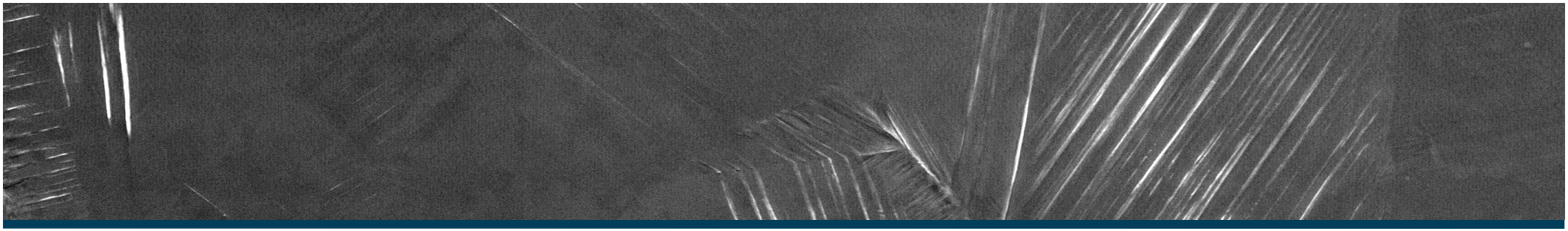
Additive Manufacturing: Microstructures, Structures and Properties

Application to fatigue

Eric Charkaluk

Laboratoire de Mécanique des Solides - UMR 7649
CNRS - Ecole Polytechnique

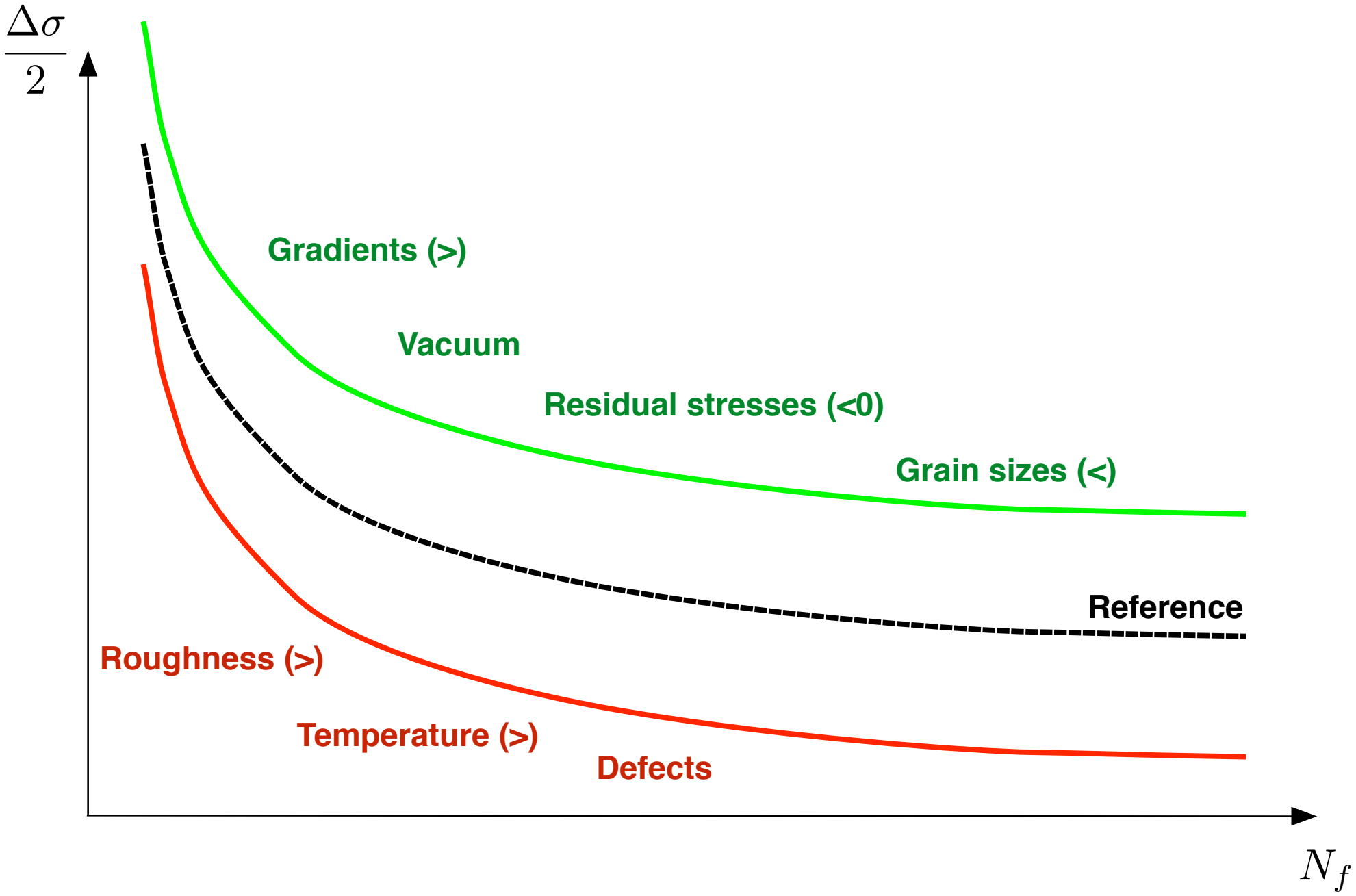


PhD works: Shadan Tabibian, Victor Chastand, Nora Dahdah, Yanis Balit

Outline

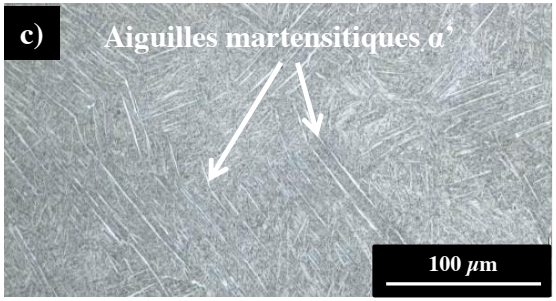
- Fatigue and Additive Manufacturing:
  - Fatigue : lifetime, crack initiation mechanisms
  - Some specificities of AM (micro)structures
- Fatigue of Ti-6Al-4V alloy produced by EBM and SLM
  - Effects of some process parameters
  - Crack initiation mechanisms
- What can we learn from other processes:
  - Some lessons from casting process
- Conclusions and prospects

