In situ three dimensional monitoring and modelling of small corner cracks in airframe Al alloys

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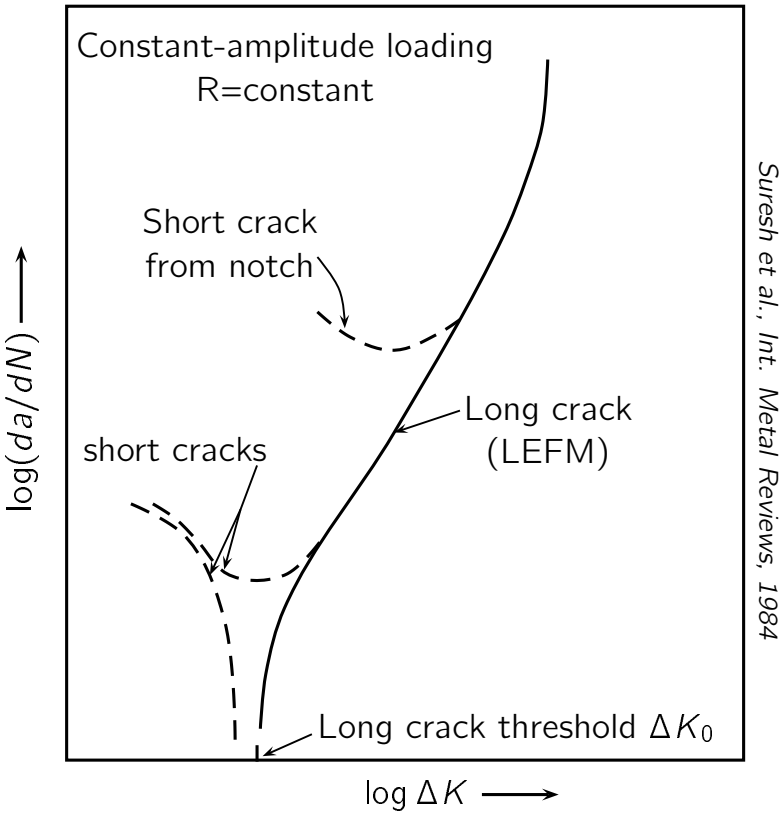
July 15th, 2009

Outline

Outline

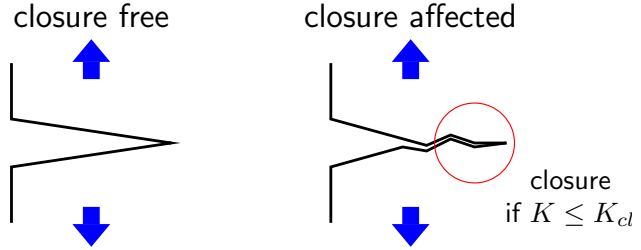
Short cracks and closure issues



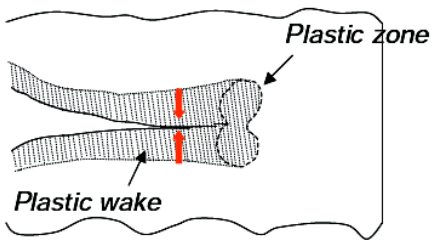
3D crack propagation effects require 3D characterization...

1 Crystallographic propagation

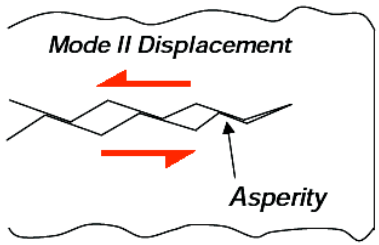
2 Crack closure mechanisms



Driving force $\Delta K_{eff} = K_{max} - K_{cl}$



'PICC'



'RICC'

Project aims

Experimental

Tomographic imaging for detailed insight of small crack evolutions (up to ~2 mm)

- Model alloy with ideally flat shape cracks
- Engineering 2027 alloy with highly complex crack shapes

Propagation model

Apply multi-mechanistic crack closure modelling to small corner cracks

- RICC and PICC
- Constant amplitude, constant ΔK and overload regimes
- Plane stress, plane strain and mixed stress state effects

Outline

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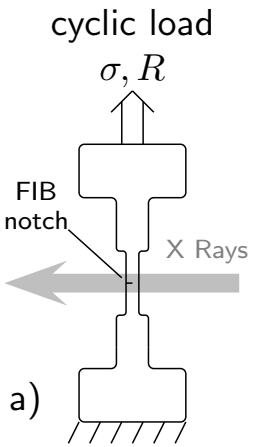
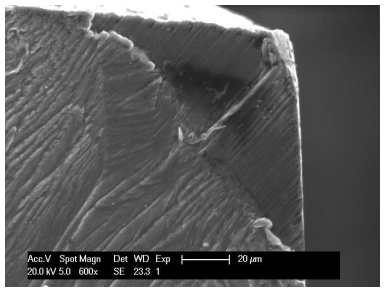
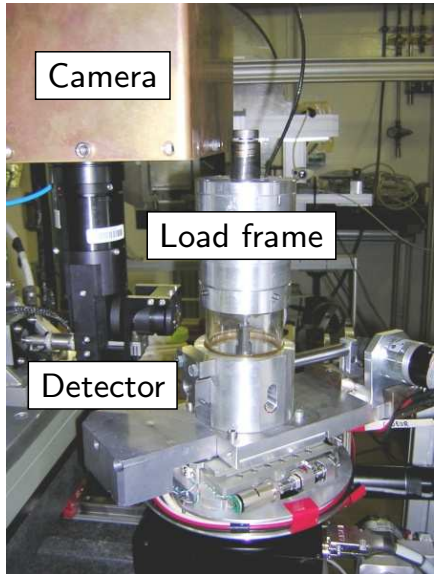
in situ X-ray tomography setup





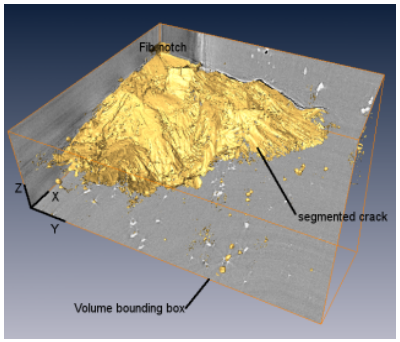


in situ crack monitoring

- Two $\neq$ alloys: 5091 (grain size ~ 1 µm) vs. 2027 (grain size ~ 100 µm)
- crack initiation is controlled via a FIB notch
- *in situ* fatigue device
- study both baseline growth ($\Delta K \sim 3\ \mathrm{MPa}\sqrt{\mathrm{m}}$) and post-overload growth

Outline

Tomographic data analysis

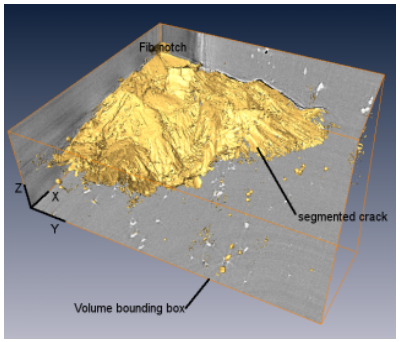


Amount of data is considerable (more than 100 scans) $\longrightarrow$ need automated data treatment *as much as possible*...

For each tomographic image (x,y,z):

- crack front location and local da/dN values
- local crack opening values
- 3D rendering of crack morphology

Tomographic data analysis



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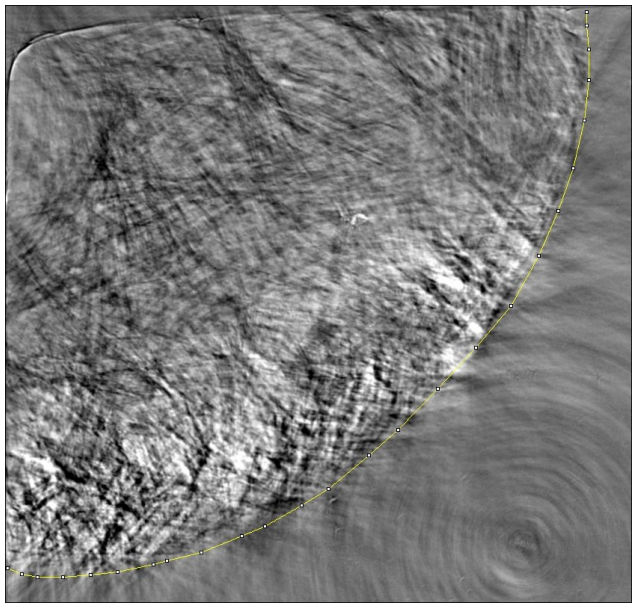

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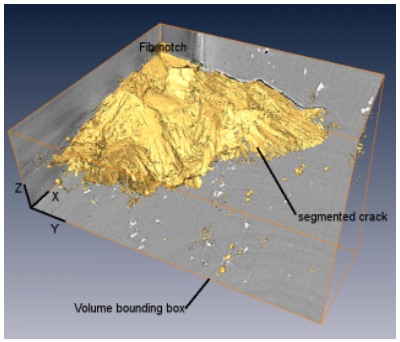

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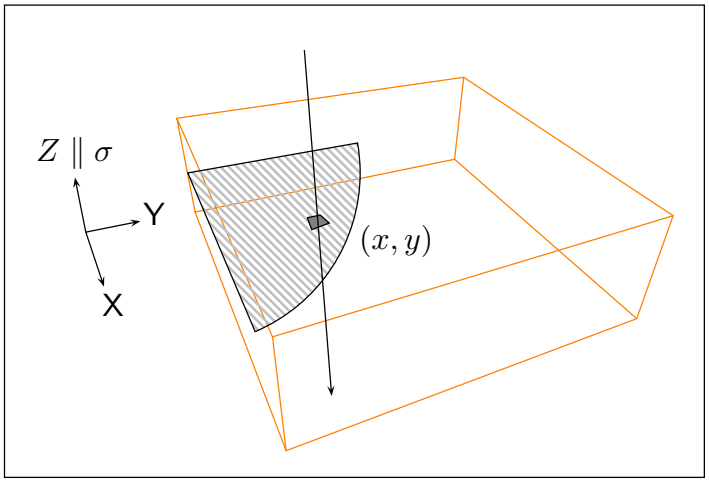
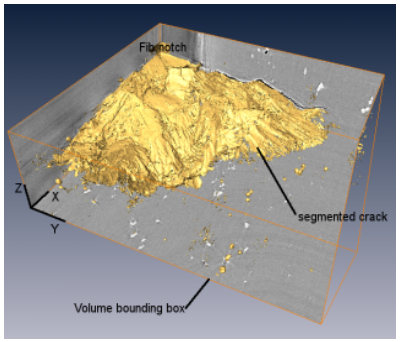


Tomographic data analysis



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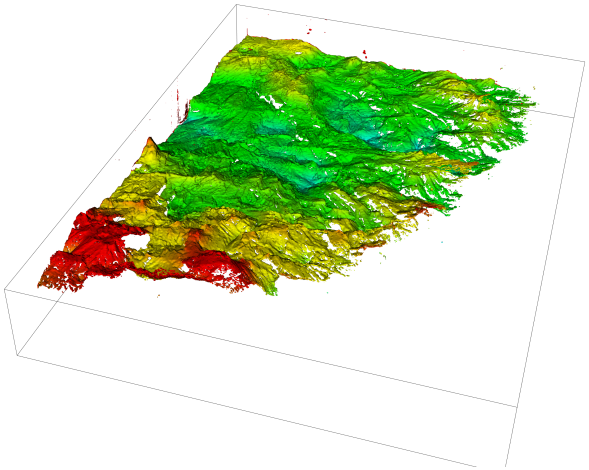
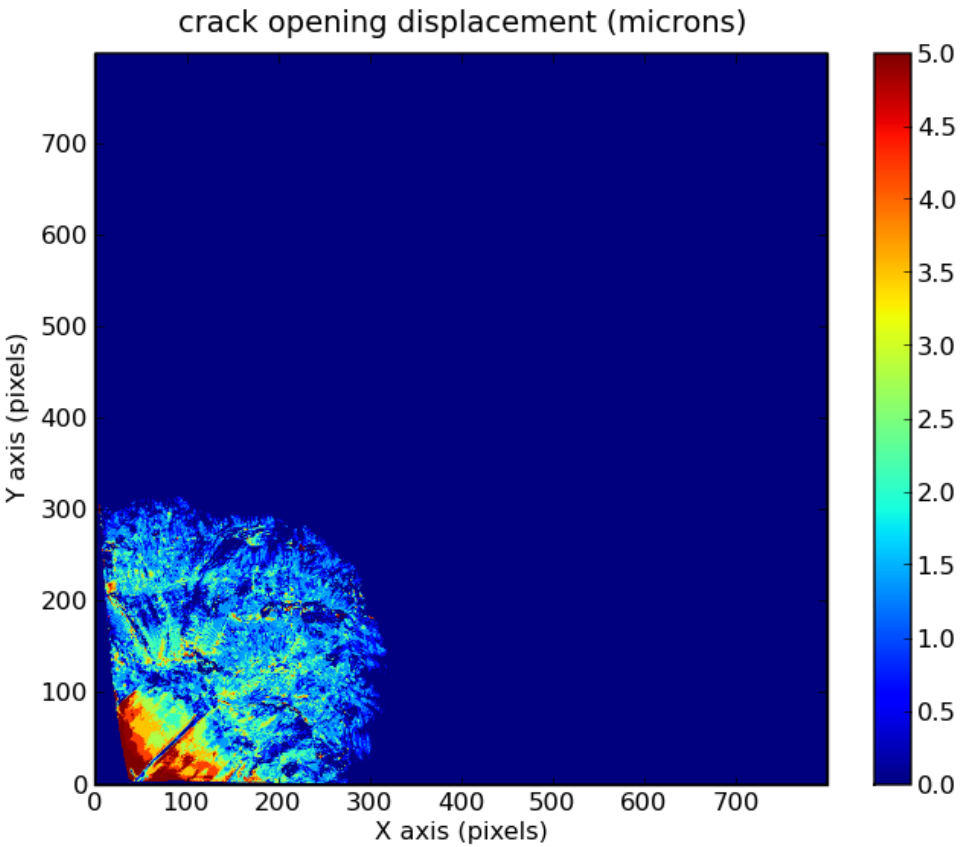


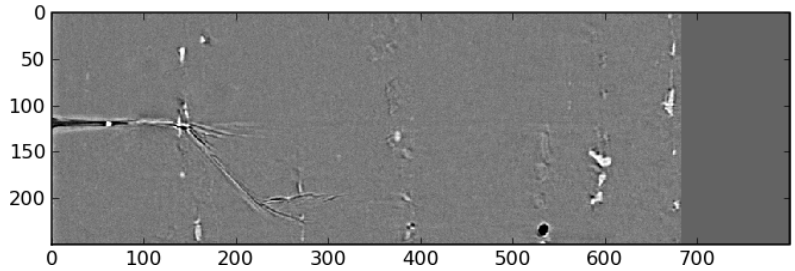
Crack opening displacement in 2027

N=208k cycles



slice extracted at $x = 100$

from raw volume data set



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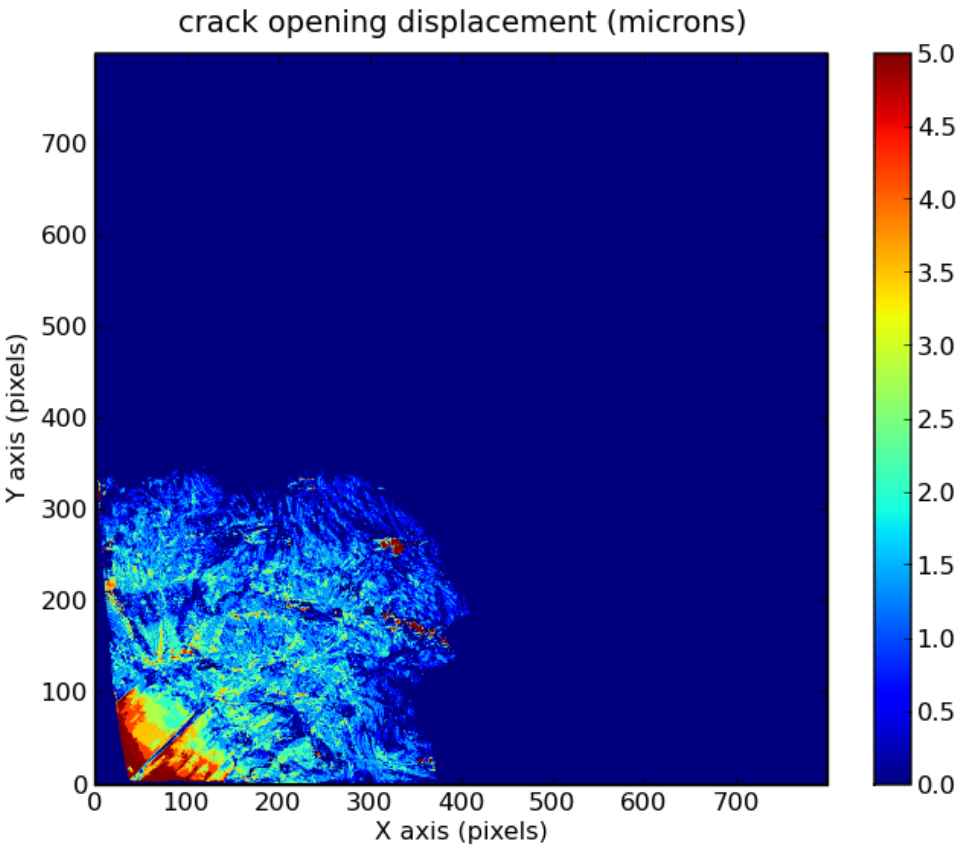
Crack opening displacement in 2027

