Image based simulation of damage development in metals under mechanical loading.

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Outline

- Introduction
- Monotonic testing
    - “Classical”
    - Tracking
    - Higher spatial resolution
- Fatigue testing
    - Fatigue crack initiation from internal defects
        - Elastic case
        - Plastic case
    - Fatigue crack initiation from surface defects (AM)
        - Small representative samples
        - Lattices
- Conclusion

Outline

- Introduction

Introduction

2006 Vtome x
(Phoenix x-ray / GE)

Standard ~ 2 µm voxel size

2013 EasyTom Nano
(Rx Solutions)

High resolution
/ low attenuation

2021 DTHE
(Rx Solutions)

High Energy / attenuation

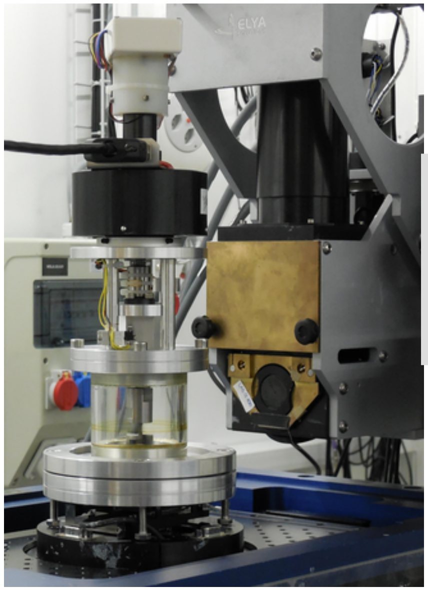
Synchrotron ***~ 1995 ID19, ID15, ID11, ID16…***
Now for very high resolution
Very fast acquisitions

Users : MATEIS research / teaching, collaboration, industrial services

Introduction

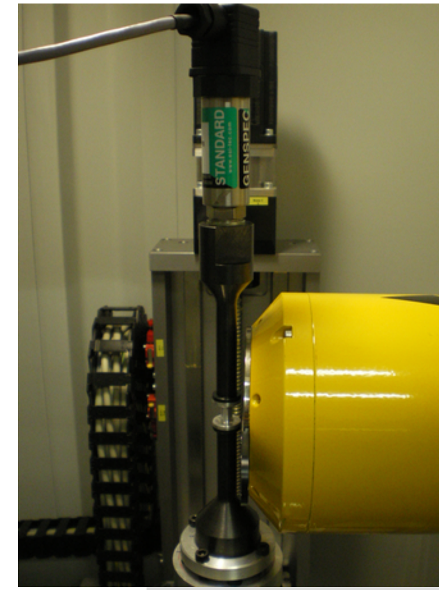
- Phase contrast, high flux, availability

In situ devices



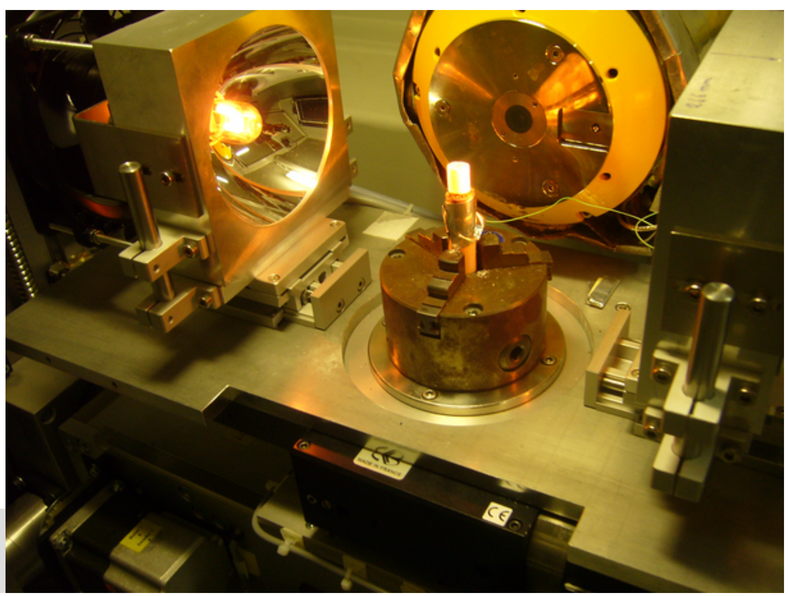
Tension compression

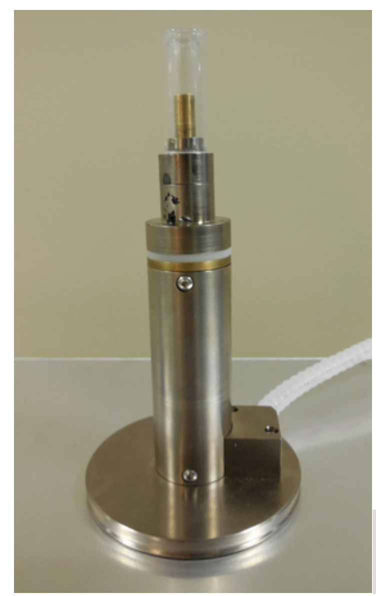
Fatigue



Hydrostatic pressure

heating





cooling

J-Y Buffiere et al. Exp. Mech. 2010

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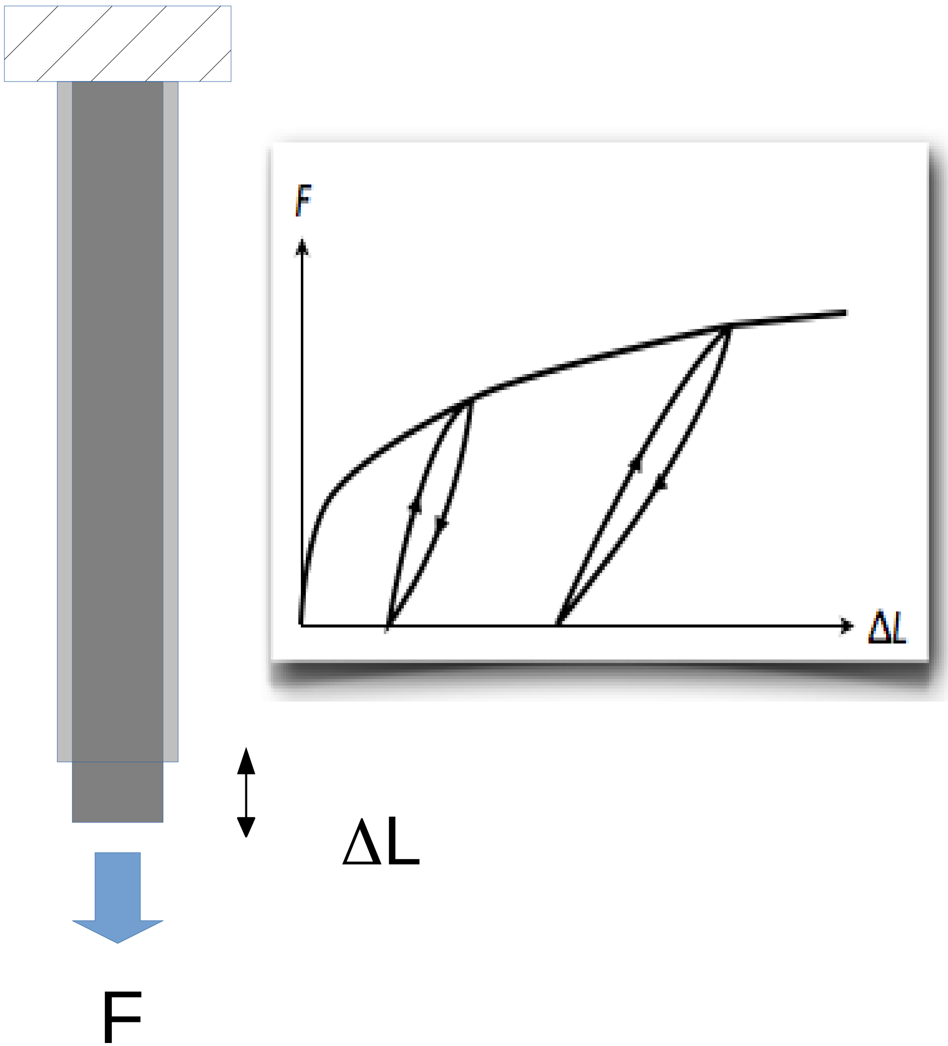
- Introduction
- Monotonic testing

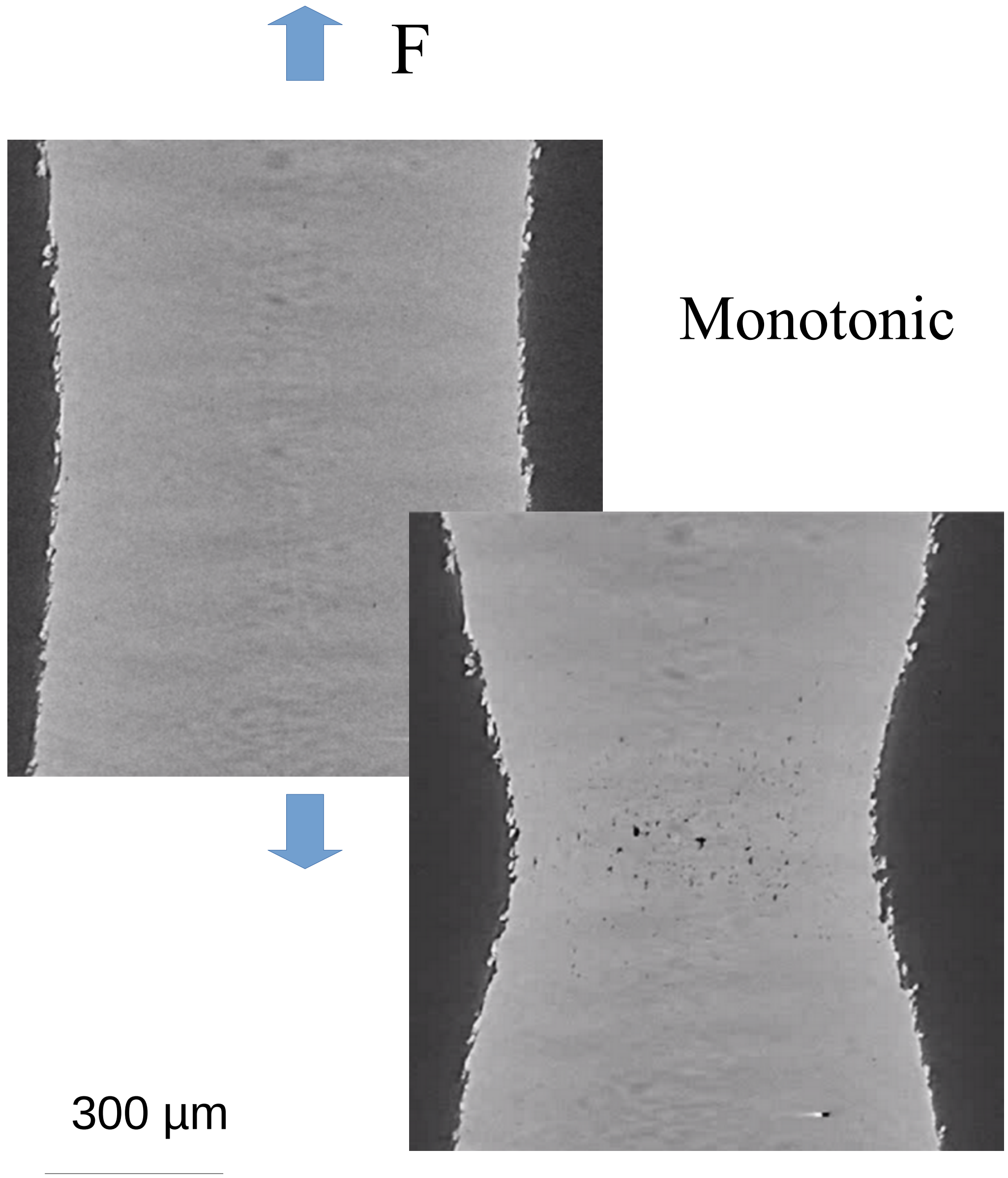
Study of damage during mechanical loading

- Monotonic



Study of damage during mechanical loading

- Damage $\rightarrow$ creation of new surfaces in the material



Monotonic

Outline

- Introduction
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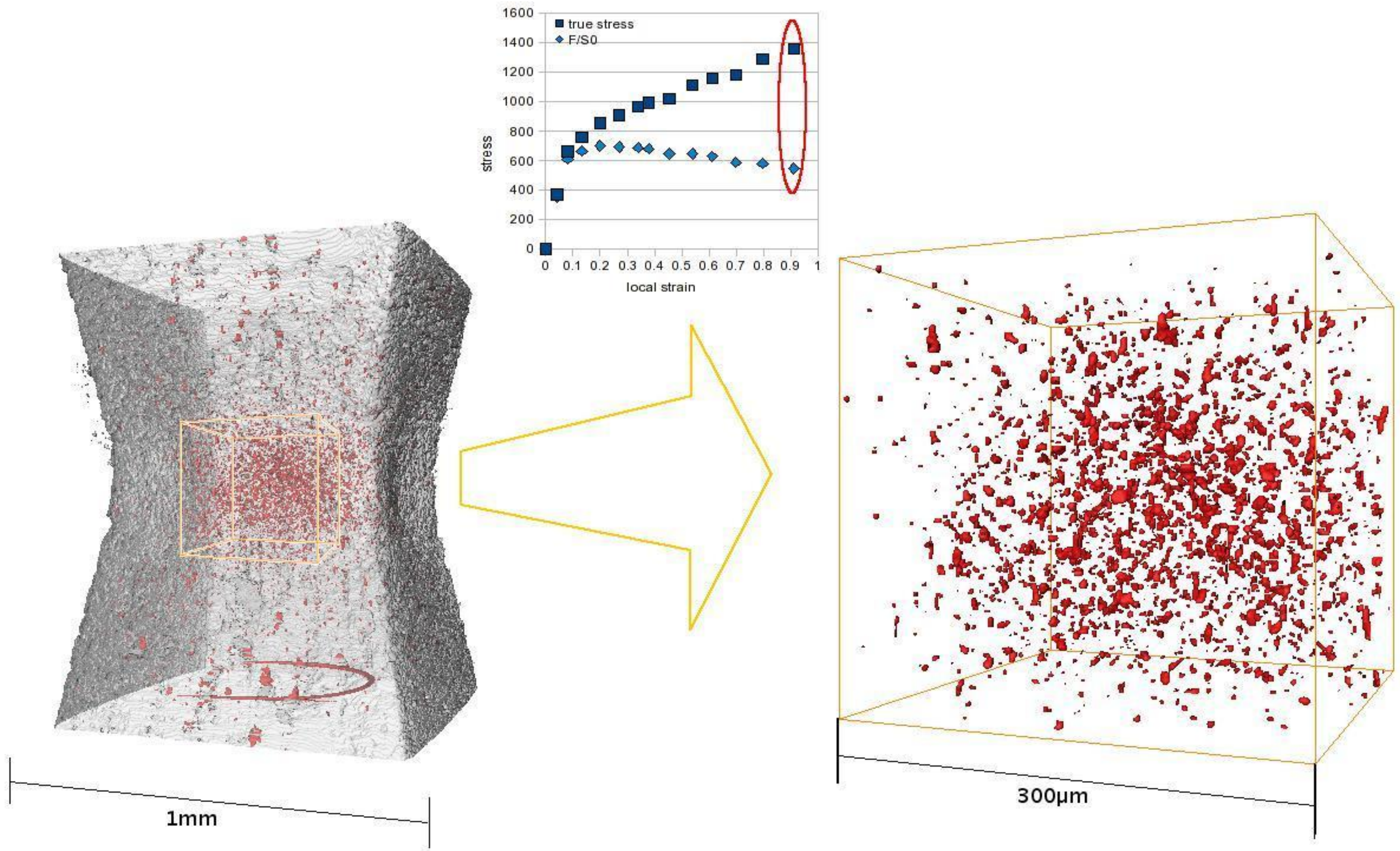
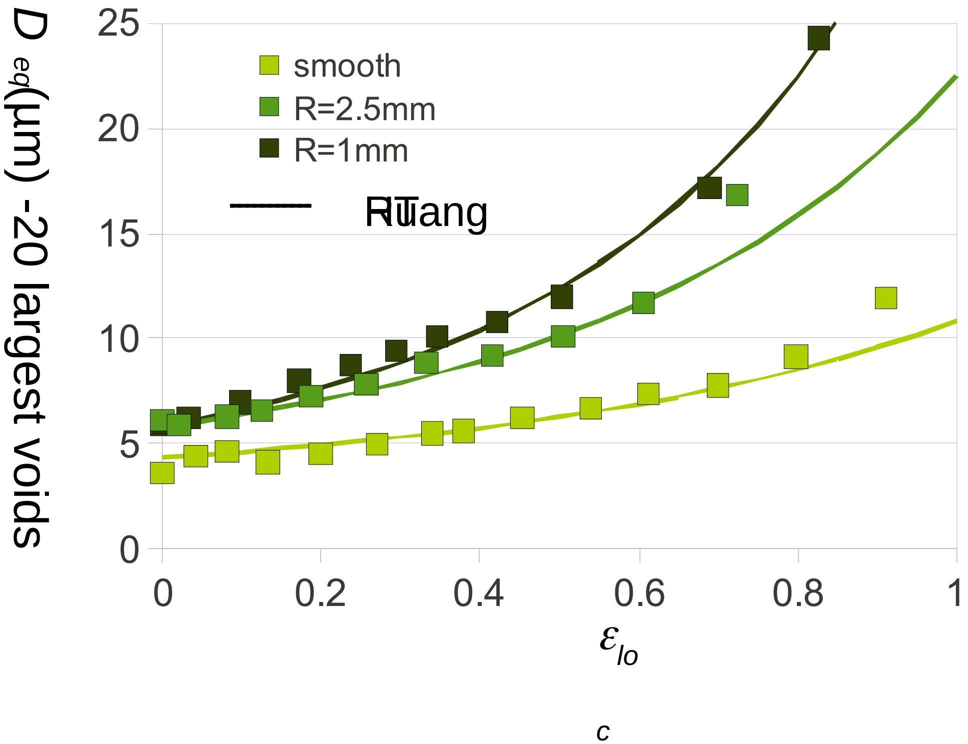
    - “Classical”

Cavity growth in steels



Hard to track all particles → average of the 20 largest

Cavity growth in steels

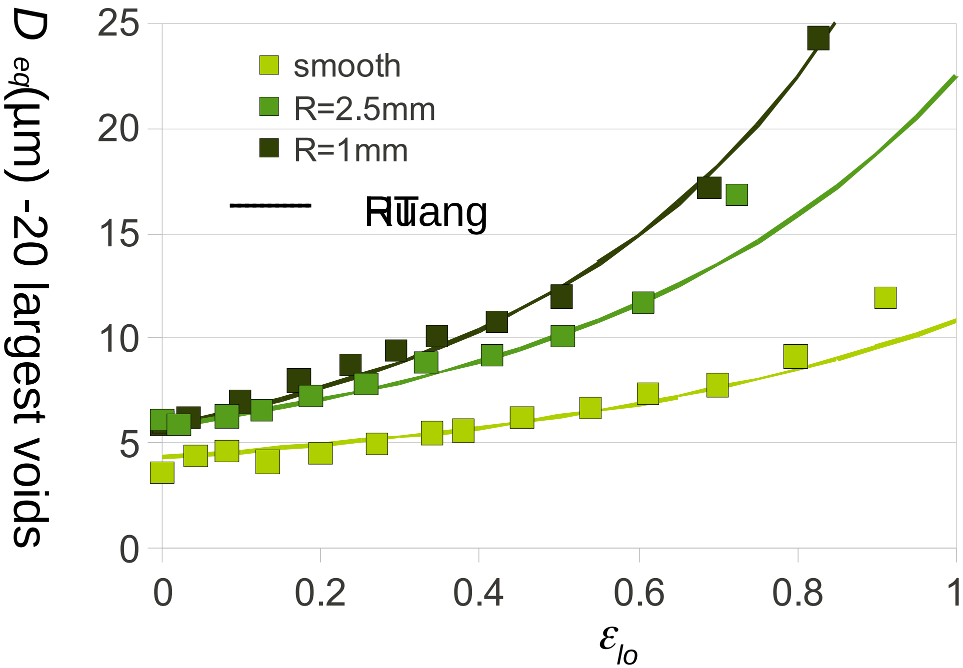


Cavity growth in steels

Growth of isolated and spherical voids in a perfectly plastic matrix
[*Rice & Tracey J. Mech. Phys. Sol. 1969*]

$$\frac{dR}{R} = \alpha_{RT} \exp\left(\frac{3}{2} T\right) d\varepsilon$$

$$\alpha_{RT} = 0.272$$



c

Cavity growth in steels

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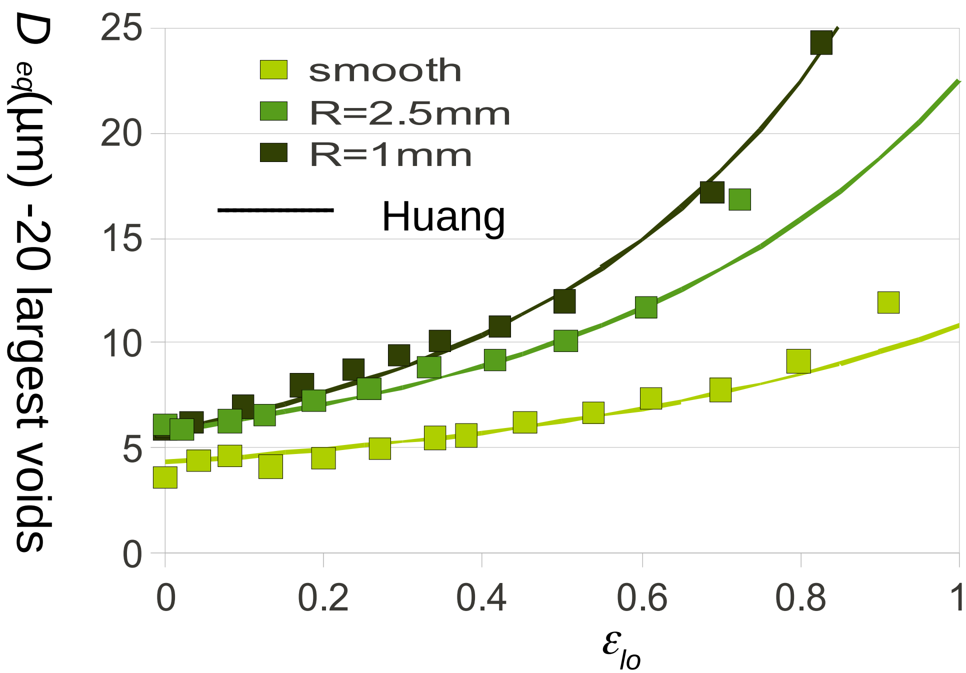
$$\alpha_{RT} = 0.272$$

Later revisited by Huang to better take *T* into account
[Huang J. Appl. Mech. 1991]

$$\frac{dR}{R} = \alpha_{Huang} T^{0.25} \exp\left(\frac{3}{2}T\right) d\varepsilon \quad \text{for } T \leqslant 1$$

$$\frac{dR}{R} = \alpha_{Huang} \exp\left(\frac{3}{2}T\right) d\varepsilon \quad \text{for } T > 1$$

$$\alpha_{Huang} = 0.427$$



c

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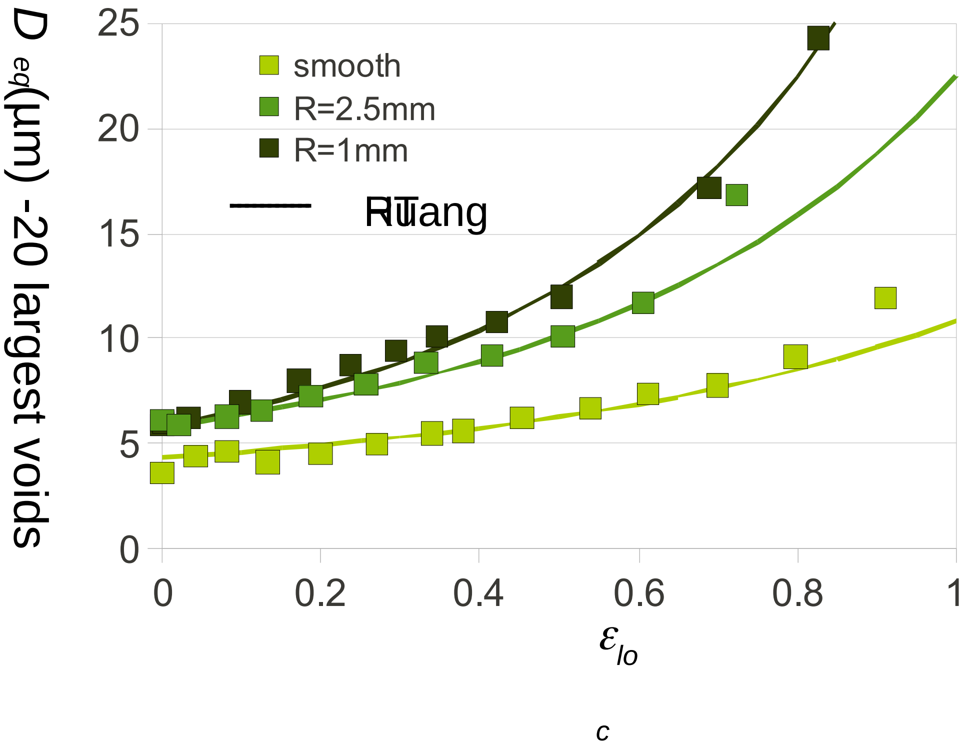
$$\alpha_{Huang} = 0.427$$