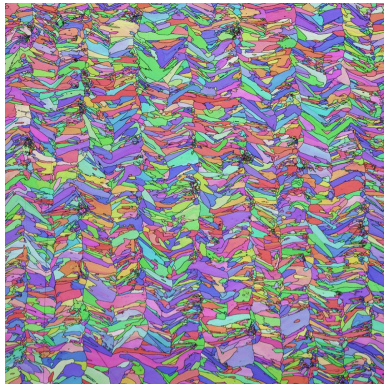
Fatigue of metallic structures: some effects on lifetime

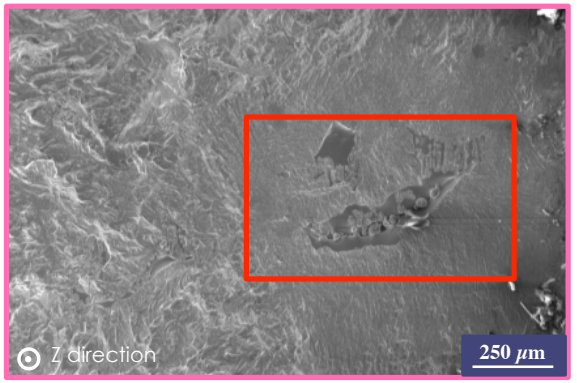


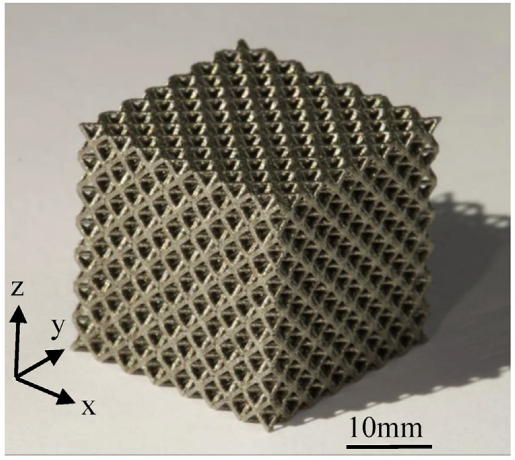
Additive Manufacturing specificities

- Materials in AM:
  - fast solidification (martensite, ...)
  - microstructure: anisotropy, gradients, ...
  - multimaterials, interfaces, HAZ, ...
  - defects: roughness, porosities, unmelted zones, ...
- & Structures in AM:
  - lattices, ...
  - residual stresses, ...
  - instabilities, buckling, ...
  - thin structures, …





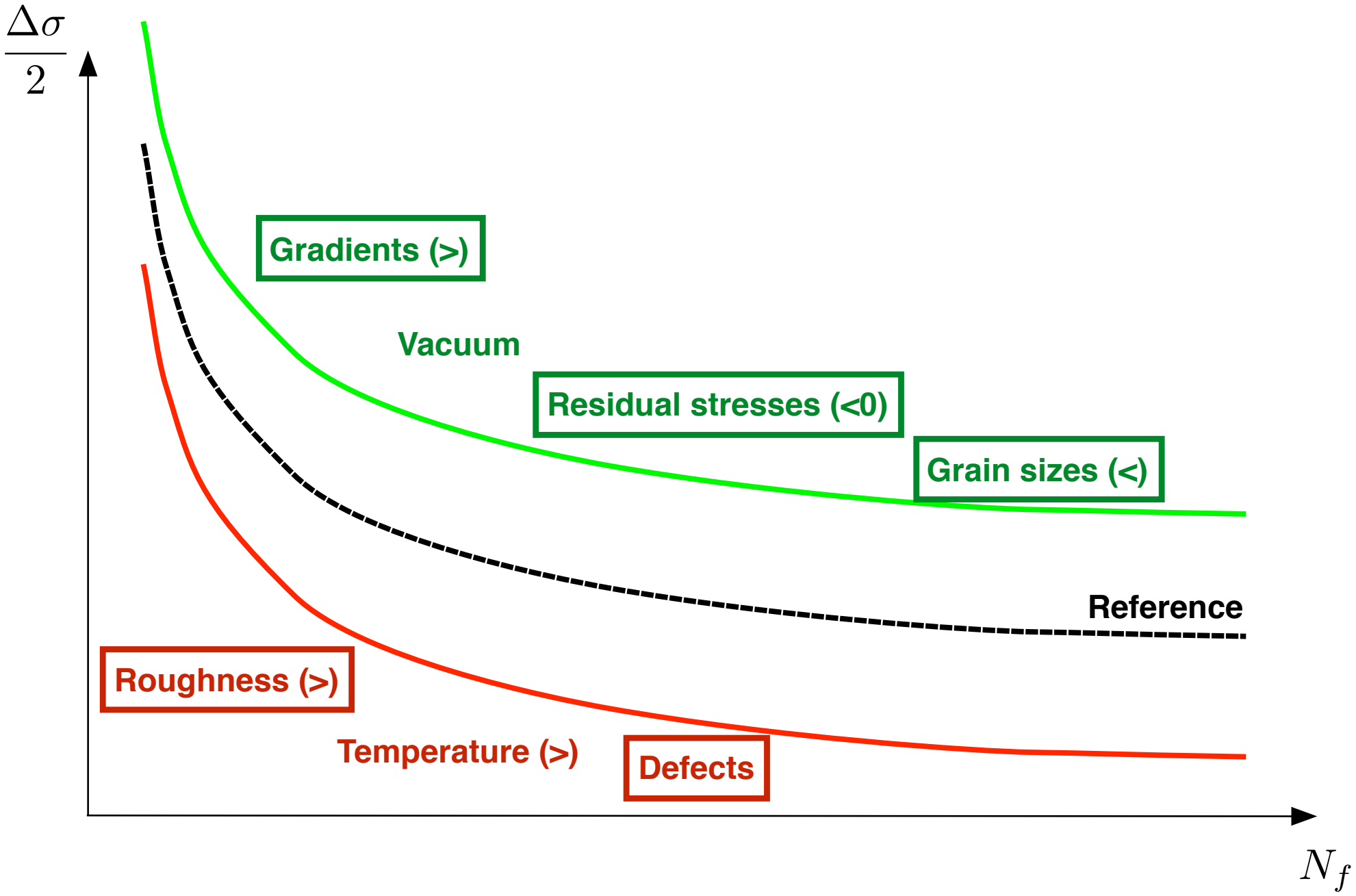




Additive Manufacturing and Fatigue: some key parameters

- Building parameters:
  - laser power, laser / substrate speed, powder flow rate, …
- As-built specimens:
  - roughness
  - residual stresses
  - porosities
  - building direction
- Post-treatments:
  - machining, polishing
  - heat-treatment (residual stresses, grain size, precipitation, …)
  - HIP (porosities)