N=598k cycles



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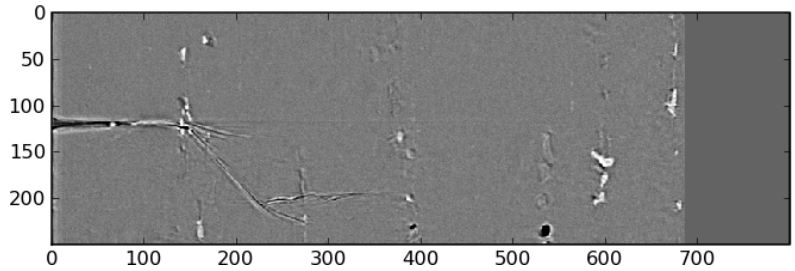

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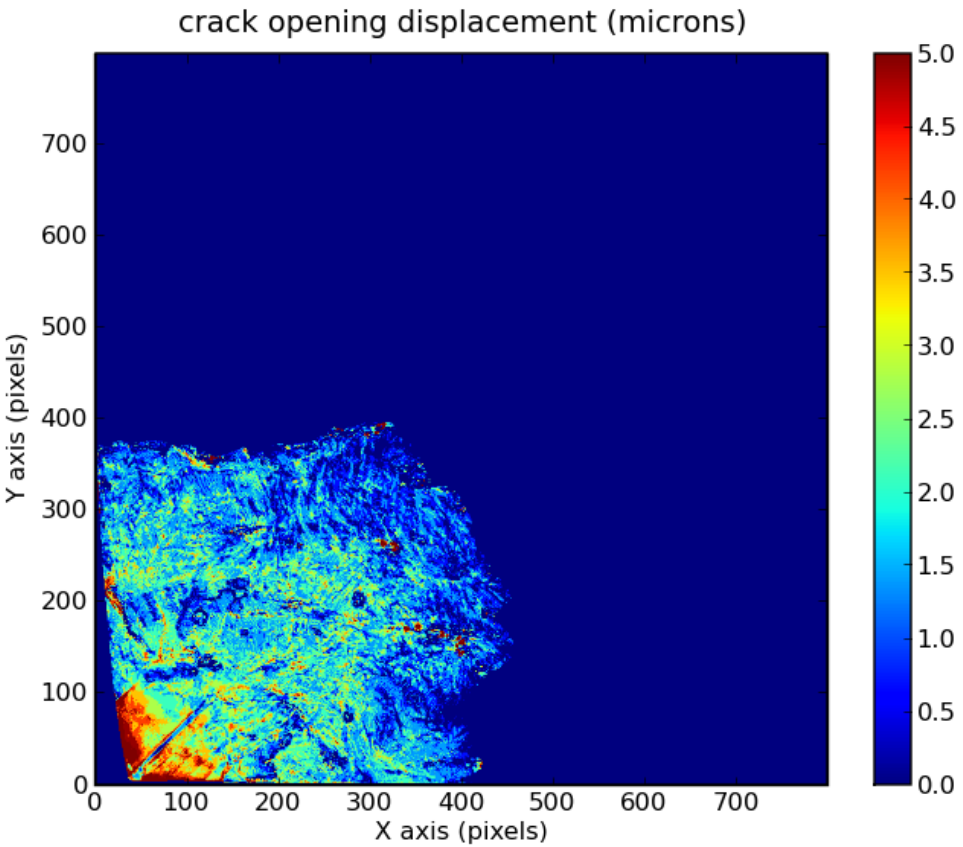
Crack opening displacement in 2027

N=758k cycles



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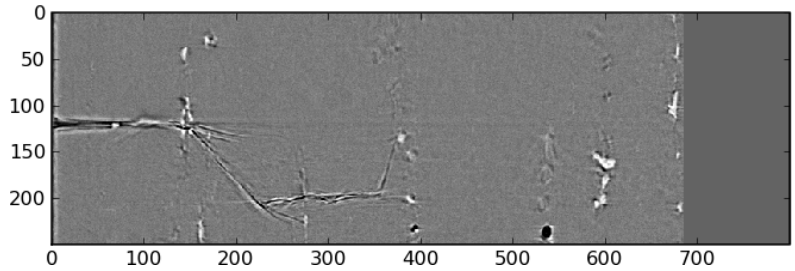

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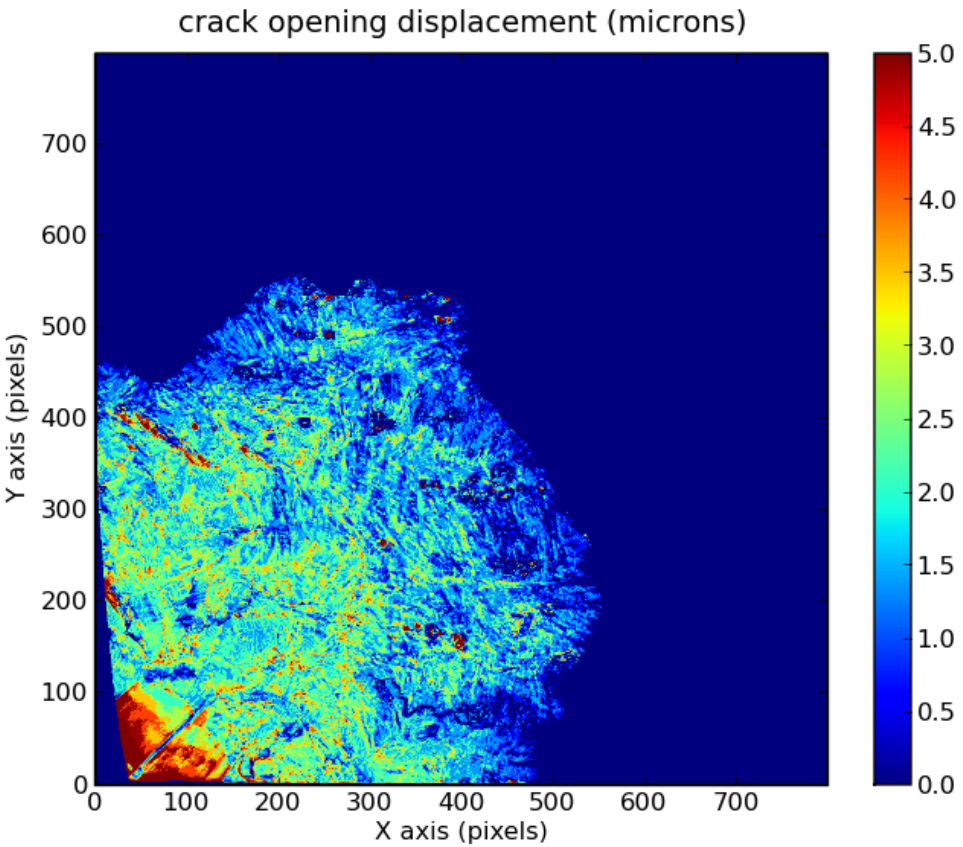
Crack opening displacement in 2027

N=838k cycles



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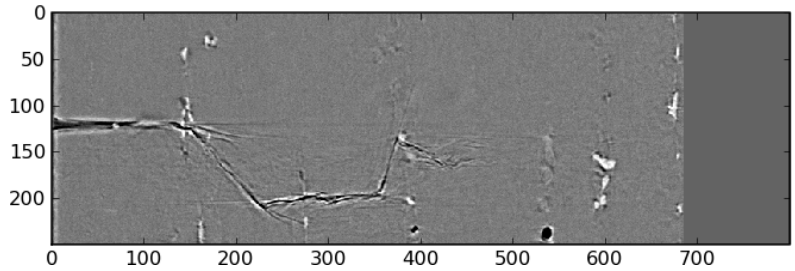

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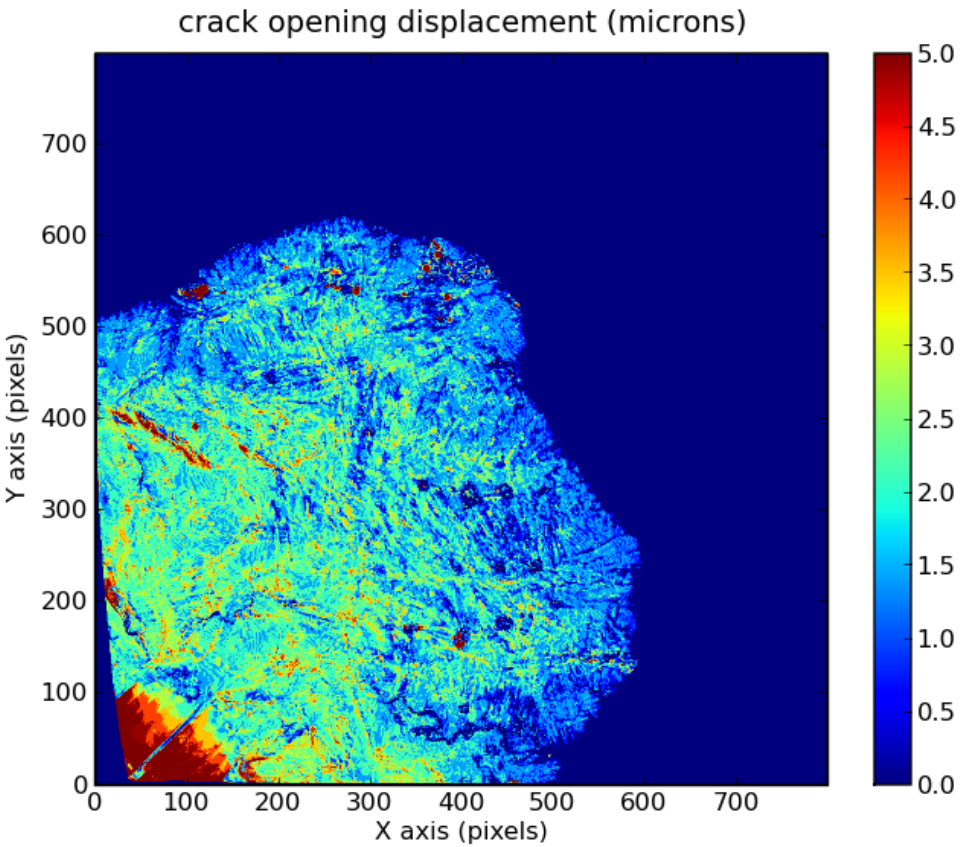
Crack opening displacement in 2027

N=853k cycles



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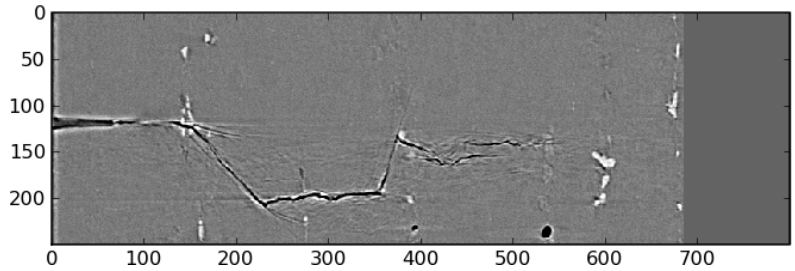

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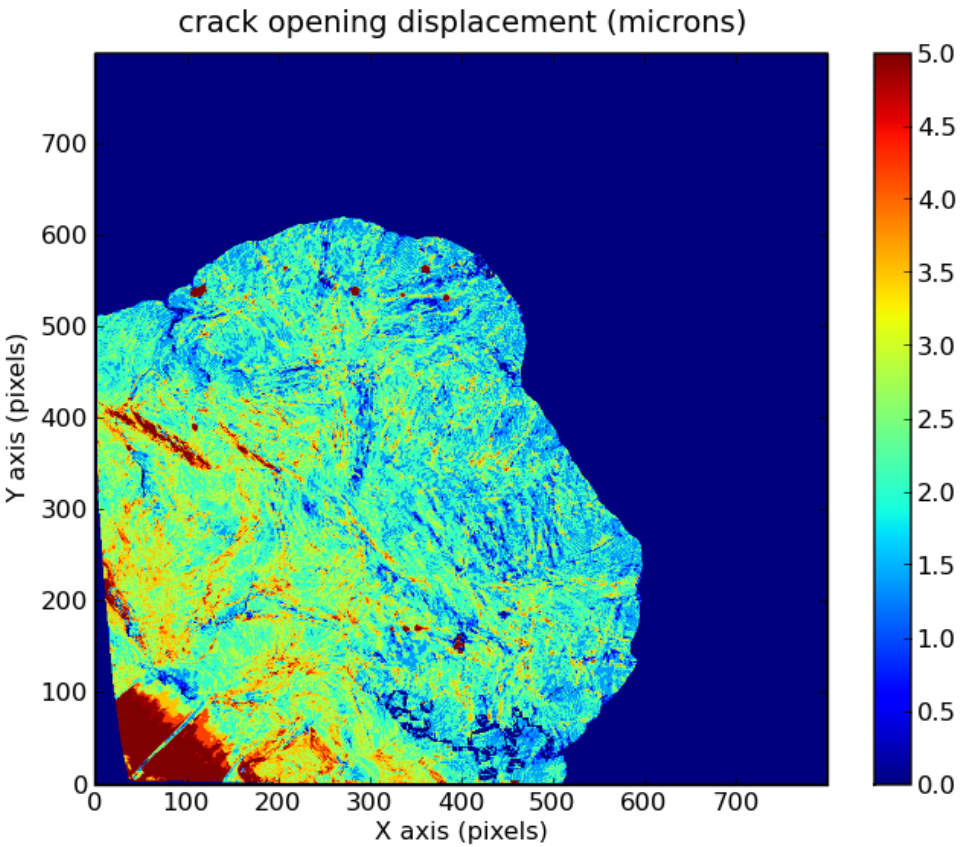
Crack opening displacement in 2027

N=853k cycles + 100% OL



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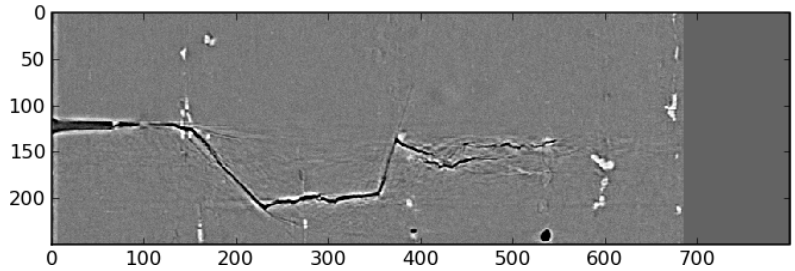

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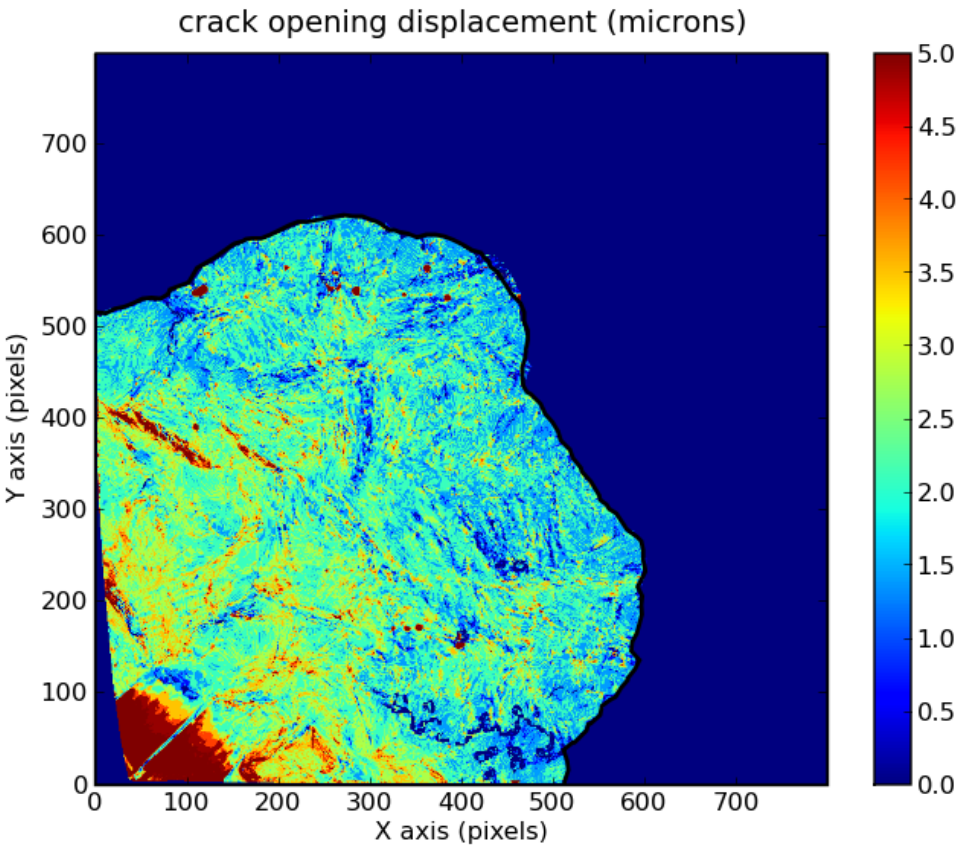
Crack opening displacement in 2027

N=853k cycles + 100% OL + 1k cycles



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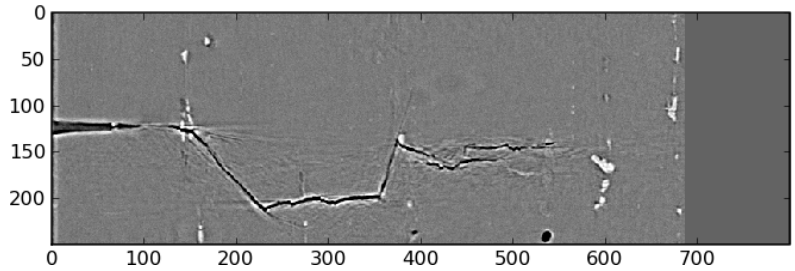