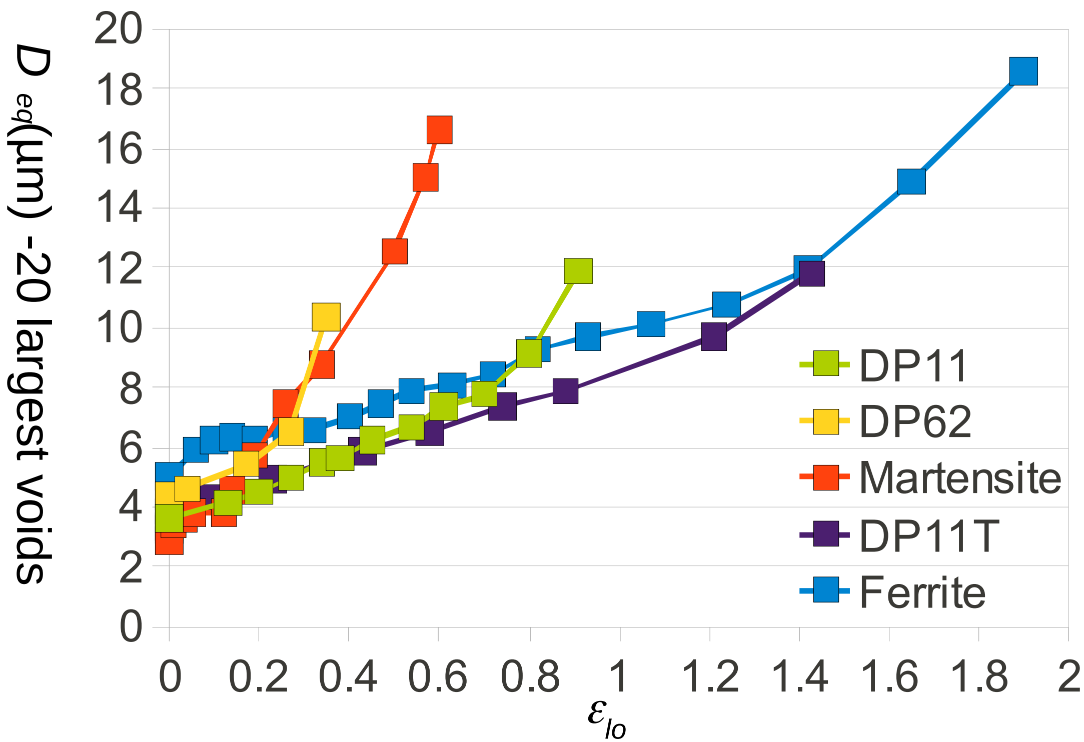


Specimens	α_{RT}	α_{Huang}
Smooth	0.47	0.55
R=2.5mm	0.50	0.55
R=1mm	0.52	0.55

Landron et al. Acta Mater. 2011

Cavity growth in steels

$$\frac{dR}{R}=\alpha_{Huang}\,T^{0.25}\exp\left(\frac{3}{2}T\right)d\,\varepsilon$$



Samples	α_{Huang}
DP11	0.55
DP11T	0.45
DP62	1.2
Ferrite	0.22
Martensite	1.6

Effects of the matrix around growing voids

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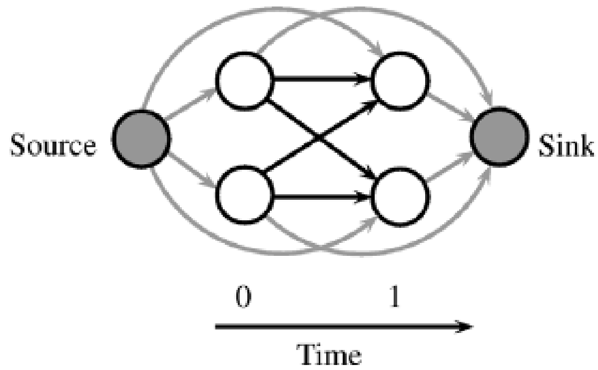
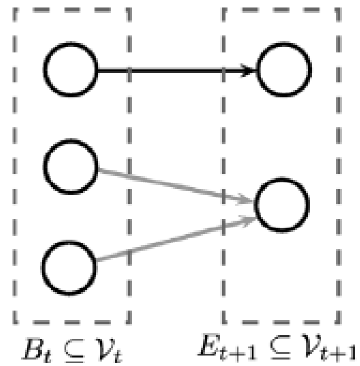
    - Tracking

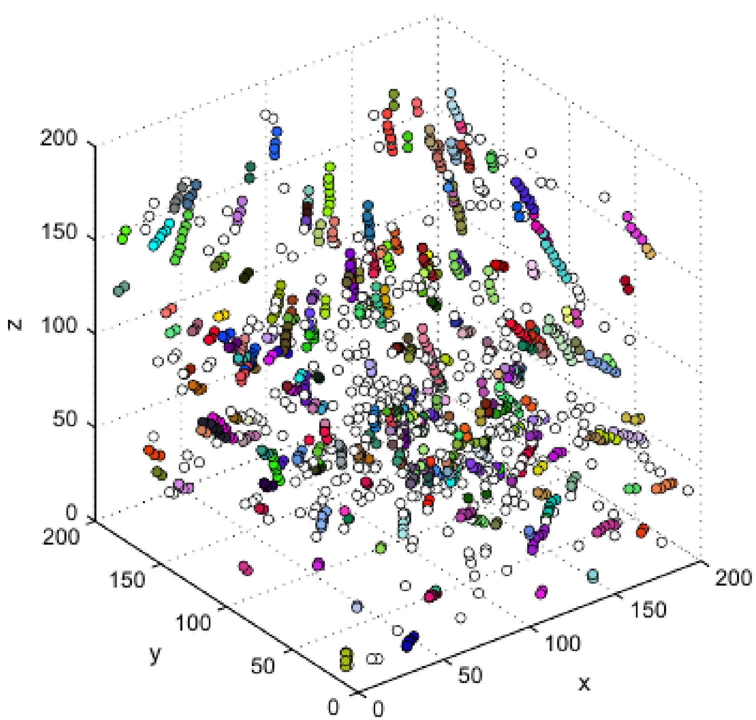
Automatic tracking of cavities



(a)

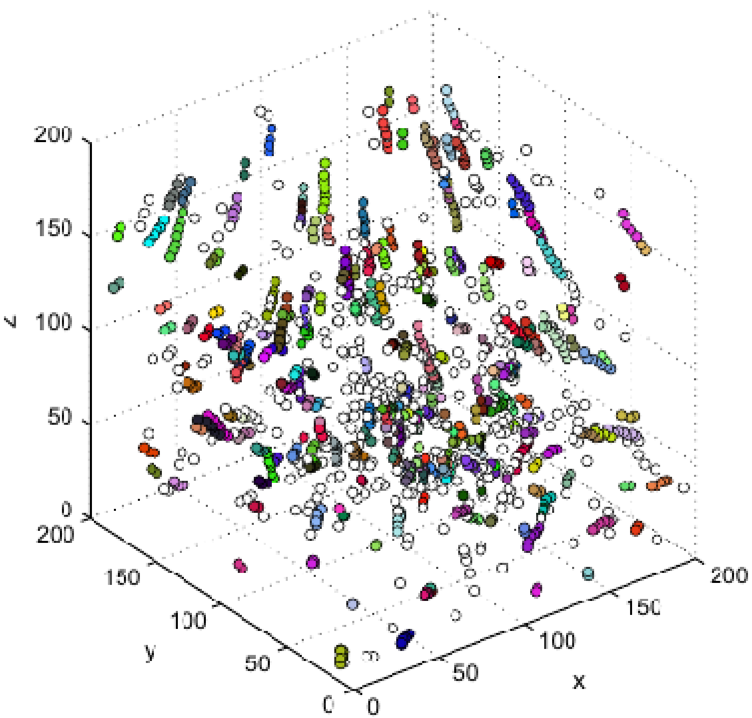


(b)

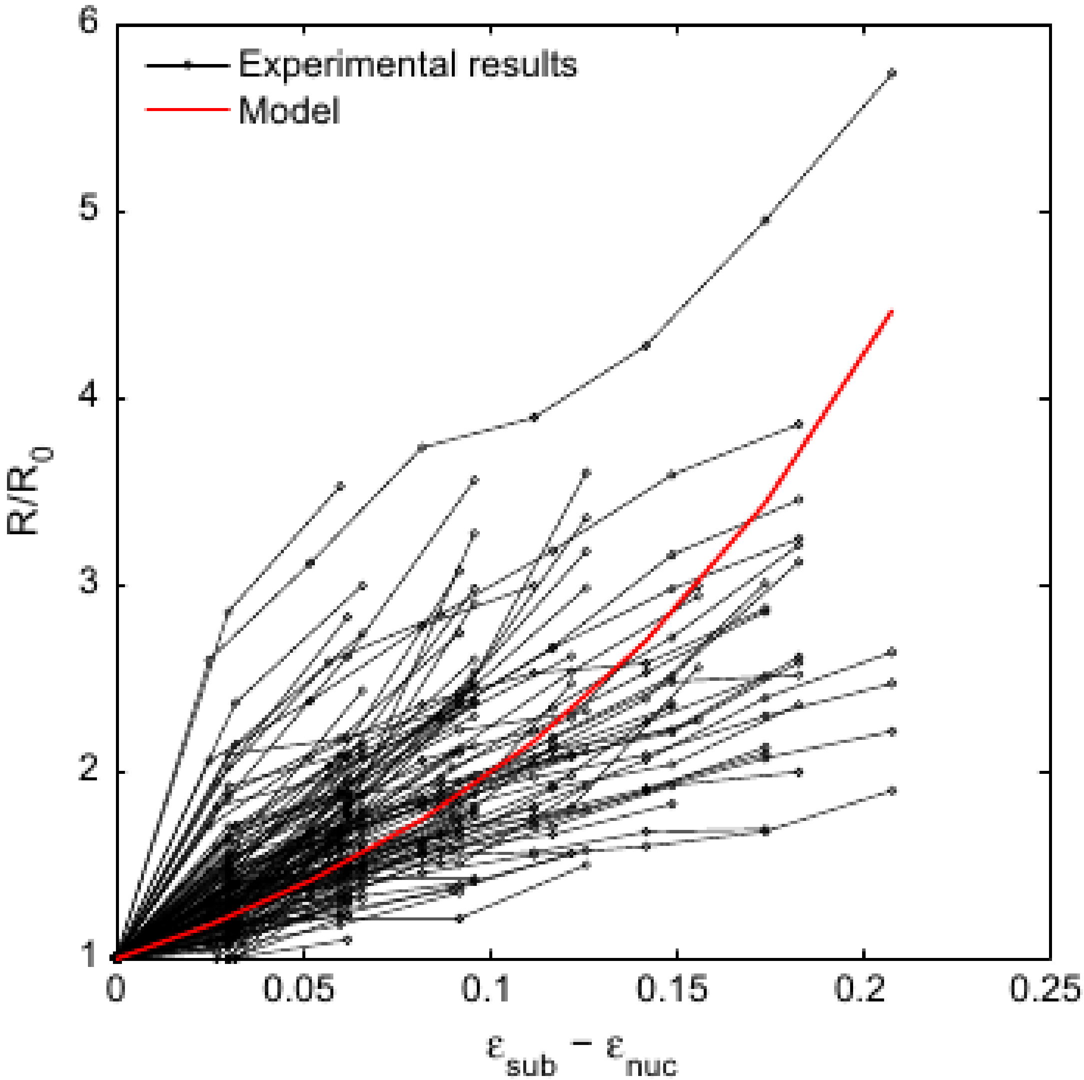


(c)

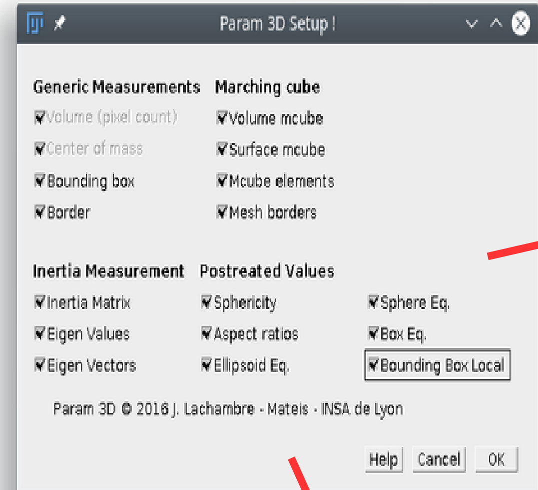
Automatic tracking of cavities



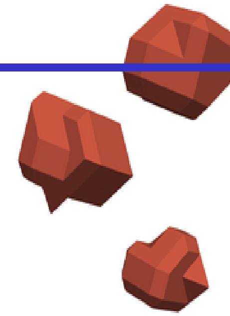
(c)



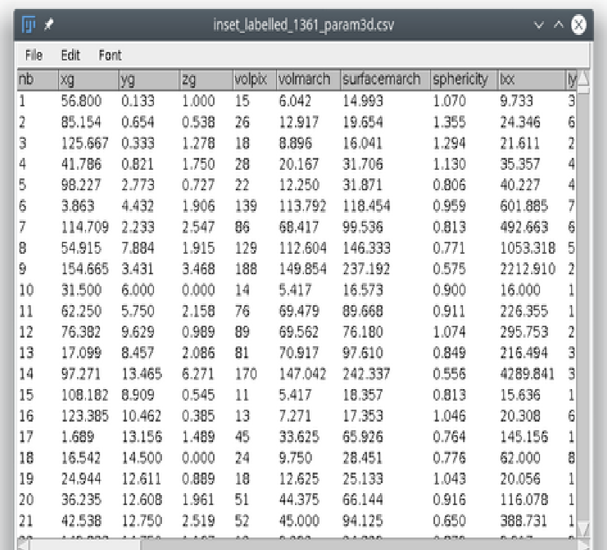
Feature extraction



.vtk



.csv



inset_labelled_1361_param3d.csv

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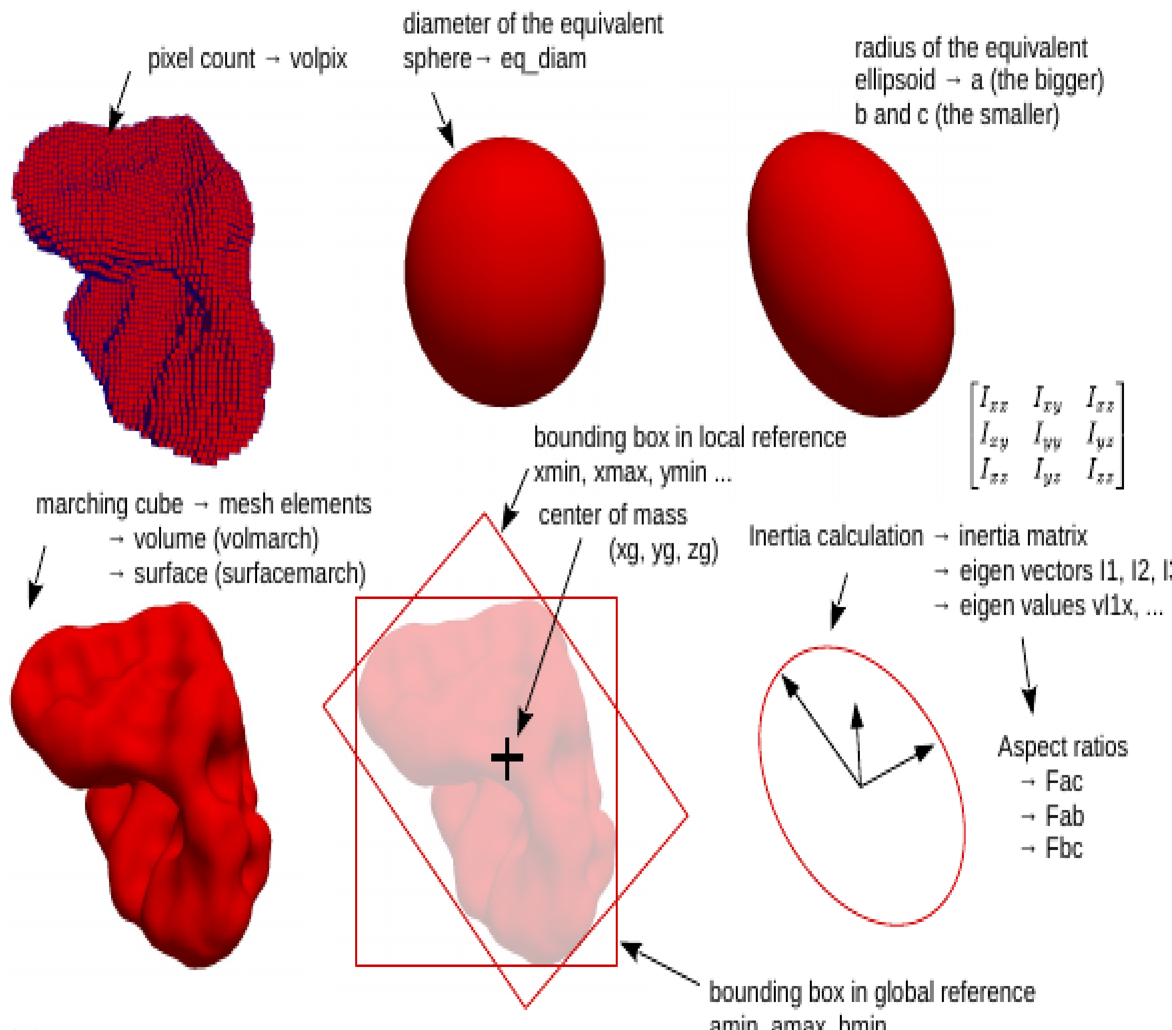
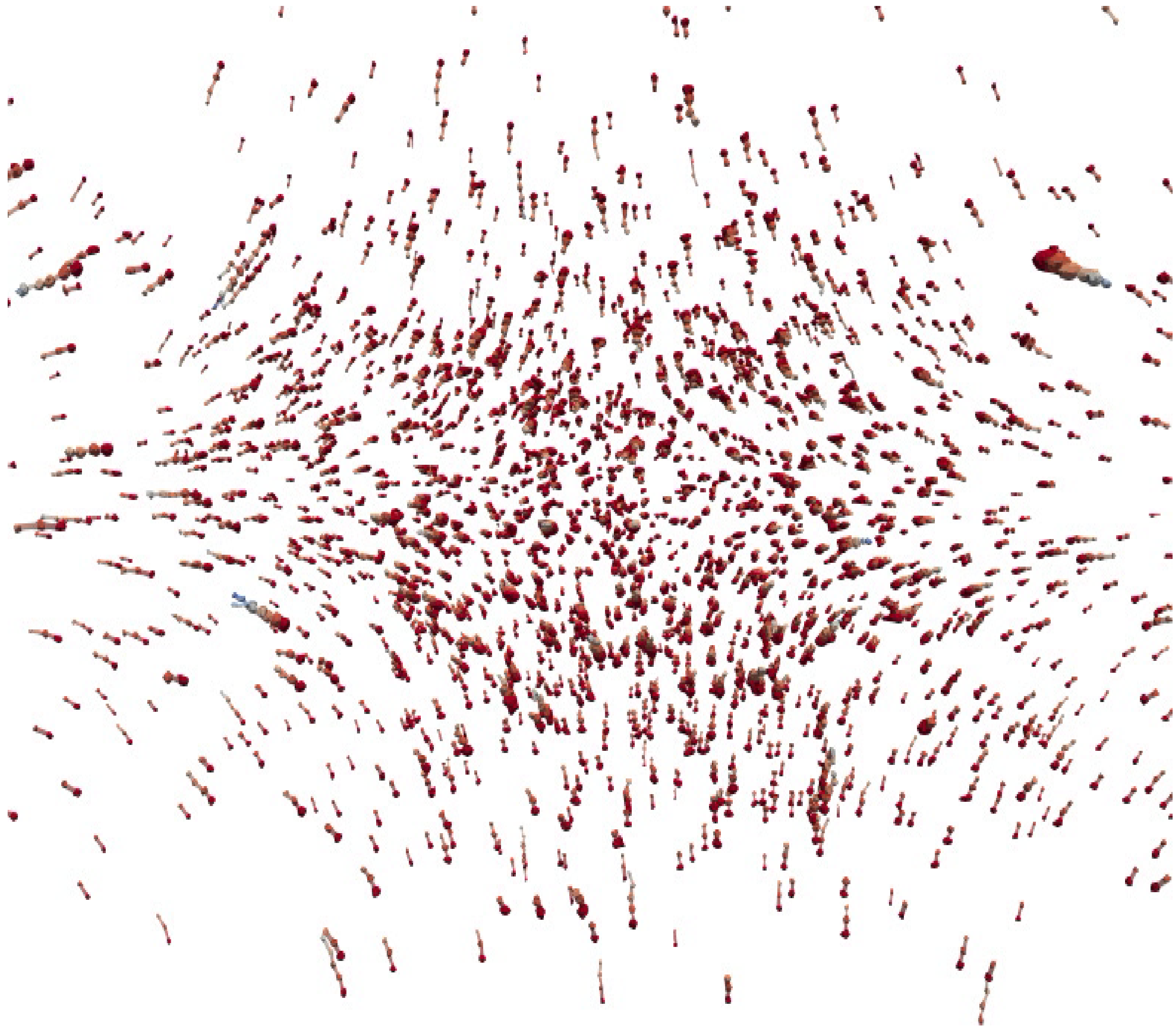
nb	xg	yg	zg	volpix	volmarch	surfacemarch	sphericity	Ixx	Iy
1	56.800	0.133	1.000	15	6.042	14.993	1.070	9.733	3
2	85.154	0.654	0.538	26	12.917	19.654	1.355	24.346	6
3	125.667	0.333	1.278	18	8.896	16.041	1.294	21.611	2
4	41.786	0.821	1.750	28	20.167	31.706	1.130	35.357	4
5	98.227	2.773	0.727	22	12.250	31.871	0.806	40.227	4
6	3.863	4.432	1.906	139	113.792	118.454	0.959	601.885	7
7	114.709	2.233	2.547	86	68.417	99.536	0.813	492.663	6
8	54.915	7.884	1.915	129	112.604	146.333	0.771	1053.318	5
9	154.665	3.431	3.468	188	149.854	237.192	0.575	2212.910	2
10	31.500	6.000	0.000	14	5.417	16.573	0.900	16.000	1
11	62.250	5.750	2.158	76	69.479	89.668	0.911	226.355	1
12	76.382	9.629	0.989	89	69.562	76.180	1.074	295.753	2
13	17.099	8.457	2.086	81	70.917	97.610	0.849	216.494	3
14	97.271	13.465	6.271	170	147.042	242.337	0.556	4289.841	3
15	108.182	8.909	0.545	11	5.417	18.357	0.813	15.636	1
16	123.385	10.462	0.385	13	7.271	17.353	1.046	20.308	6
17	1.689	13.156	1.489	45	33.625	65.926	0.764	145.156	1
18	16.542	14.500	0.000	24	9.750	28.451	0.776	62.000	8
19	24.944	12.611	0.889	18	12.625	25.133	1.043	20.056	1
20	36.235	12.608	1.961	51	44.375	66.144	0.916	116.078	1
21	42.538	12.750	2.519	52	45.000	94.125	0.650	388.731	1