Fatigue of AM metallic structures



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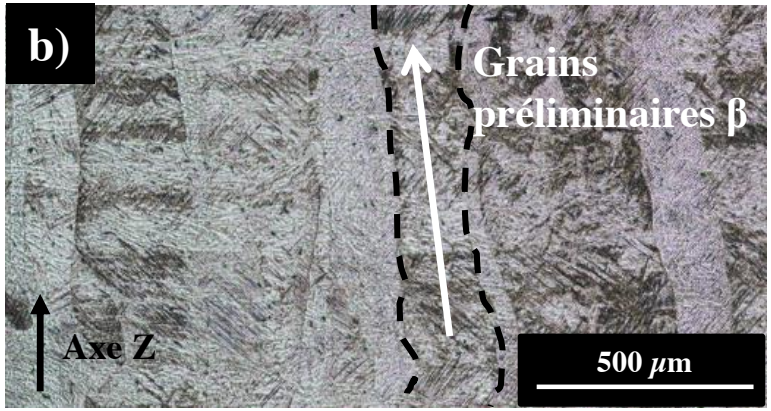
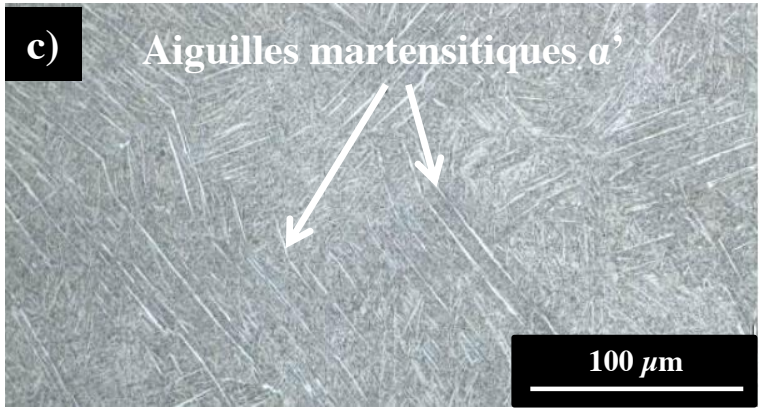
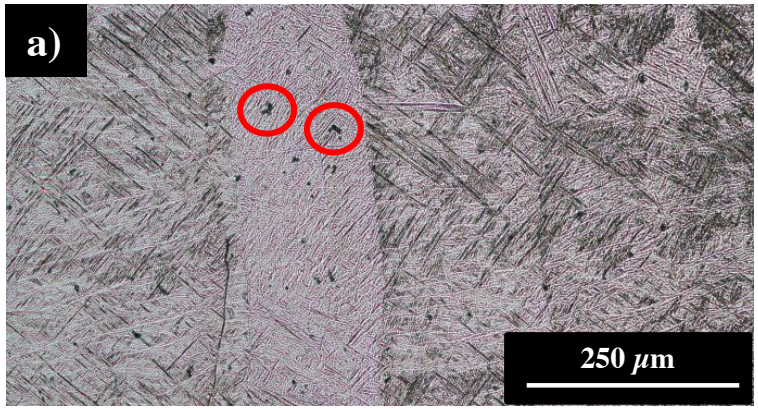
Ti-6Al-4V alloy produced by EBM and SLM

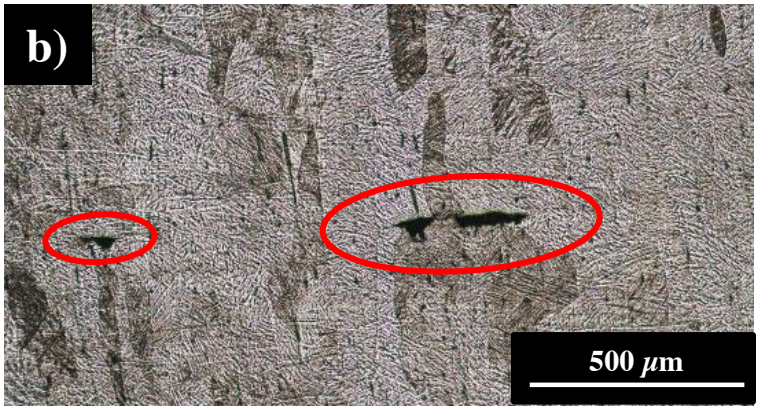
THALES

- EBM & SLM: Powder-bed additive manufacturing process
- Microstructure: polycrystal with pores