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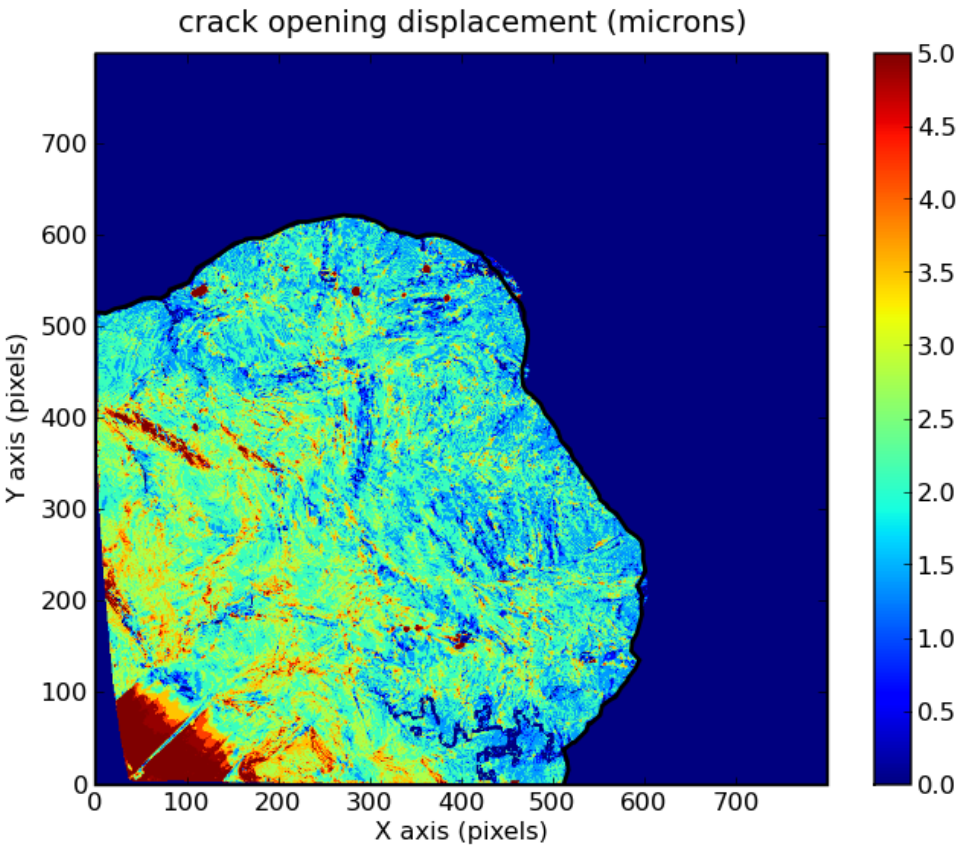
Crack opening displacement in 2027

N=853k cycles + 100% OL + 2k cycles



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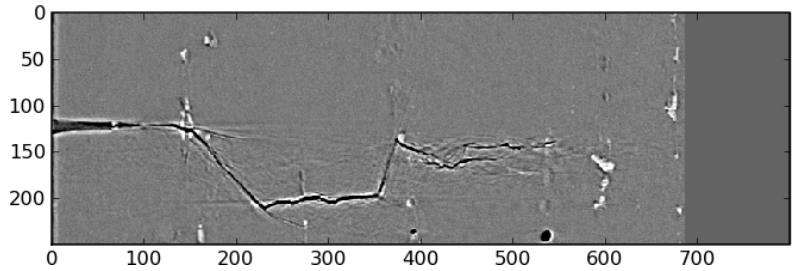

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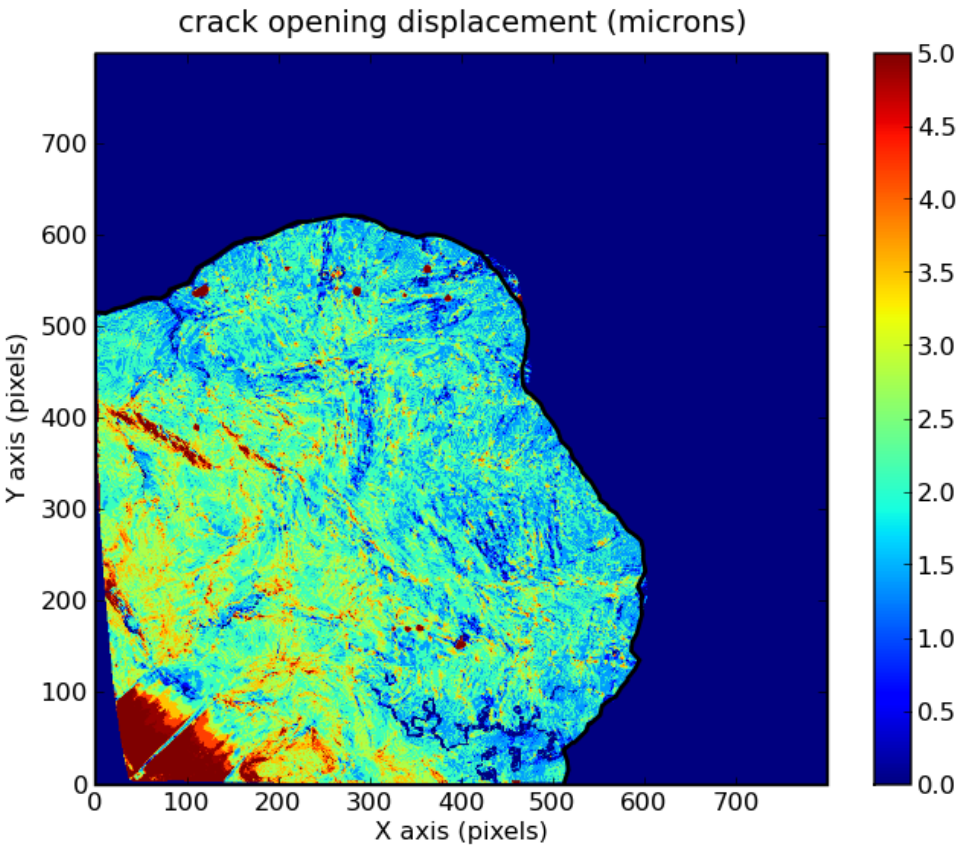
Crack opening displacement in 2027

N=853k cycles + 100% OL + 3k cycles



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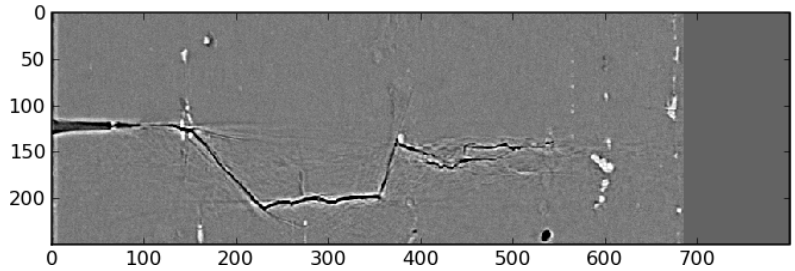

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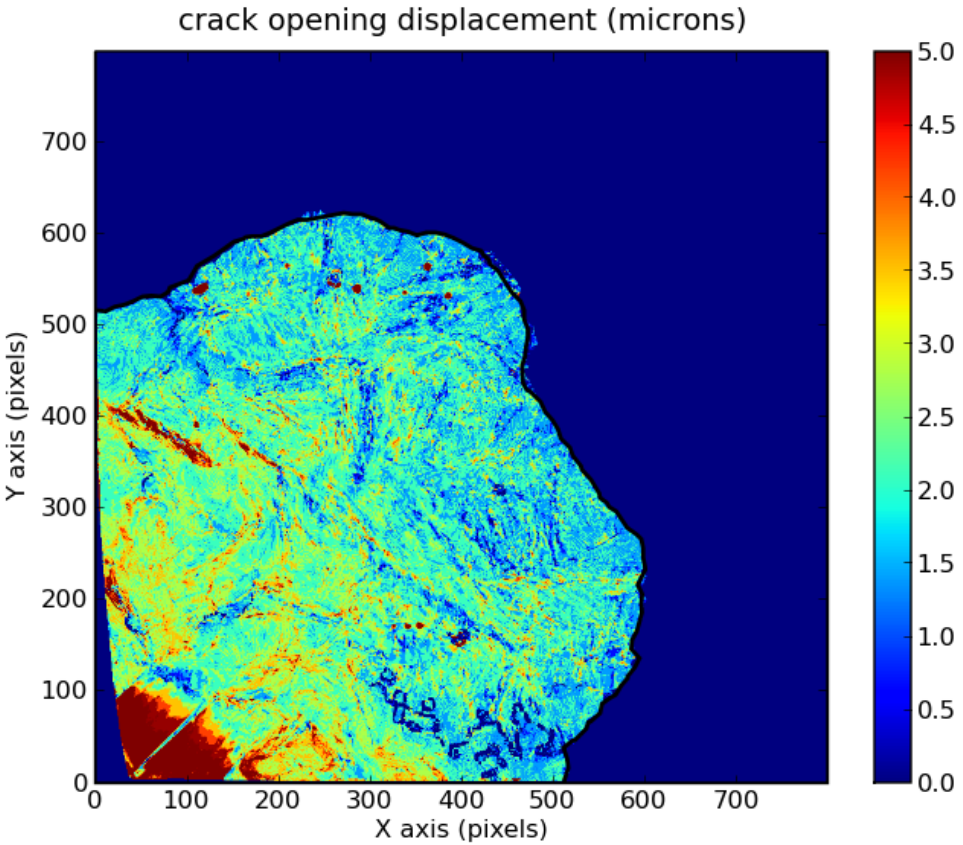
Crack opening displacement in 2027

N=853k cycles + 100% OL + 6k cycles



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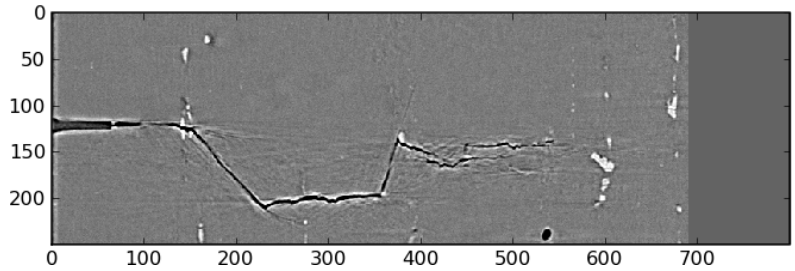

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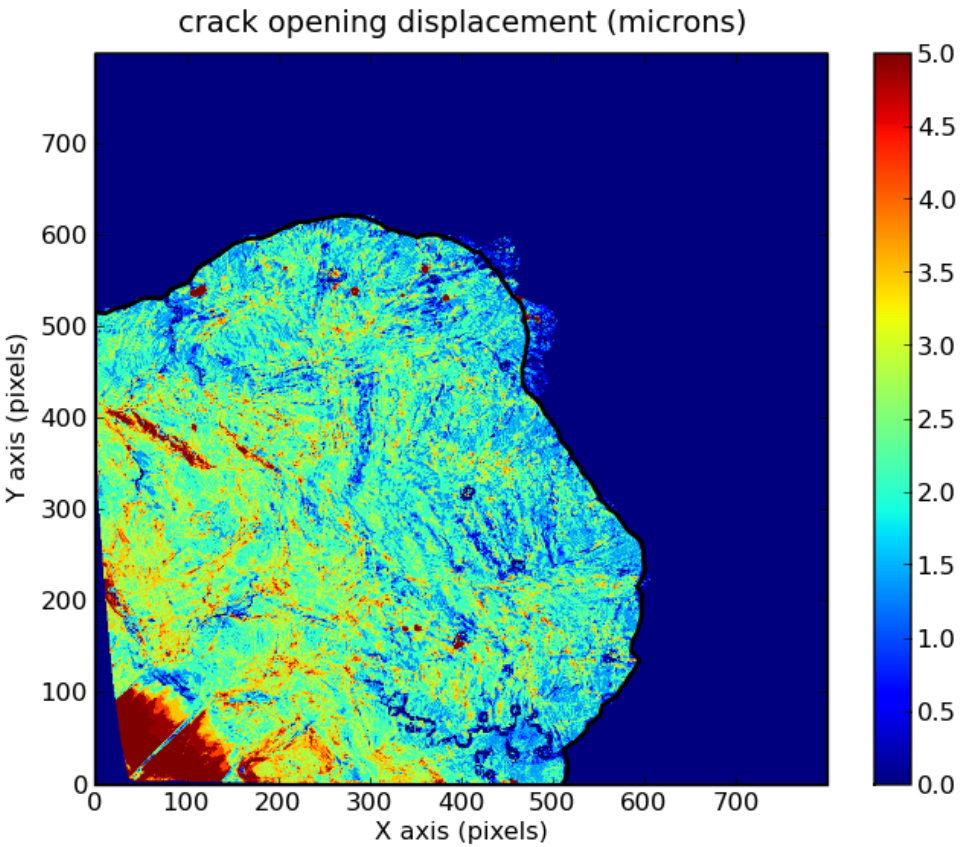
Crack opening displacement in 2027

N=853k cycles + 100% OL + 14k cycles



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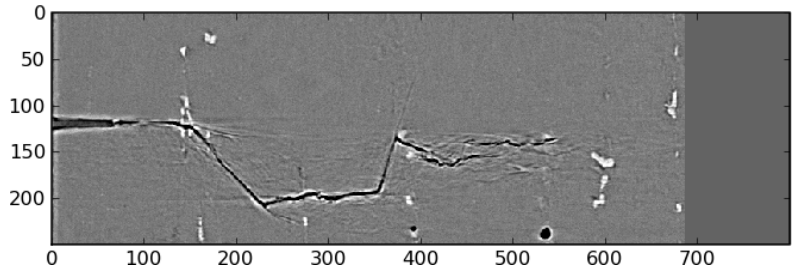

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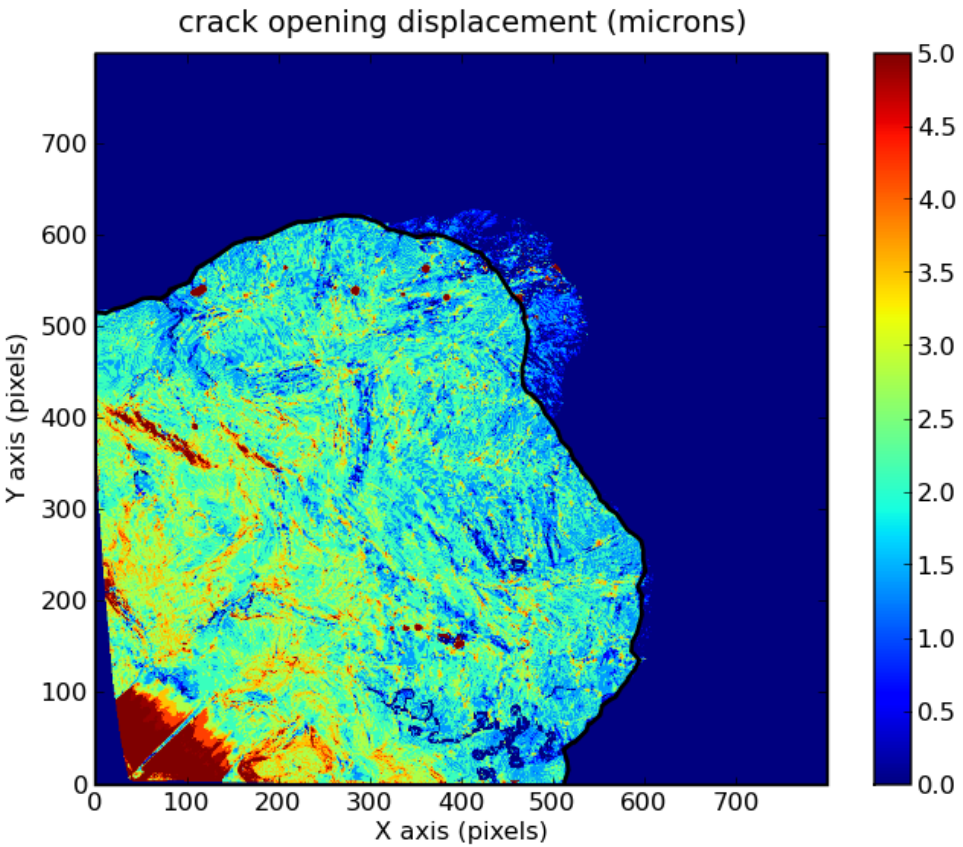
Crack opening displacement in 2027

N=853k cycles + 100% OL + 24k cycles



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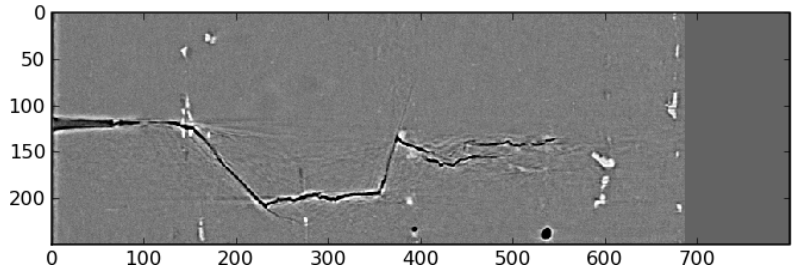