C. Le Bourlot S. Dancette

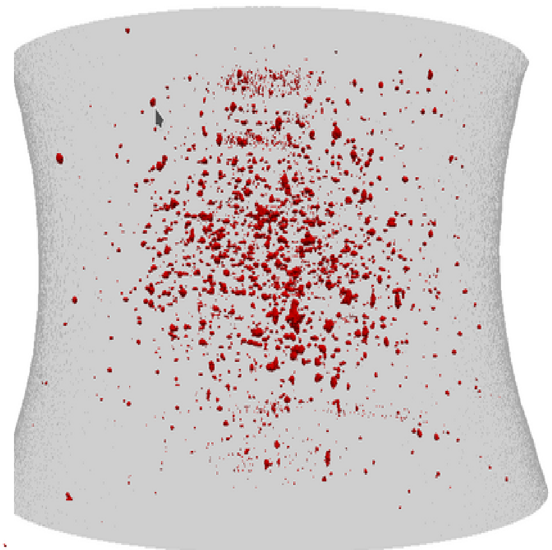
Tracks for TiAL6V alloy



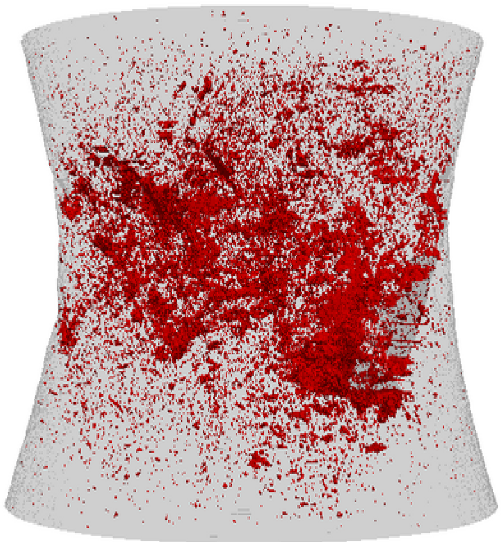
Application to pure metals

Pure Aluminium

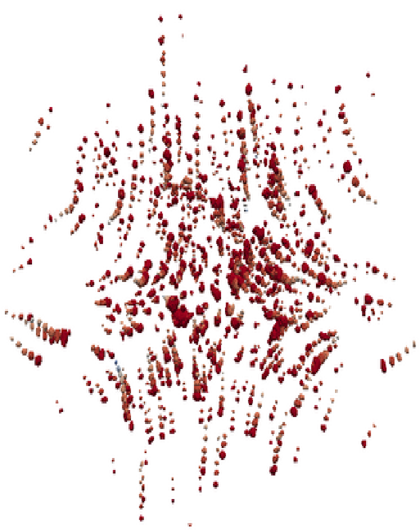
Pure Iron

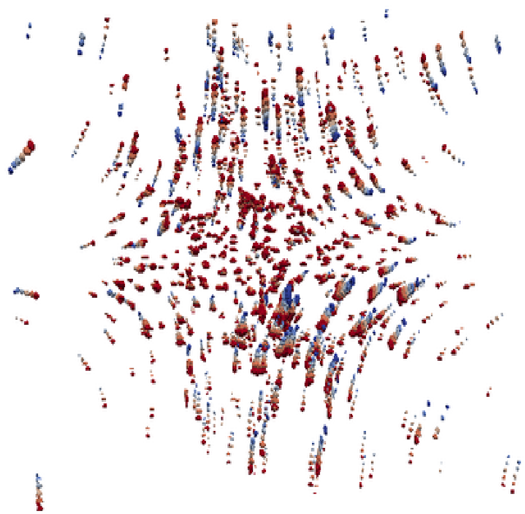


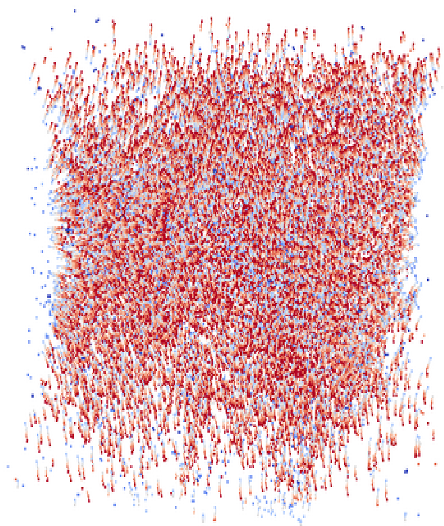
Pure Zirconium

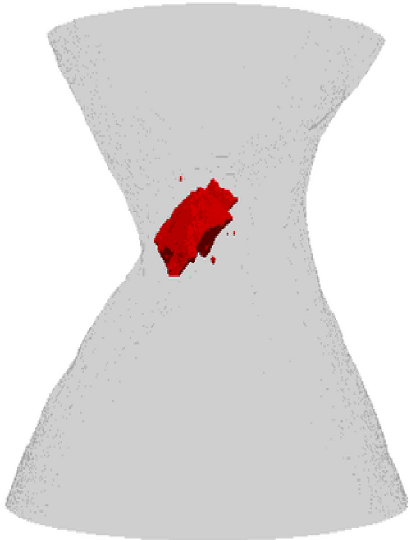


Pure Magnesium









Pure Silver

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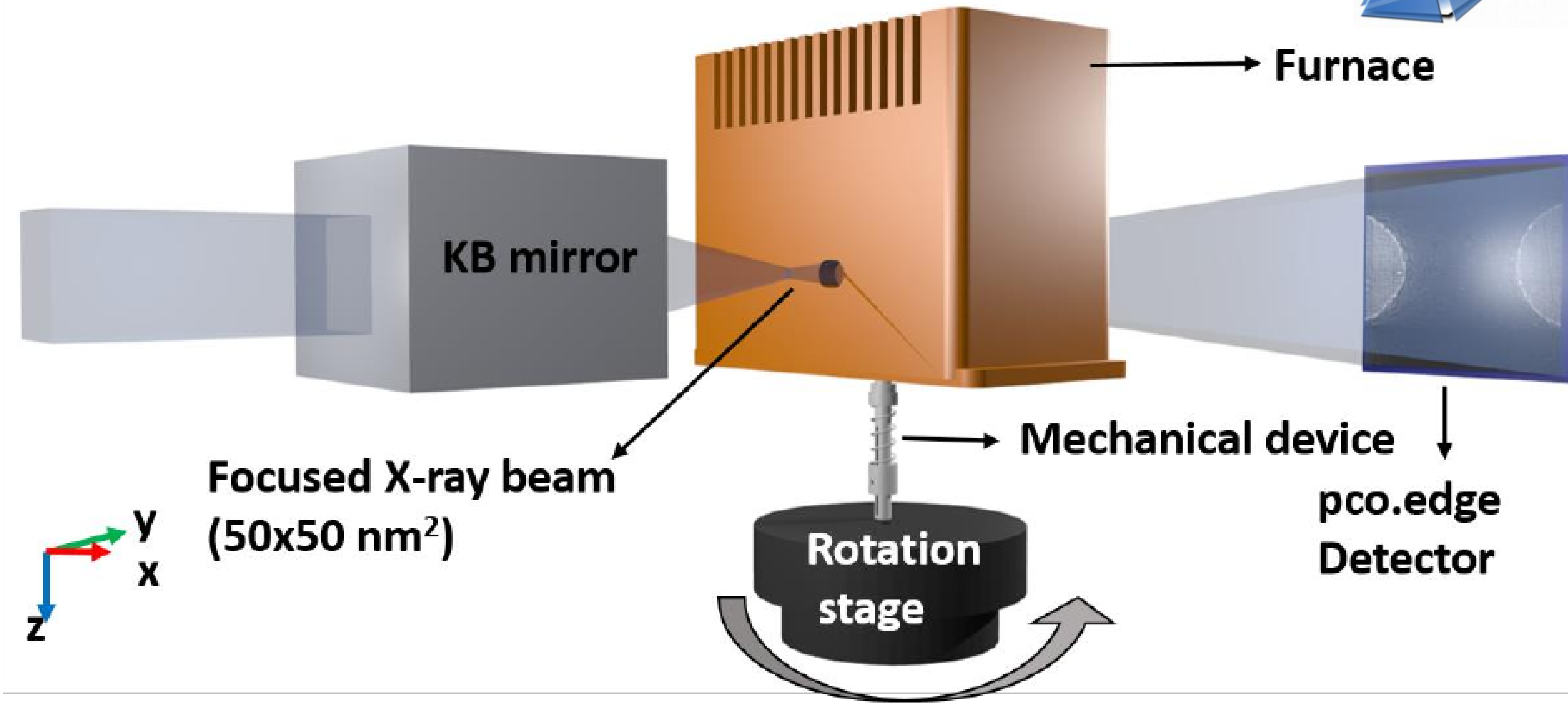
    - Higher spatial resolution

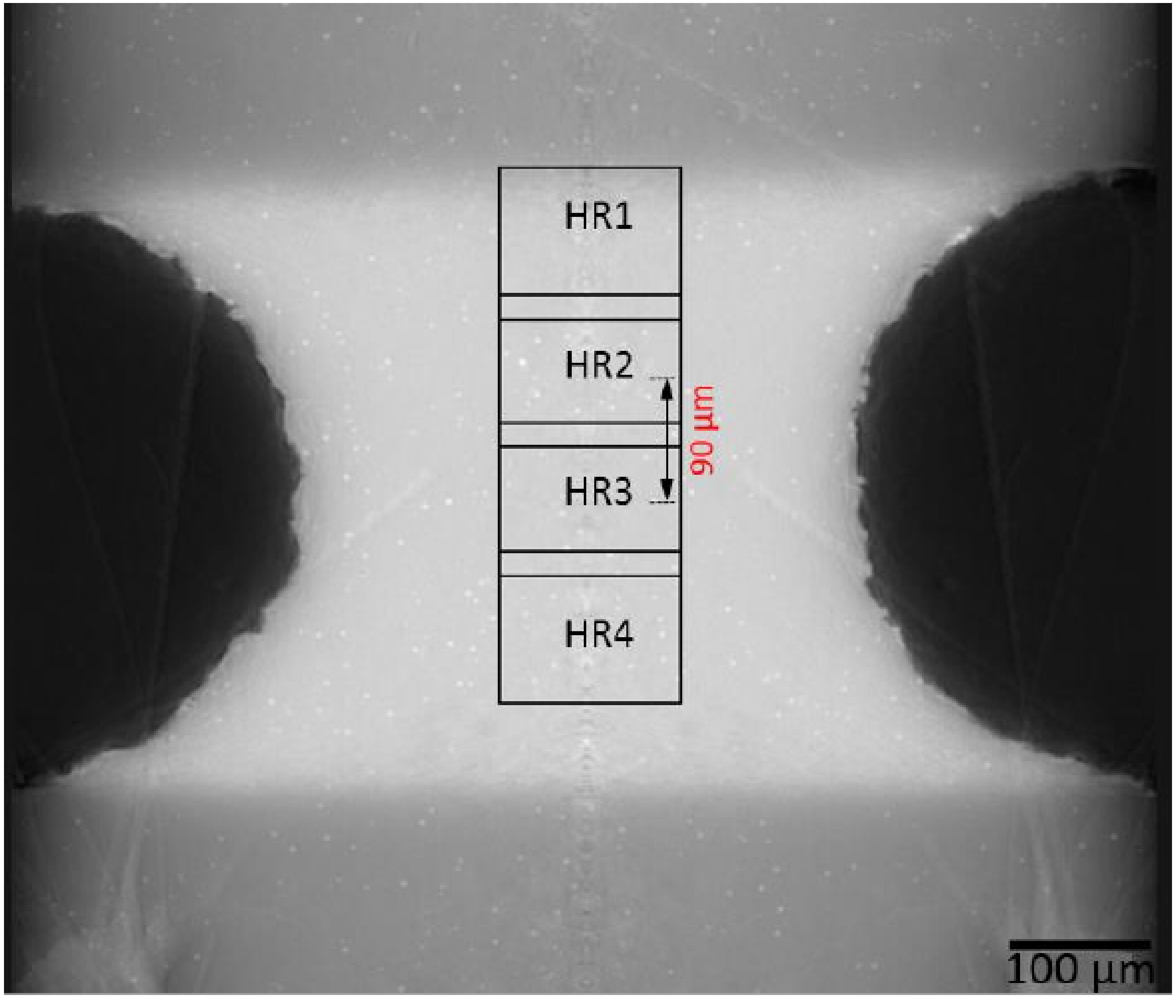
Towards higher spatial resolution



- Ultra high resolution during tensile test on a metal at high temperature
- Experimental setup at ID16B at ESRF **J.Villanova and P.Lhuissier (SIMAP)**

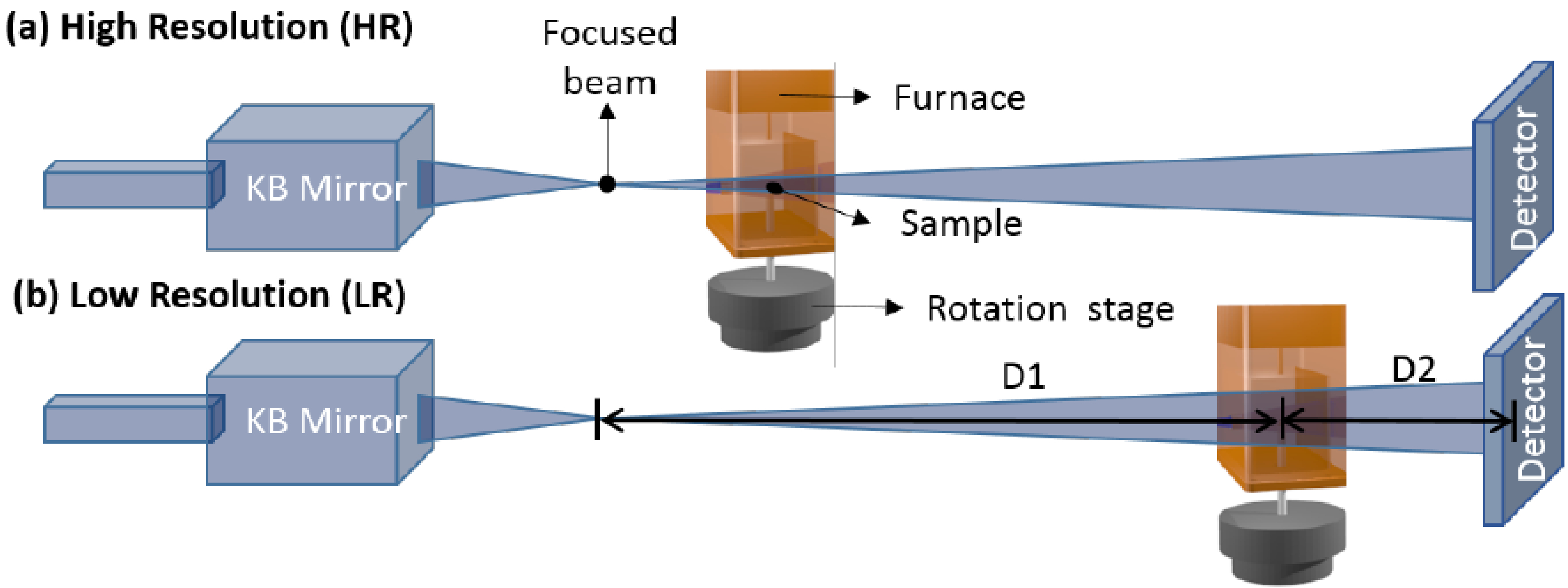
Kumar, R., Villanova, J., Lhuissier, P., Salvo, L., 2019. Acta Materialia 166, 18–27. https://doi.org/10.1016/j.actamat.2018.12.020

Towards higher spatial resolution



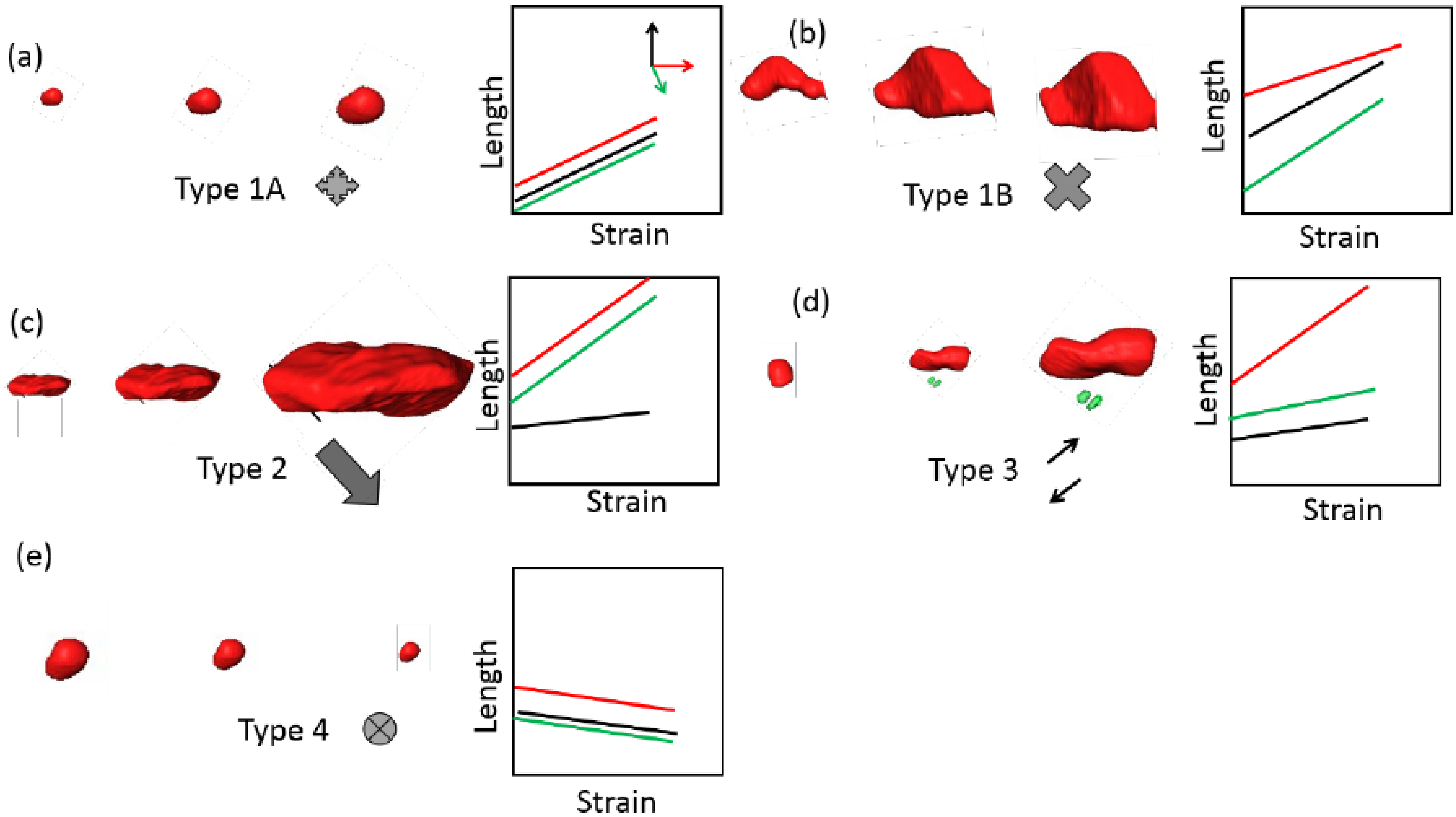
- Sample preparation !
- FOV smaller and smaller

Towards higher spatial resolution



- High resolution voxel size : 100nm
- « Low » resolution voxel size : 645nm
- Temperature + Mech. Load → creep issues

Towards higher spatial resolution



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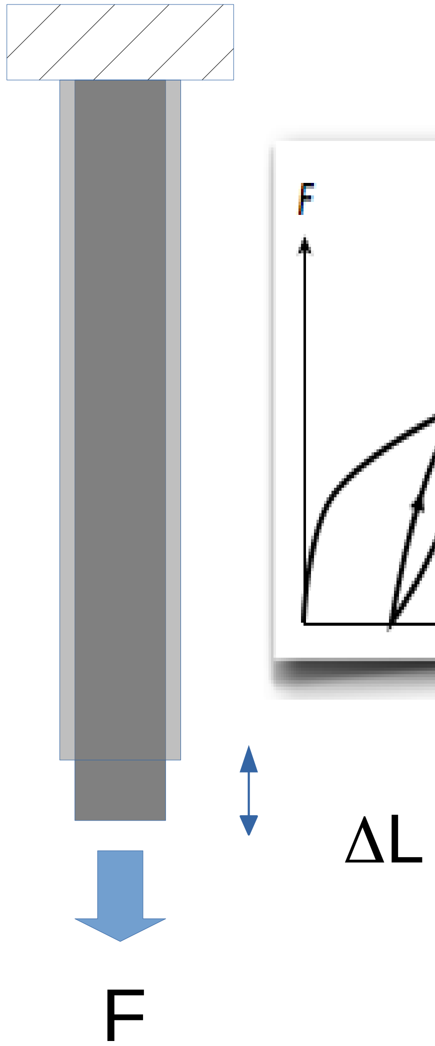
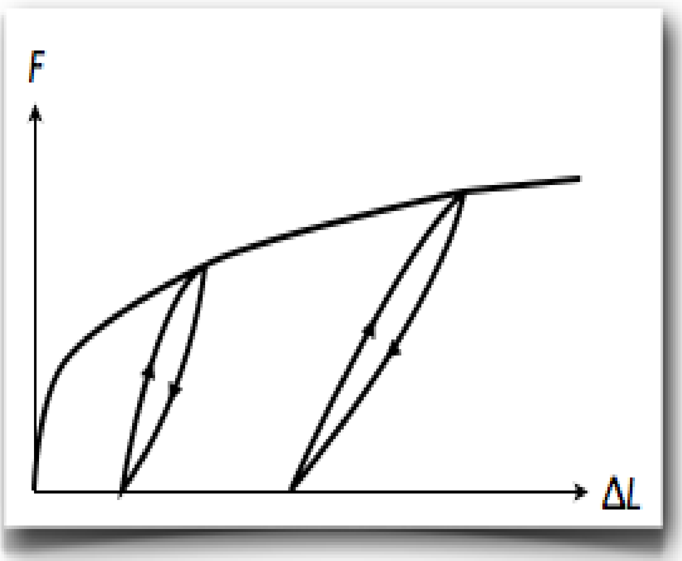
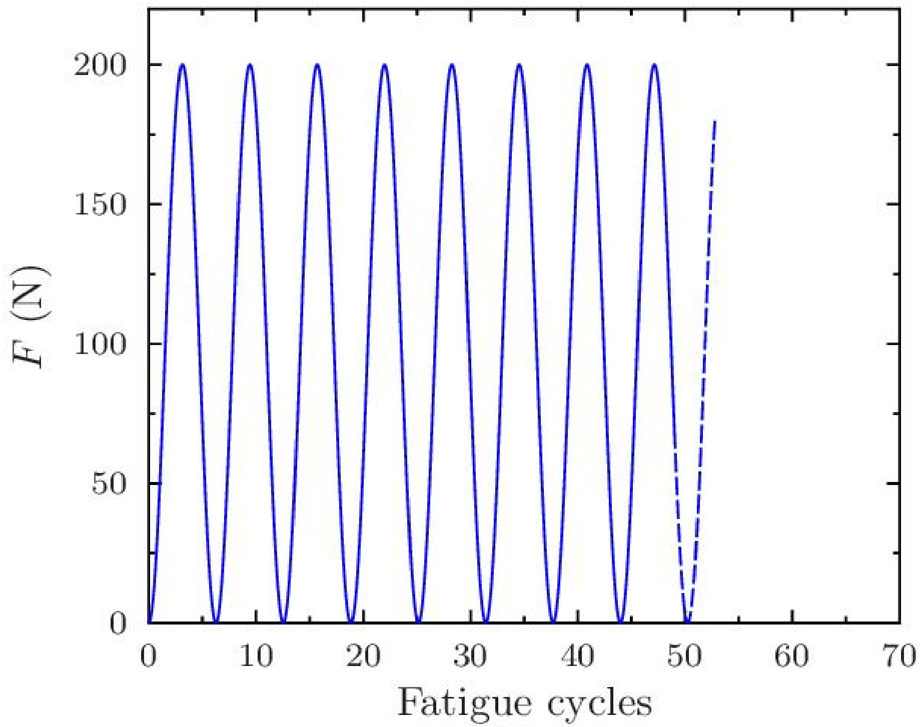
Damage characterization during cyclic loading