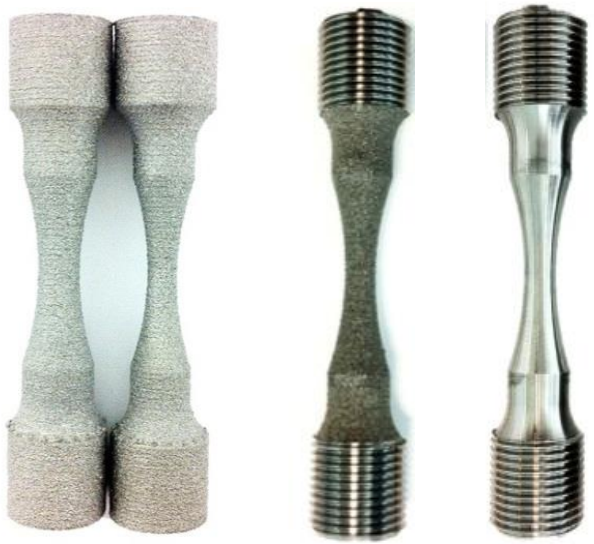




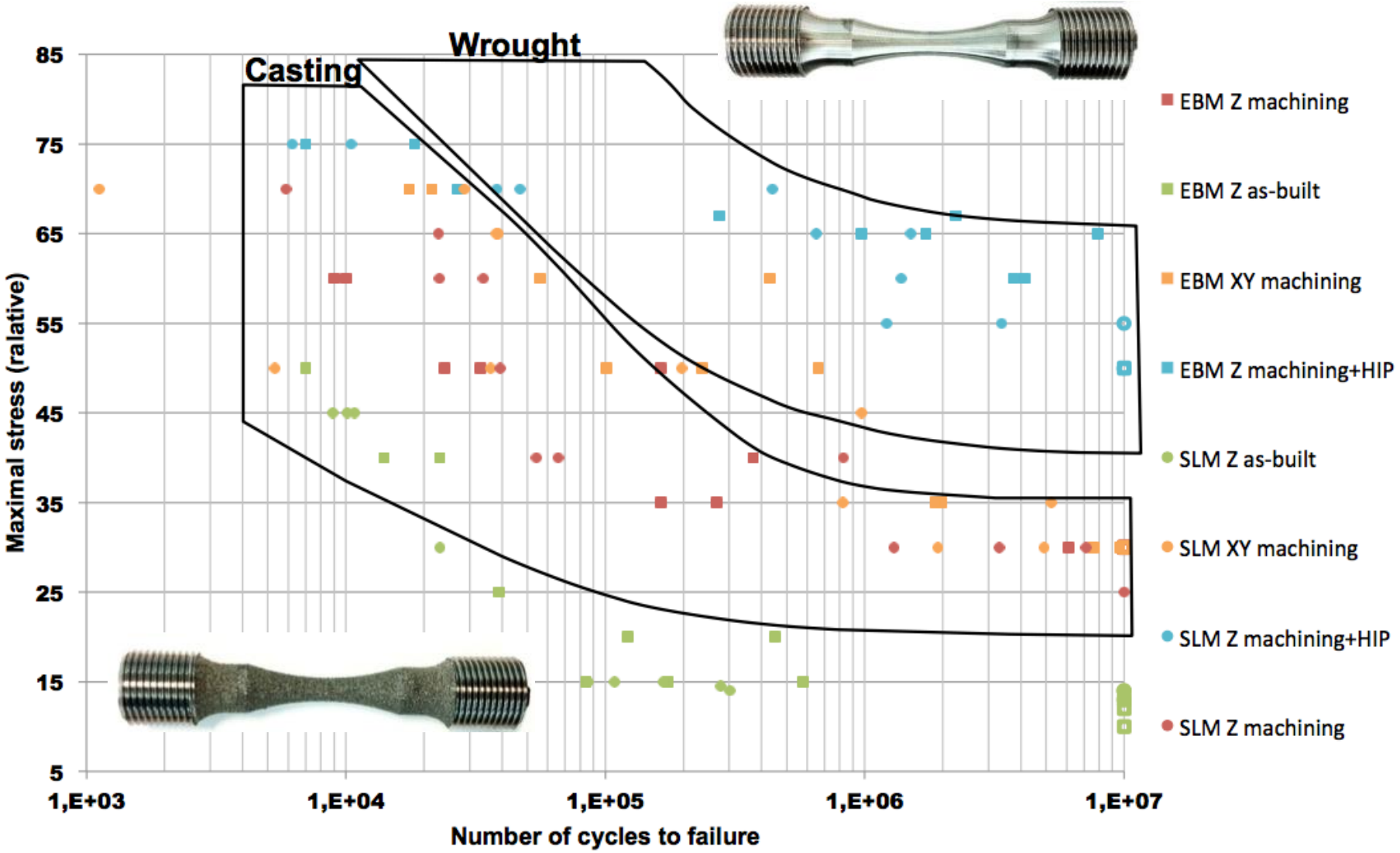


Ti-6Al-4V alloy produced by EBM and SLM

- Building parameters:
  - laser power, laser / substrate speed, powder flow rate, …
- **As-built** specimens:
  - roughness
  - residual stresses
  - porosities
  - **building direction** (XY et Z)
- Post-treatments:
  - **machining, polishing**
  - heat-treatment (residual stresses, grain size, precipitation, …)
  - **HIP (porosities)**



Fatigue tests results



[Li et al. (2016) *IJF*]

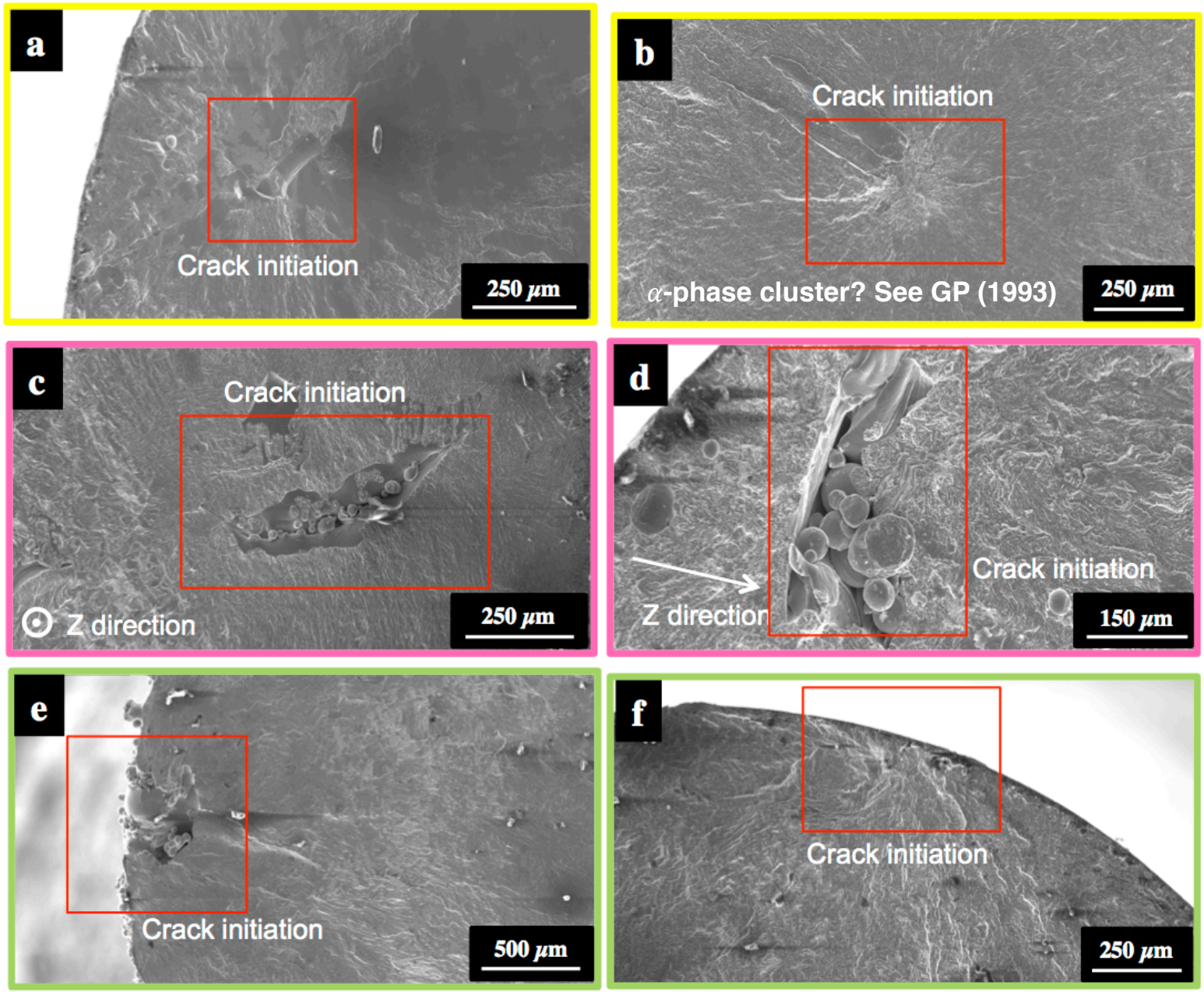
[Chastand et al. (2018) *Mat. Char., in press*]