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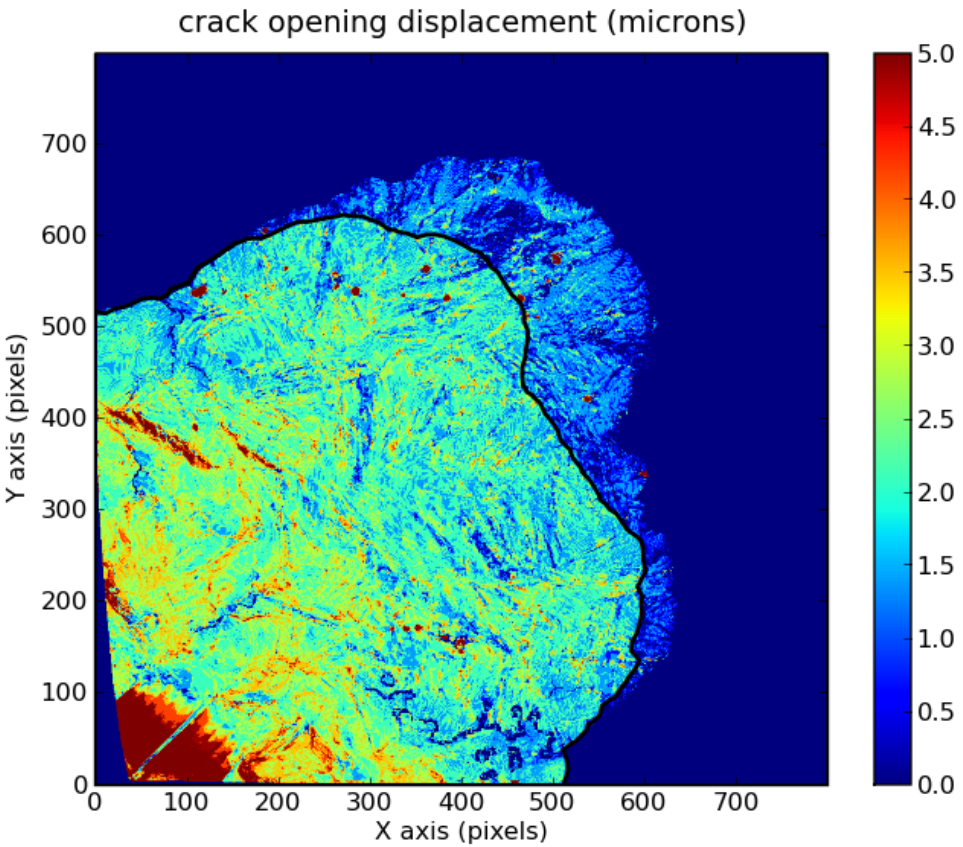
Crack opening displacement in 2027

N=853k cycles + 100% OL + 39k cycles



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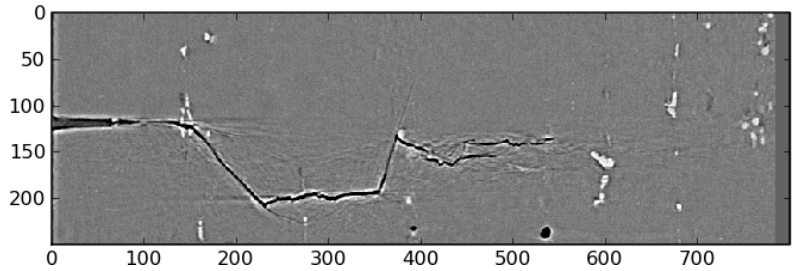

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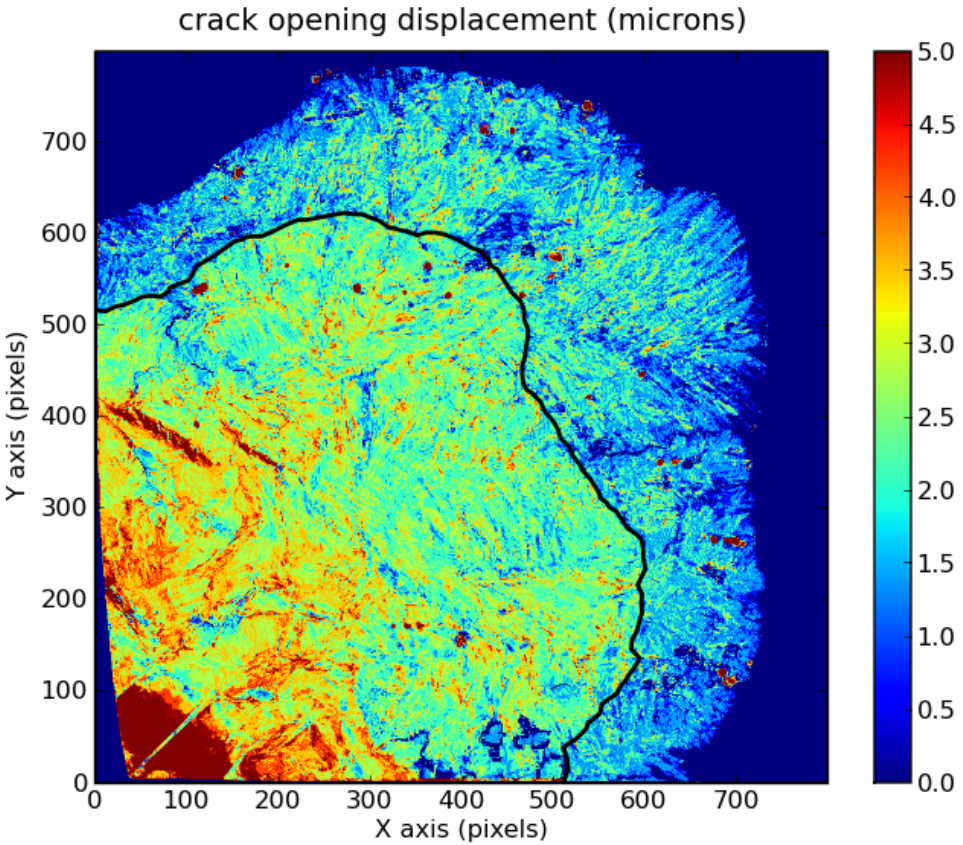
Crack opening displacement in 2027

N=853k cycles + 100% OL + 59k cycles



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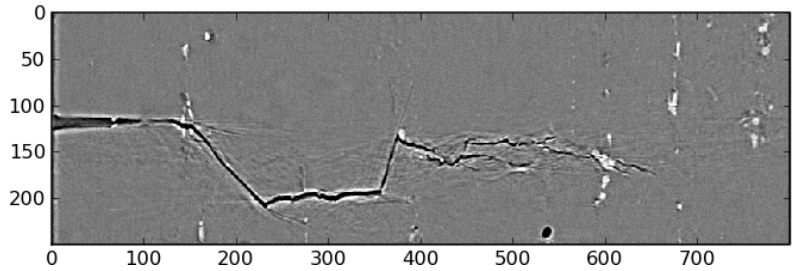

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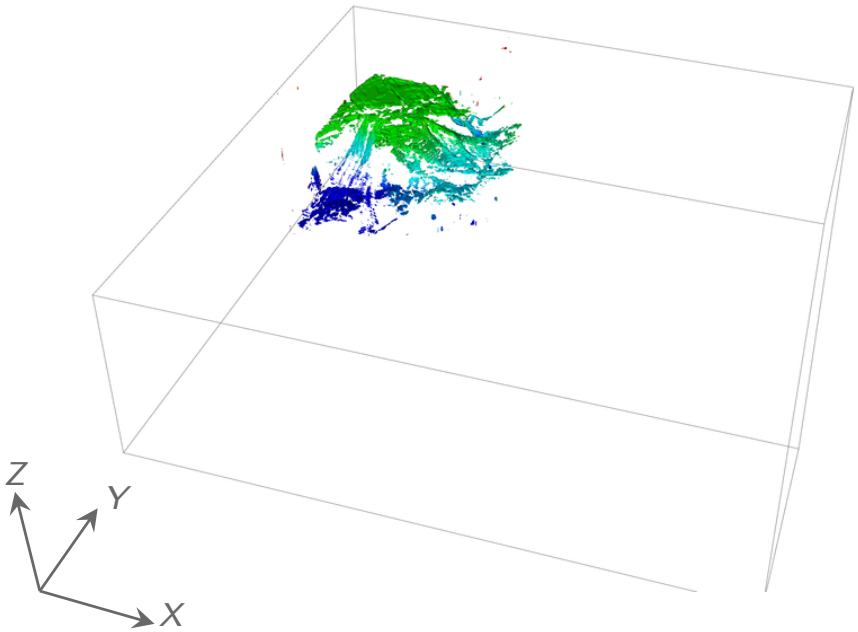
3D crack rendering in 2027

N=208k cycles

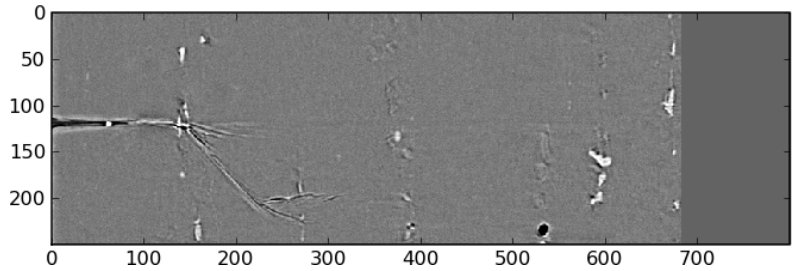
3d rendering with position mapping

box is ($560 \times 560 \times 175\ \mu m$)



slice extracted at $x = 100$

from raw volume data set



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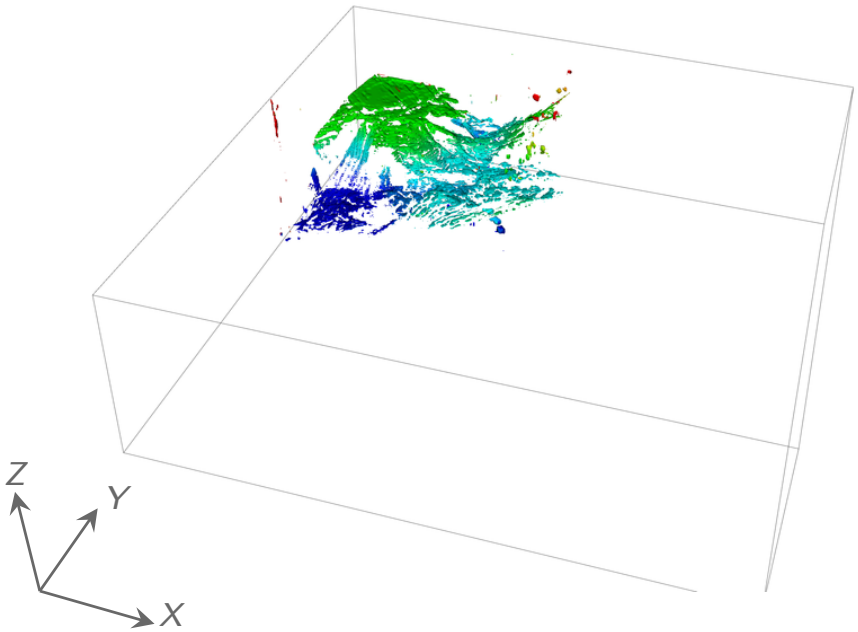
3D crack rendering in 2027

N=598k cycles

3d rendering with position mapping

box is $(560 \times 560 \times 175\ \mu m)$



slice extracted at $x = 100$

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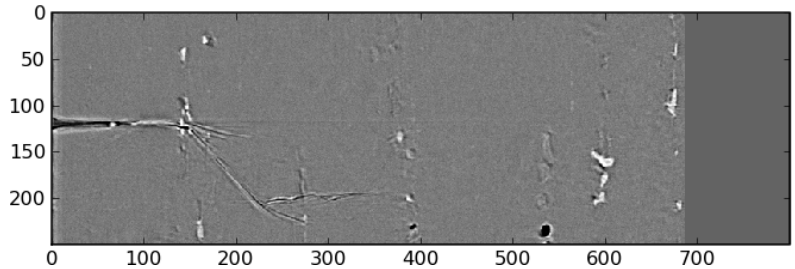

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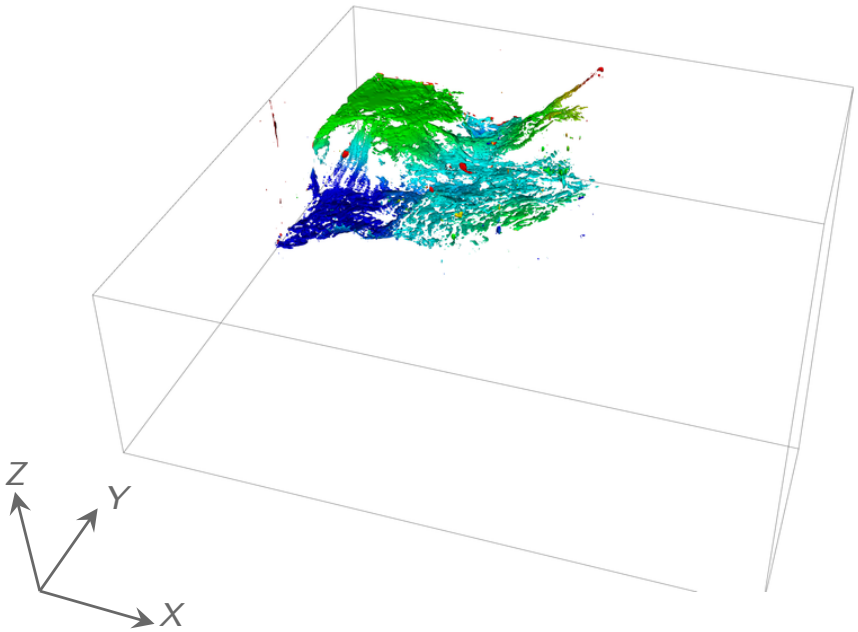
3D crack rendering in 2027

N=758k cycles

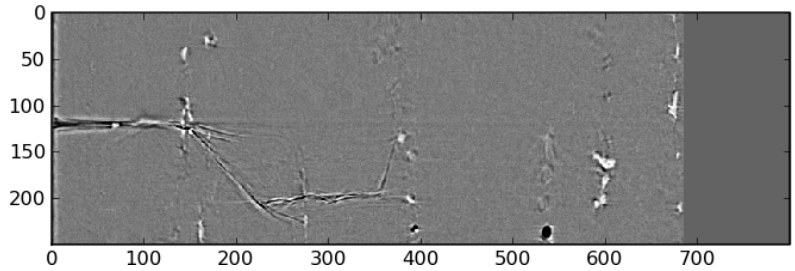
3d rendering with position mapping

box is ($560 \times 560 \times 175\ \mu m$)



slice extracted at $x = 100$

from raw volume data set



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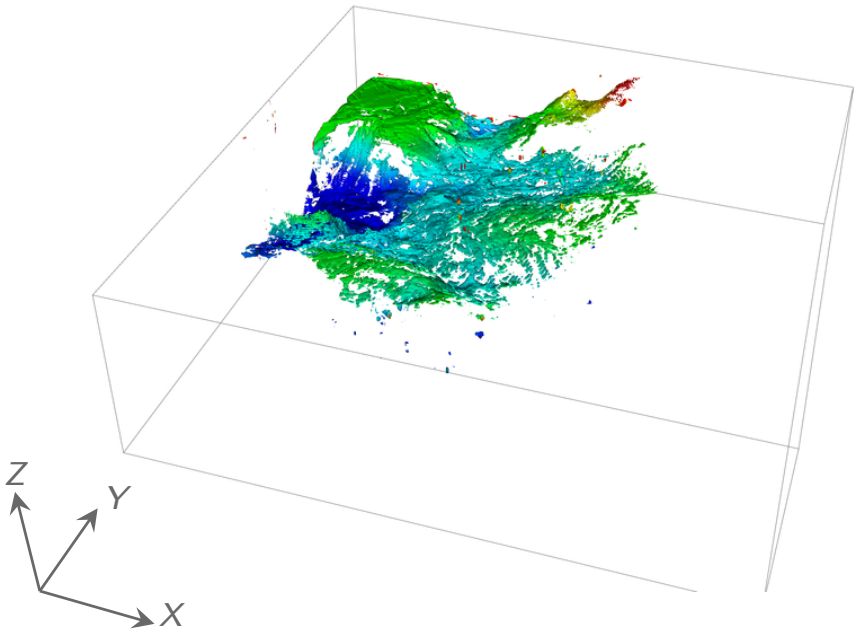
3D crack rendering in 2027

N=838k cycles

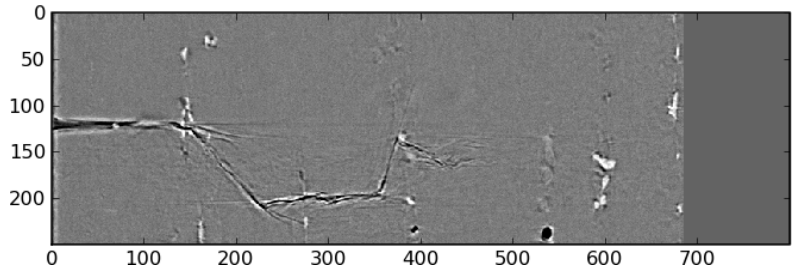
3d rendering with position mapping

box is ($560 \times 560 \times 175\ \mu m$)



slice extracted at $x = 100$

from raw volume data set



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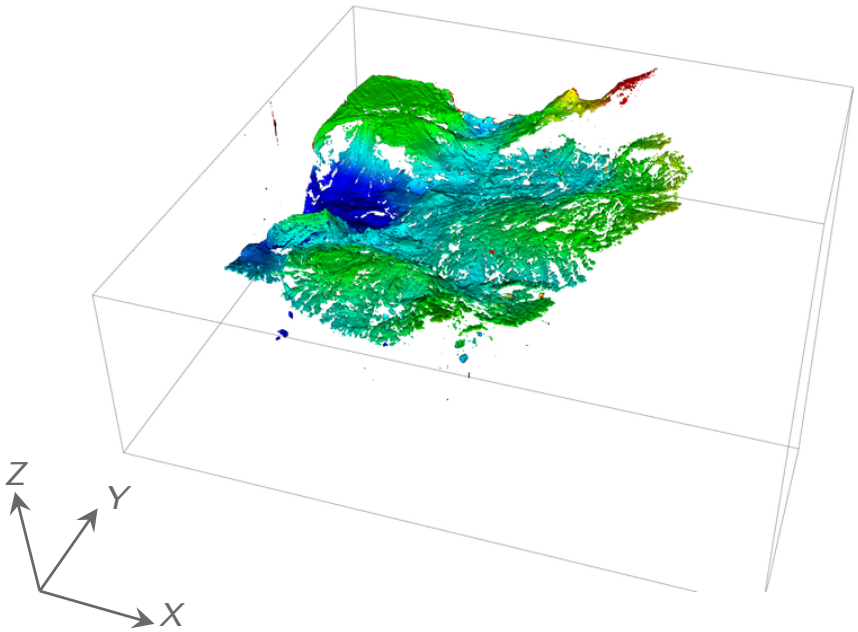
3D crack rendering in 2027