- Monotonic *v.s.* cyclic

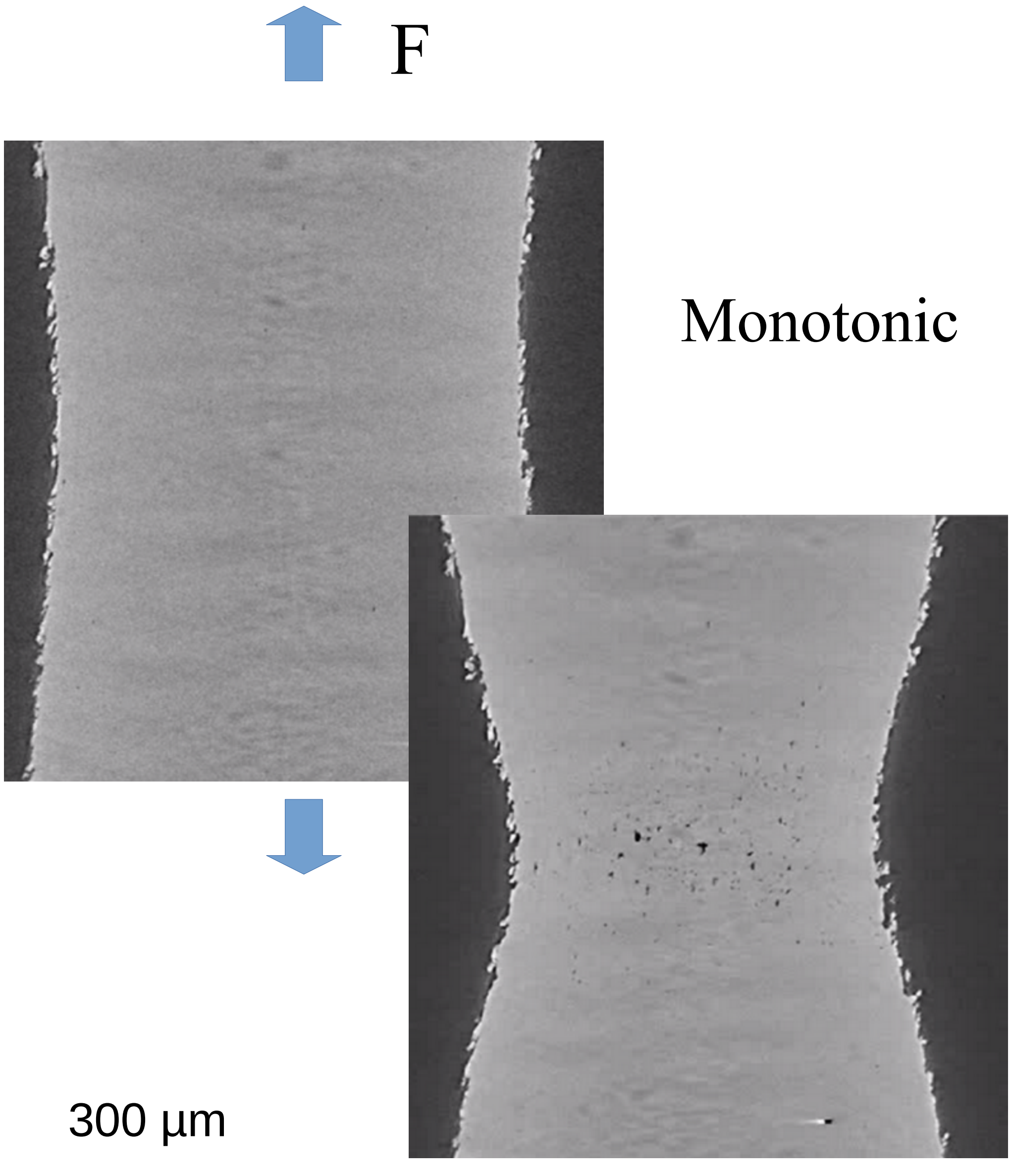


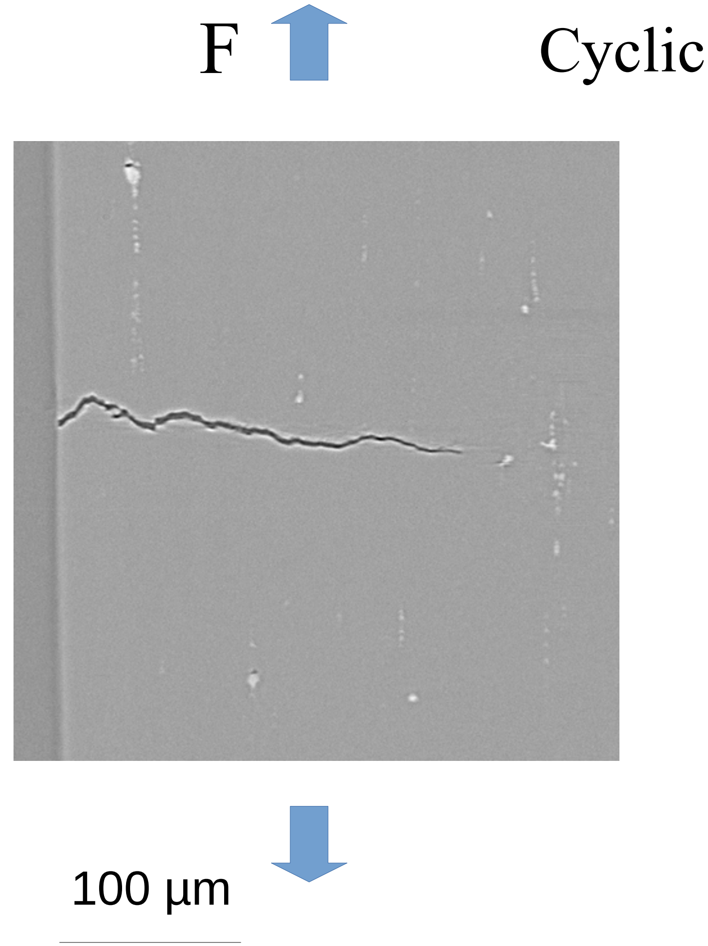




Study of damage during cyclic loading

- Damage $\rightarrow$ creation of new surfaces in the material





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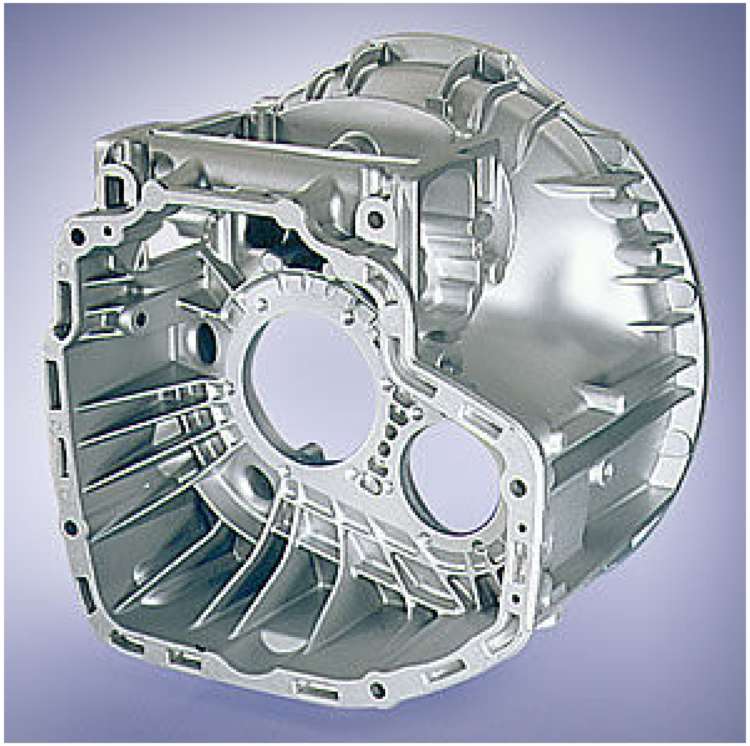
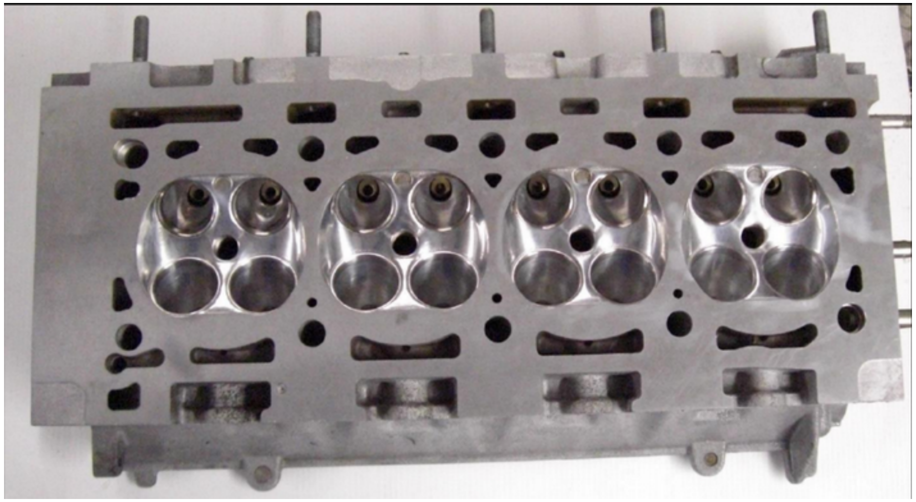
    - Fatigue crack initiation from internal defects
        - Elastic case

Fatigue crack initiation from defects : cast alloys

- Low production costs
- Complex shapes
- Massively used in car industry
- Attractive for aerospace industry



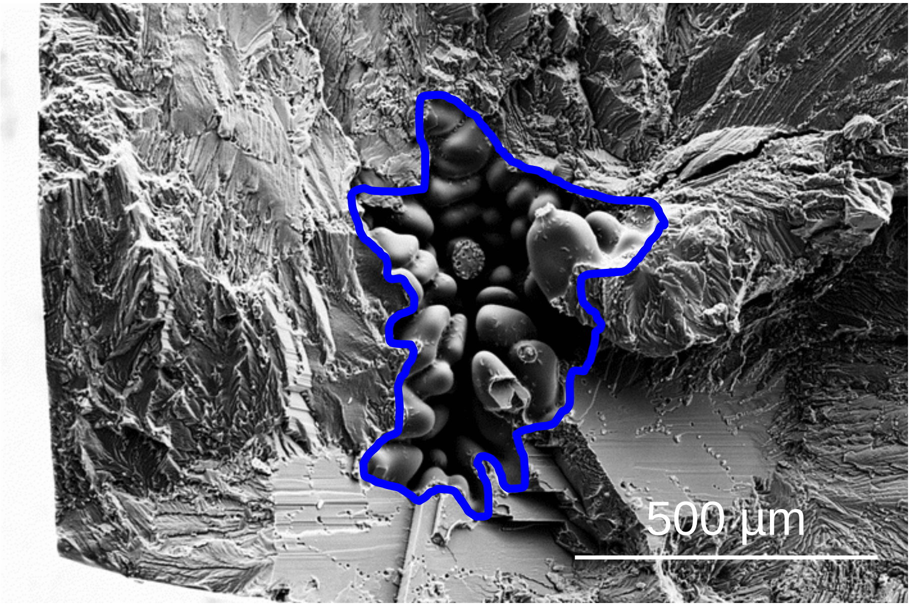


Initiation from defects : cast alloys

But ...

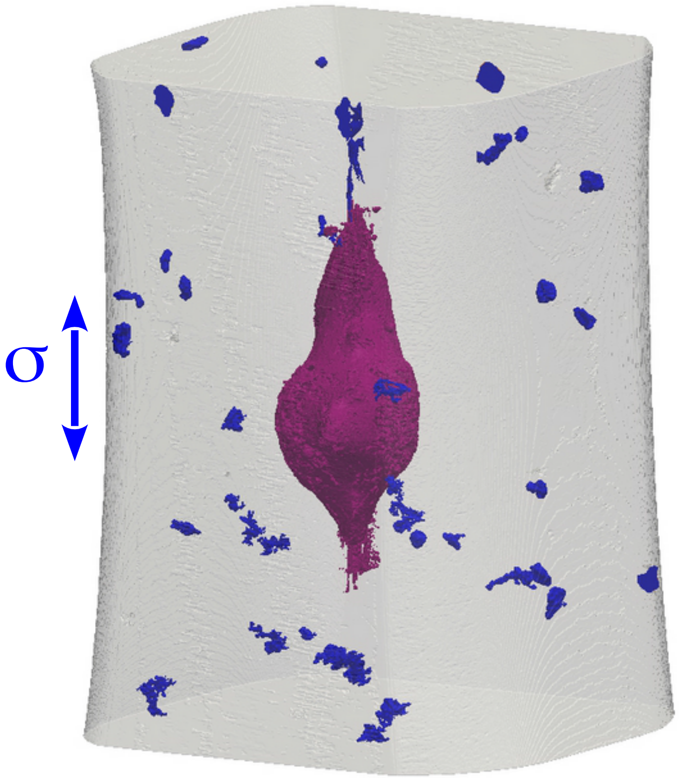
- Casting defects (shrinkages, gas pores, oxides)
- Low fatigue properties
- Safety regulations → limited use
- Non Destructive Inspection

Crack initiation from a sub surface micro-shrinkage in A357 alloy



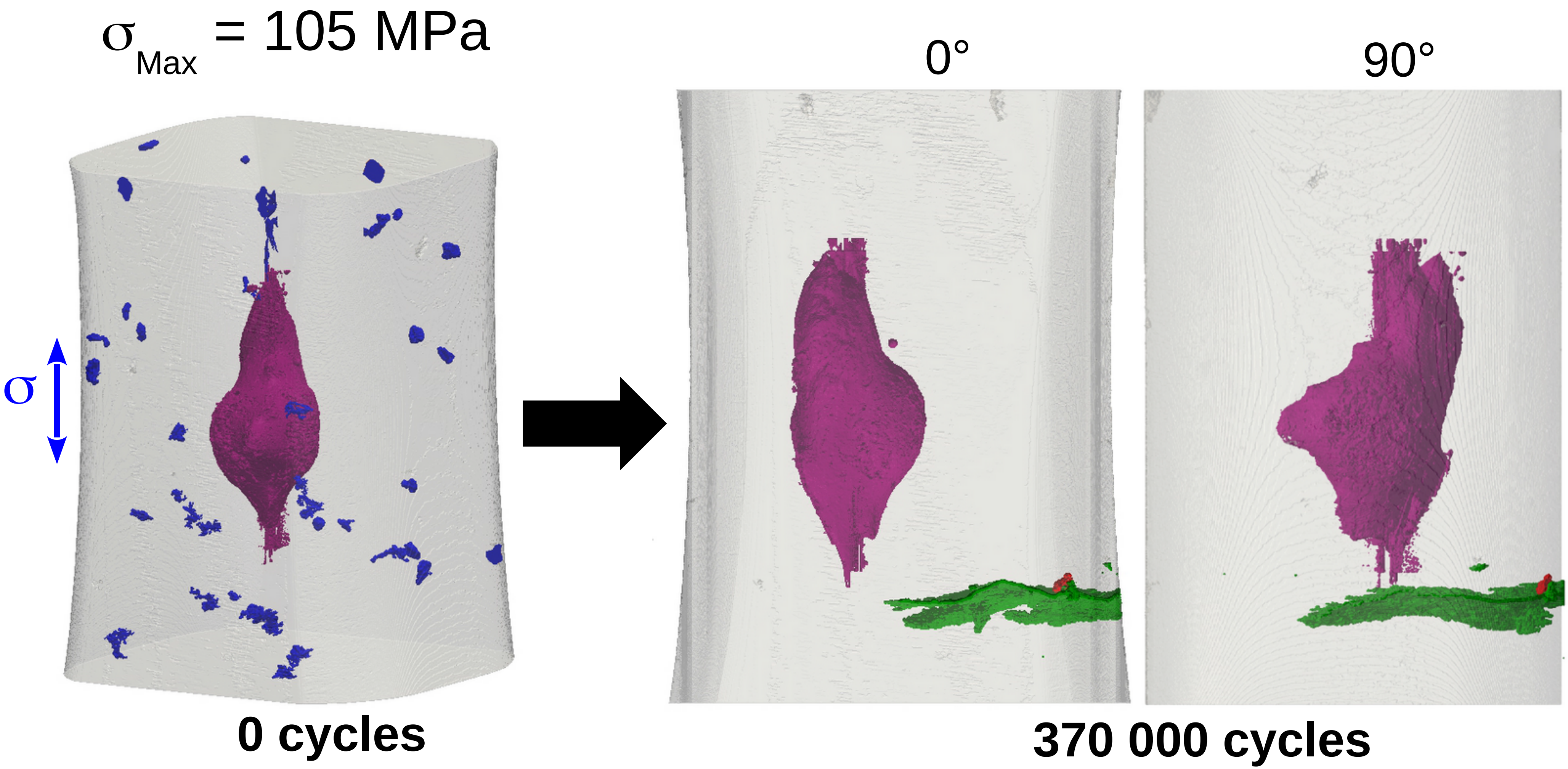
HCF – artificial defects

σ_{Max} = 105 MPa



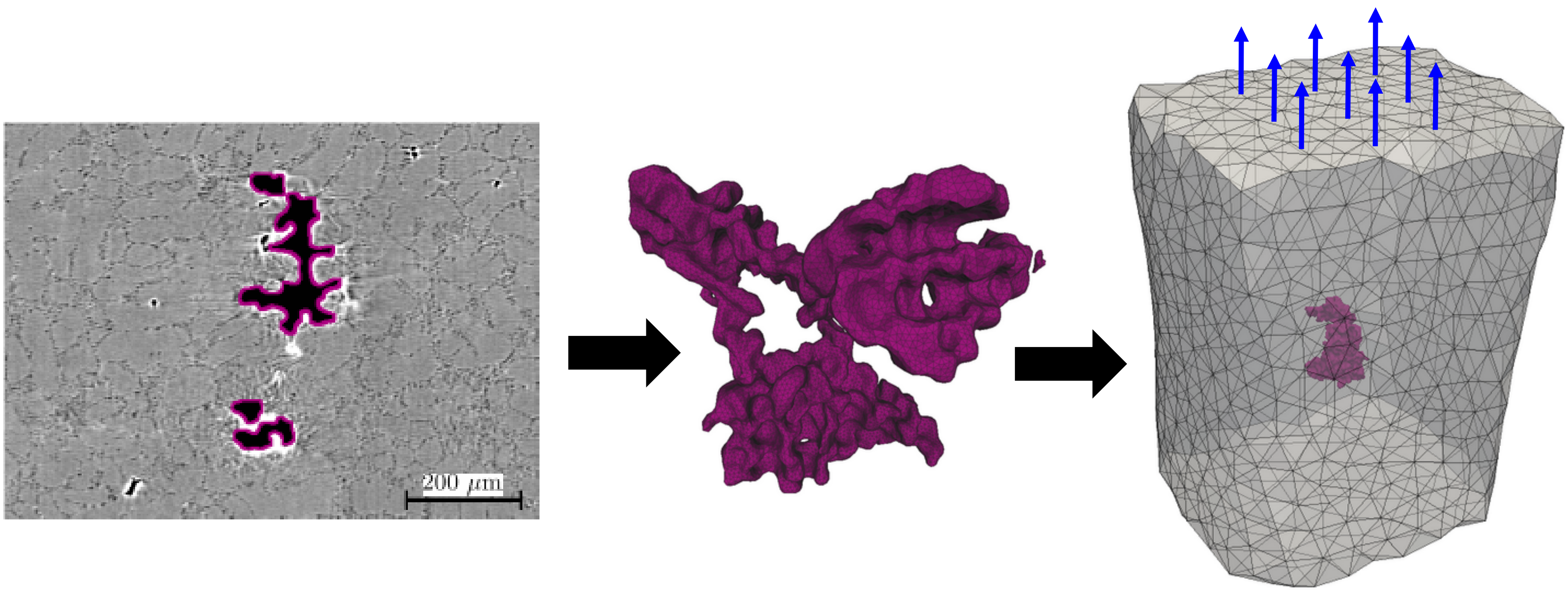
0 cycles

HCF – artificial defects



- Internal pores → **No crack nucleation**
- Final failure due to a **surface crack**

Analysis: local stress state (elastic case)

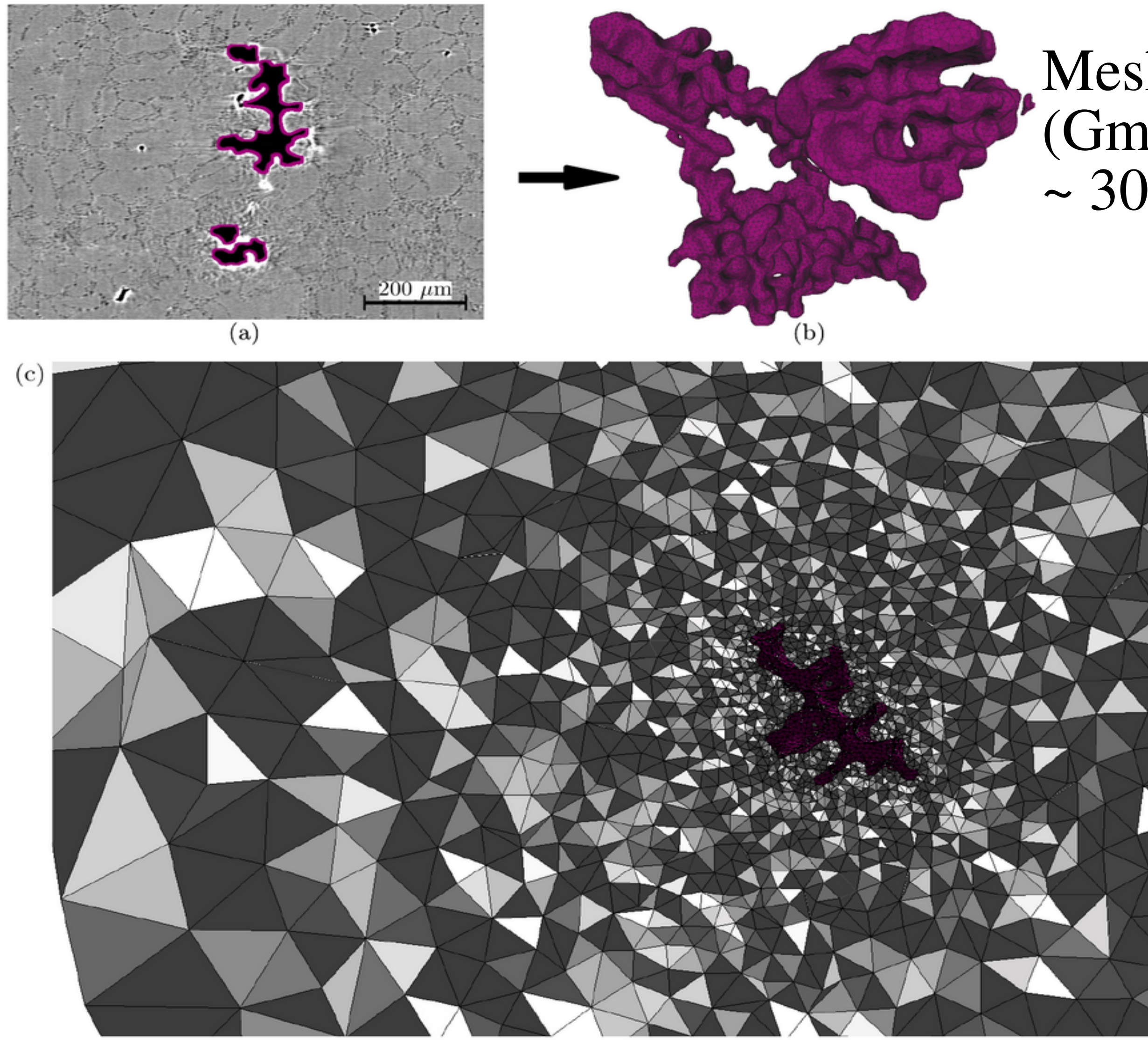


i) 3D image ii) 3D mesh iii) FE calculation

Analysis: local stress state (elastic case)

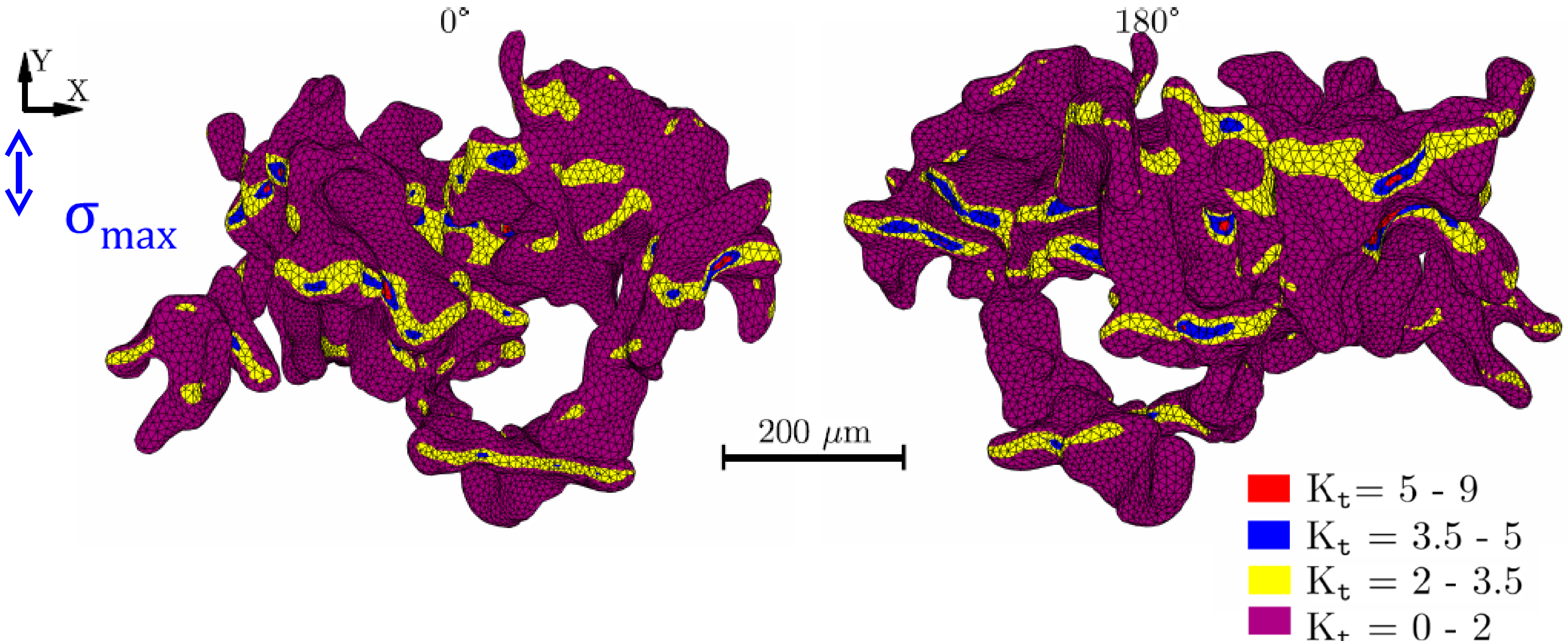
Direct mesh from *Avizo* ~ 300 000 triangles

Mesh reduction (Gmsh) ~ 30000 triangles



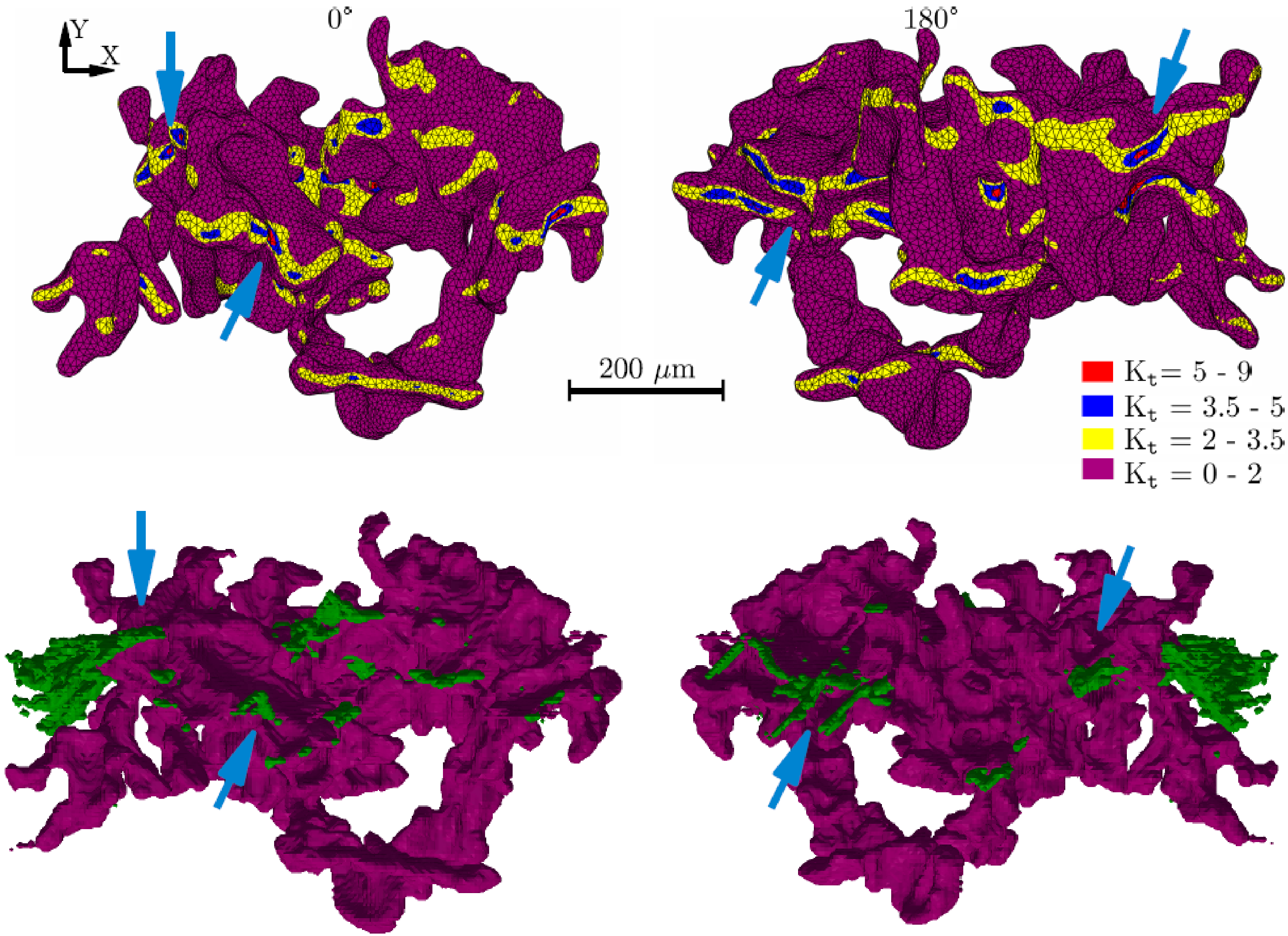
Further mesh reduction for pore + sample surface (Gmsh) → 300 000 to 500 000 elements