Crack initiation mechanisms and « defects »

Small internal defects

Unmelted zones

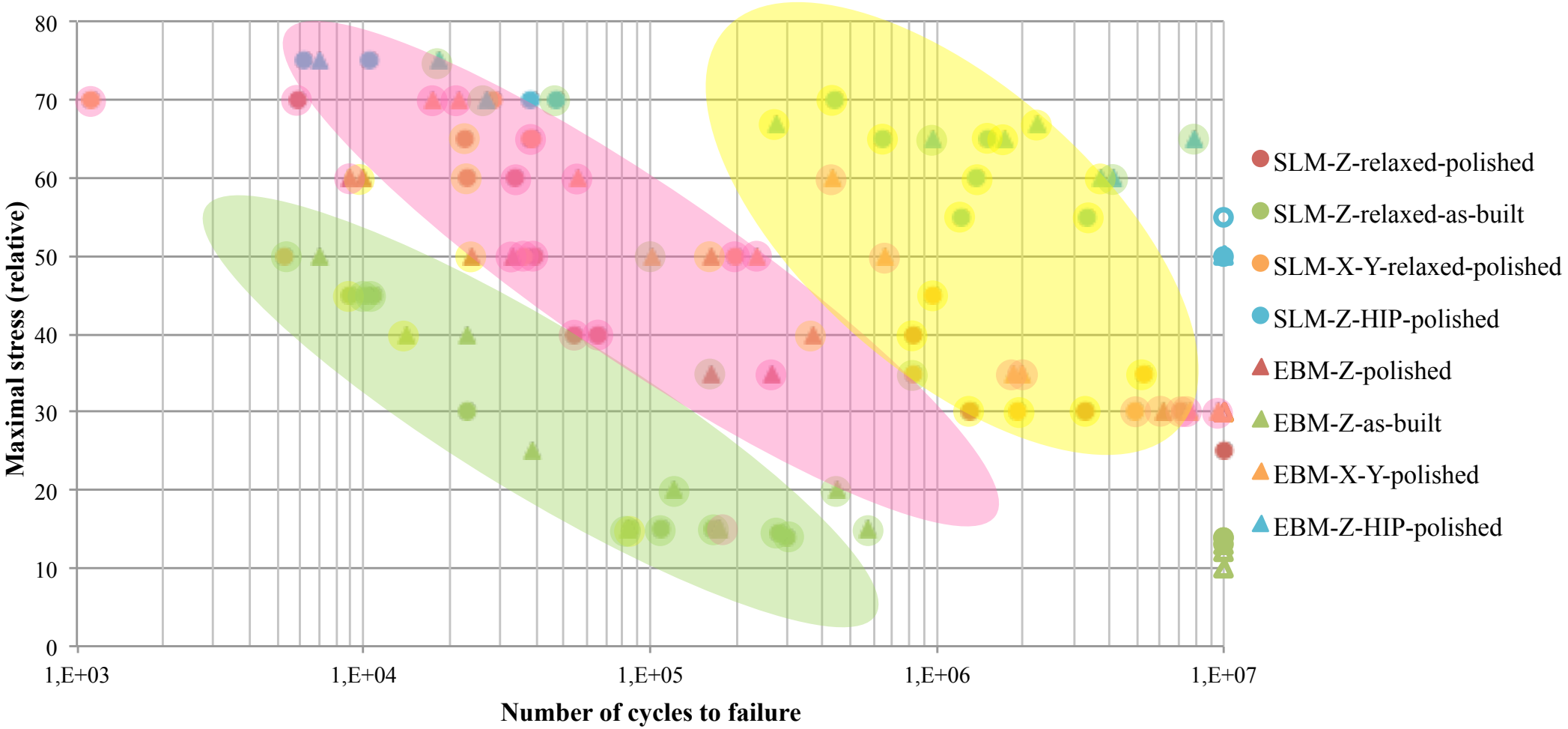
Surface defects



[Gilbert and Piehler (1993) *Met Trans*]