N=853k cycles

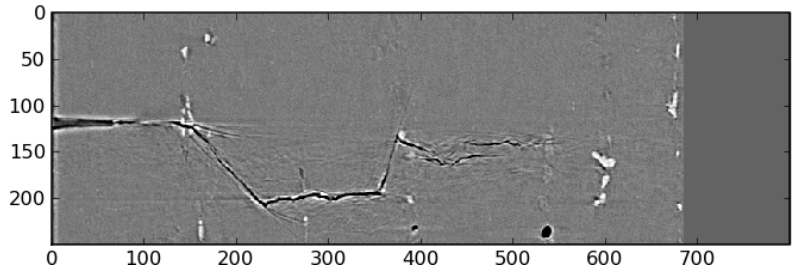
3d rendering with position mapping

box is ($560 \times 560 \times 175\ \mu m$)



slice extracted at $x = 100$

from raw volume data set



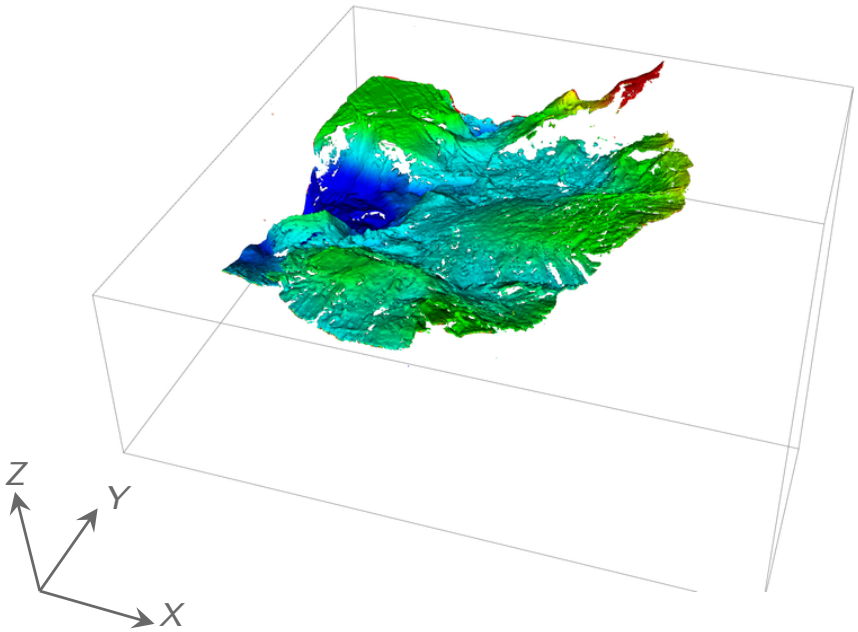
◂ Return ▸ Play ▸ End

3D crack rendering in 2027

N=853k cycles + 100% OL

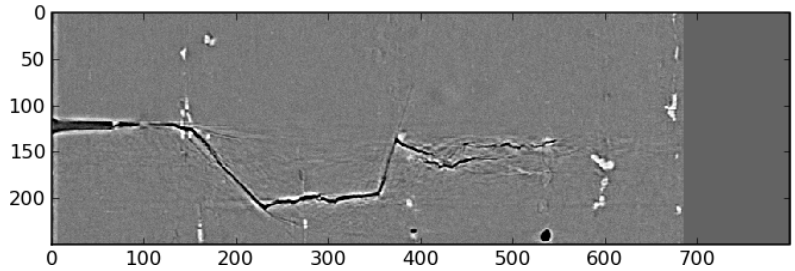
3d rendering with position mapping

box is (560 × 560 × 175 μm)



slice extracted at $x = 100$

from raw volume data set



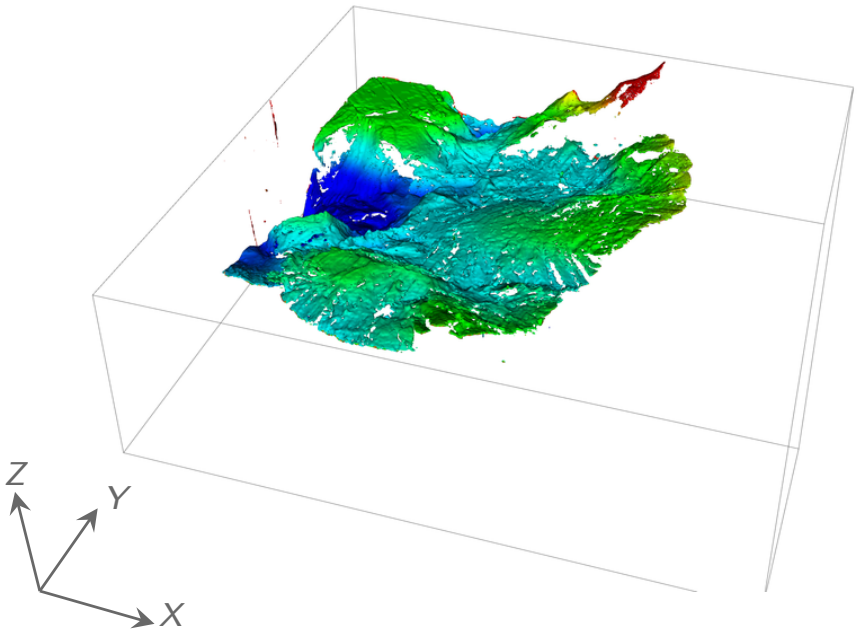
◂ Return ▸ Play ▸ End

3D crack rendering in 2027

N=853k cycles + 100% OL + 1k cycles

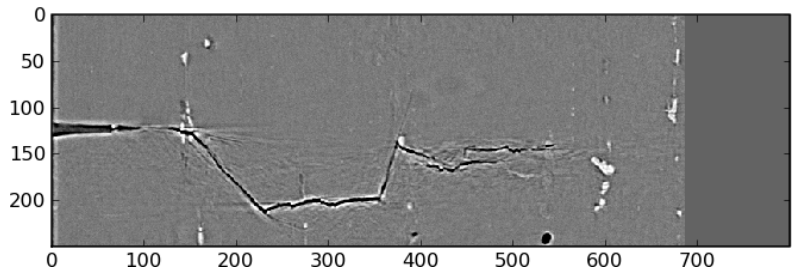
3d rendering with position mapping

box is (560 × 560 × 175 μm)



slice extracted at $x = 100$

from raw volume data set



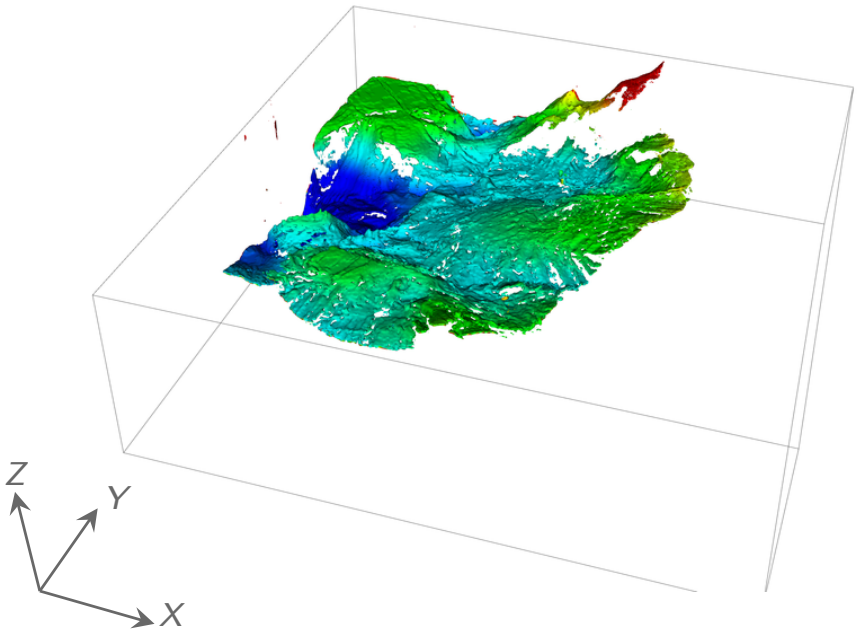
◂ Return ▸ Play ▸ End

3D crack rendering in 2027

N=853k cycles + 100% OL + 2k cycles

3d rendering with position mapping

box is (560 × 560 × 175 μm)



slice extracted at $x = 100$

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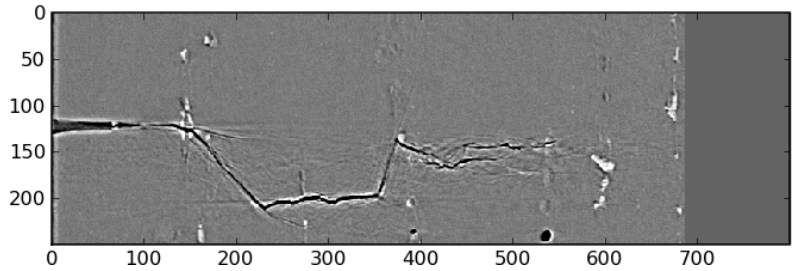


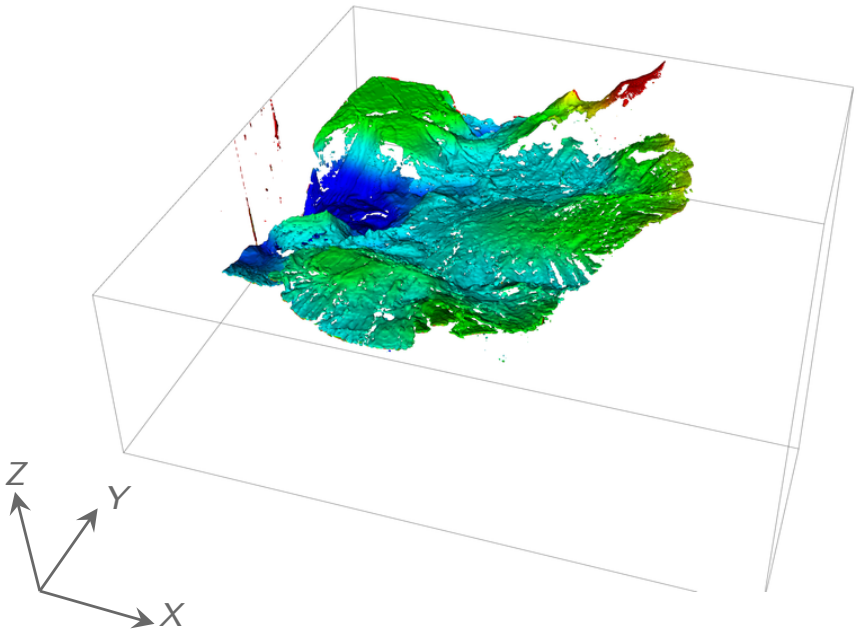
Return Play End

3D crack rendering in 2027

N=853k cycles + 100% OL + 3k cycles

3d rendering with position mapping

box is (560 × 560 × 175 μm)



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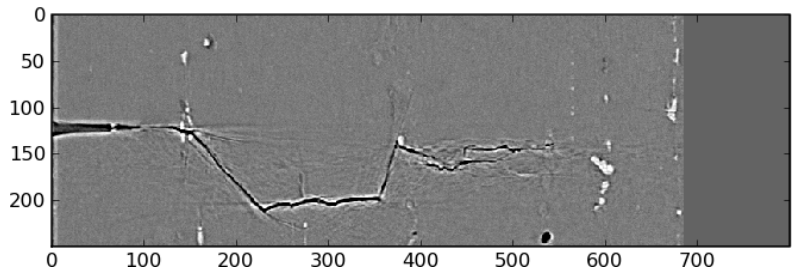

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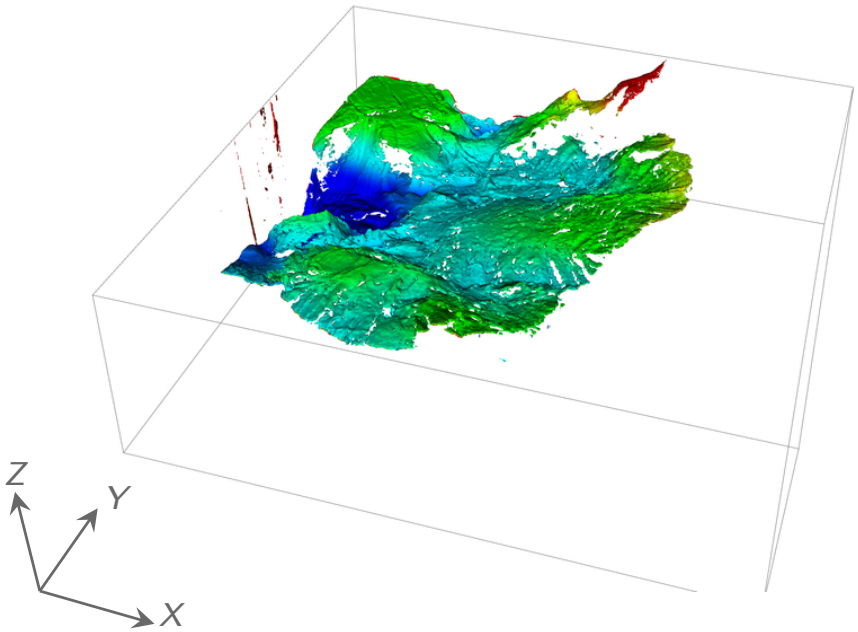
3D crack rendering in 2027

N=853k cycles + 100% OL + 6k cycles

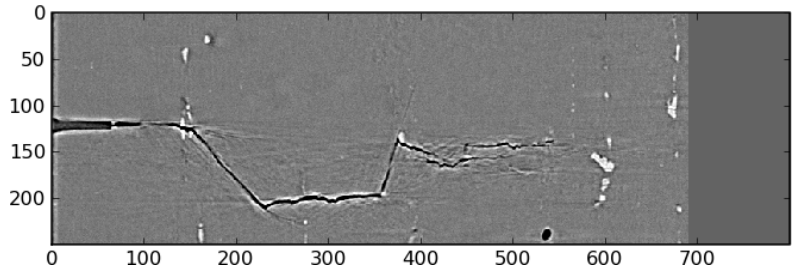
3d rendering with position mapping

box is (560 × 560 × 175 μm)



slice extracted at $x = 100$

from raw volume data set



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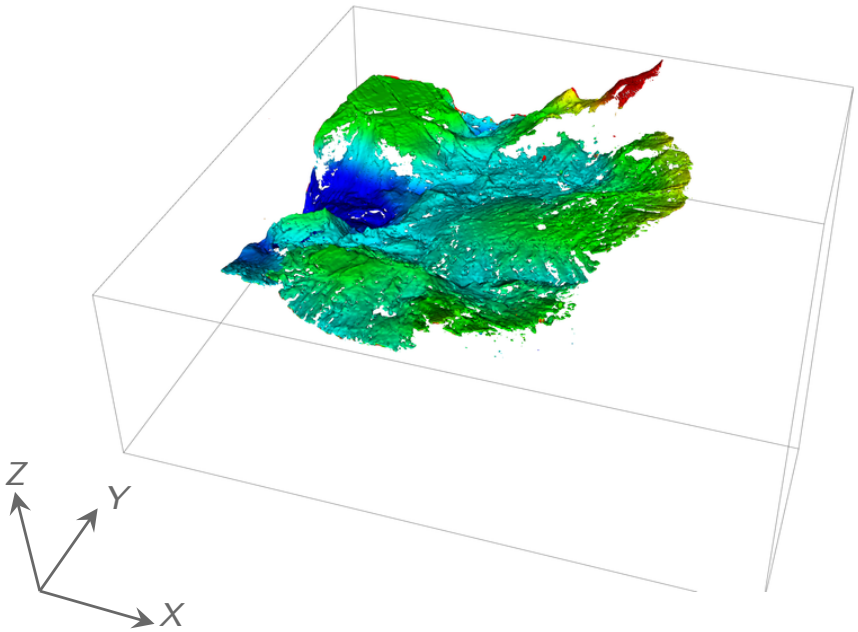
3D crack rendering in 2027

N=853k cycles + 100% OL + 14k cycles

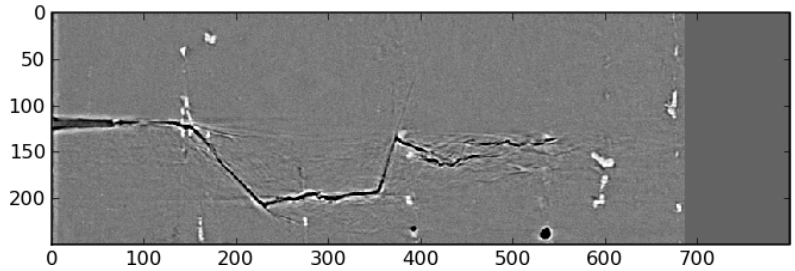
3d rendering with position mapping

box is (560 × 560 × 175 μm)



slice extracted at $x = 100$

from raw volume data set



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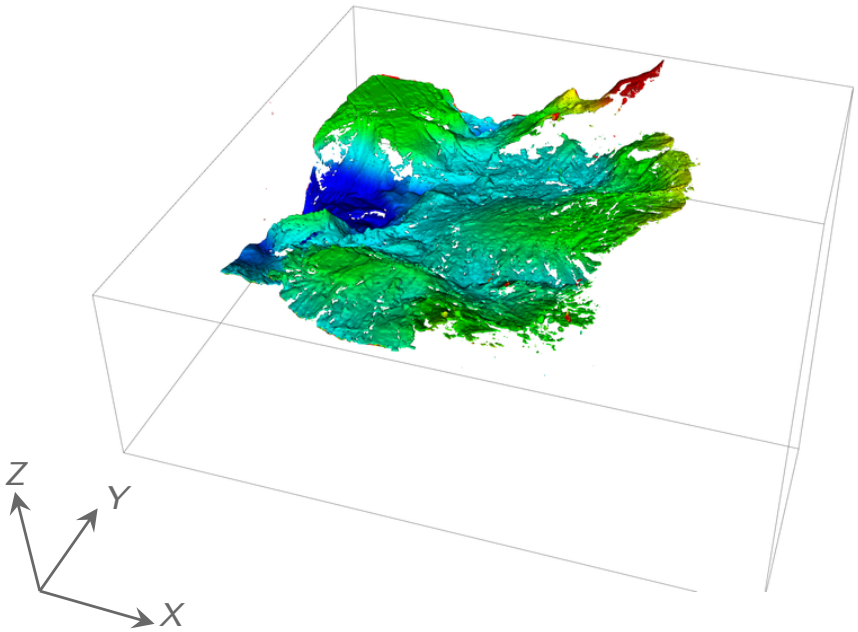
3D crack rendering in 2027