Analysis: local stress state



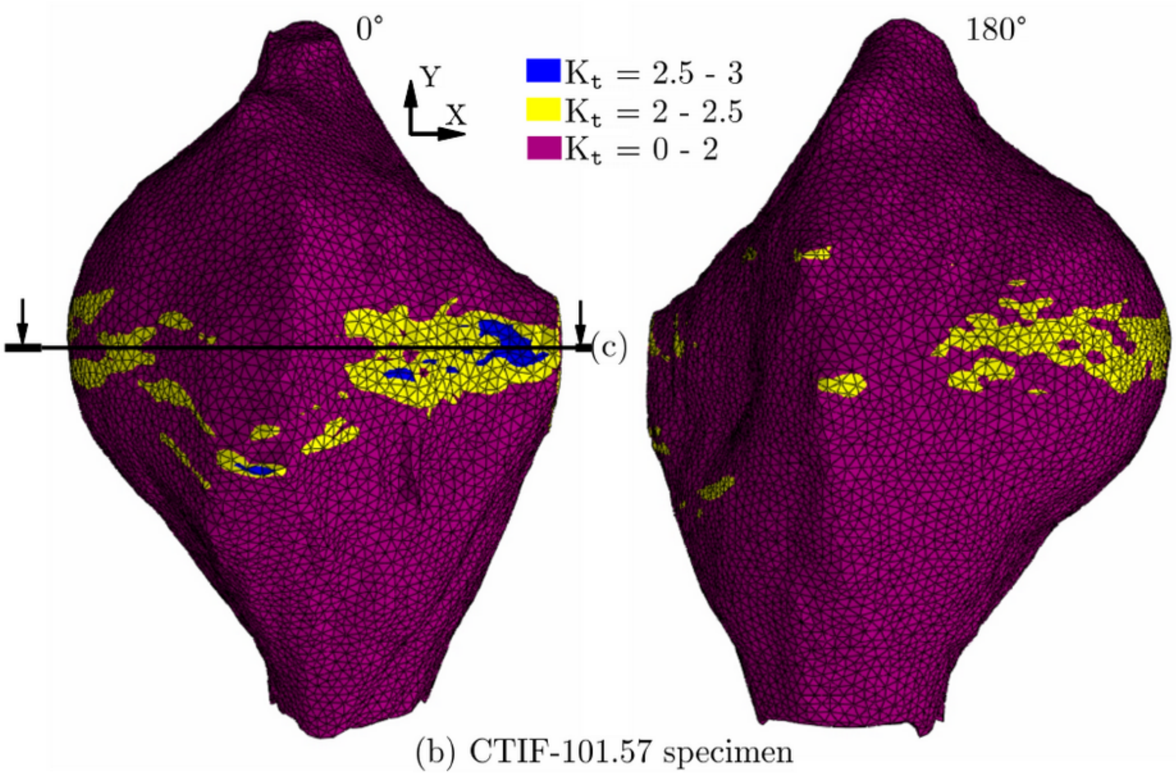
- $\sigma_{local} \sim K_t\, \sigma_{section}$
- Elastic simulation
- Convex parts of the pores → large stress concentrations

Analysis: local stress state

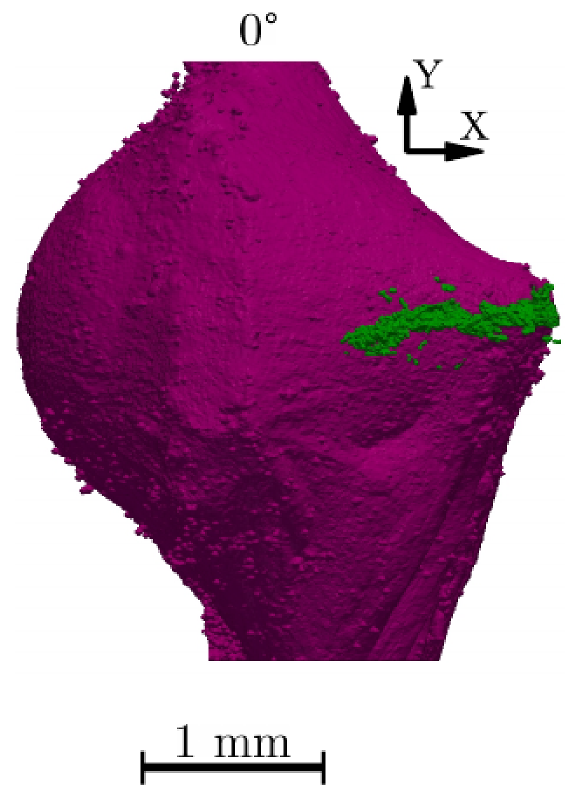


- Crack location correlate well with large K_t values

Analysis: local stress state



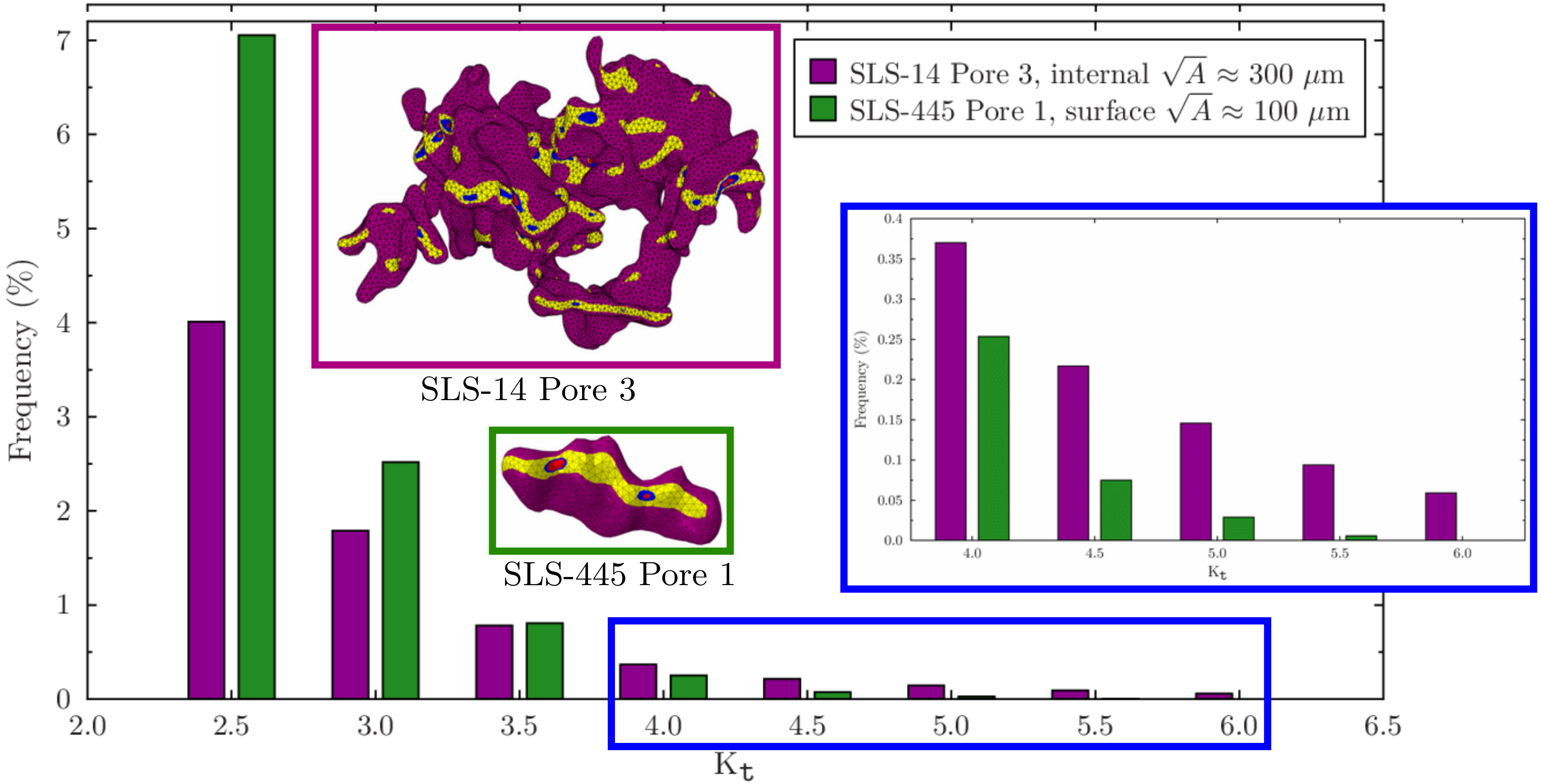
(b) CTIF-101.57 specimen



- Also true for artificial defects

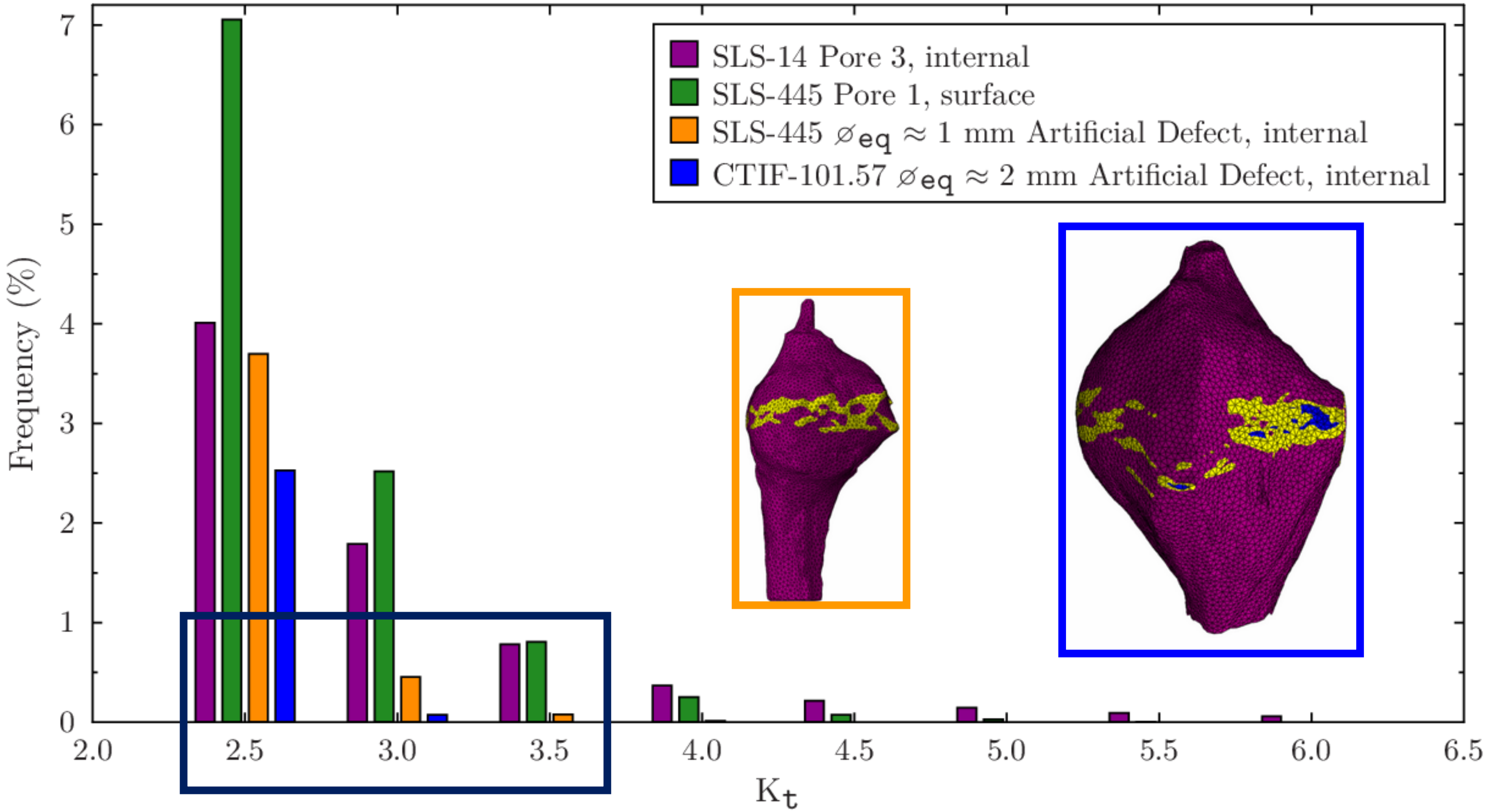
(*N.B.* not a synchrotron sample)

Analysis: local stress state



- Convoluted shapes → K_t as high as 4-6

Analysis: local stress state



- Artificial defects → K_t values between 2.5-3.5
- Artificial defects ≠ natural defects

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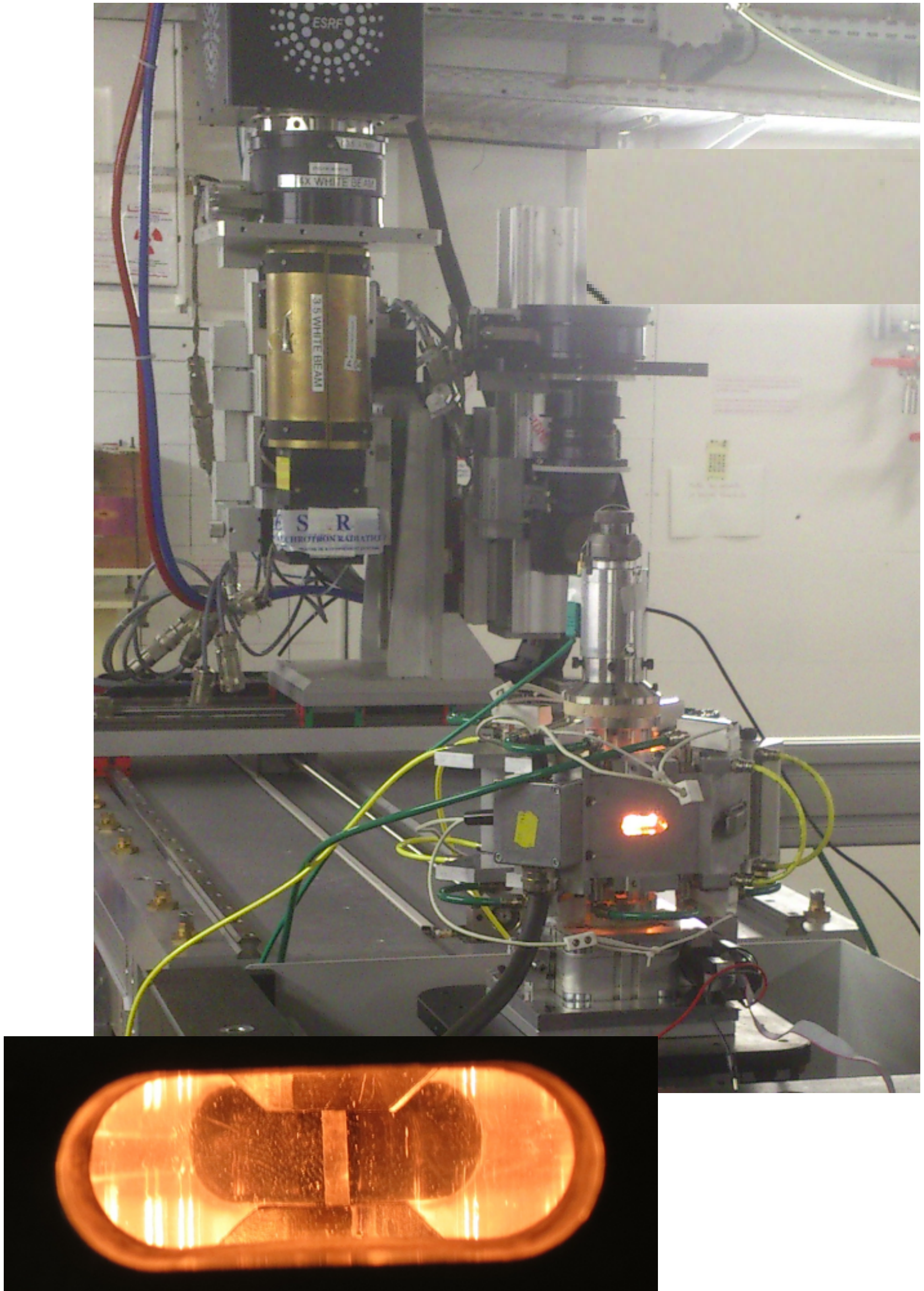
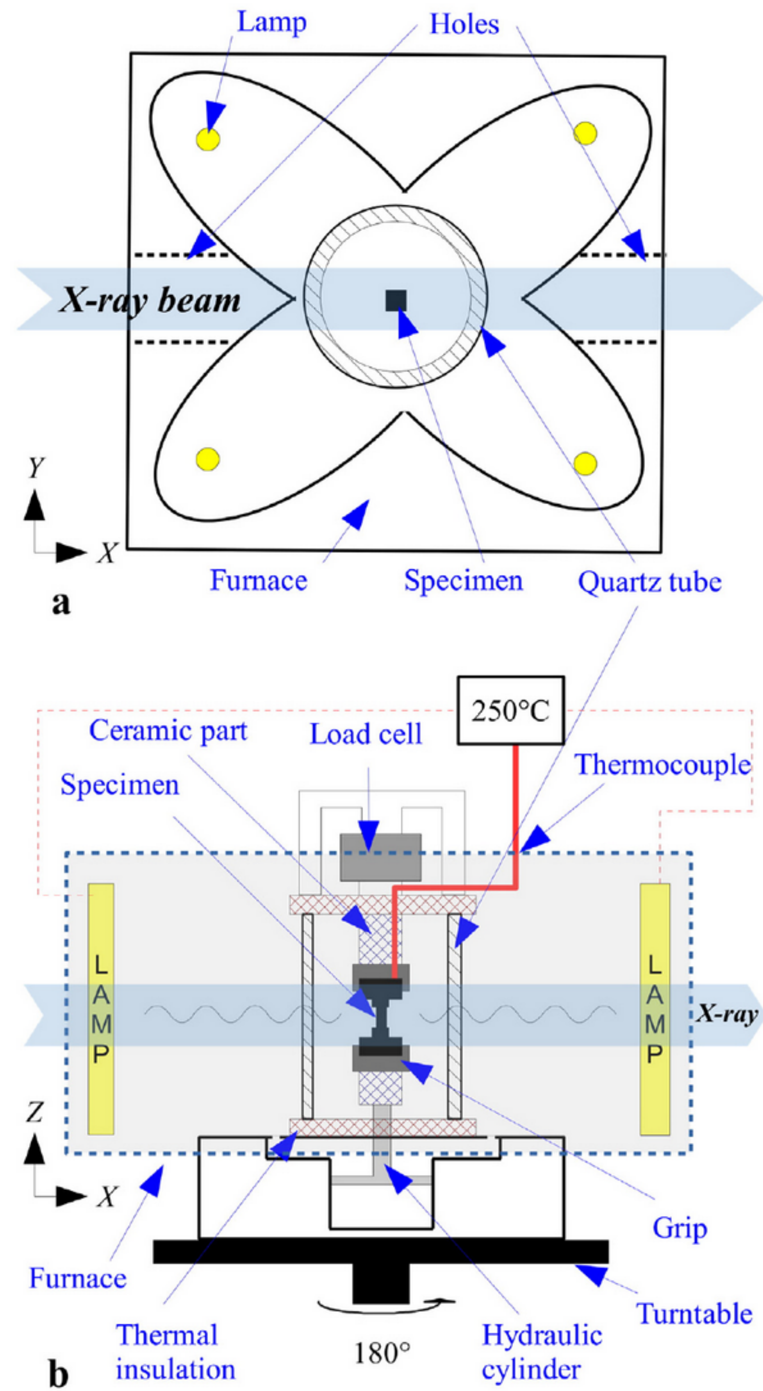
- Fatigue testing
    - Fatigue crack initiation from internal defects
        - Elastic case
        - Plastic case

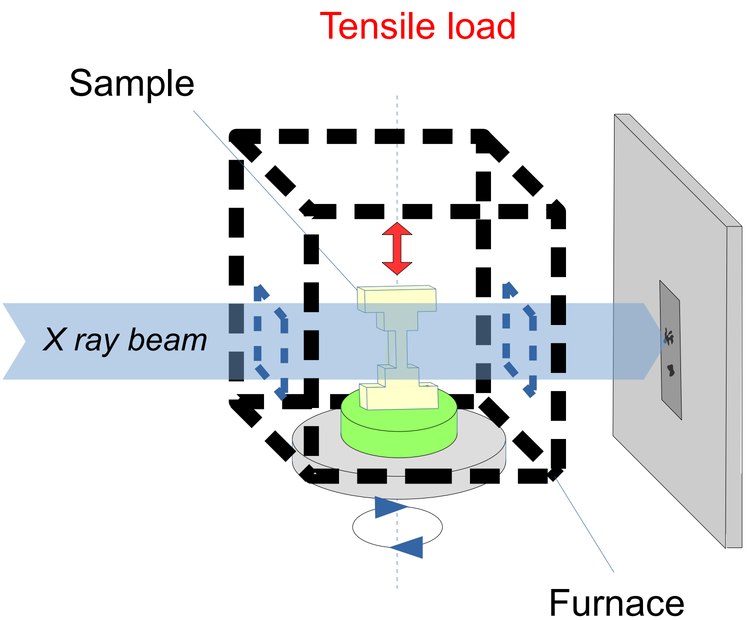
Experimental

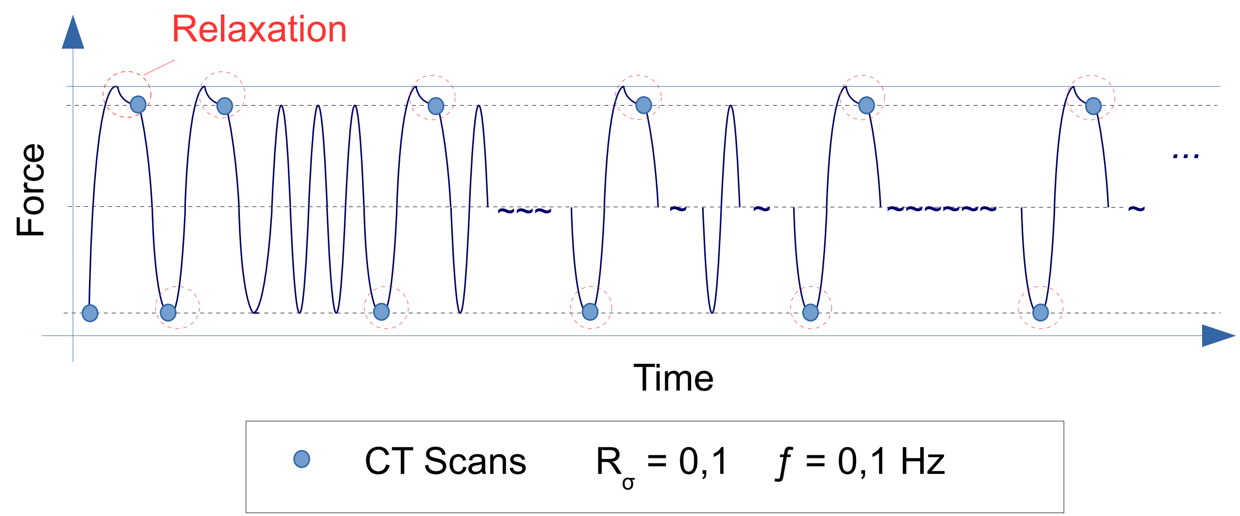




Coll. A.Koster V.Maurel (ENMP)

