
- Anisotropy in crack propagation law
- Anisotropic fracture criterion
- Numerical results
- Concluding remarks and future work

Introduction and motivation of work



Plastic flow in the surface layer of rail

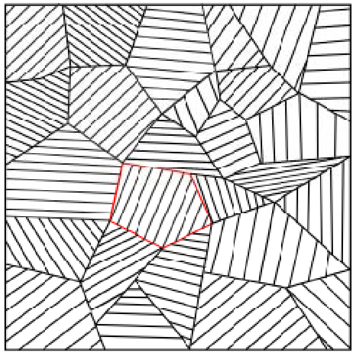


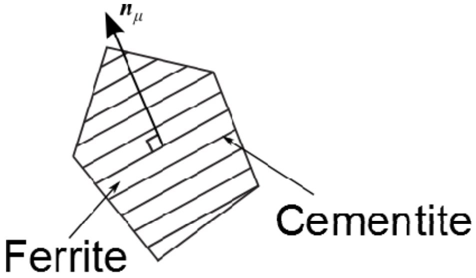
A surface crack at the gauge corner (head check)

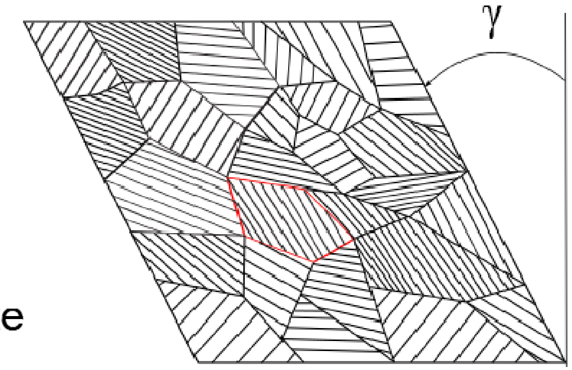
- Large plastic deformations close to the rail surface
- Evolution of anisotropy in pearlitic steel in the surface layer
- **Main goal**: Increase our understanding of how anisotropy influences initiation and propagation of surface cracks

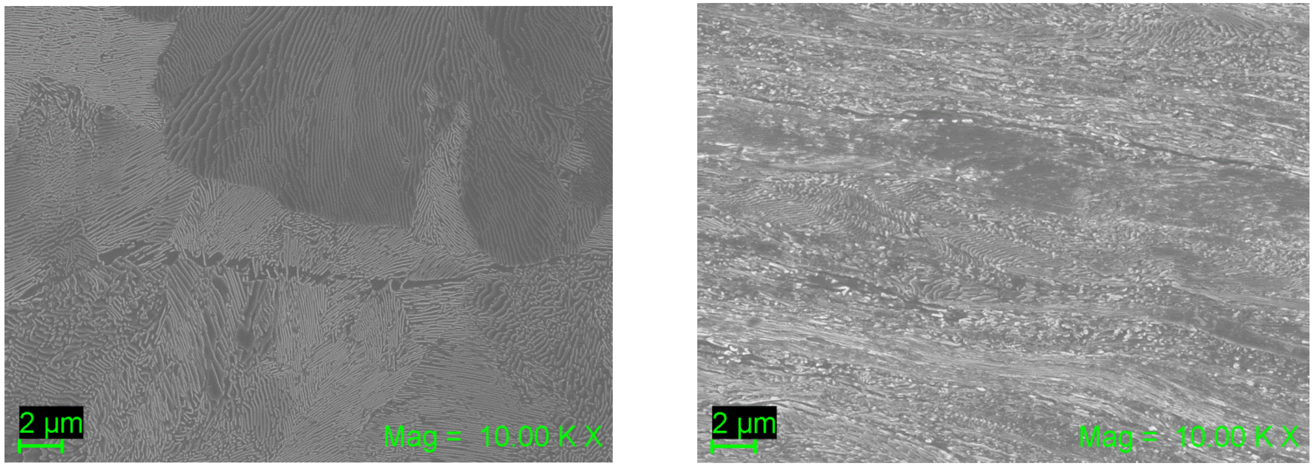
- DB: RCF maintenance costs up to €150 million in year
- 90% rail grinding is due to head checks, €40 million in year
- Improve simulation tools to obtain more accurate fatigue life predictions

Pearlite structure and evolution of anisotropy



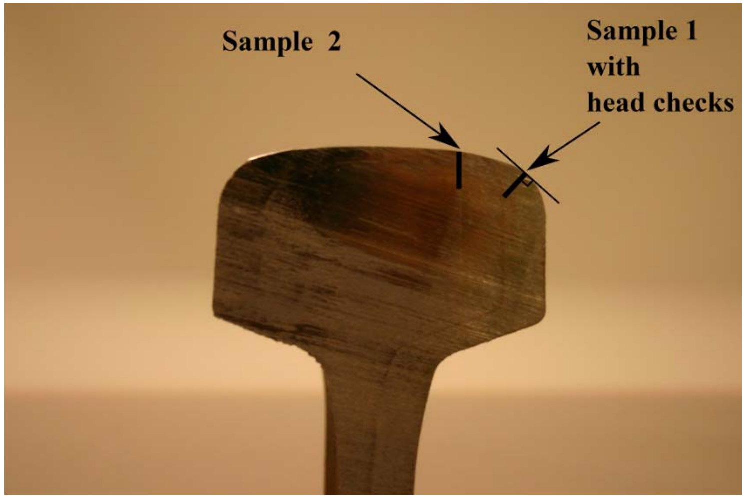


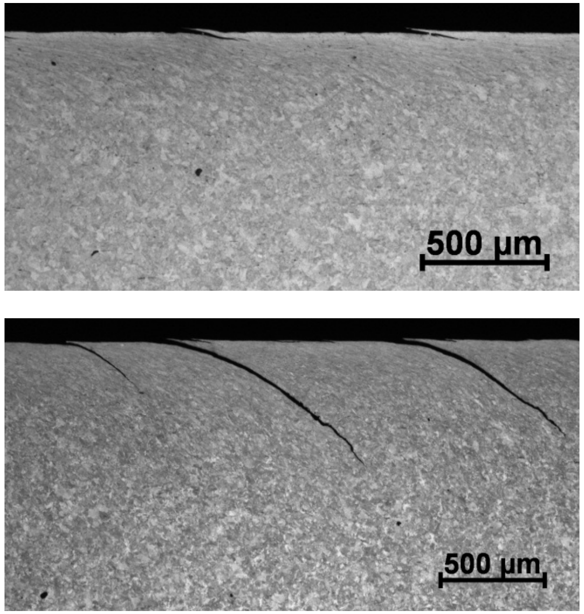




Micrographs of a pearlitic steel rail at the depth of $2\,\mathrm{mm}$ & $100\,\mu\mathrm{m}$

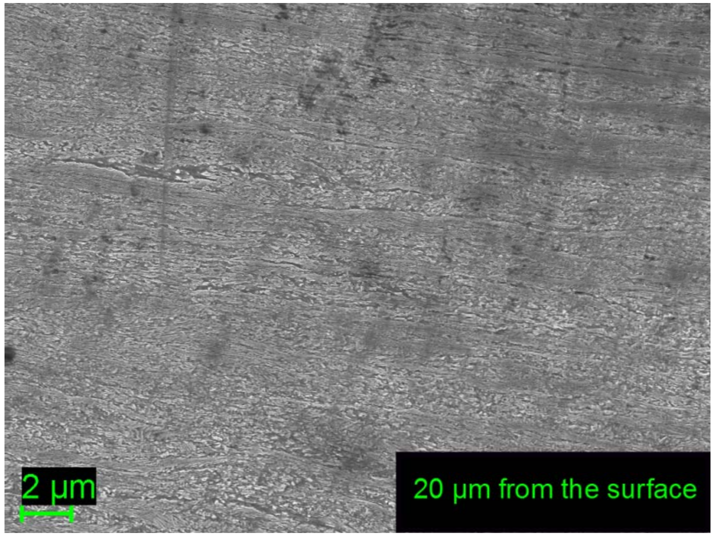
Microstructural investigations:



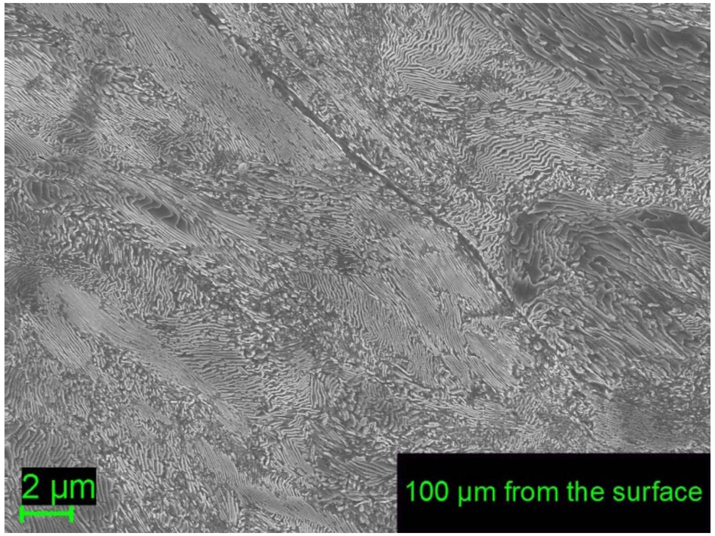


- Rail segment produced by voestalpine Schienen GmbH
- Pearlitic rail steel 350HT
  (0.79% C, 0.44% Si, 1.19% Mn, 0.014% P, 0.013% S, 0.08% Cr)
- Tested in a full scale test rig:
  - 23 t vertical, 4 t lateral force
  - 100000 passes
  - No rail inclination, no angle of attack

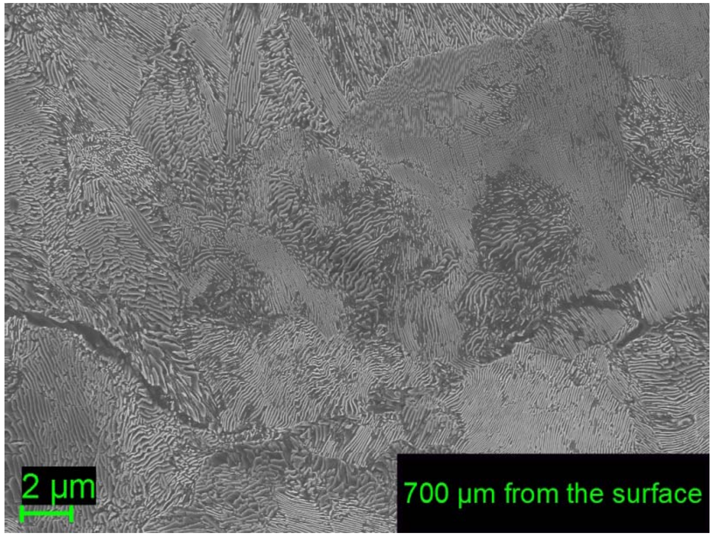
Microstructural investigations:



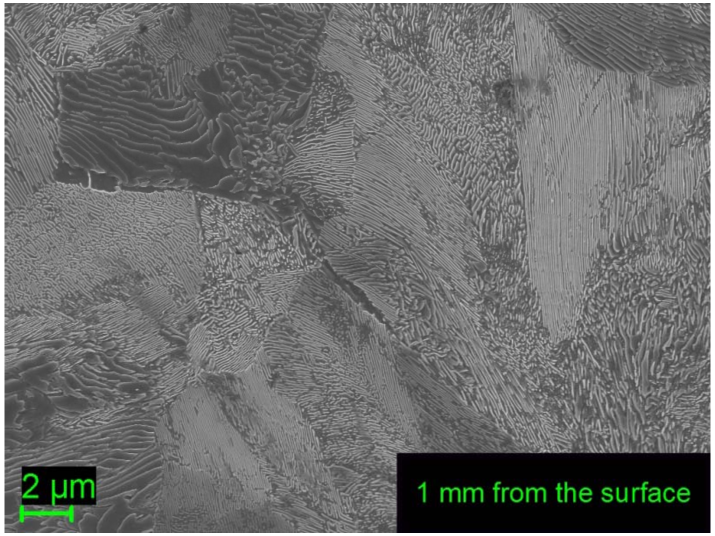
20 µm from the surface



100 µm from the surface



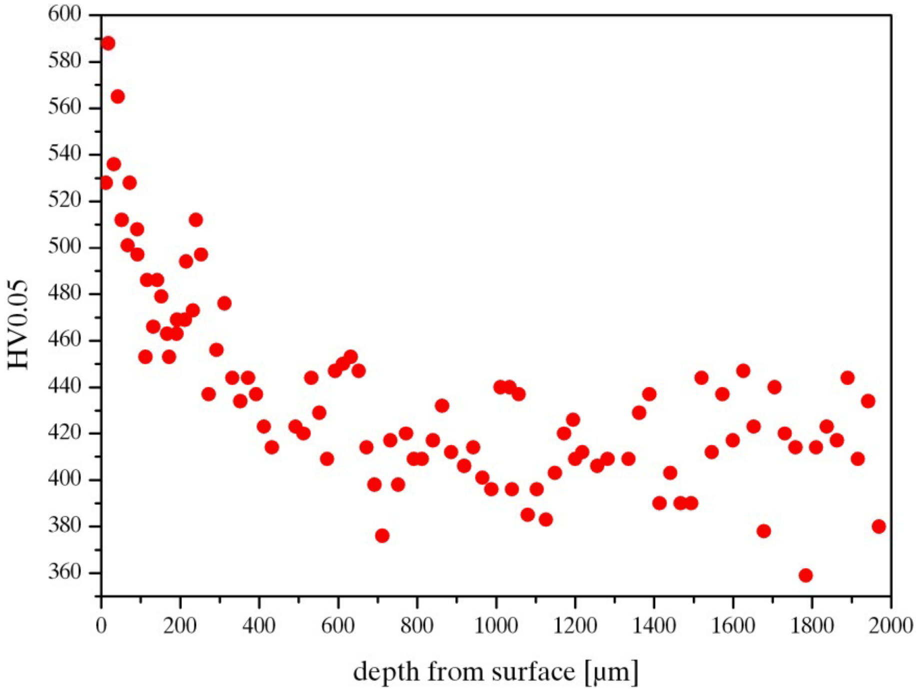
700 µm from the surface



1 mm from the surface

Anisotropic surface layer:

- Anisotropic surface layer has a very small thickness ($\approx 1\,\mathrm{mm}$)
- Material properties have a large gradient through the surface layer



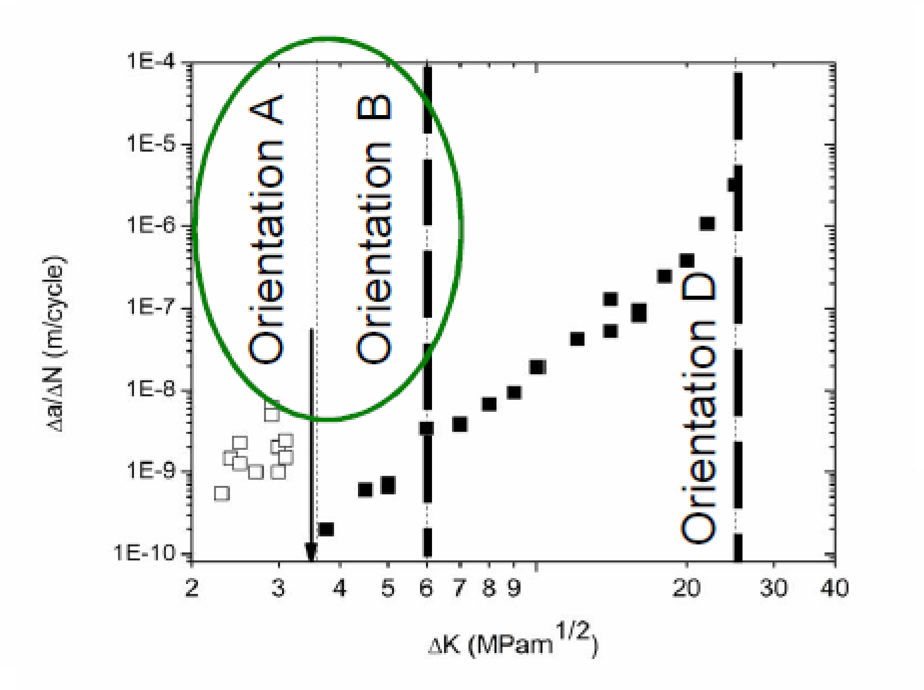
Changes in mechanical properties:

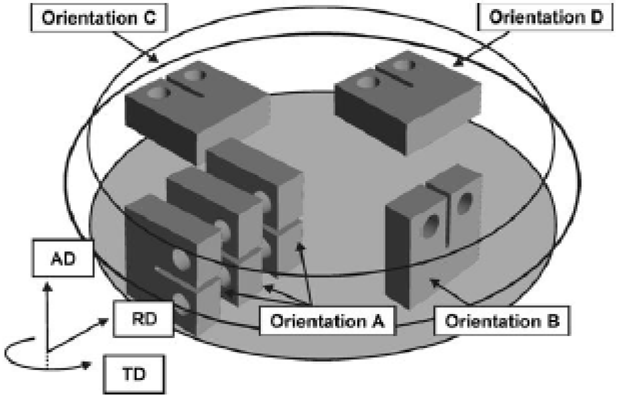
Hohenwarter et al, 2011, Metall. Mater. Trans. A 42 (6)
&
Wetscher et al, 2007, Mat. Sci. Eng. A 445-446

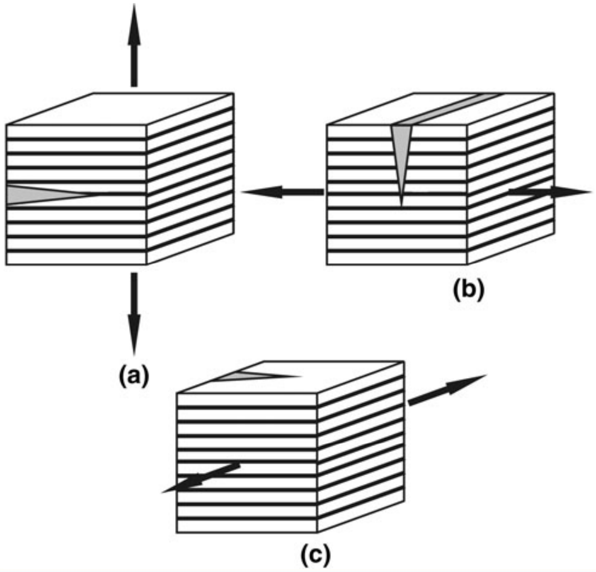
- Changes in:
  - Yield stress
  - Tensile strength
- Significant anisotropy in:
  - Fracture toughness
  - Cyclic threshold values
  - Crack propagation rate

Anisotropic fracture toughness

From: Hohenwarter et al, 2011, Metall. Mater. Trans. A 42 (6)

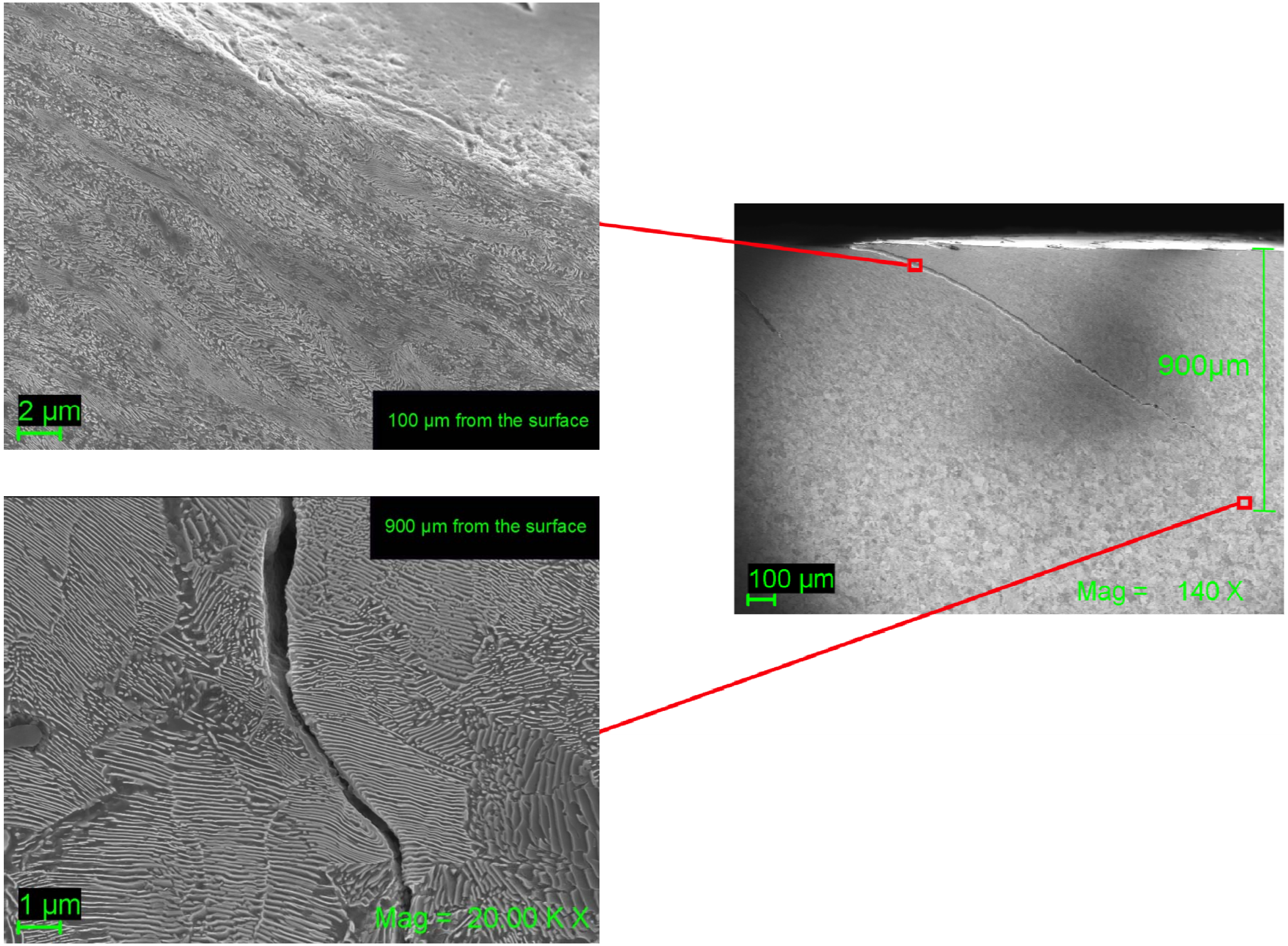






- Strong anisotropy both for monotonic and cyclic loading
- Cylcic threshold values smaller than fracture toughness

Surface cracks and crack paths:



Anisotropy in the crack propagation law:

- Anisotropic fracture toughness
- Resistance against crack propagation is directional dependent
- Crack driving force $\boldsymbol{\mathcal{G}}$; based on the concept of material forces:

  Tillberg et al, 2010, Int. J. Plasticity 26(7)
  &
  Denzer et al, 2003, Int. J. Numer. Meth. Eng. 58 (12)

- Crack driving potential, $\boldsymbol{\Phi}$:

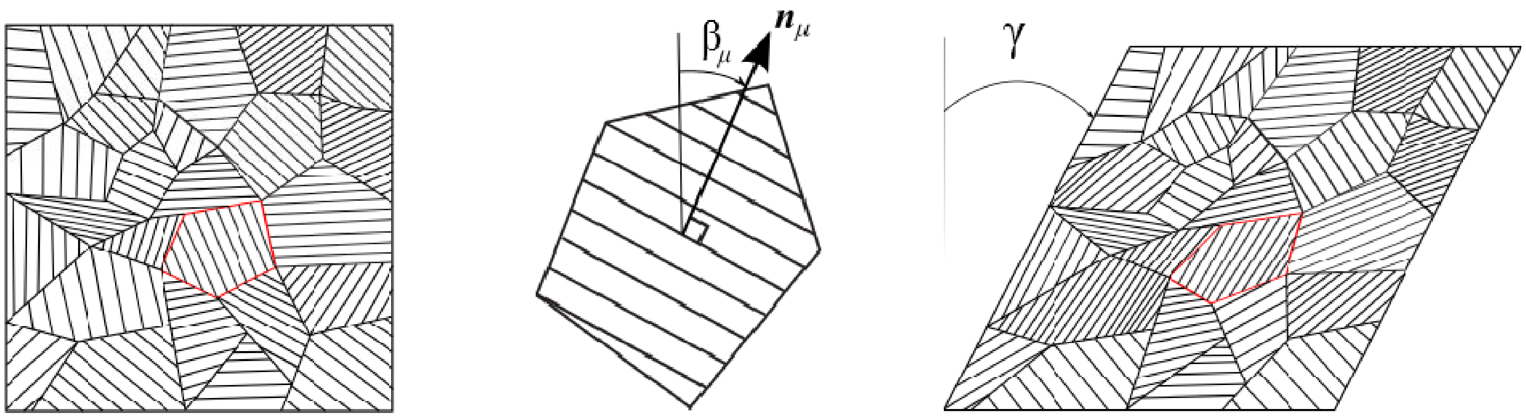
$$\boldsymbol{\Phi}(\boldsymbol{e}) = \langle \boldsymbol{\mathcal{G}} \cdot \boldsymbol{e} - \mathcal{G}_{\mathrm{th}}(\boldsymbol{e}) \rangle$$

- Propagation in the direction of maximum parallel dissipation, $\boldsymbol{e}^*$:

$$\boldsymbol{e}^* = \arg\max_{\boldsymbol{e}} \lim_{\epsilon \to 0} \boldsymbol{\mathcal{G}}(\boldsymbol{a} + \epsilon \boldsymbol{e}) \cdot \boldsymbol{e} - \mathcal{G}_{\mathrm{th}}(\boldsymbol{e})$$

Anisotropic fracture threshold:

- Fracture threshold, $\mathcal{G}_{\mathrm{th}} \rightarrow$ resistance against crack propagation



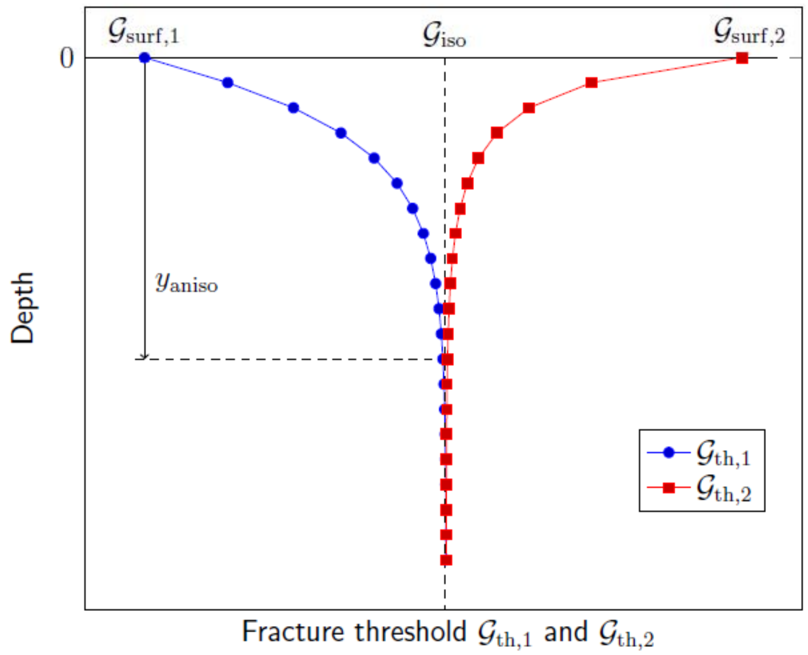
- Orientation angle in each colony, β_μ: $\beta_\mu = \arctan(\frac{|n_{\mu x}|}{n_{\mu y}})$
- Average orientation angle, β:

$$\beta = \langle \beta_\mu \rangle = \frac{1}{N_{\mathrm{tot}}} \sum_{n=1}^{N_{\mathrm{tot}}} \beta_{\mu,n}$$

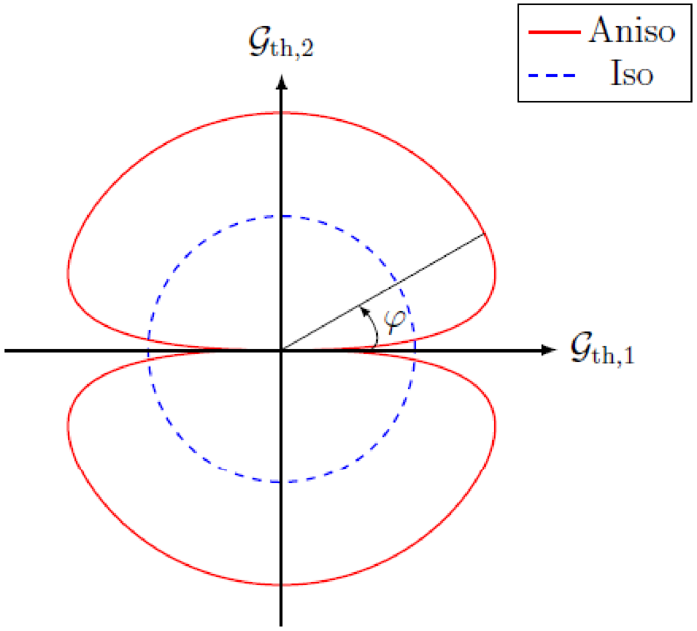
- A measure of degree of alignment $\rightarrow$ degree of anisotropy
- Orientation with lowest resistance against crack propagation

An anisotropic fracture surface

- Lowest and highest fracture threshold, $\mathcal{G}_{\mathrm{th},1}$ and $\boldsymbol{\mathcal{G}}_{\mathbf{th},\mathbf{2}}$ → functions of β
- Transition in the microstructure → variation of β over the depth