N=853k cycles + 100% OL + 24k cycles

3d rendering with position mapping

box is (560 × 560 × 175 μm)



slice extracted at $x = 100$

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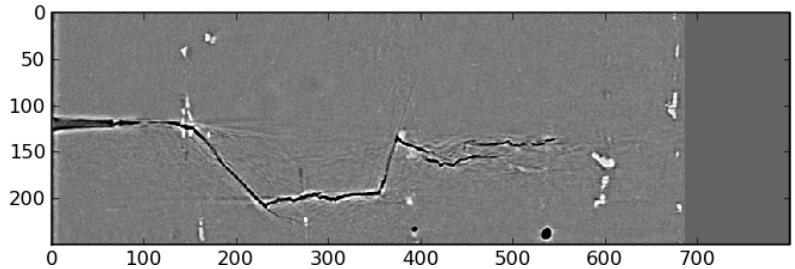

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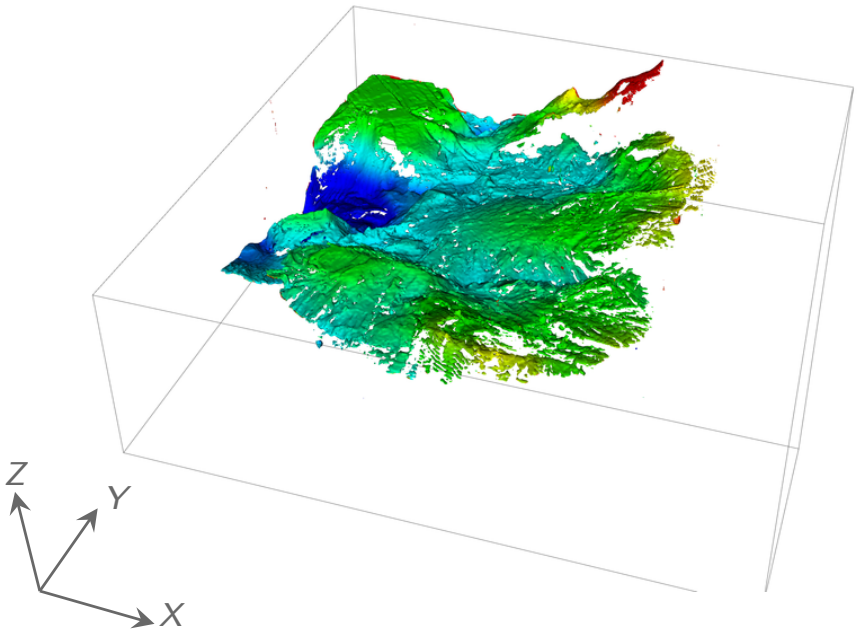
3D crack rendering in 2027

N=853k cycles + 100% OL + 39k cycles

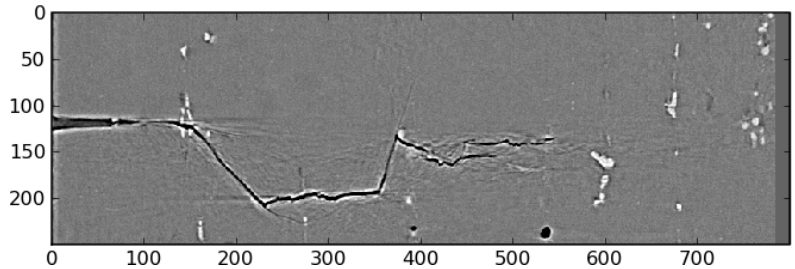
3d rendering with position mapping

box is (560 × 560 × 175 μm)



slice extracted at $x = 100$

from raw volume data set



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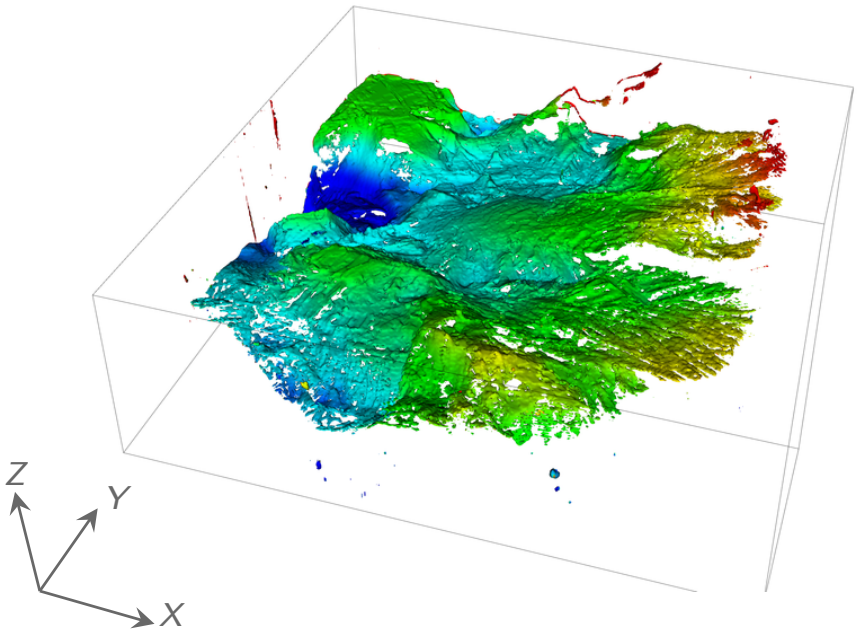
3D crack rendering in 2027

N=853k cycles + 100% OL + 59k cycles

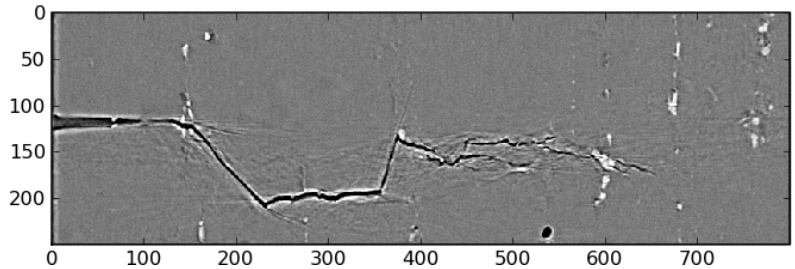
3d rendering with position mapping

box is (560 × 560 × 175 μm)



slice extracted at $x = 100$

from raw volume data set



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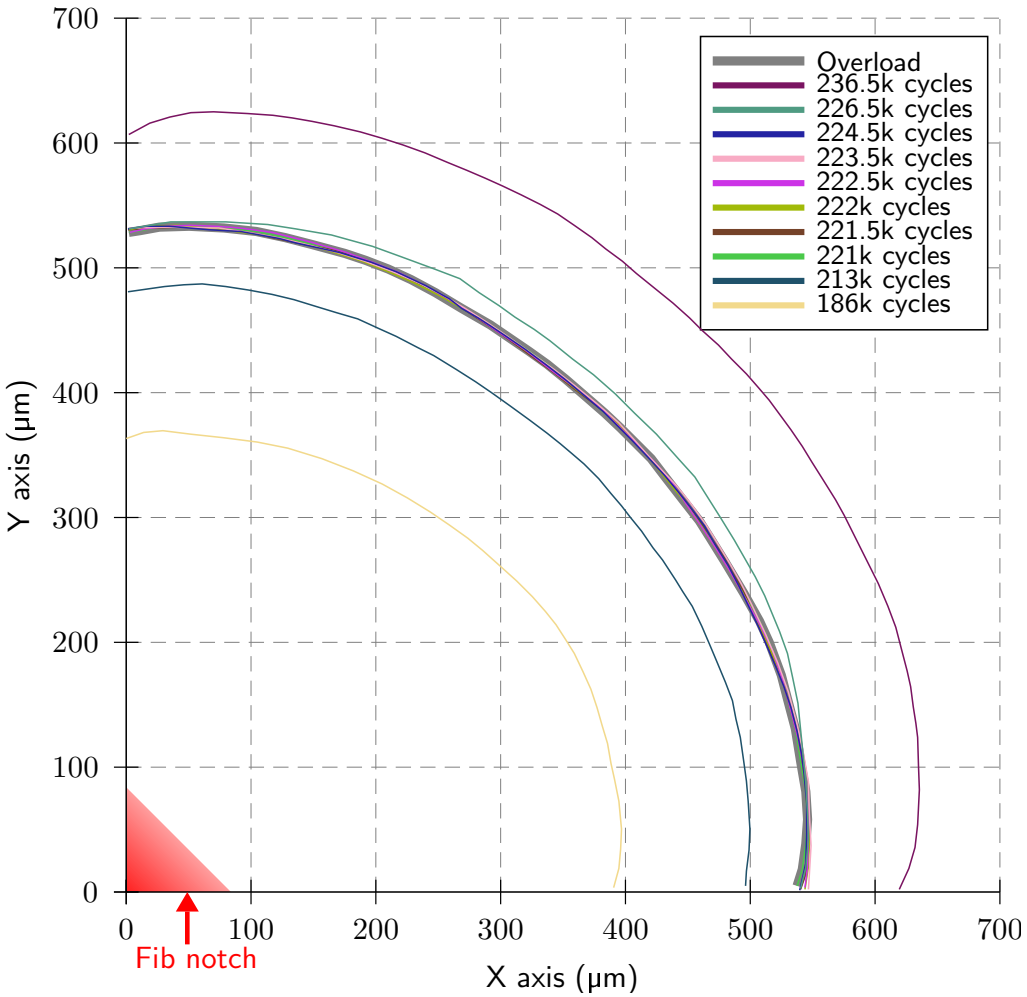
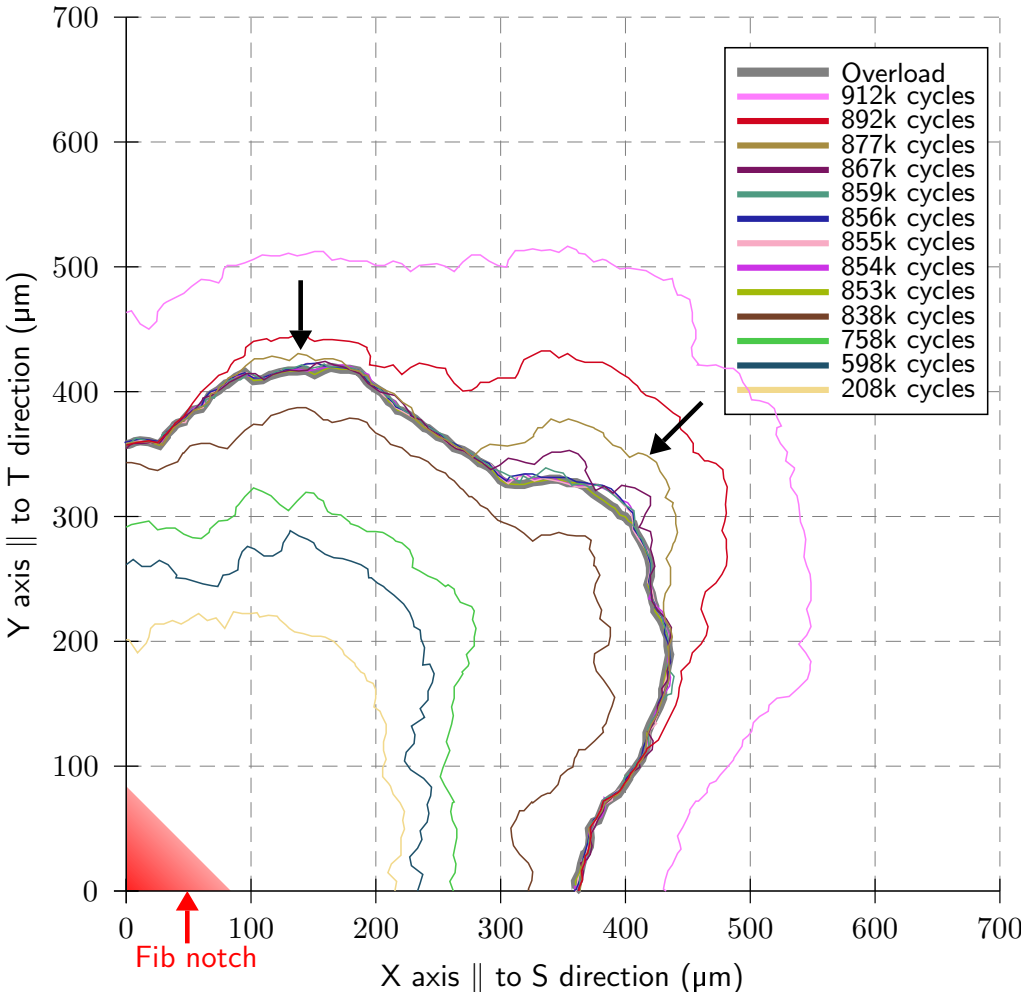
5091 vs. 2027 growth behavior



5091 crack growth

- Highly planar
- Microstructure independent
- Tunnelling 2-3%
- Overload stopped the crack, growth resumes from the bulk

5091 vs. 2027 growth behavior



2027 crack growth

- Tortuous crack path
- Strongly microstructure dependent
- Multiple crack branching
- Tunnelling more pronounced
- Overload stopped the crack longer than in 5091, growth resumes from the bulk also

Outline

Outline

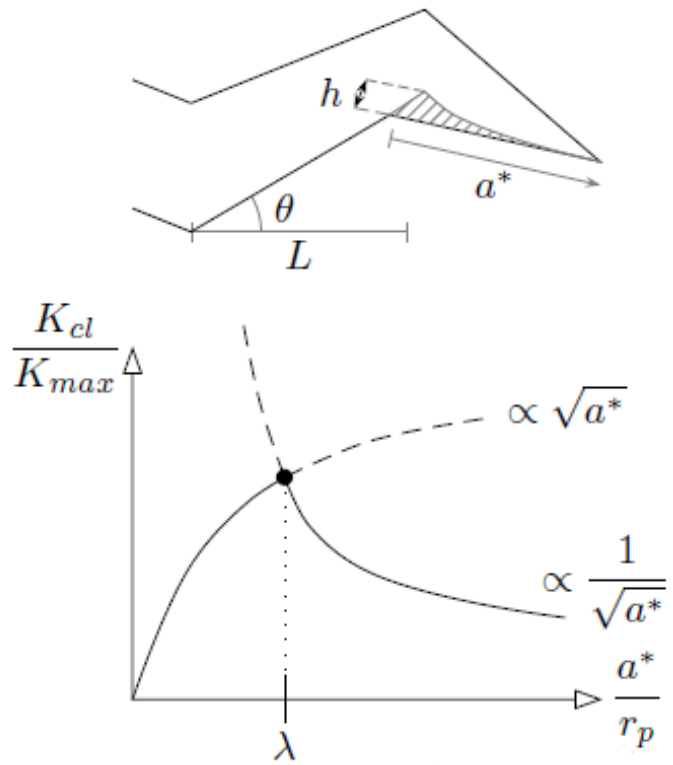
Model overview

Extended Southampton multi-mechanistic crack closure model

Apply to both CA growth and post-overload growth with mixed regime plane stress/plane strain description

K_{cl} determination

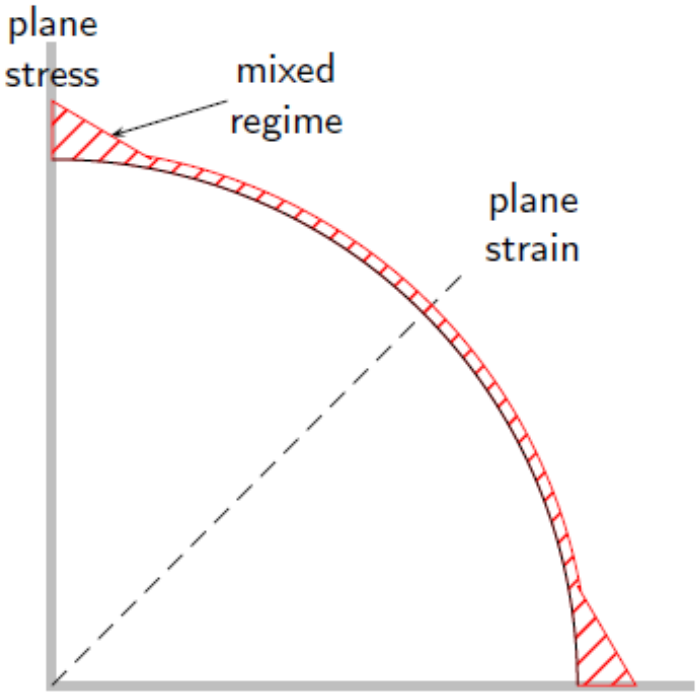
- Plastically deformed material in the crack wake acts as a wedge
- h is directly related to crack opening at the point of overload
- When h is equal to crack opening, closure occurs
- RICC linked to CTSD, PICC linked to CTOD