Experimental



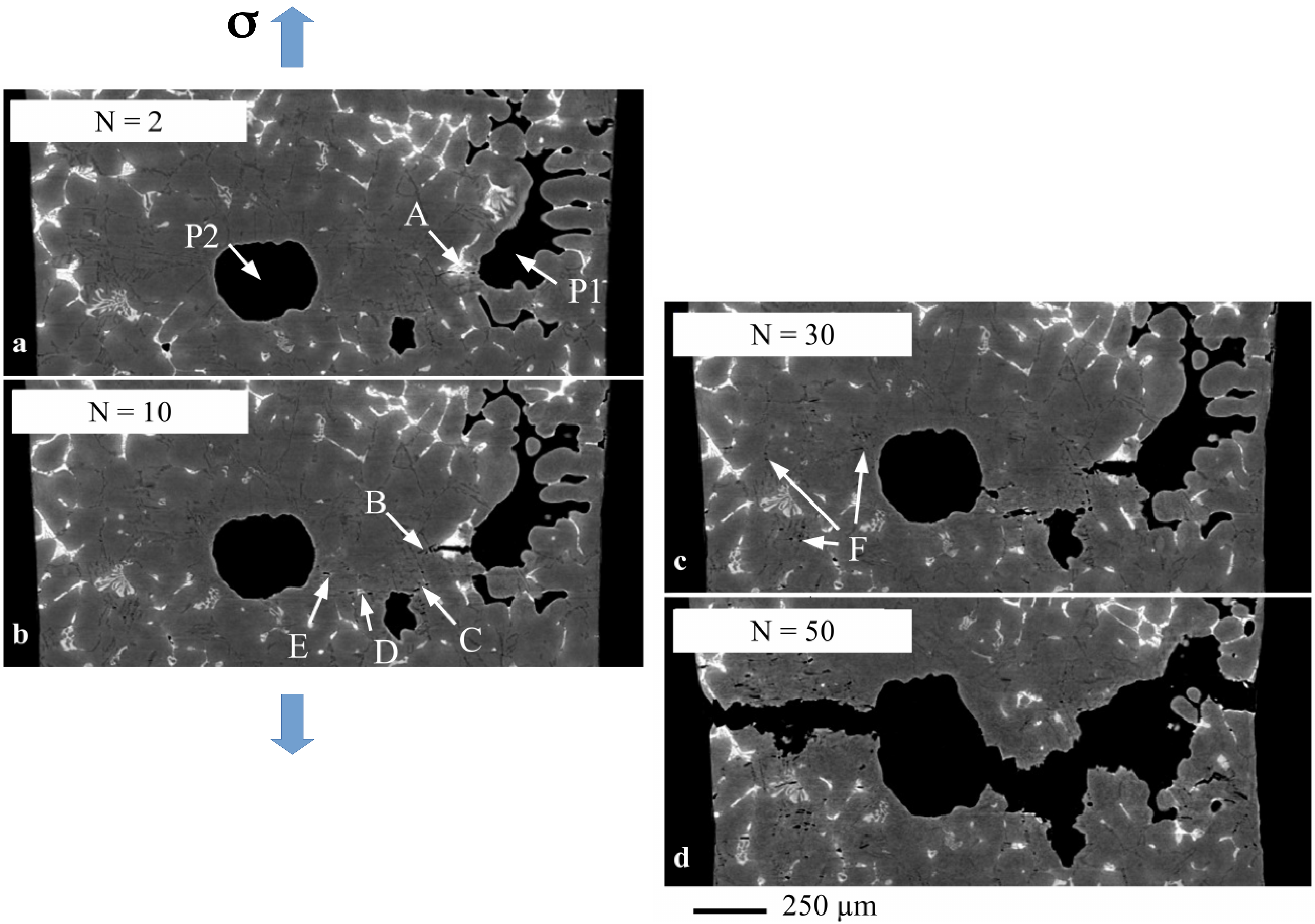


- ESRF ID19
- 35 KeV
- Voxel sizel = 2,75 µm
- Scan duration = 45 s.
- PCO camera

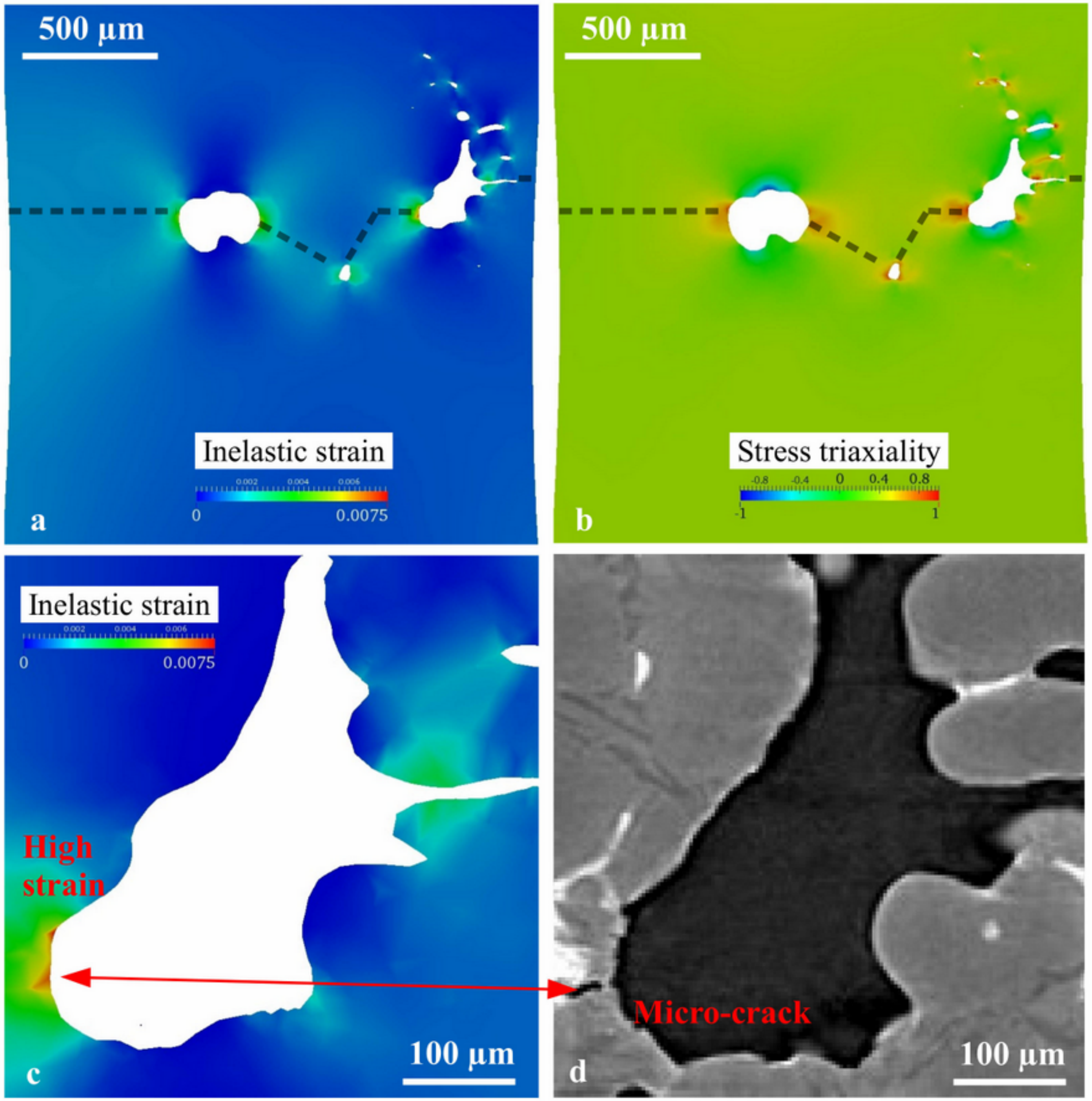
- Sp./Detector distance = 200 mm
- Temperature range up to 250°C

S.Dezecot et al. Scripta Mater. 2016

Damage mechanisms



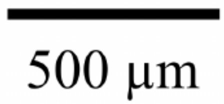
Modelling



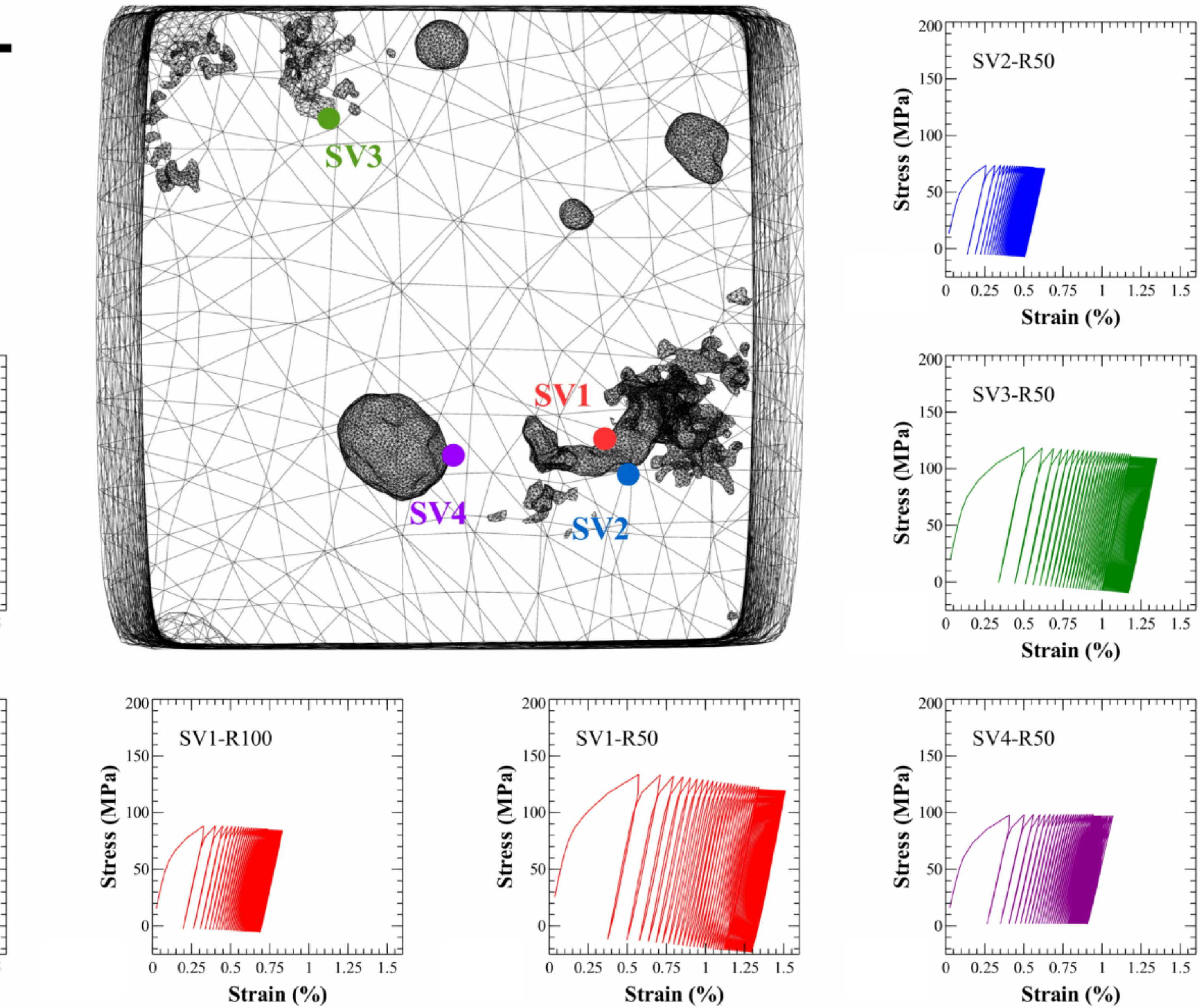
Inelastic strain and stress triaxiality

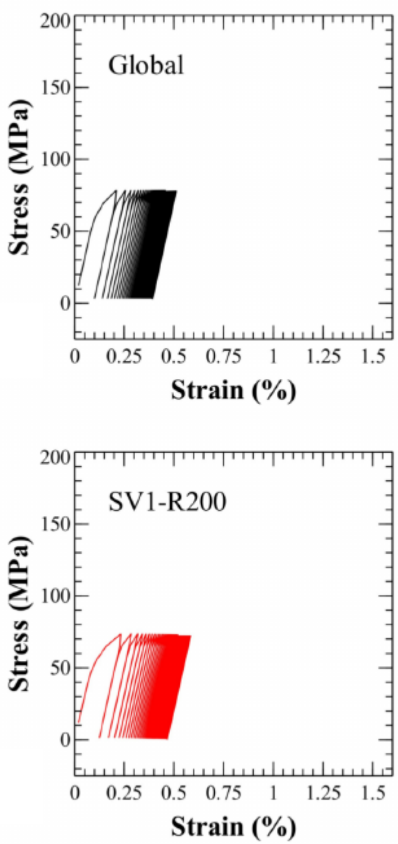
S.Dezecot et al. Acta Mater. 2017

Modelling



Local probes





- Cracks initiate at large strain heterogeneities

Outline

- Introduction
- Monotonic testing
  - “Classical”
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    - Plastic case
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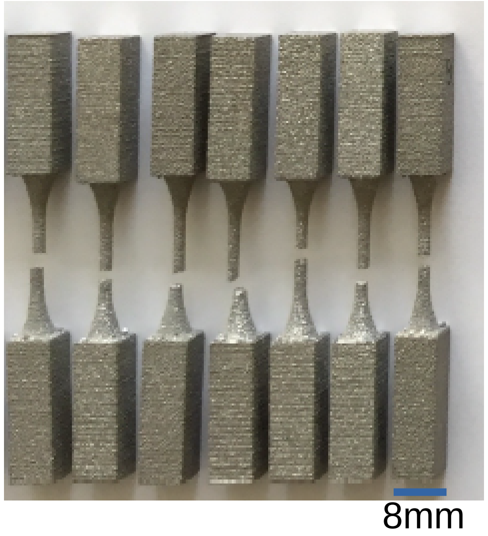
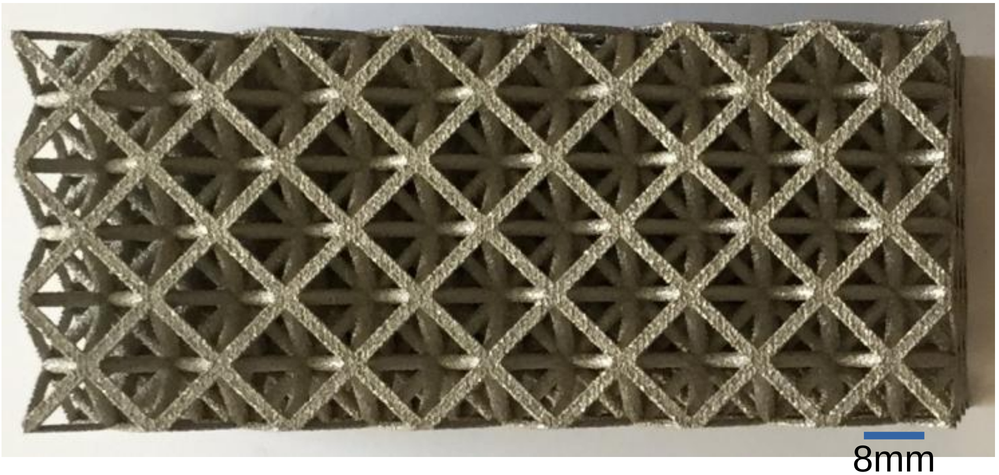
    - Small representative samples

Crack initiation in AM materials

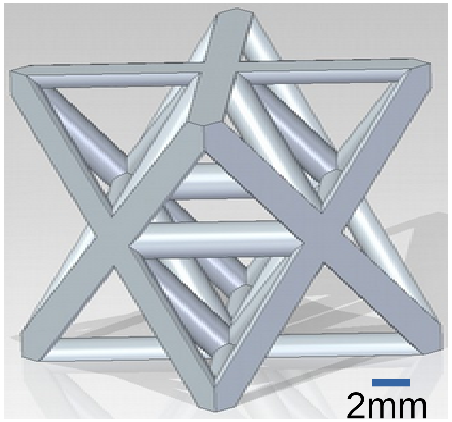
- In search of the critical defect
  - Tomographic scans before and after fatigue tests
- Single struts
  - As-built
  - Post-treatment (chemical etching, HIP, …)
- Lattice structures

Single struts samples





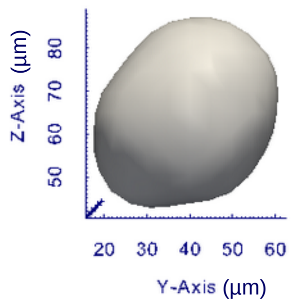
Octet-truss cell



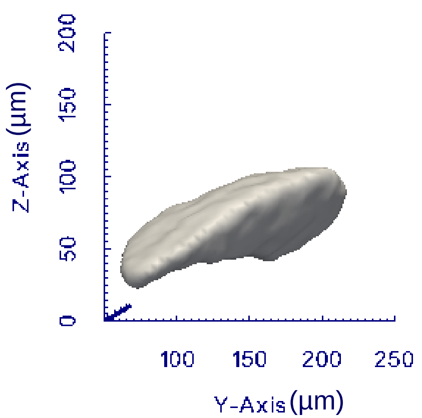
Crack initiation in AM materials

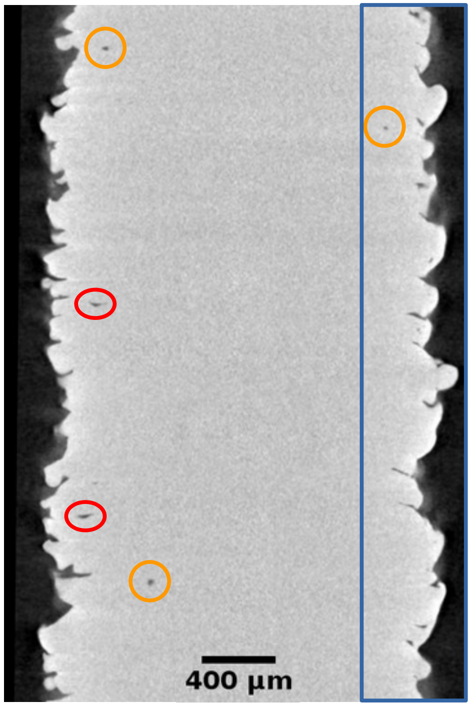
Internal

Spherical pores (from **atomisation**)

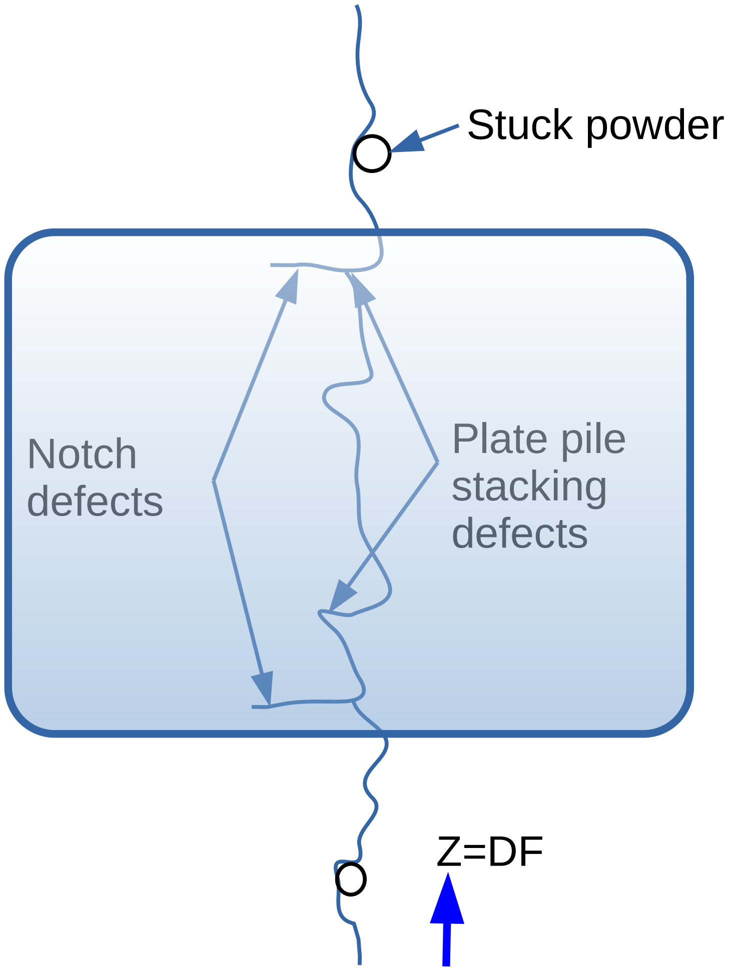


LOF defects





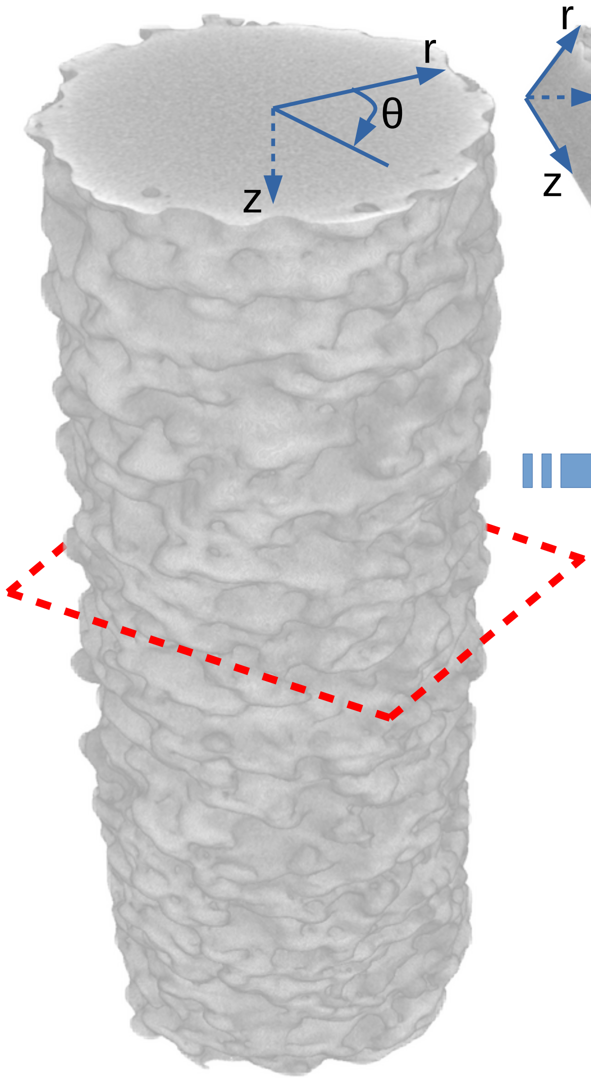
Surface

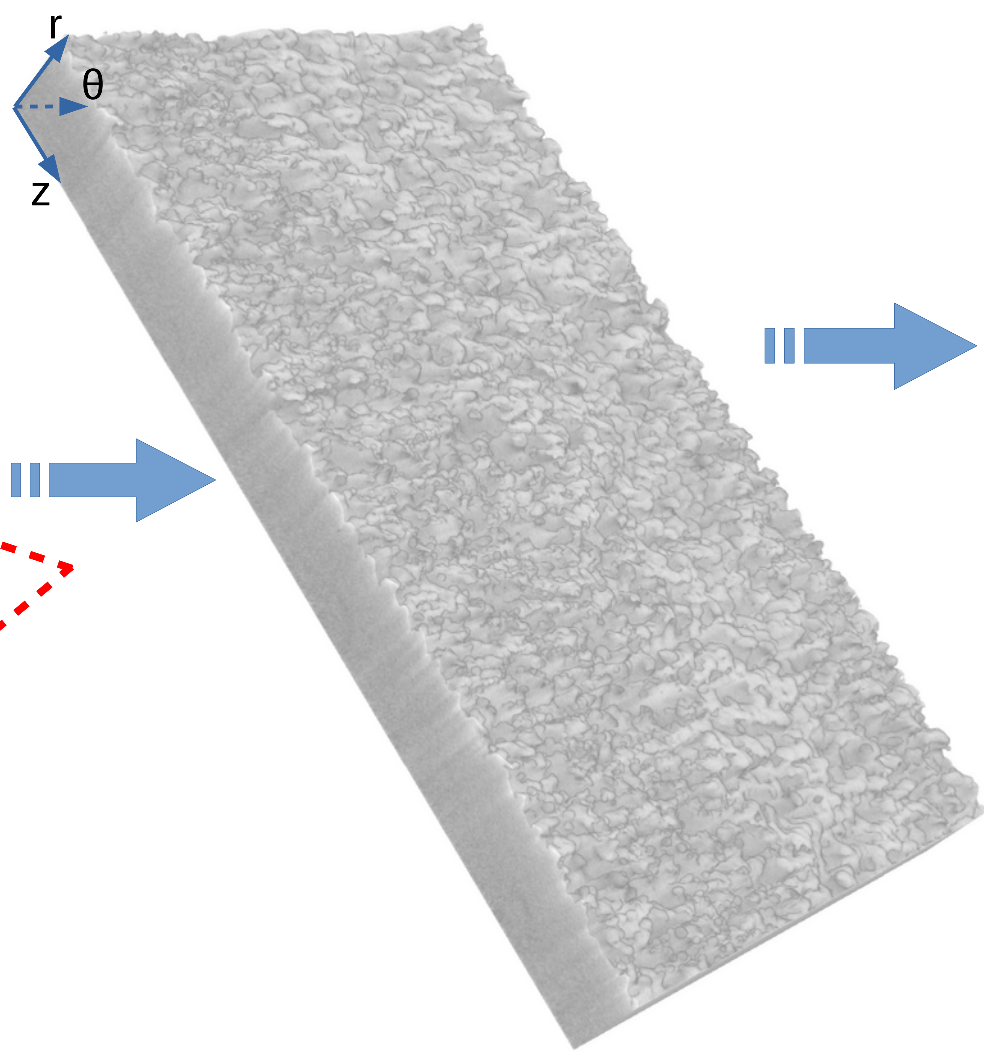


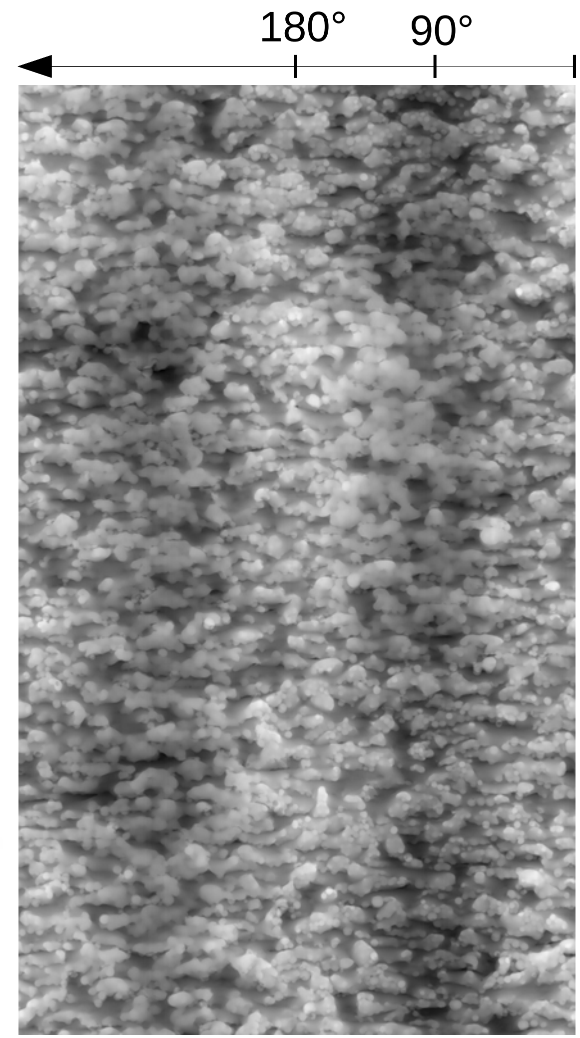
Limited porosity (<0.05 % vol.)