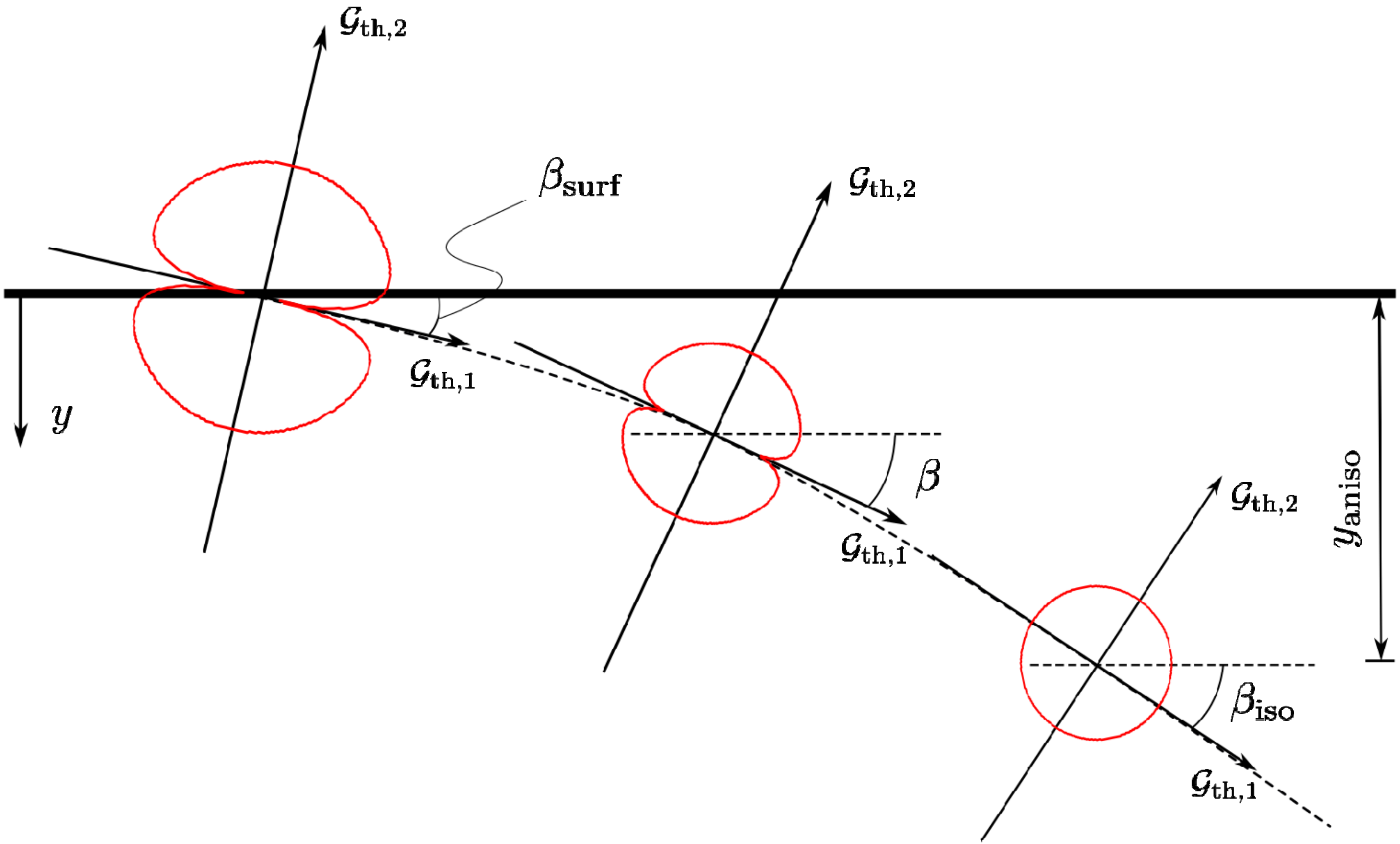


$$\boldsymbol{\mathcal{G}}_{\mathbf{th},\mathbf{1}} = A_1 \exp\left(\frac{-t_1}{\beta}\right)$$
$$\boldsymbol{\mathcal{G}}_{\mathbf{th},\mathbf{2}} = A_2 \exp\left(\frac{t_2}{\beta}\right)$$

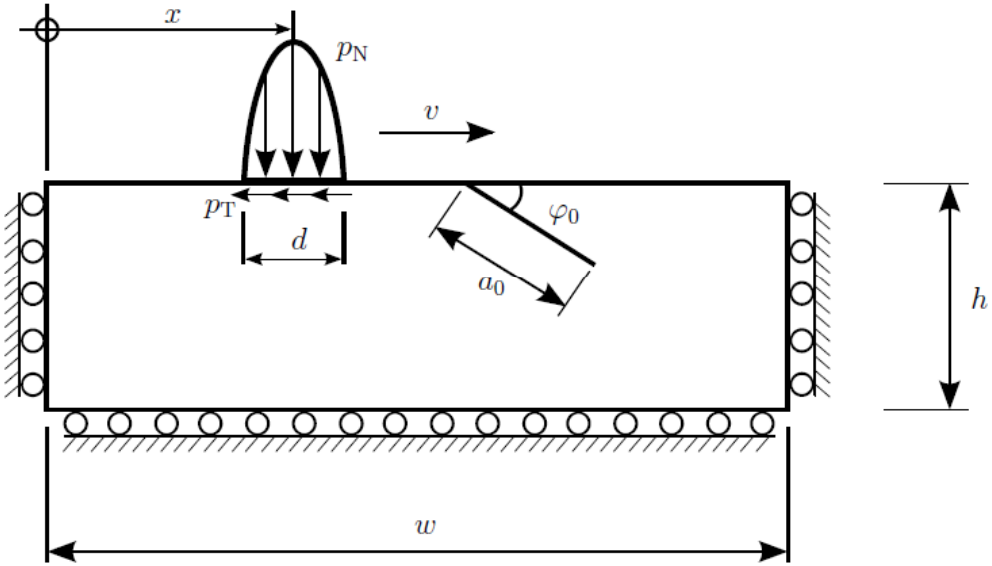


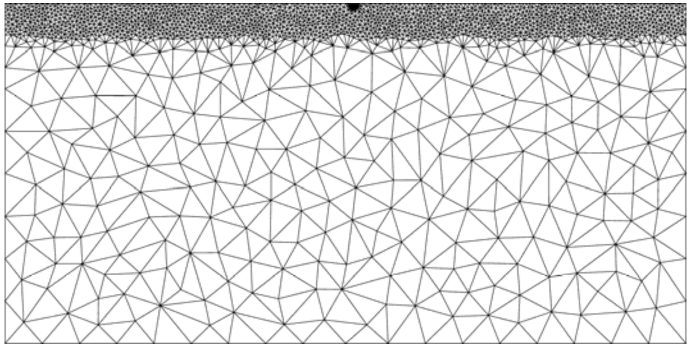
$$\mathcal{G}_{\mathrm{th}}(\varphi) = \mathcal{G}_{\mathrm{th},1} + (\mathcal{G}_{\mathrm{th},2} - \mathcal{G}_{\mathrm{th},1})(1 - e^{-A|\sin(\varphi)|})$$

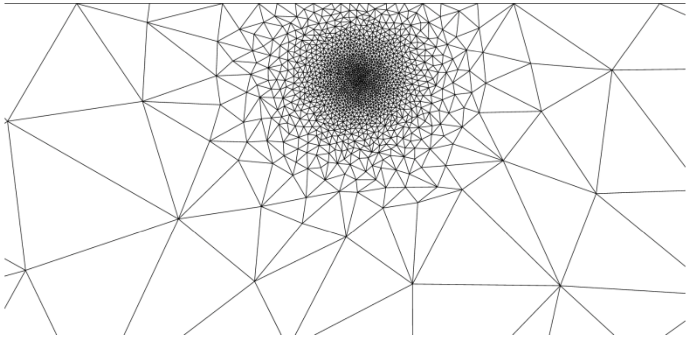
Evolution of fracture surface over the depth



Simulation setup:







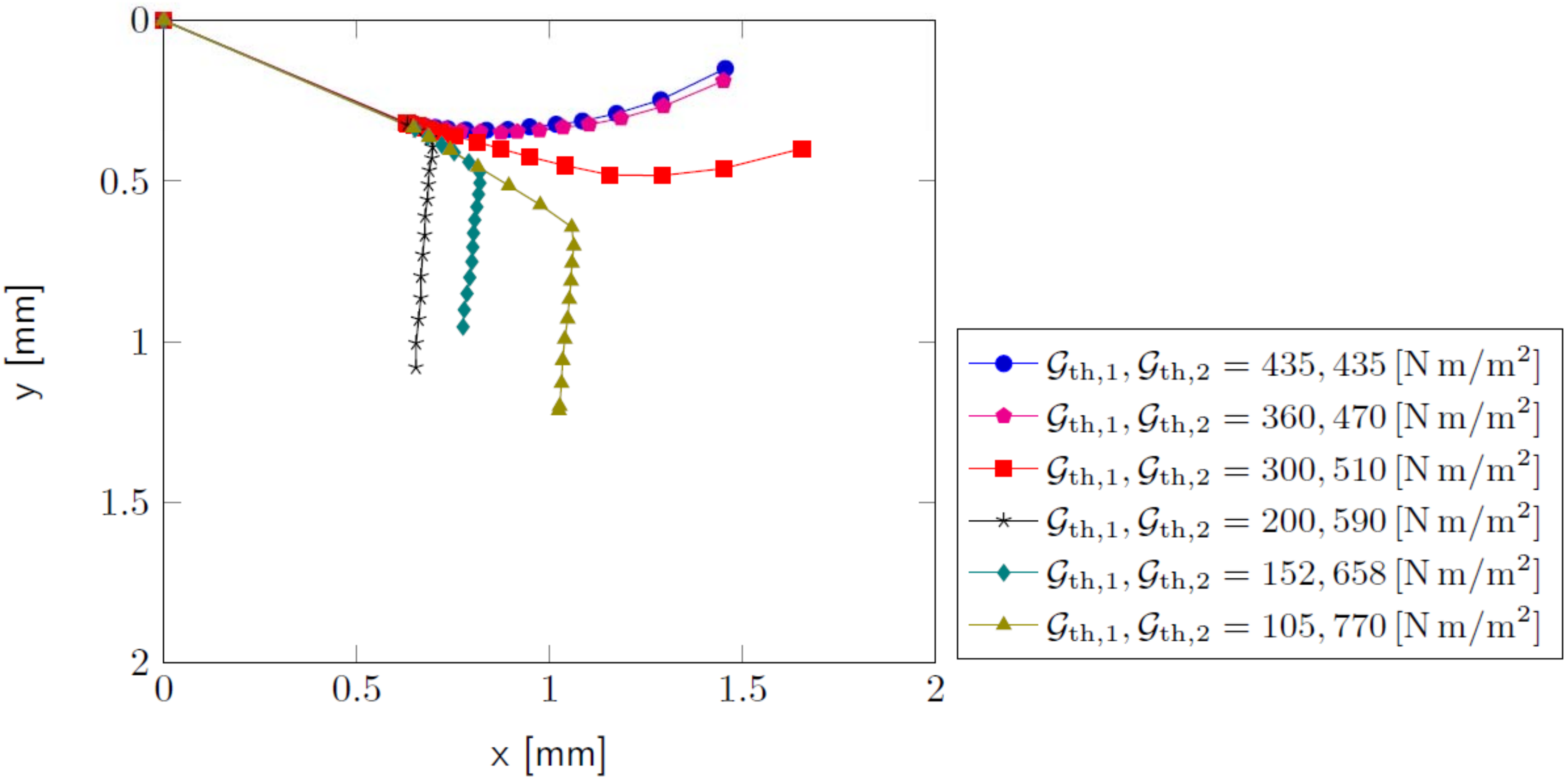
- Hertzian contact

$$p_N(x,t) = p_{\mathrm{N}0}\sqrt{1-\left(\frac{x-vt}{d/2}\right)^2}$$

$$p_{\mathrm{N}0} = 800\,\mathrm{MPa}, \;\; d = 14.8\,\mathrm{mm}$$

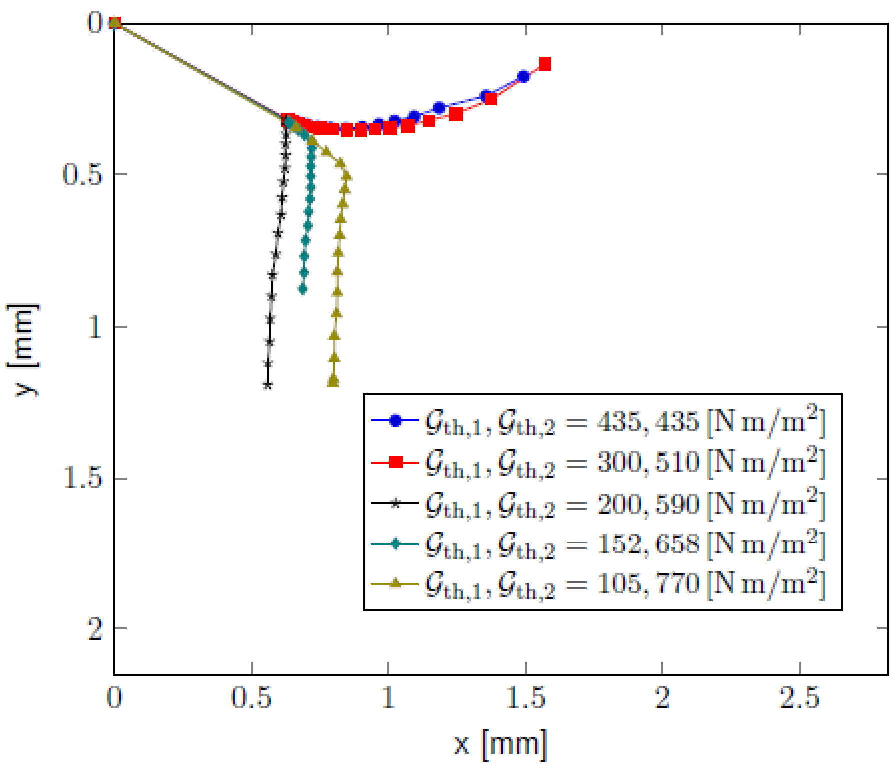
$$p_T(x,t) = \mu\, p_N(x,t)$$

Effect of degree of anisotropy on crack propagation

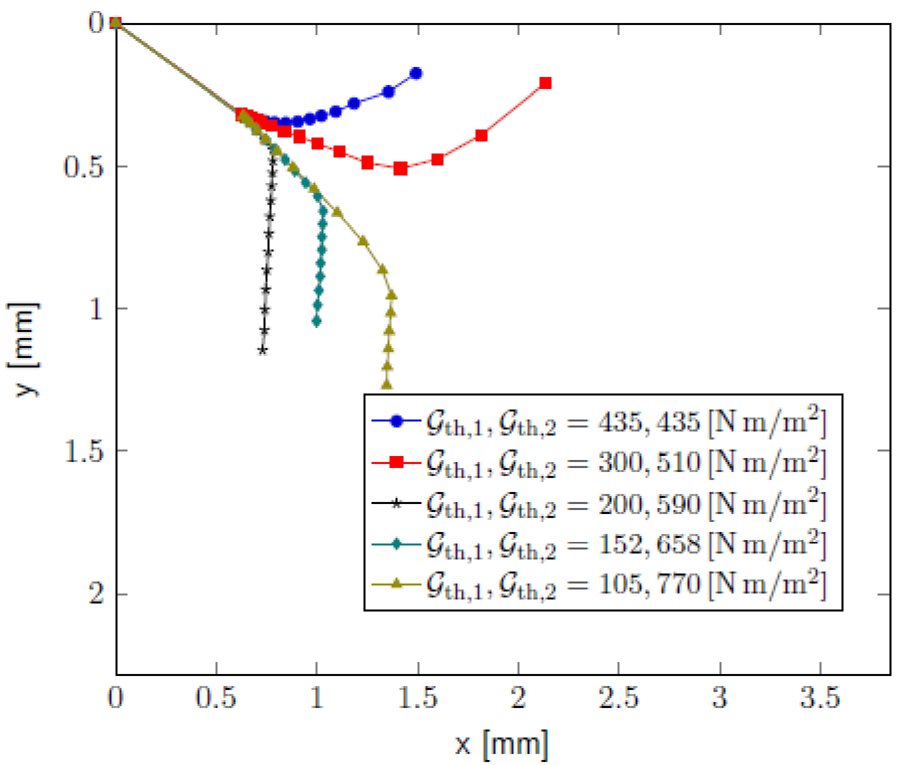


Thickness of the anisotropic surface layer: 1 mm

Effect of thickness of anisotropic surface layer



Thickness of the anisotropic surface layer: 0.8 mm



Thickness of the anisotropic surface layer: 1.2 mm

Concluding Remarks / Future Work :