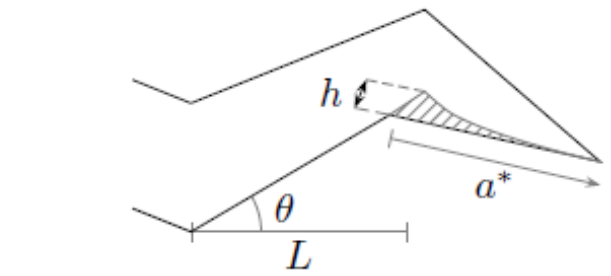


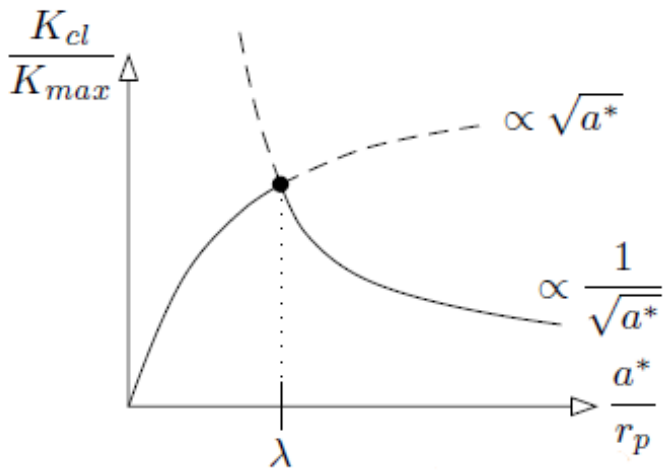
Model overview

Extended Southampton multi-mechanistic crack closure model

Apply to both CA growth and post-overload growth with mixed regime plane stress/plane strain description







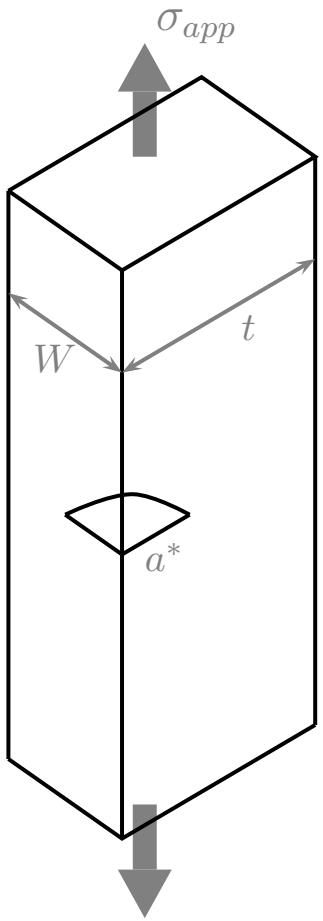
Model equations

	Plane strain	Plane stress
PICC CA	$\frac{K_{cl}}{K_{max}} = R$	$\frac{K_{cl}}{K_{max}} = 0.47 + 0.53R^2$
PICC OL	$\frac{K_{cl}}{K_{max}} = \beta_I \frac{K_{max}\sqrt{\pi a}}{8\sigma_y(1-\nu^2)\sqrt{l(2a-l)}} \frac{F}{V} \left(\xi^2 + 2R\xi - 2R - 1\right)$	$\frac{K_{cl}}{K_{max}} = \beta_I \frac{K_{max}\sqrt{\pi a}}{4\sigma_y\sqrt{l(2a-l)}} \frac{F}{V} \left(\xi^2 + 2R\xi - 2R - 1\right)$
RICC CA	$\frac{K_{cl}}{K_{max}} = \beta_{II} \frac{\sqrt{3\pi}K_{max}\left(\sin\frac{\theta}{2} + \sin\frac{3\theta}{2}\right)^2 \sin 2\theta}{32\sigma_y\sqrt{a^*}\left(3\cos\frac{\theta}{2} + \cos\frac{3\theta}{2}\right)} \left(\frac{1}{2} + R - \frac{1}{2}R^2\right)$	
RICC OL	$\frac{K_{cl}}{K_{max}} = \beta_{II} \frac{\sqrt{3\pi}K_{max}\left(\sin\frac{\theta}{2} + \sin\frac{3\theta}{2}\right)^2 \sin 2\theta}{32\sigma_y\sqrt{a^*}\left(3\cos\frac{\theta}{2} + \cos\frac{3\theta}{2}\right)} \xi^2 \left(\frac{1}{2} + R - \frac{1}{2}R^2\right)$	

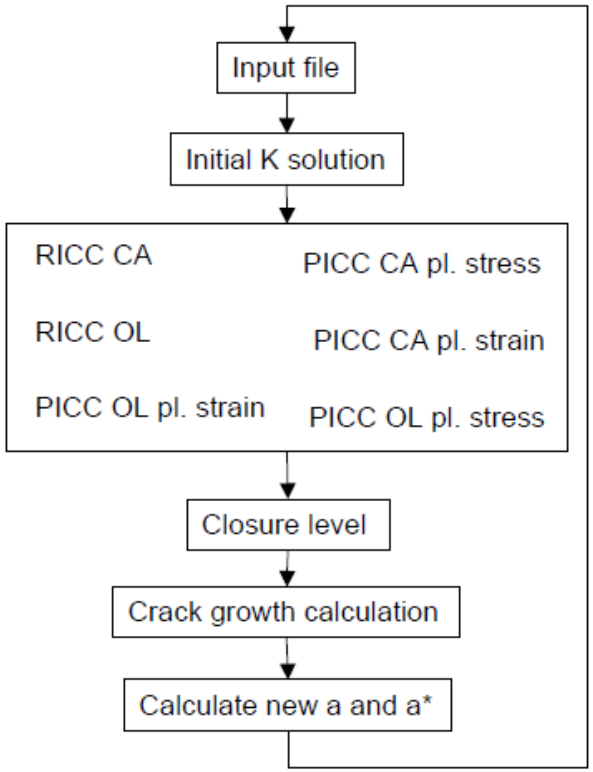
Mixed state

Closure level is determined at each point of the crack front assuming competition between the two PICC/RICC models.

Model parameters and flowchart

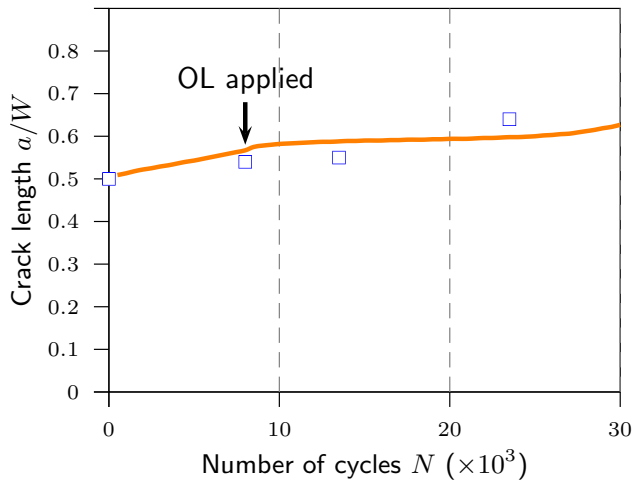


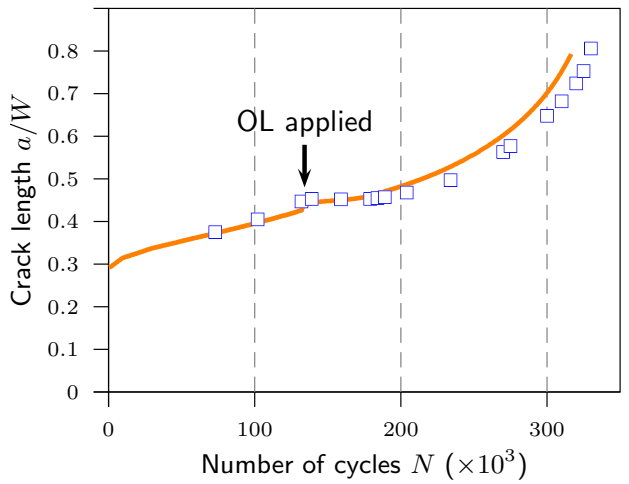
- Geometrical parameters
  a^*, t, W
- Materials properties
  E, ν, σ_y, L, θ
- Test parameters
  σ_{app}, R-ratio, %OL
- Crack growth parameters
  C, m
- Adjustable parameters
  λ, β_I, β_{II}

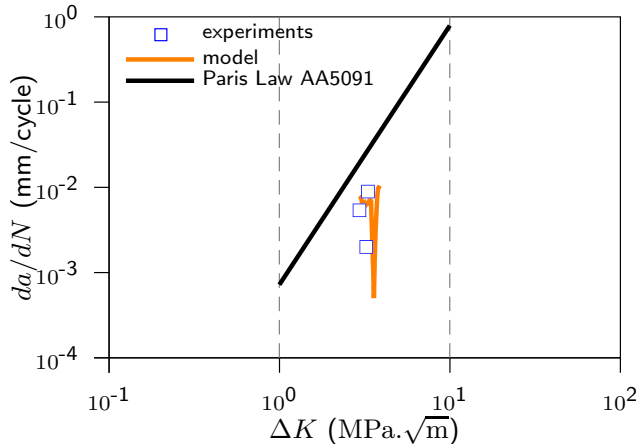


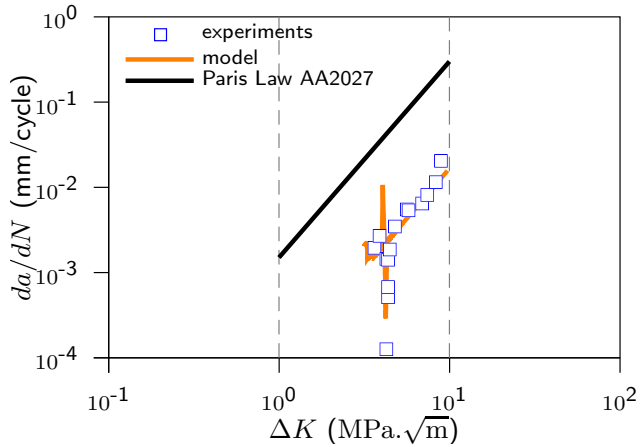
Outline

Model predictions









The model is able to predict baseline growth and OL transient behavior for both materials within a factor of 2 in terms of number of cycles (equivalent crack length).

Outline

Summary

Experimental

- An extensive set of 3D crack propagation data (two materials, baseline growth, $\neq$ R ratios, OL) has been produced
- Crack growth in the 5091 alloy is mostly microstructure independent
- Crack growth in the 2027 alloy is very dependent on the microstructure and is expected to be predominantly controlled by RICC
- Overloads systematically stop the cracks. After some cycling, the crack growth resume from the bulk (in the middle for the 5091 and from a likely well oriented grain for the 2027)

Modelling

- Good baseline description for both materials
- 5091 growth is more PICC driven while 2027 is more RICC driven
- Southampton model seems reasonably extendable to small crack description
- Overload retardation can be predicted within a factor of 2 for all experiments with a single set of fitting parameters

Acknowledgements

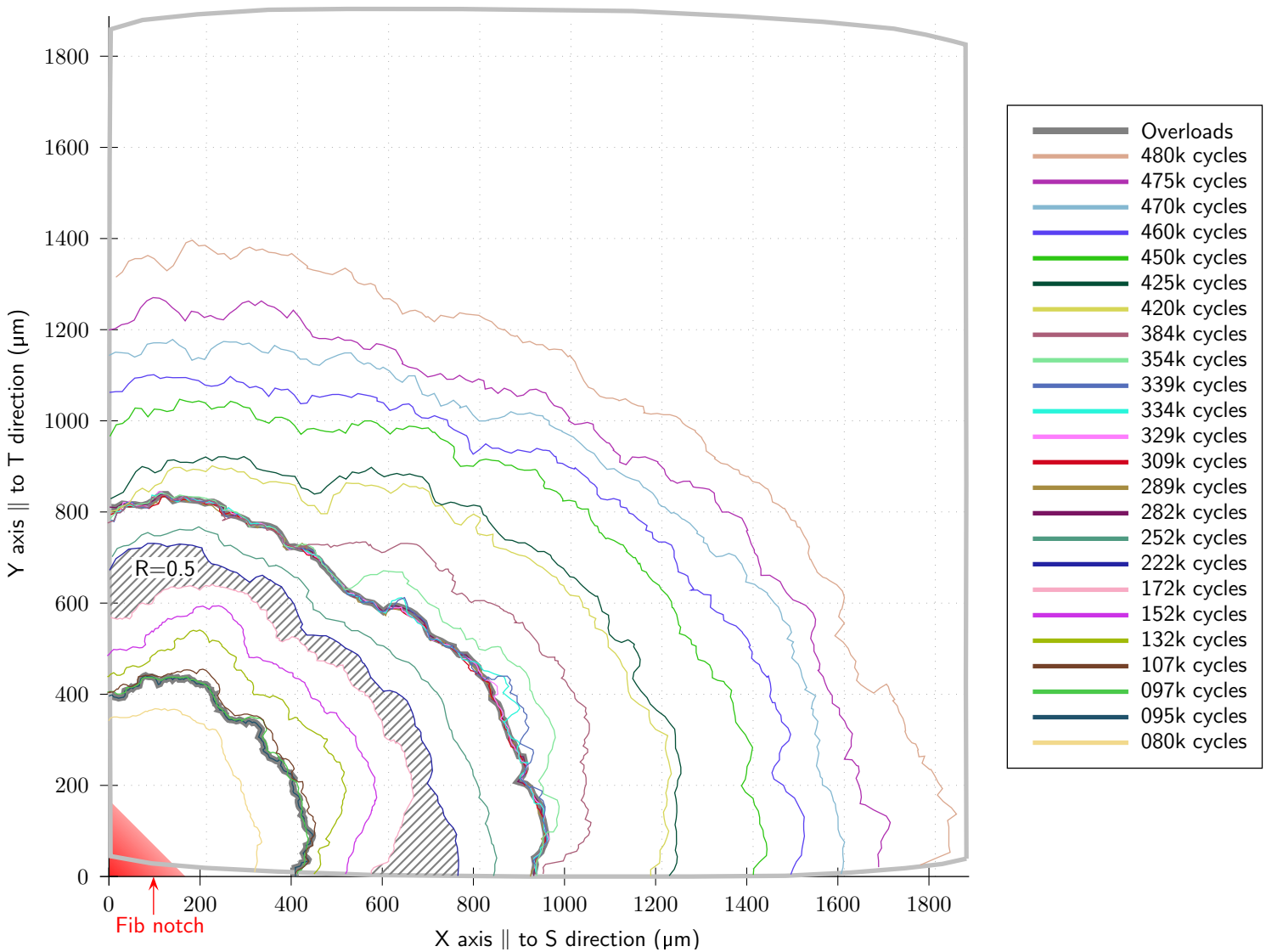
THANK YOU

special thanks to:

- R. Collins and D. Dai from Airbus UK
- G. Johnson and E. Boller from ID19, ESRF
- Michail Vidiassov for his VTK to U3D exporter

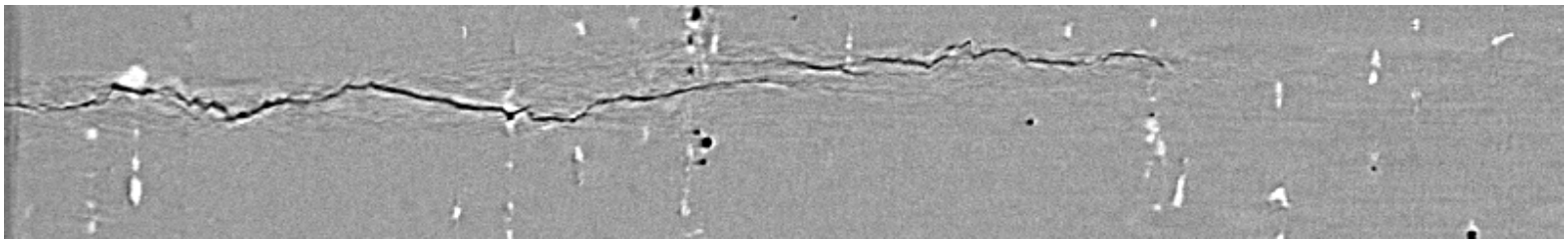
Outline

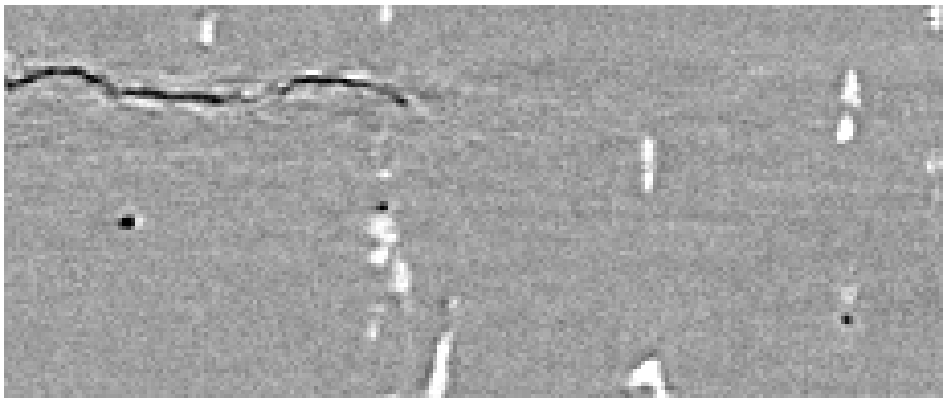
Crack fronts in 2×2 2027 sample



Overload details

$N = 289k$





Overload details

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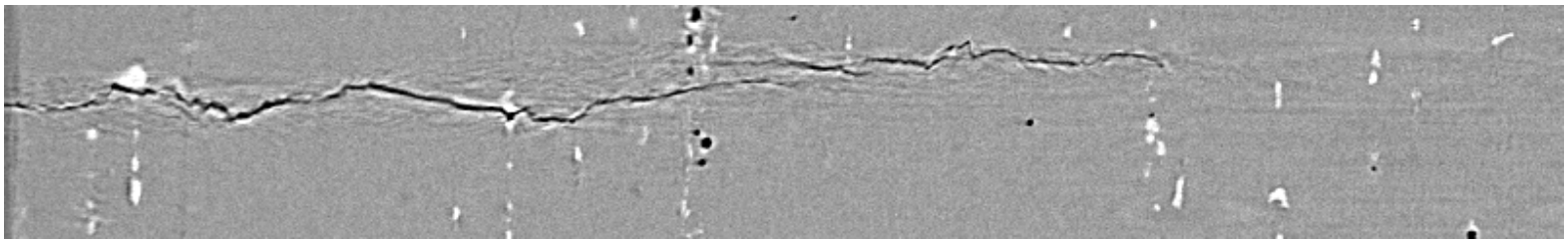