Critical defects

- Surface defects > Unmelted zones > Small internal defects

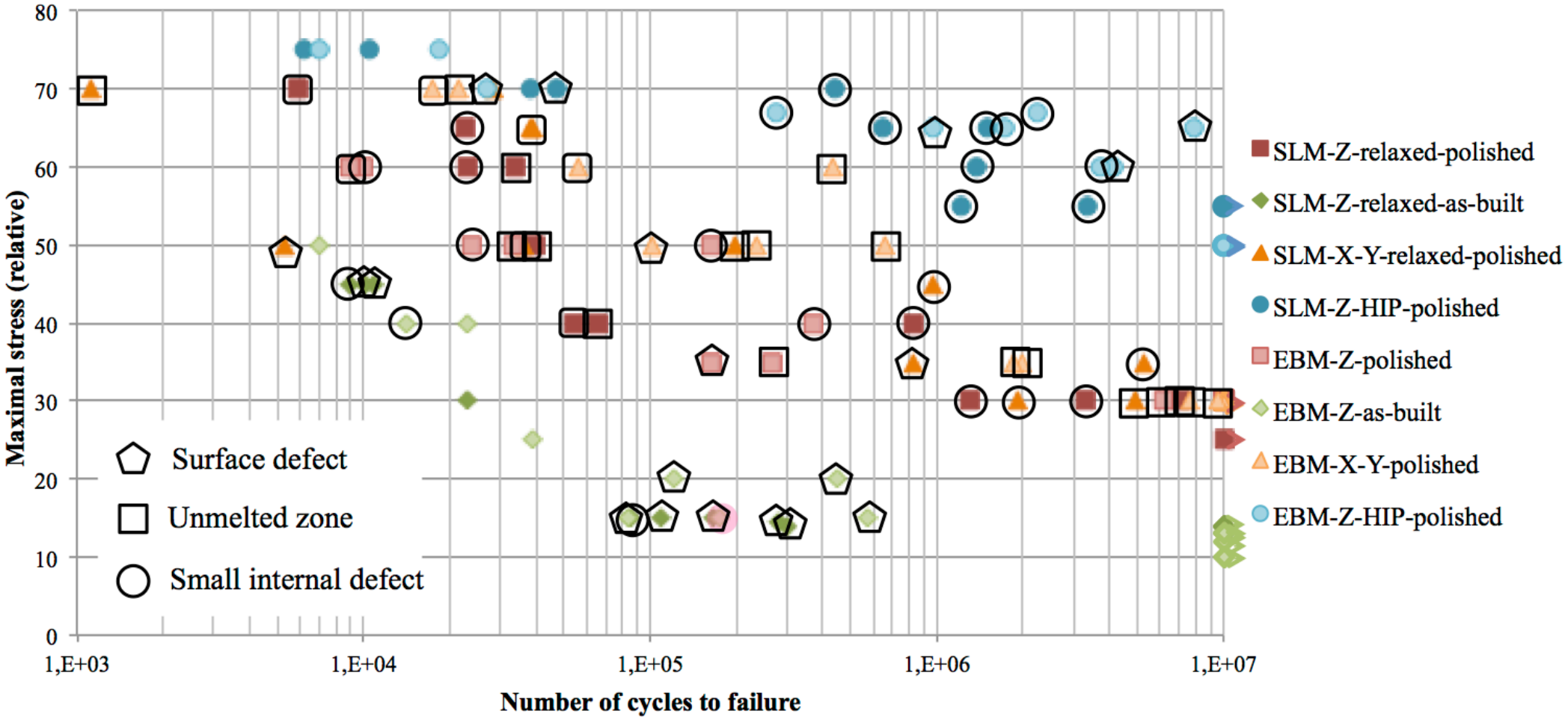


[Gunther et al. (2017) *IJF*]

[Chastand et al. (2018) *Mat. Char., in press*]

Critical defects

- Surface defects > Unmelted zones > Porosities



[Chastand et al. (2018) *Mat. Char., in press*]

Critical defects

- Surface defects > Unmelted zones > Porosities

	Surface	Internal unmelted zones	Small internal defects
As-built	**10**	0	3
XY and Z polished	4	**25**	12
HIP-polished	5	0	**10**

[Chastand et al. (2018) *Mat. Char., in press*]

Fatigue of Ti-6Al-4V alloy produced by EBM and SLM

- Pores:
  - size
  - shape : « porosities » vs « unmelted zones »
- and position regarding:
  - the surface : « surface defects »
  - the other pores (cluster)

- Crack initiation and propagation at the microstructure scale?
- What can we learn from other processes?

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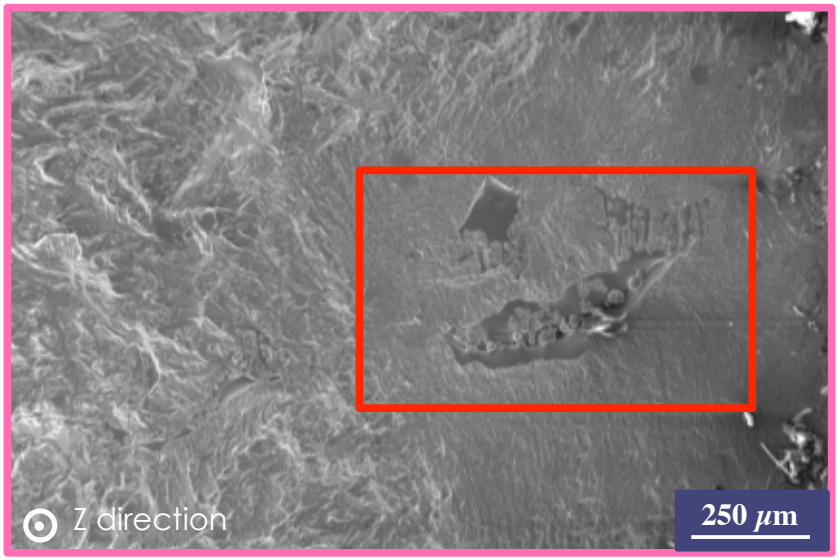
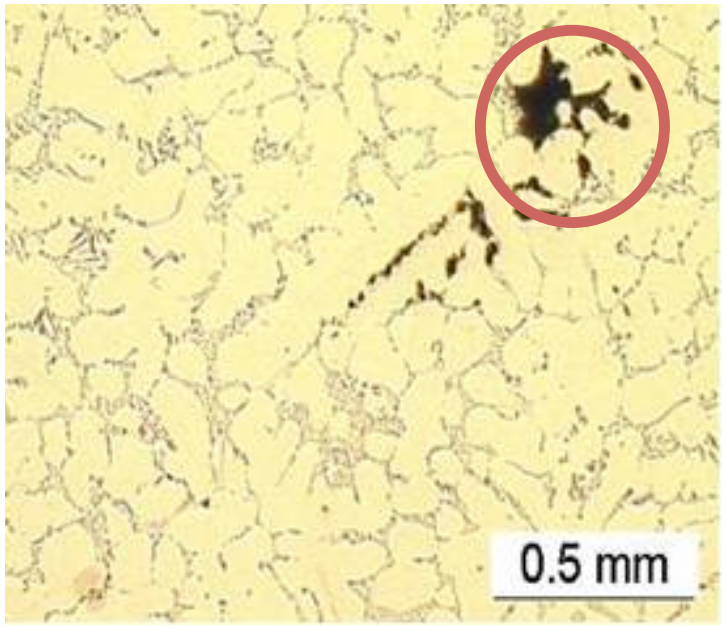
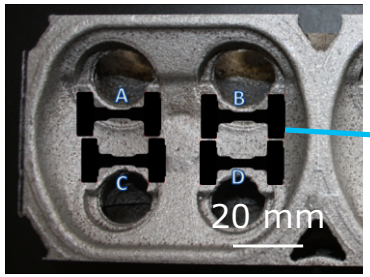
Some lessons from casting process

