The effect of anisotropy on crack propagation in pearlitic rail steel

Nasim Larijani, Jim Brouzoulis, Martin Schilke, Magnus Ekh

Department of Applied Mechanics
Chalmers University of Technology
Gothenburg, Sweden
Swedish National Centre of Excellence in Railway Mechanics (CHARMEC)

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**

- 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 mm & 100 μm
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:
Anisotropic surface layer:

• Anisotropic surface layer has a very small thickness (≈ 1 mm)
• Material properties have a large gradient through the surface layer

Changes in mechanical properties:


• Changes in:
  ▪ Yield stress
  ▪ Tensile strength

• Significant anisotropy in:
  ▪ Fracture toughness
  ▪ Cyclic threshold values
  ▪ Crack propagation rate
Anisotropic fracture toughness


- Strong anisotropy both for monotonic and cyclic loading
- Cyclic 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 $\mathcal{G}$; based on the concept of material forces:

  Tillberg et al, 2010, Int. J. Plasticity 26(7)
  &

- Crack driving potential, $\Phi$:

  \[
  \Phi(e) = \langle \mathcal{G} \cdot e - \mathcal{G}_{th}(e) \rangle
  \]

- Propagation in the direction of maximum parallel dissipation, $e^*$:

  \[
  e^* = \arg \max_{e} \lim_{\epsilon \to 0} \mathcal{G}(a + \epsilon e) \cdot e - \mathcal{G}_{th}(e)
  \]
Anisotropic fracture threshold:

- Fracture threshold, $G_{th}$ → resistance against crack propagation

- Orientation angle in each colony, $\beta_\mu$:

- Average orientation angle, $\bar{\beta}$:

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

- A measure of degree of alignment → degree of anisotropy
- Orientation with lowest resistance against crack propagation
An anisotropic fracture surface

- Lowest and highest fracture threshold, $g_{th,1}$ and $g_{th,2} \to$ functions of $\beta$
- Transition in the microstructure $\to$ variation of $\beta$ over the depth

\[ g_{th,1} = A_1 \exp\left(\frac{-t_1}{\beta}\right) \]
\[ g_{th,2} = A_2 \exp\left(\frac{t_2}{\beta}\right) \]

\[ g_{th}(\varphi) = g_{th,1} + (g_{th,2} - g_{th,1})(1 - e^{-A|\sin(\varphi)|}) \]
Evolution of fracture surface over the depth

\( g_{th,1} \)

\( g_{th,2} \)

\( \beta_{surf} \)

\( y \)

\( y_{aniso} \)

\( g_{th,1} \)

\( g_{th,2} \)

\( \beta \)

\( \beta_{iso} \)
Simulation setup:

- Hertzian contact

\[ p_N(x, t) = p_{N0} \sqrt{1 - \left( \frac{x - vt}{d/2} \right)^2} \]

- \( p_{N0} = 800 \text{ MPa} \), \( d = 14.8 \text{ mm} \)

- \( p_T(x, t) = \mu p_N(x, t) \)
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.


- 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

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

Average crack driving potential at the probing directions
Longer cracks:

Starting fracture threshold values

\[ G_{th,1} = 220 \text{ Nm/m}^2 \text{ and } G_{th,2} = 590 \text{ Nm/m}^2 \]

Starting fracture threshold values

\[ G_{th,1} = 105 \text{ Nm/m}^2 \text{ and } G_{th,2} = 770 \text{ Nm/m}^2 \]

Thickness of the anisotropic surface layer \( y_{aniso} = 1 \text{ mm} \)
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


$$\mathcal{G} = \mathcal{G}_{\text{int}} + \mathcal{G}_{\text{sur}} = \int_{\Omega_x} -\Sigma \cdot (W \nabla x) \, d\Omega_x + \int_{\Gamma_x} W \Sigma \cdot \mathbf{N} \, d\Gamma_x$$

$$\Sigma = \psi I - F^T P$$


$$\frac{da}{dt} = \dot{a} = \frac{1}{\gamma} \langle \dot{\Phi}(\mathbf{e}^*) \rangle \mathbf{e}^*$$

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

$$\mathbf{e}^* = \arg \max_{\mathbf{e}} \lim_{\mathbf{e} \to 0} \mathcal{G}(a + \varepsilon \mathbf{e}) \cdot \mathbf{e} - \mathcal{G}_{\text{th}}(\mathbf{e})$$

- Crack-driving potential, $\Phi$:

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