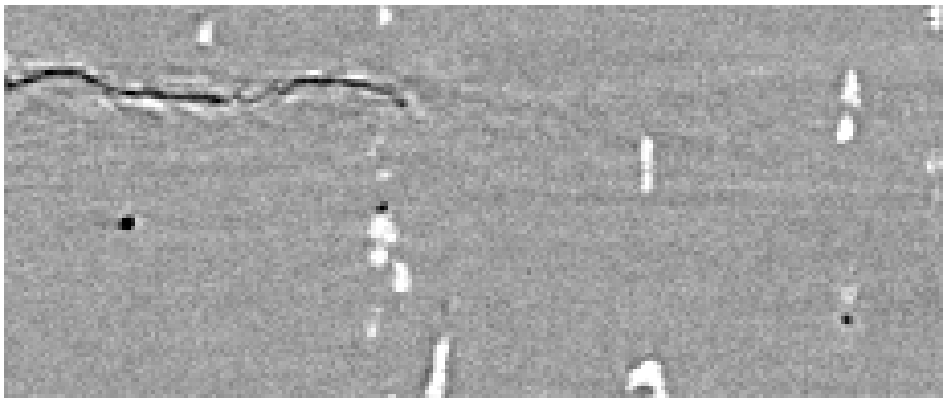

Overload details

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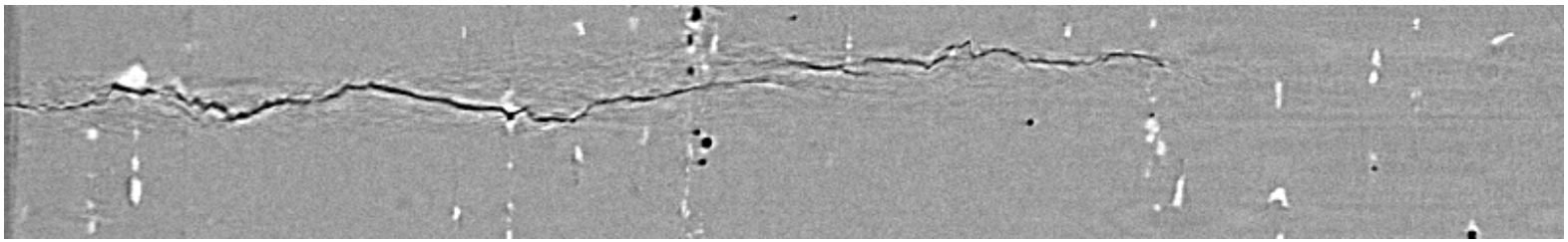

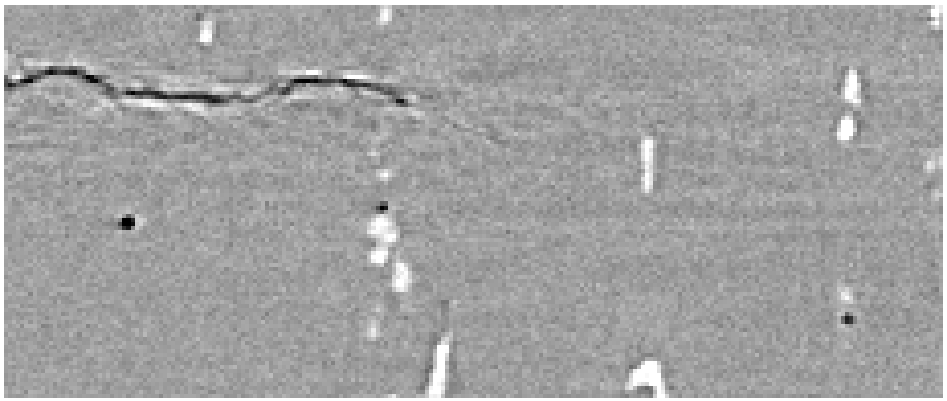

Overload details

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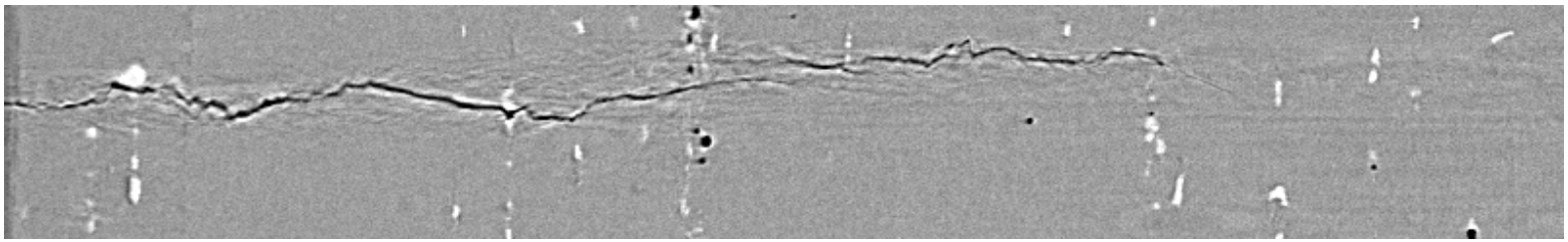

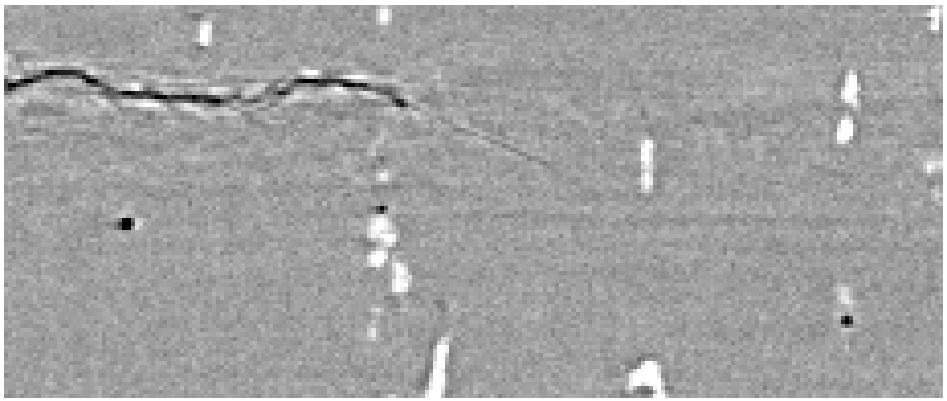

Overload details

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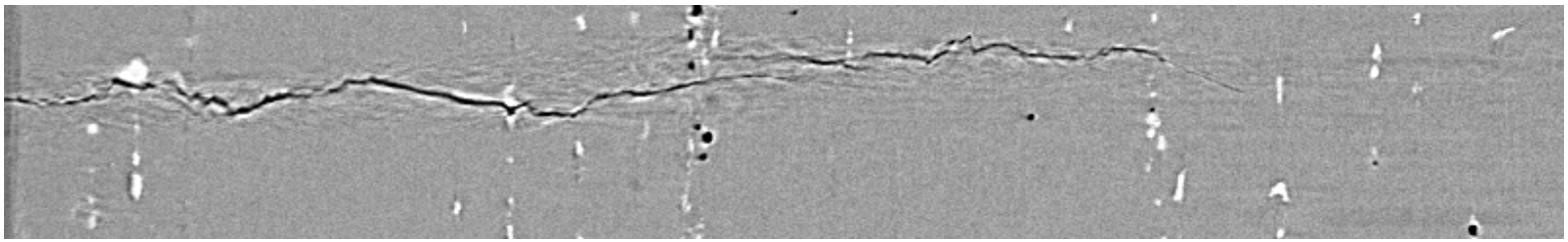

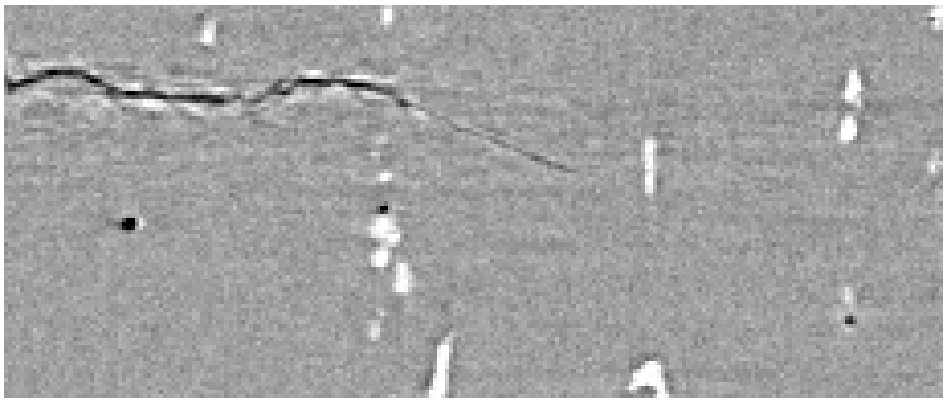

Overload details

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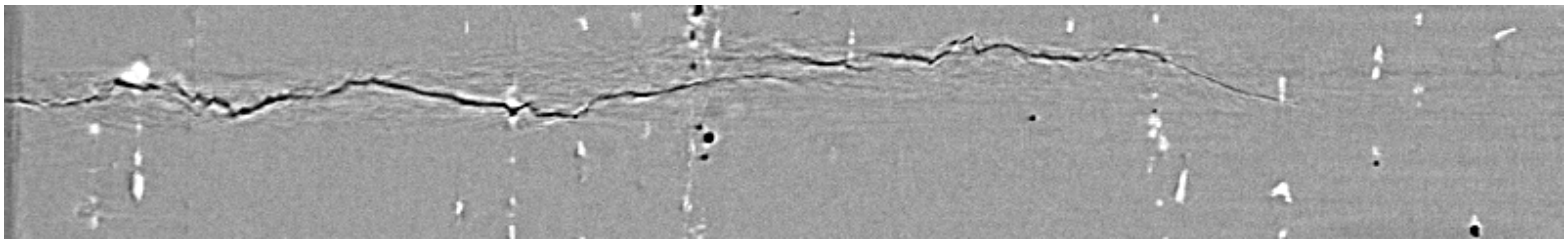
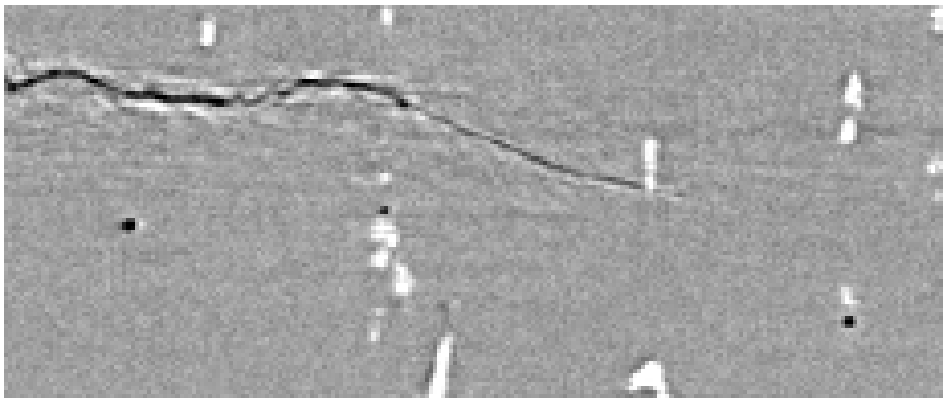
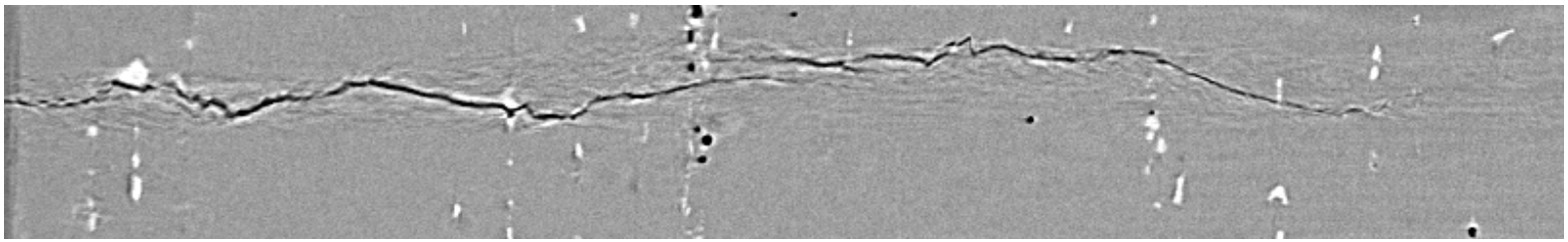
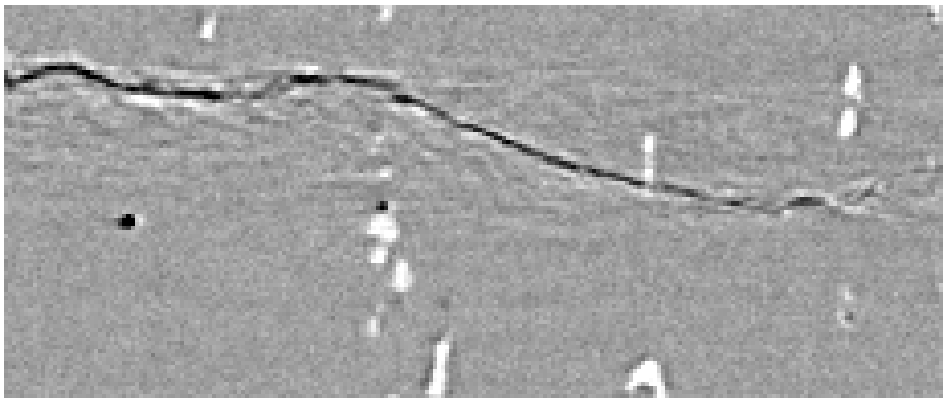




Overload details

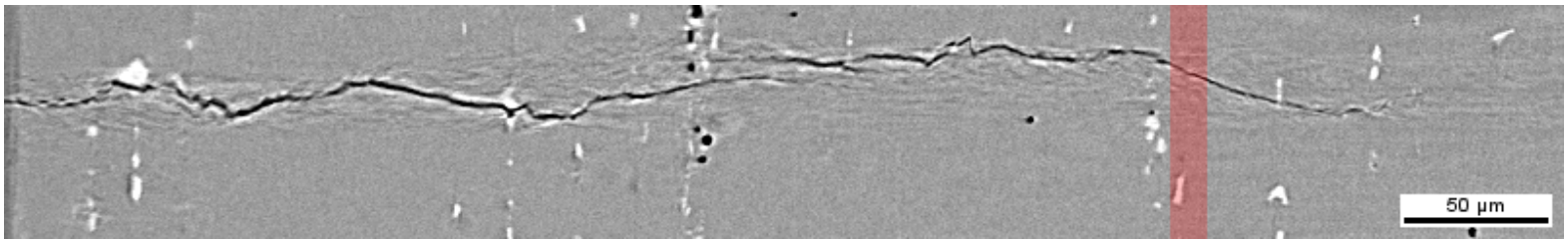
$N = 384k$

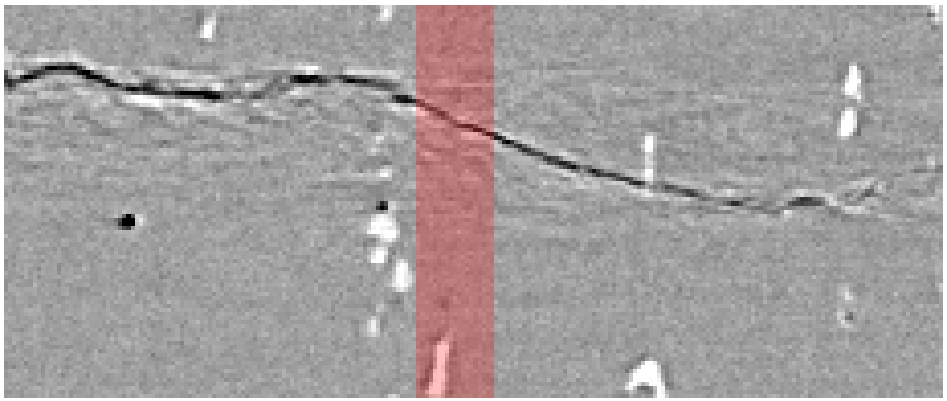




Overload details

$N = 384k$





Model parameters

Material parameters

.: 5091 :.

- $L = 10$ µm
- $\theta = 36°$
- Paris law: $m = 3.04 \quad C = 7.2\,10^{-10}$

.: 2027 :.

- $L = 30$ µm
- $\theta = 45°$
- Paris law: $m = 2.35 \quad C = 13.0\,10^{-10}$

Fitting parameters

.: 5091 :.

- $\lambda = 0.75/0.42$
- $\beta_I = 1.5/1.3$
- $\beta_{II} = 2.0/2.0$

.: 2027 :.

- $\lambda = 0.75/0.42$
- $\beta_I = 1.5/1.3$
- $\beta_{II} = 2.0/3.0$