- Casting process / Additive Manufacturing : similarities
  - Solidification microstructures (but at different rates: AM > Casting)
  - Grains and porosities
  - Residual stresses (thermal gradients)
  - « Shrinking » vs « Unmelted zones »

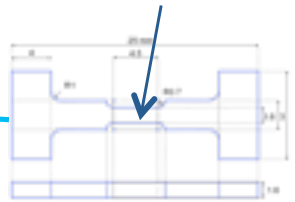


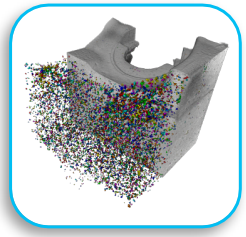


Fatigue of cast aluminum alloys: in-situ tests



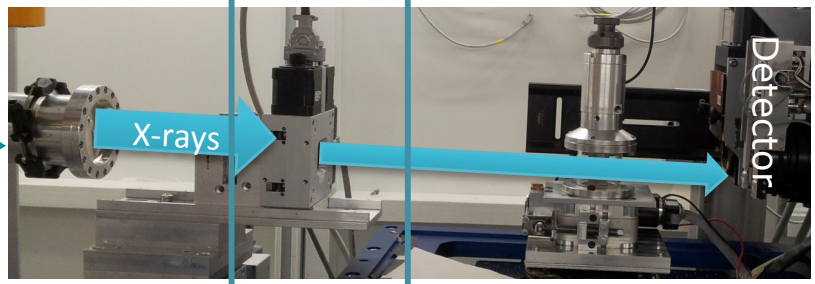
~2×2mm



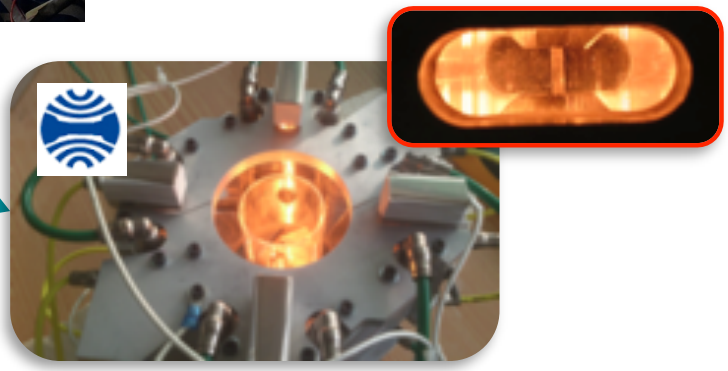


Representative specimens

At 20°C



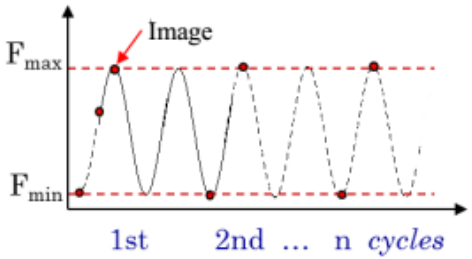
At 250°C



Halogen furnace

Loading conditions

- Displacement controlled
- Rσ=0.1 (tensile-tensile)
- Freq.=1Hz

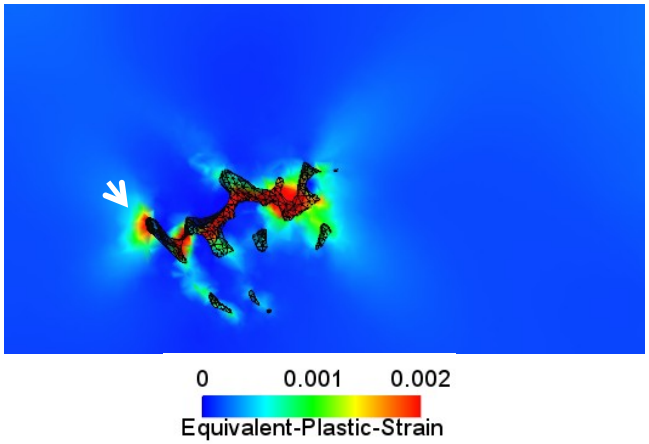


[Dezecot et al. (2016) *Scripta Mat.*]

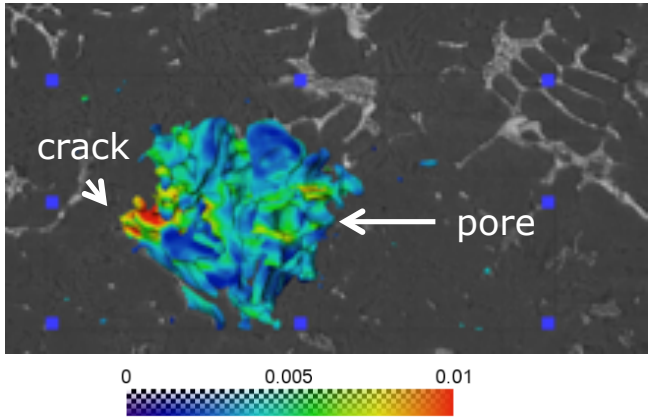
Crack initiation mechanisms: pores and shrinkage

- Crack initiation:
  - biggest pores or shrinkage, close to the surface, cluster effect
  - quite **similar as Additive Manufacturing**
  - CT-Tomography and in-situ tests in AM? **And crack growth?**

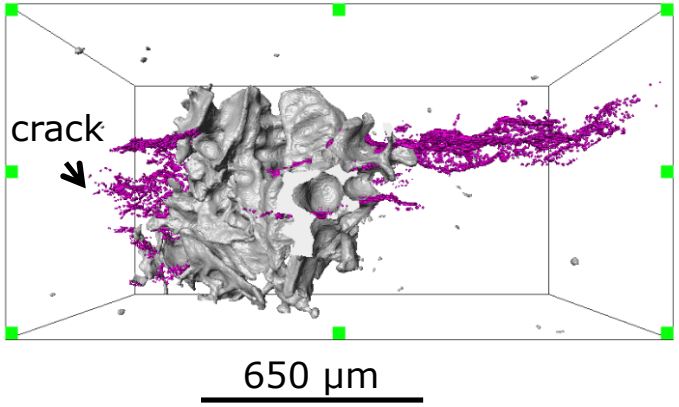
Elastoplastic FE computation



Tomographic slice and 3D rendering of Von Mises strain field after 2c.