- Evolution of anisotropy in pearlitic steel as a railway material has an important effect on the properties and behavior of the material in service

- Included the effect of anisotropy in a fatigue crack propagation law based on the concept of material forces adopted *[Brouzoulis et al, 2011, Comput. Mech. 47]*

- Changes in the resistance against crack propagation in different directions:
  - Fracture threshold function of degree and orientation of alignment

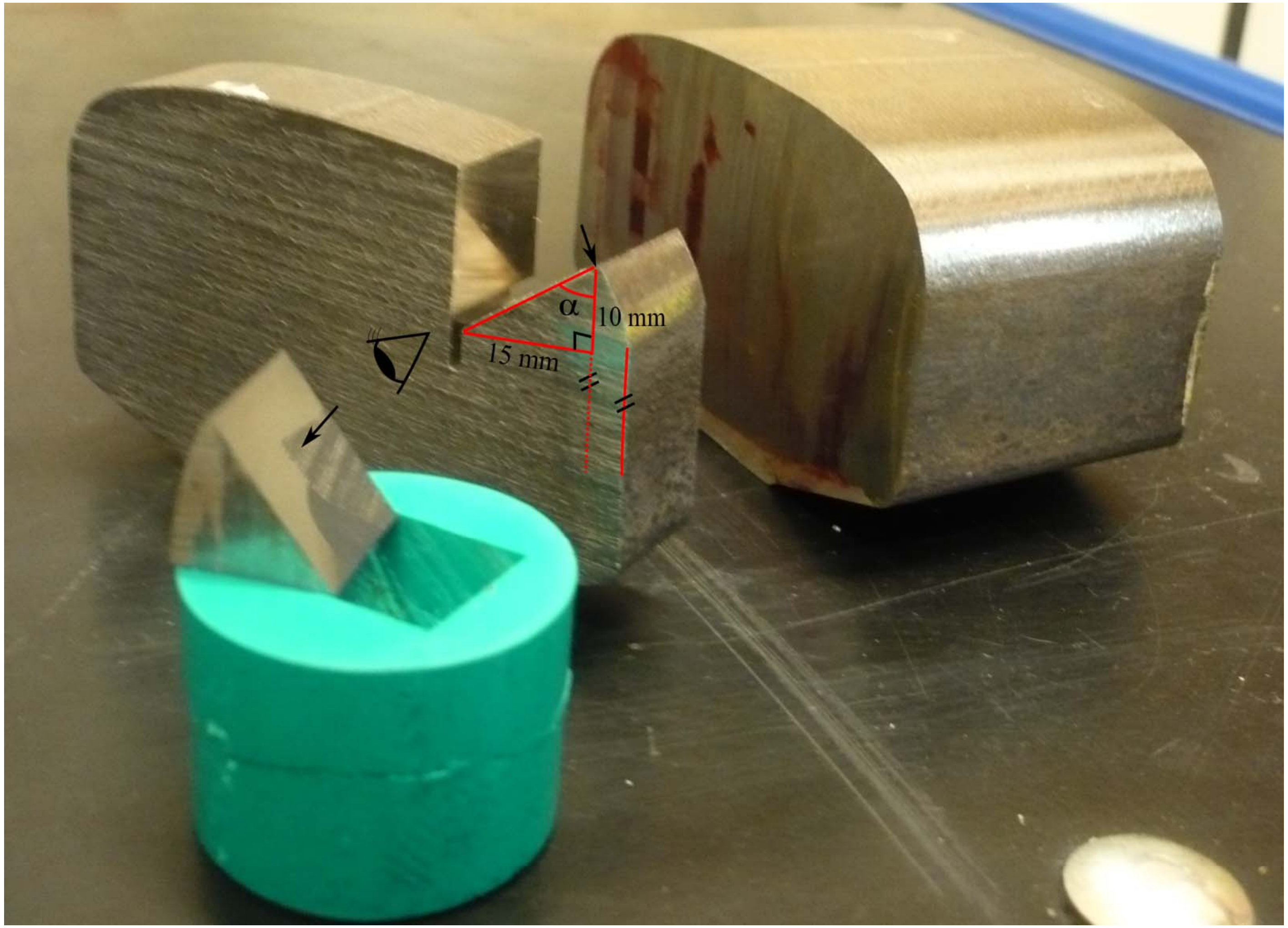
- Parametric studies of crack growth simulations for a simple 2D model of wheel-rail contact:
  - **Crack path highly sensitive to the degree of anisotropy evolved and thickness of the anisotropic surface layer**

- More realistic material model that takes into account plasticity, hardening and anisotropy evolution

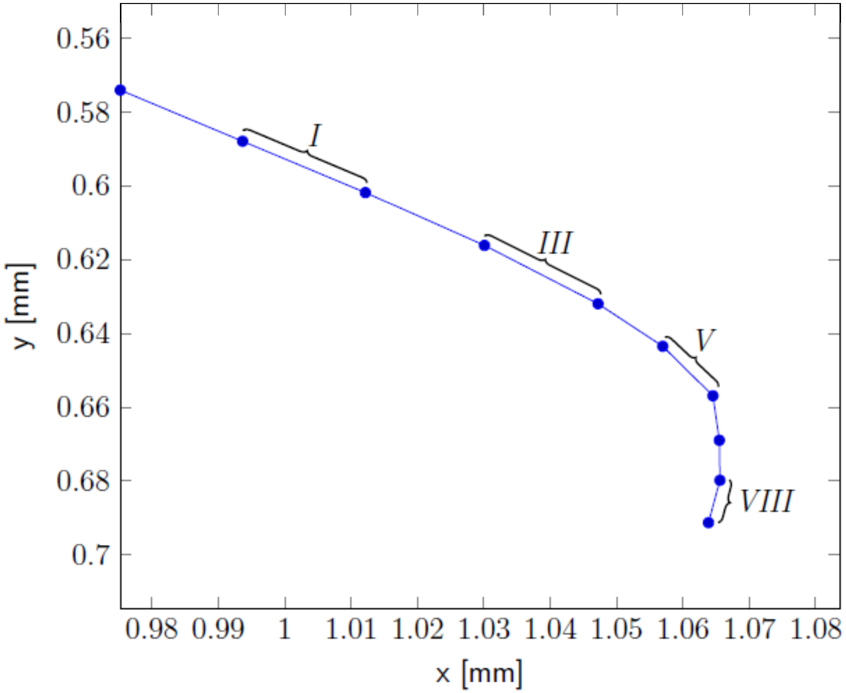
- Develop a model to study the effect of anisotropy on crack initiation

Thank You For Your Attention!

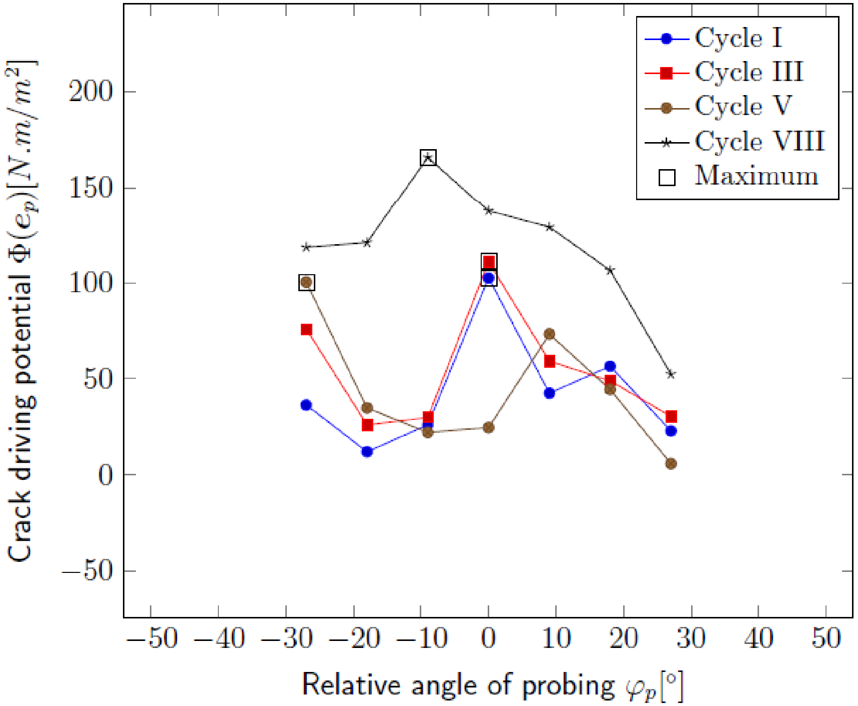
Gauge corner sample:



Discussion:



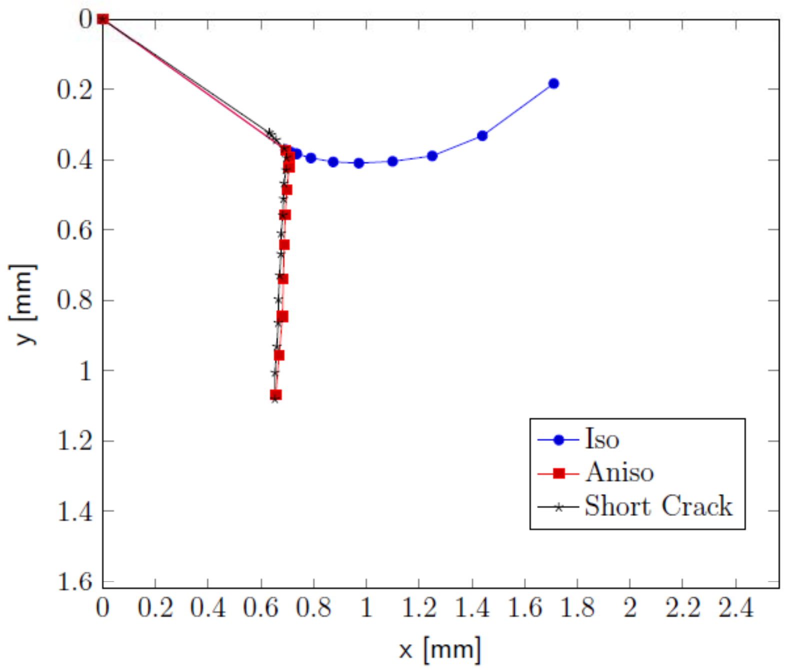
Crack path in the region of abrupt turn to the vertical direction



Average crack driving potential at the probing directions

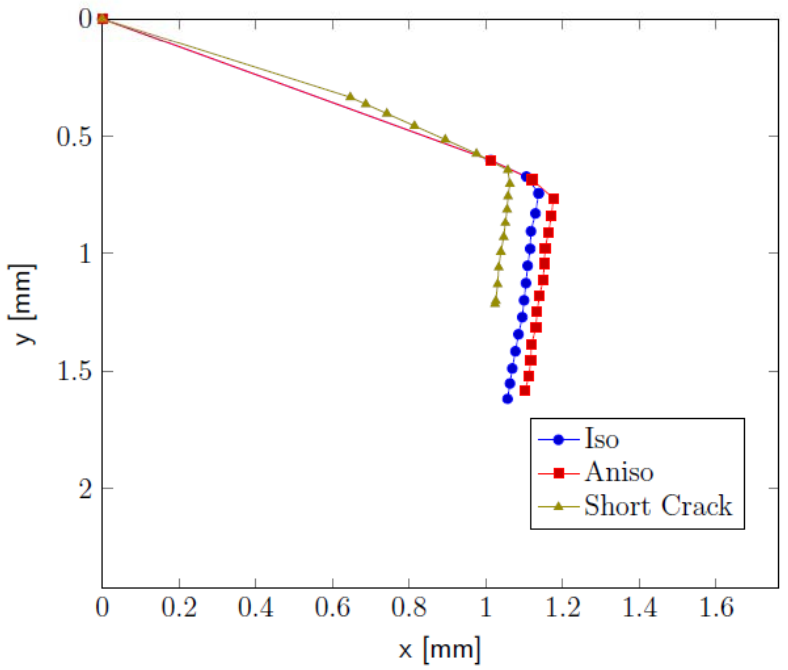
Starting fracture threshold values $\mathcal{G}_{\text{th},1} = 105\,\text{Nm/m}^2$ and $\mathcal{G}_{\text{th},2} = 770\,\text{Nm/m}^2$ and thickness of the anisotropic surface layer $y_{\text{aniso}} = 1\,\text{mm}$

Longer cracks:



Starting fracture threshold values

$\mathcal{G}_{\mathbf{th,1}} = 220\,\mathrm{Nm/m^2}$ and $\mathcal{G}_{\mathbf{th,2}} = 590\,\mathrm{Nm/m^2}$



Starting fracture threshold values

$\mathcal{G}_{\mathbf{th,1}} = 105\,\mathrm{Nm/m^2}$ and $\mathcal{G}_{\mathbf{th,2}} = 770\,\mathrm{Nm/m^2}$

Thickness of the anisotropic surface layer $y_{\mathbf{aniso}} = 1\,\mathrm{mm}$

Influence of anisotropy in numerical prediction of RCF

- *Anisotropy in the material model (stress-strain behavior) :*
  - anisotropic yield criterion (yield stress depends on loading direction)
    (“Hybrid micro-macromechanical modeling of anisotropy evolution in pearlitic steel” submitted for international publication)
  - crack-driving force depends on anisotropy

- *Anisotropy in the crack propagation law :*
  - anisotropic fracture toughness *(present work)*

- *Anisotropy in crack initiation criterion:*
  - anisotropic initiation resistance

Crack-driving force and crack propagation

- Crack-driving force, $\boldsymbol{\mathcal{G}}$: *[Tillberg et al, 2010, Int. J. Plasticity 26 (7) & Denzer et al, 2003, Int. J. Numer. Meth. Eng. 58 (12)]*

$$\boldsymbol{\mathcal{G}} = \boldsymbol{\mathcal{G}}_{\mathrm{int}} + \boldsymbol{\mathcal{G}}_{\mathrm{sur}} = \int_{\Omega_{\mathrm{X}}} -\boldsymbol{\Sigma} \cdot (W\,\boldsymbol{\nabla}_{\mathrm{X}})\,\mathrm{d}\Omega_{\mathrm{X}} + \int_{\Gamma_{\mathrm{X}}} W\boldsymbol{\Sigma} \cdot \boldsymbol{N}\,\mathrm{d}\Gamma_{\mathrm{X}}$$

$$\boldsymbol{\Sigma} = \psi \boldsymbol{I} - \boldsymbol{F}^T \boldsymbol{P}$$

- Rate independent propagation law: *[Brouzoulis et al, 2011, Comput. Mech. 47]*

$$\frac{\mathrm{d}\boldsymbol{a}}{\mathrm{d}t} = \dot{\boldsymbol{a}} = \frac{1}{\gamma}\langle \dot{\Phi}(\boldsymbol{e}^*)\rangle \boldsymbol{e}^*$$

- Direction of maximum parallel dissipation, $\boldsymbol{e}^*$:

$$\boldsymbol{e}^* = \arg\max_{\boldsymbol{e}} \lim_{\epsilon \to 0} \boldsymbol{\mathcal{G}}(\boldsymbol{a} + \epsilon \boldsymbol{e}) \cdot \boldsymbol{e} - \boxed{\mathcal{G}_{\mathrm{th}}(\boldsymbol{e})}$$

- Crack-driving potential, Φ:

$$\Phi(\boldsymbol{e}) = \langle \boldsymbol{\mathcal{G}} \cdot \boldsymbol{e} - \boxed{\mathcal{G}_{\mathrm{th}}(\boldsymbol{e})} \rangle$$