Crack initiation in AM materials

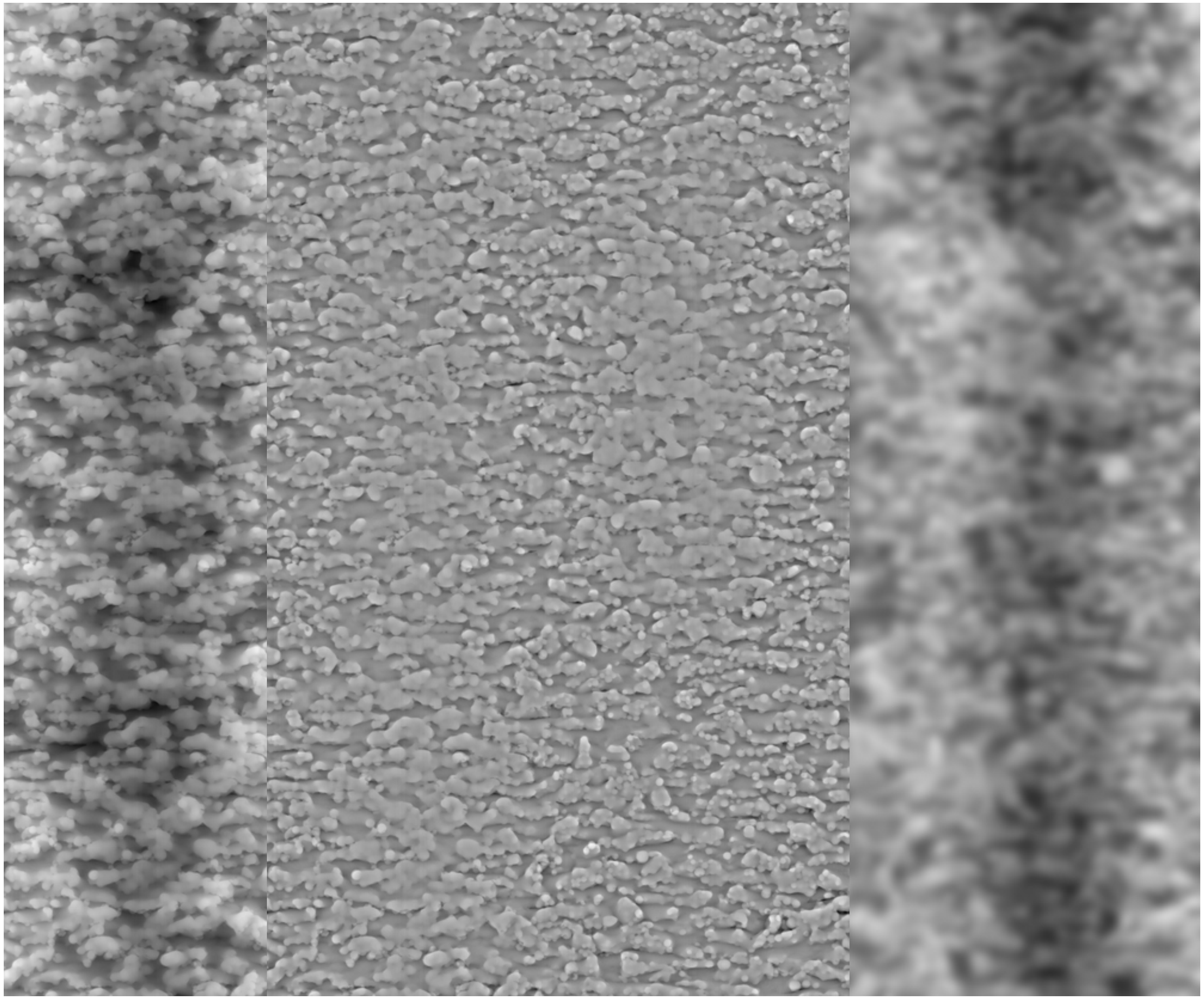
“unfolding” of the surface **Height measurement**

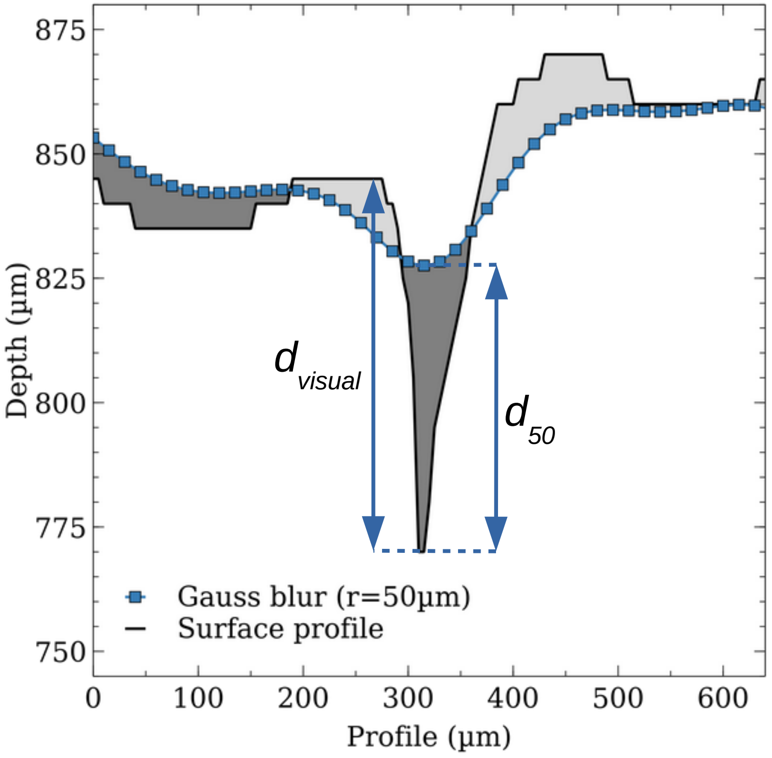






Crack initiation in AM materials

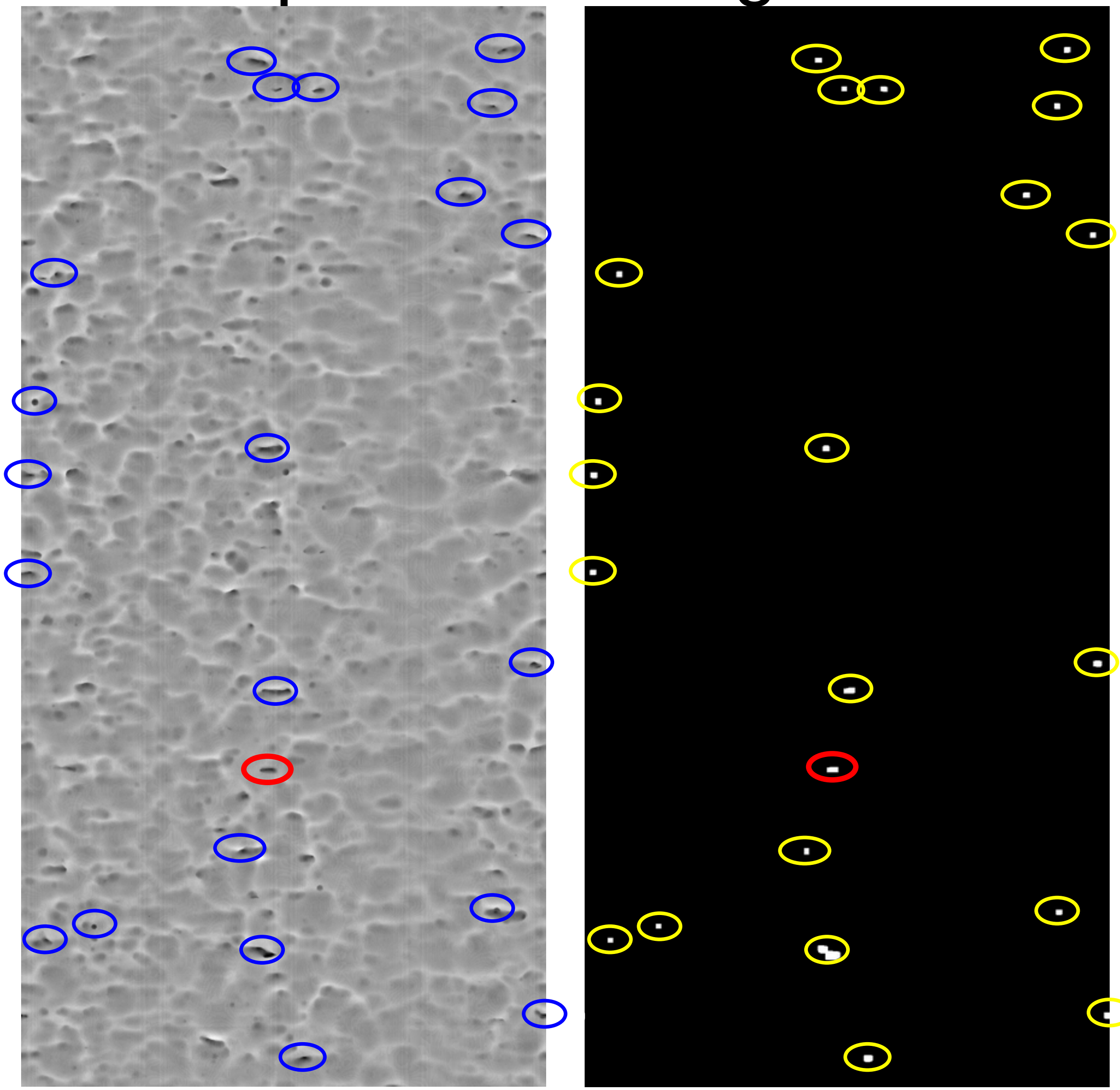




2D map of local height variations ✓

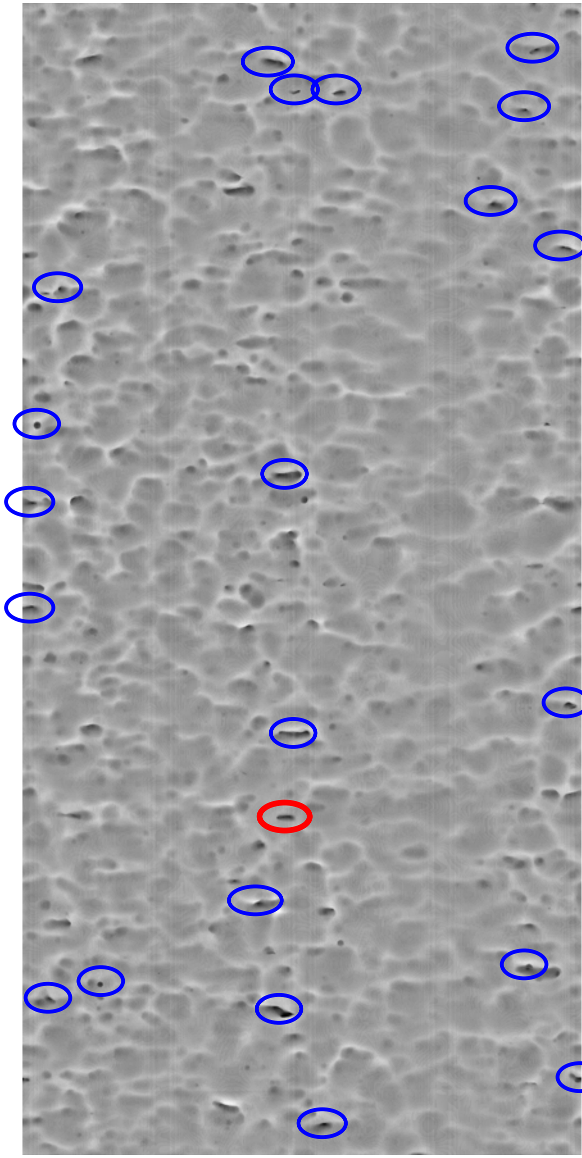
Crack initiation in AM materials

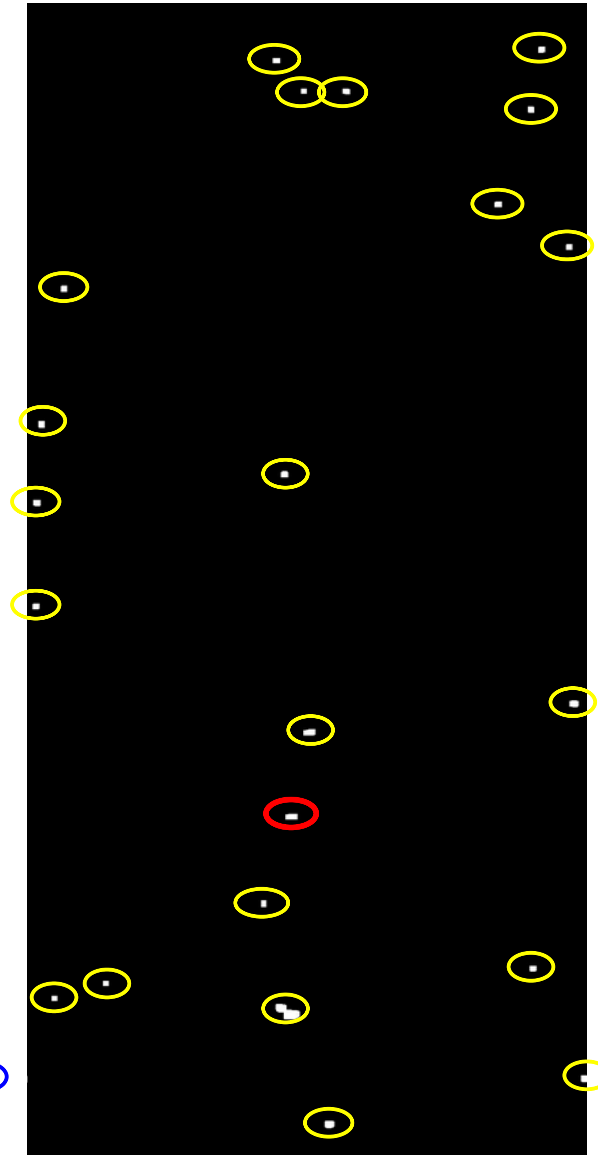
- 2D map thresholding



22 detected defects
Including the critical one ✓

Crack initiation in AM materials





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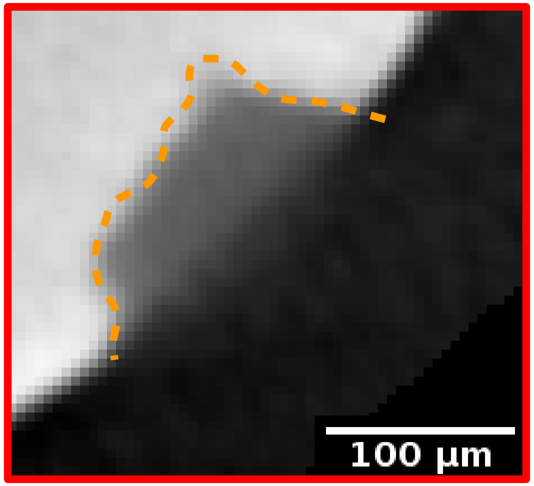
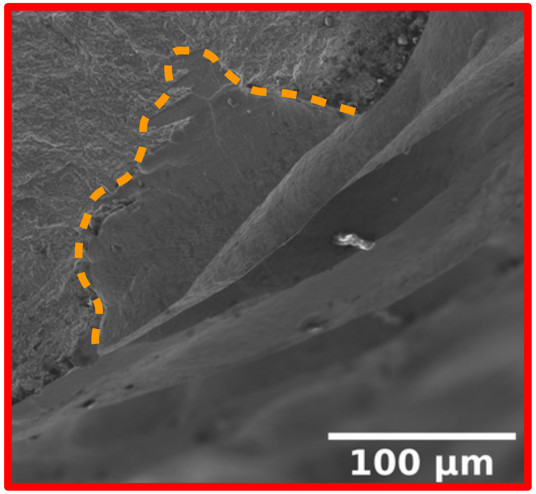
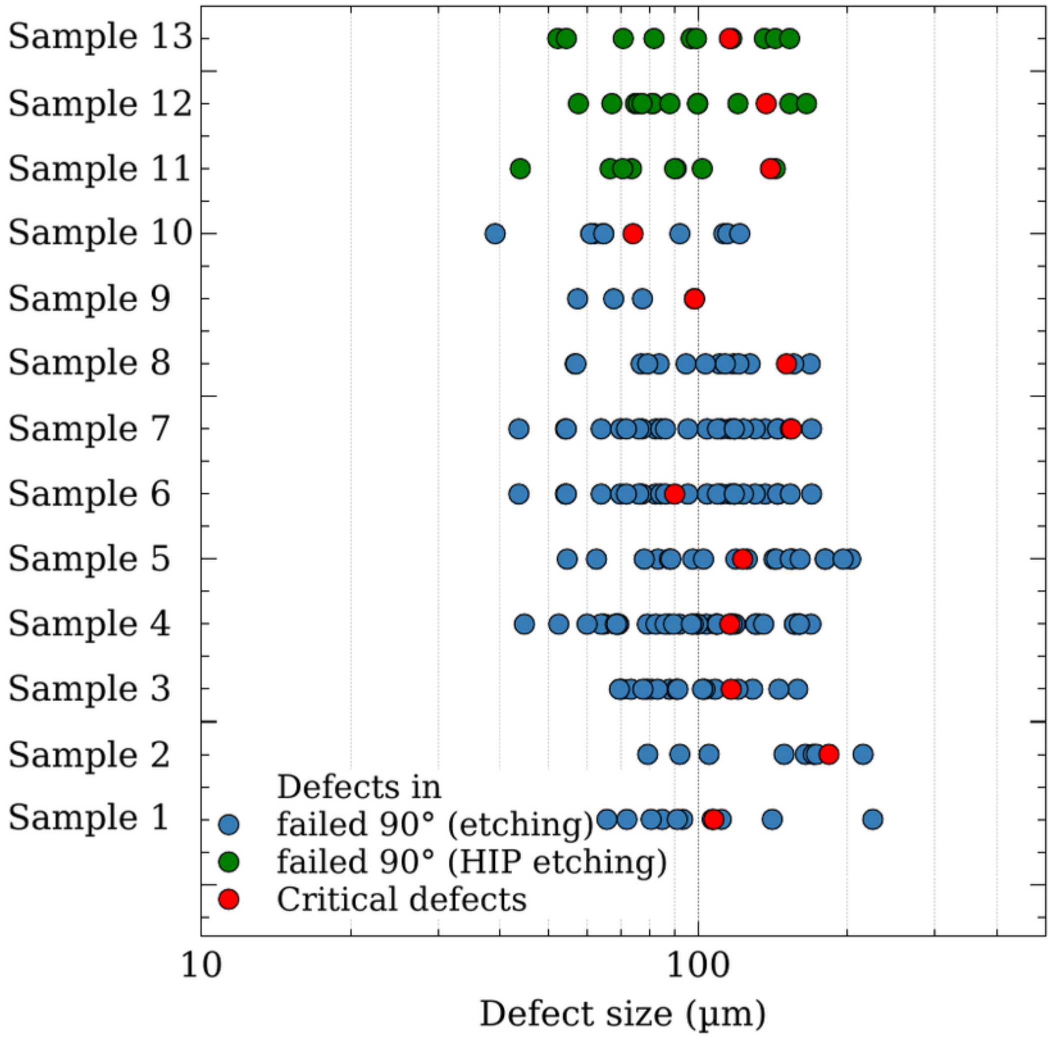




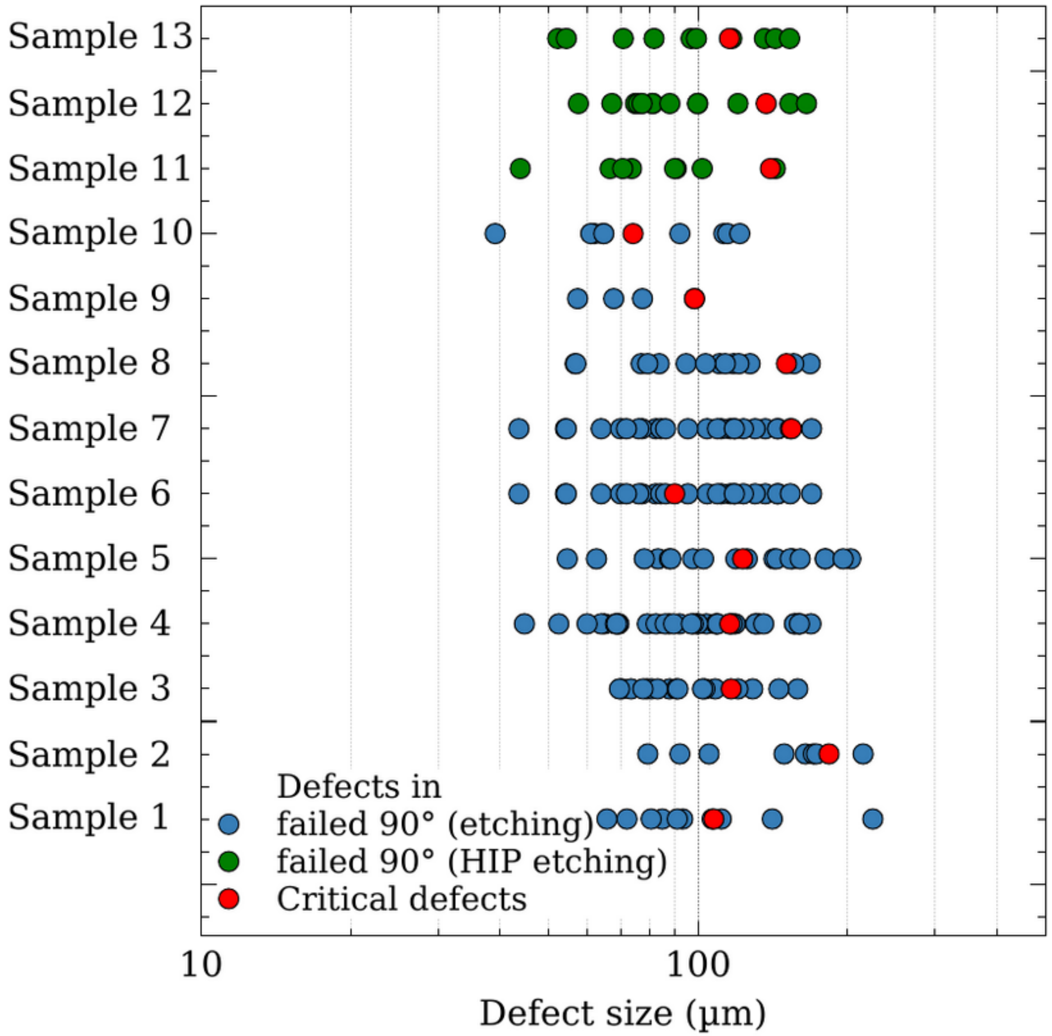
Crack initiation in AM materials

- “Killer” defect : **not** the largest (area)$^{1/2}$

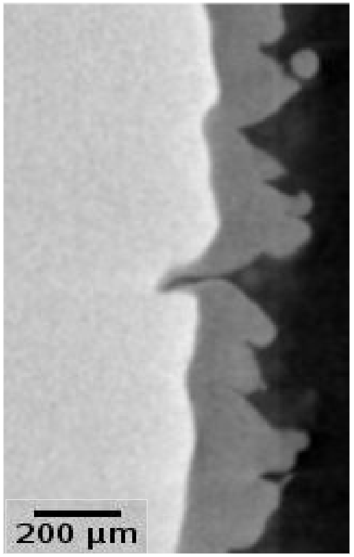


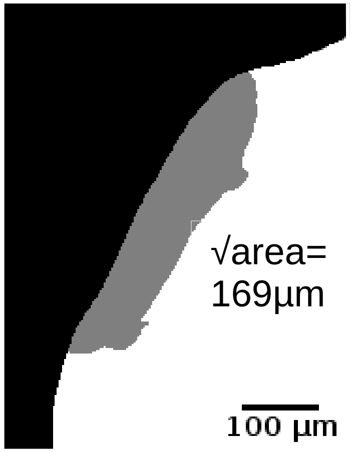
Crack initiation in AM materials

- “Killer” defect **not** the largest (area)$^{1/2}$



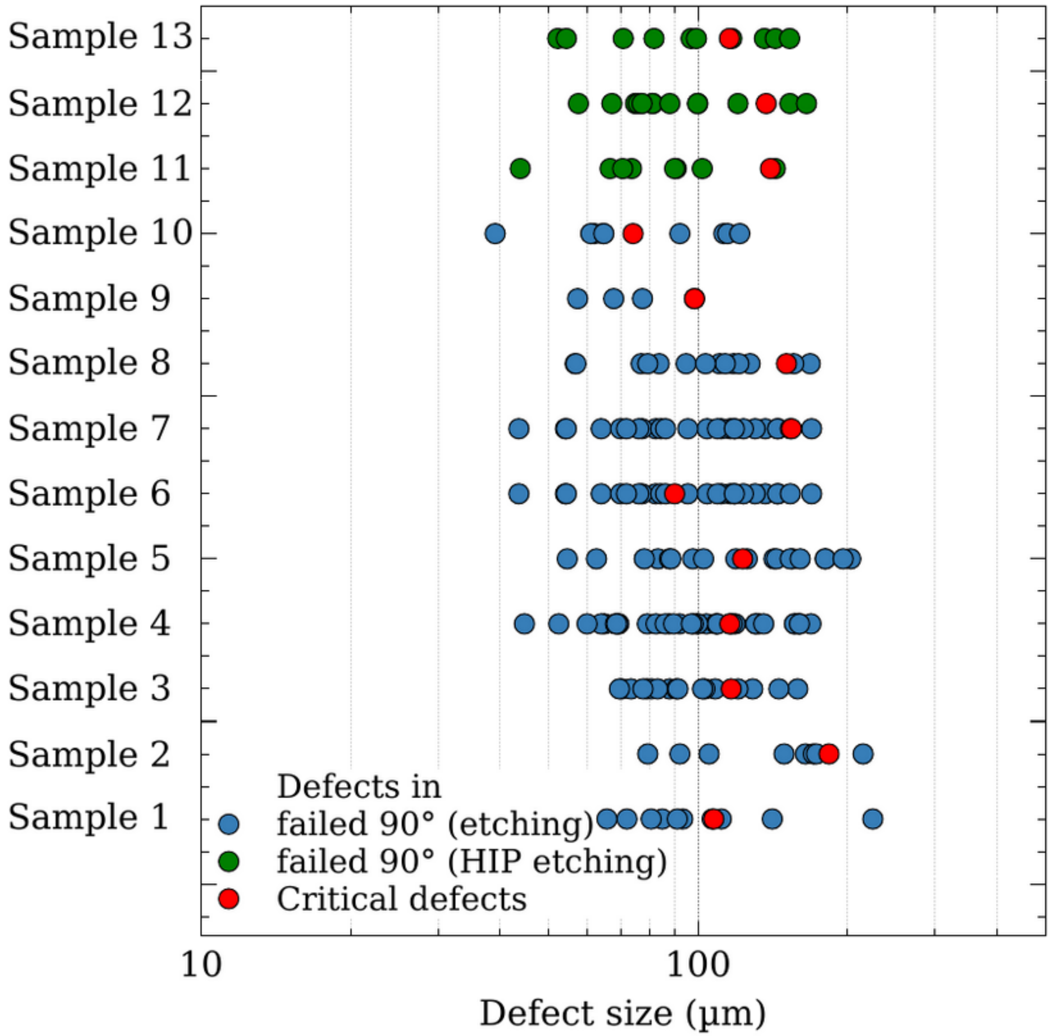
Largest defect

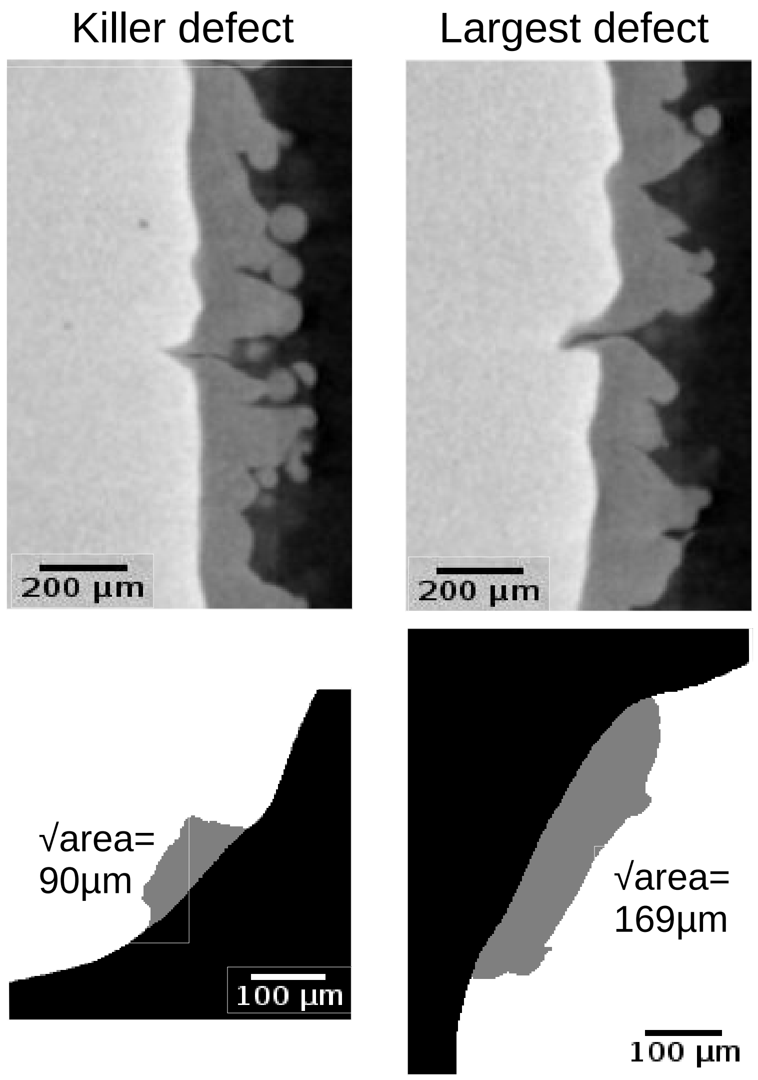




Crack initiation in AM materials

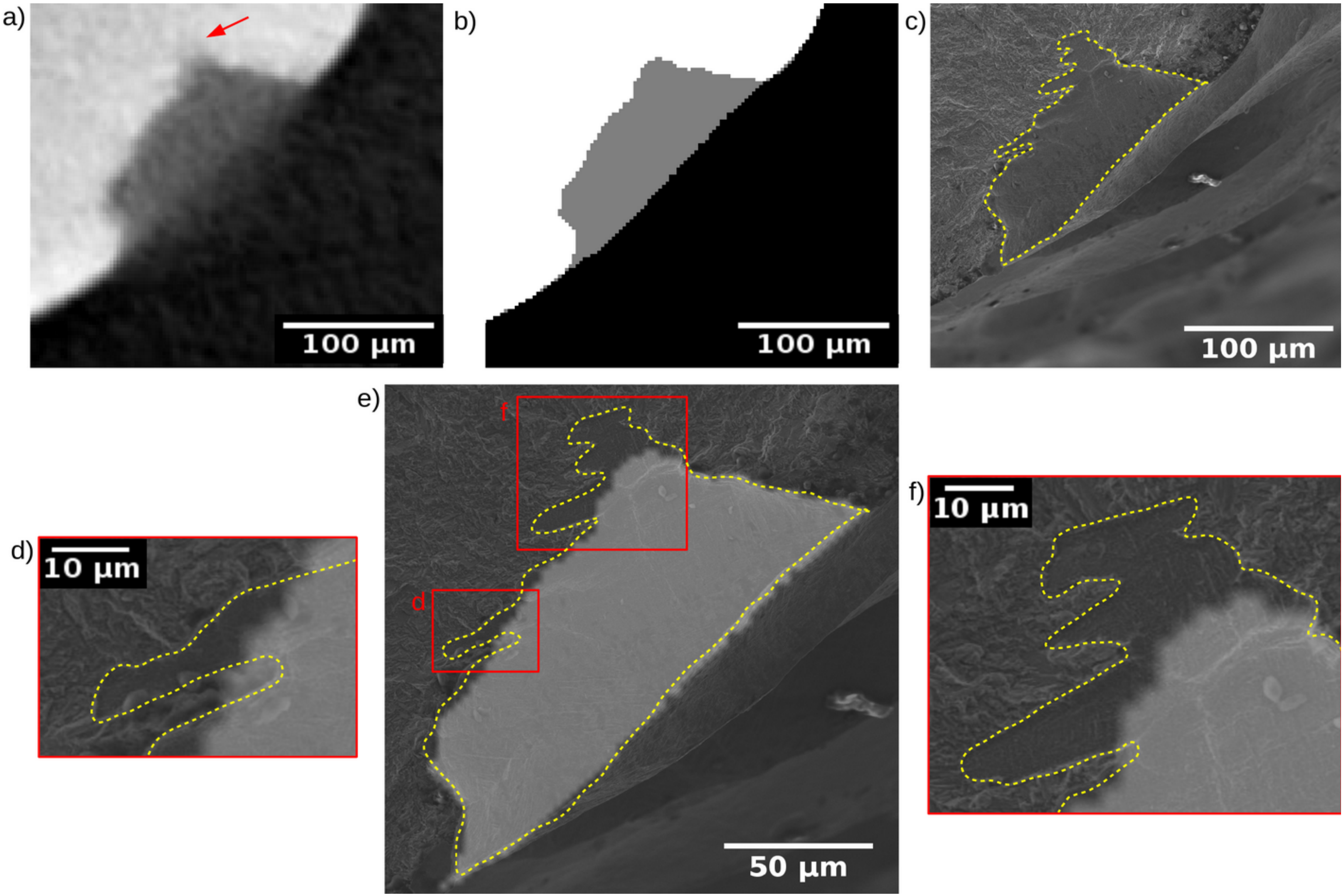
- “Killer” defect **not** the largest (area)$^{1/2}$





Crack initiation in AM materials

- Deep very thin defects are truncated by tomography



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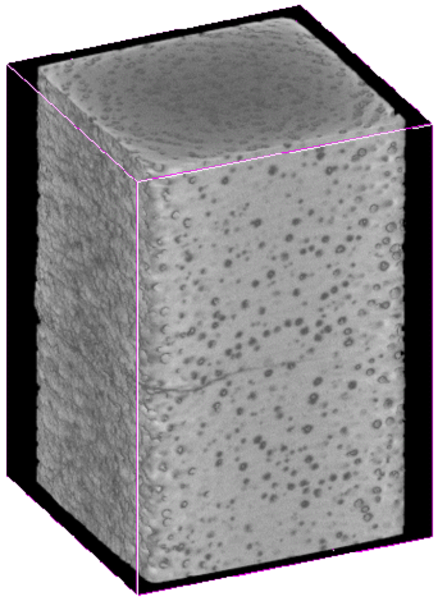
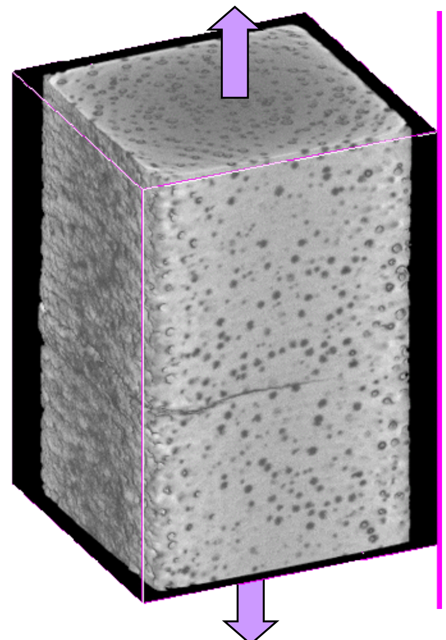
Improving crack detection: DVC



Reference f(**x**)



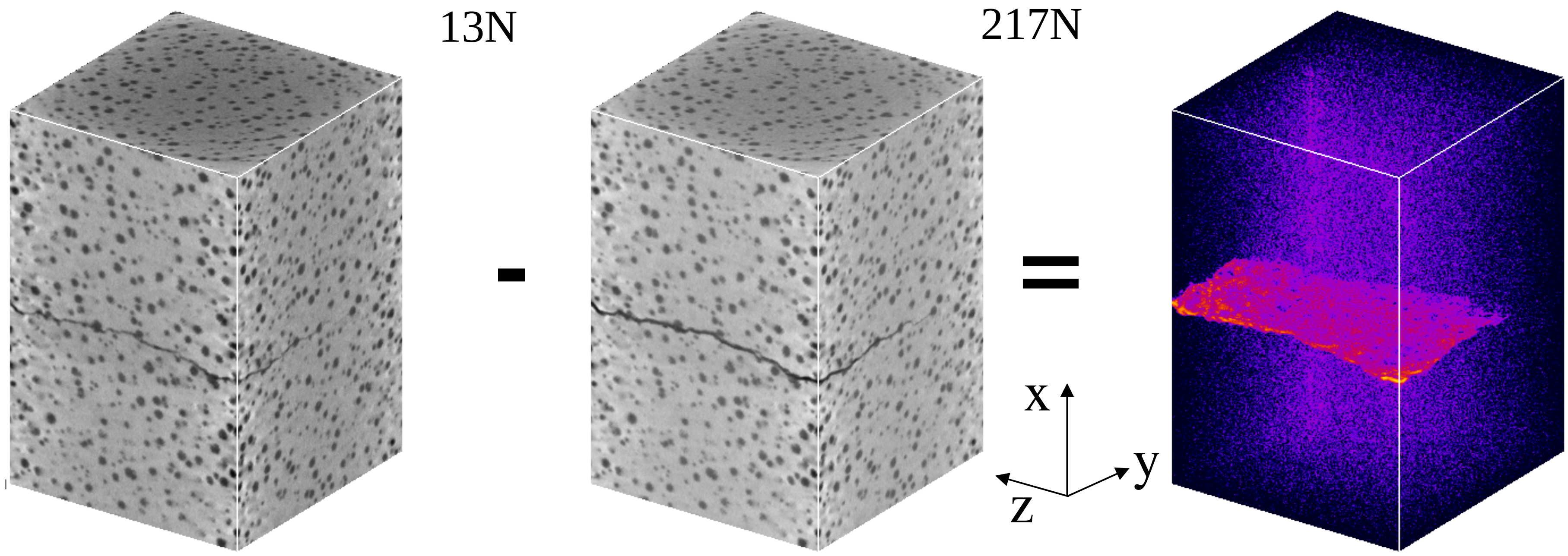
Deformed g(**x**)

•Two images of the specimen in reference state and in deformed state:

$$f(\mathbf{x})=g(\mathbf{x}-\mathbf{u}) \quad \textit{optical flow conservation}$$

•From the knowledge of f and g, the problem consists in estimating **u** as accurately as possible

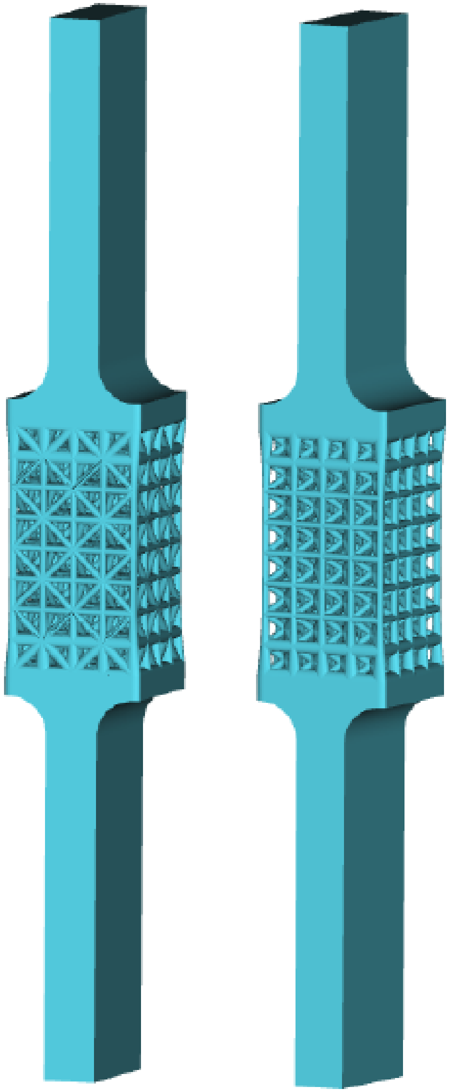
Improving crack detection: DVC

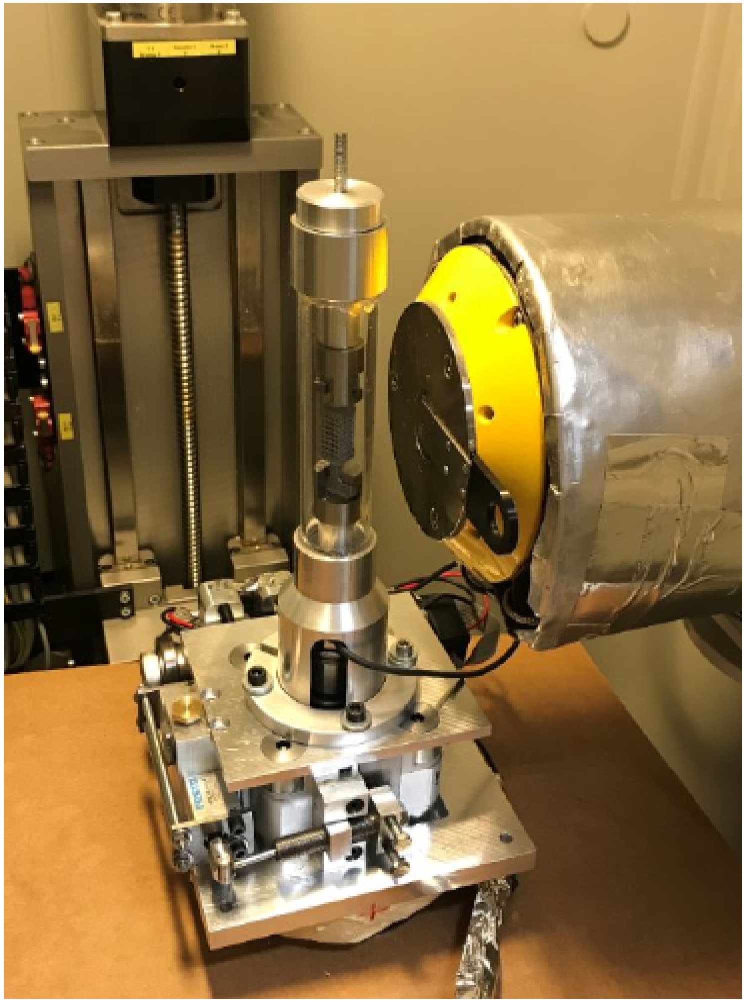


Ref. image f(**x**)   Corrected image g(**x**-**u**)   Residual error

Example on additive manufacturing materials

Lattice structures (AlSi10Mg alloy)





Coll. L Boniotti S.Foletti and S.Beretta

POLITECNICO MILANO 1863

- “large” voxel size to image the sample :8 µm

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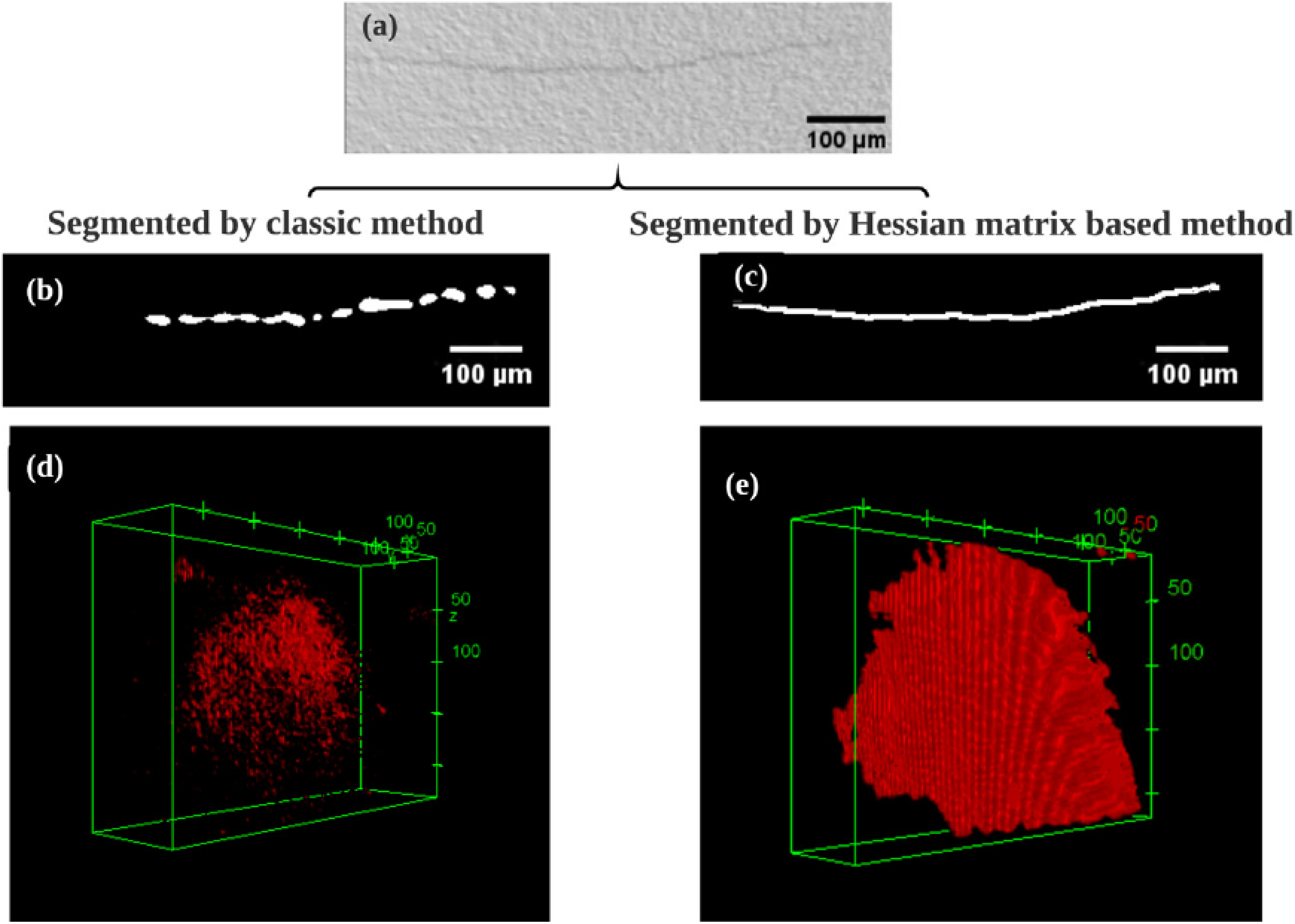
Conclusion

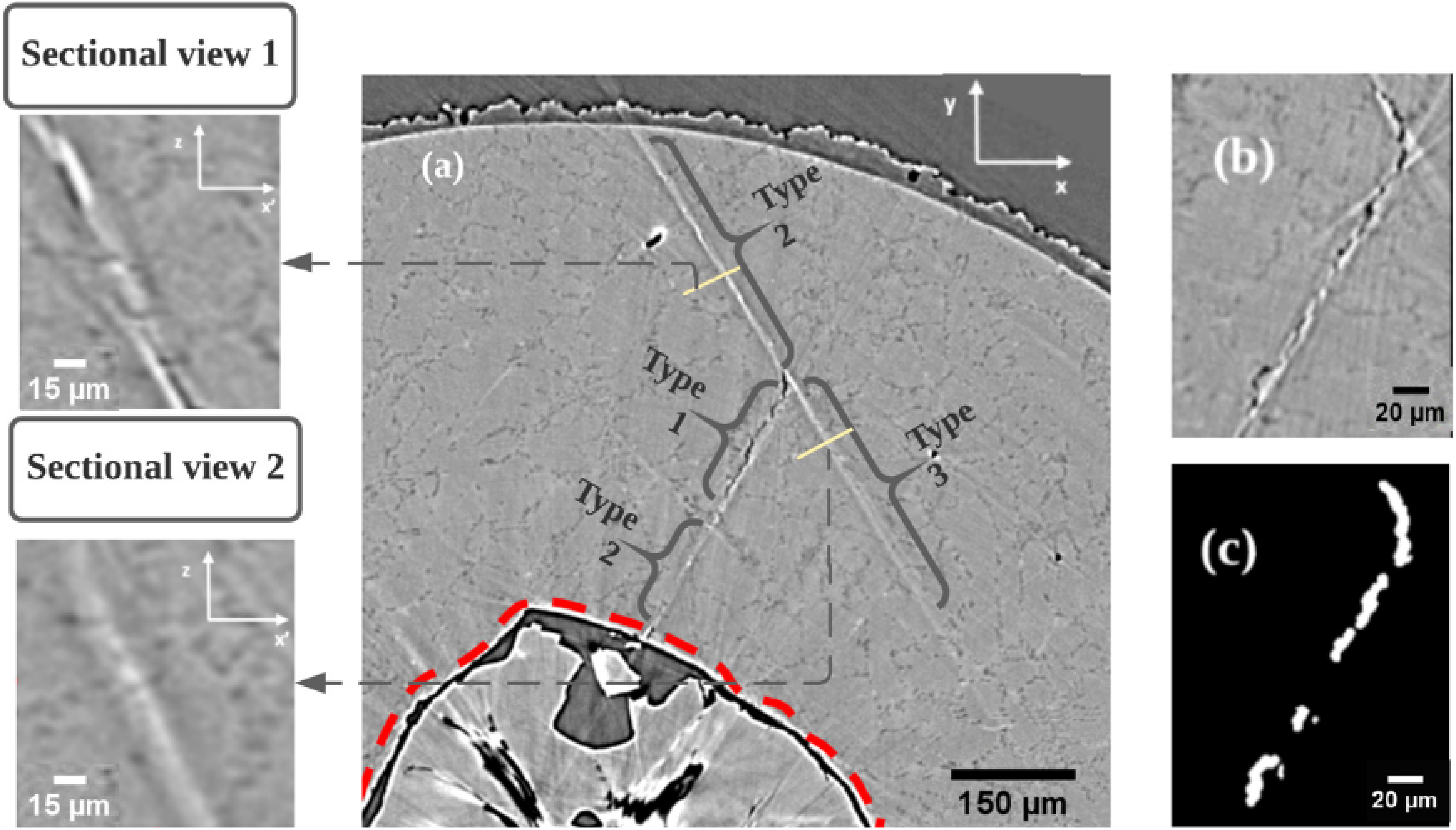
- X-ray tomography: a unique tool for studying damage during mechanical loading
- 3D images are key to test/validate models
- Can be used with various types of models
- Very often FE (in the field of damage studies)
- Going from the grey level image to meshes is crucial
- High spatial resolution: always good but complementary techniques can help!

Limits



C.Xiao, J-Y Buffiere *Eng. Frac. Mech.* 2021

Limits



- Synchrotron tomography: gray level not straightforward → requires user judgment !
- Solution Artificial Intelligence

C.Xiao, J-Y Buffiere *Eng. Frac. Mech.* 2021