3D rendering of Von Mises strain field and crack 2 after 10500c.



[Dahdah et al. (2016) *Strain*]

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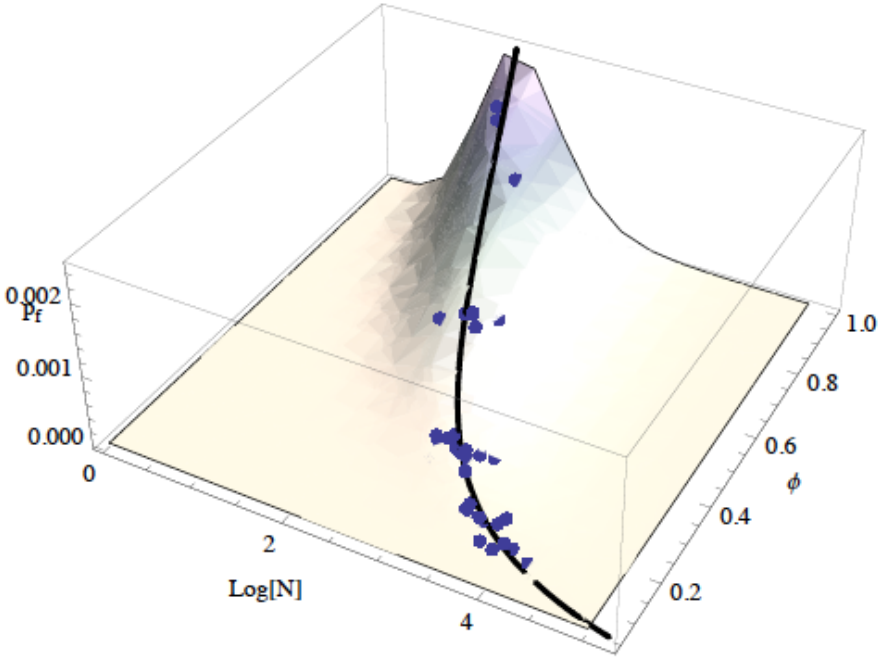
Conclusions

- Microstructure and damage:
  - **as-built structures not acceptable in fatigue:** post-treatments (roughness, residual stresses, porosities)
  - **damage depends on:**
    - geometrical gradient (notch effect)
    - building direction
    - microstructure gradient (surface / bulk)
    - residual stresses (or relieved)
    - distribution of size and shapes of pores or defects, location, cluster effect

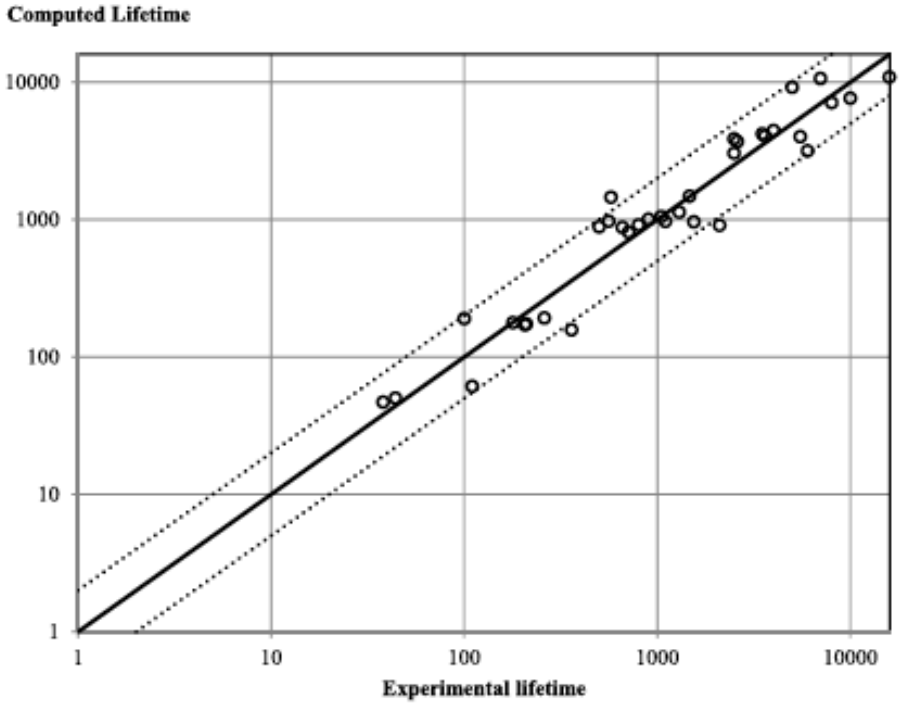
- Porosities: **probability** to find the **biggest** defect in the more critical zone

Prospects: towards probability of failure

- Failure probability:
  - Feret diameter or apogee of equivalent ellipse from porosities
  - Probability distribution: lognormal or exponential
  - Optimization method: maximum likehood or least-square minimization



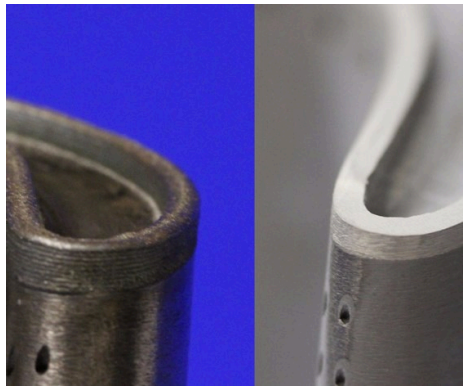
Failure probability



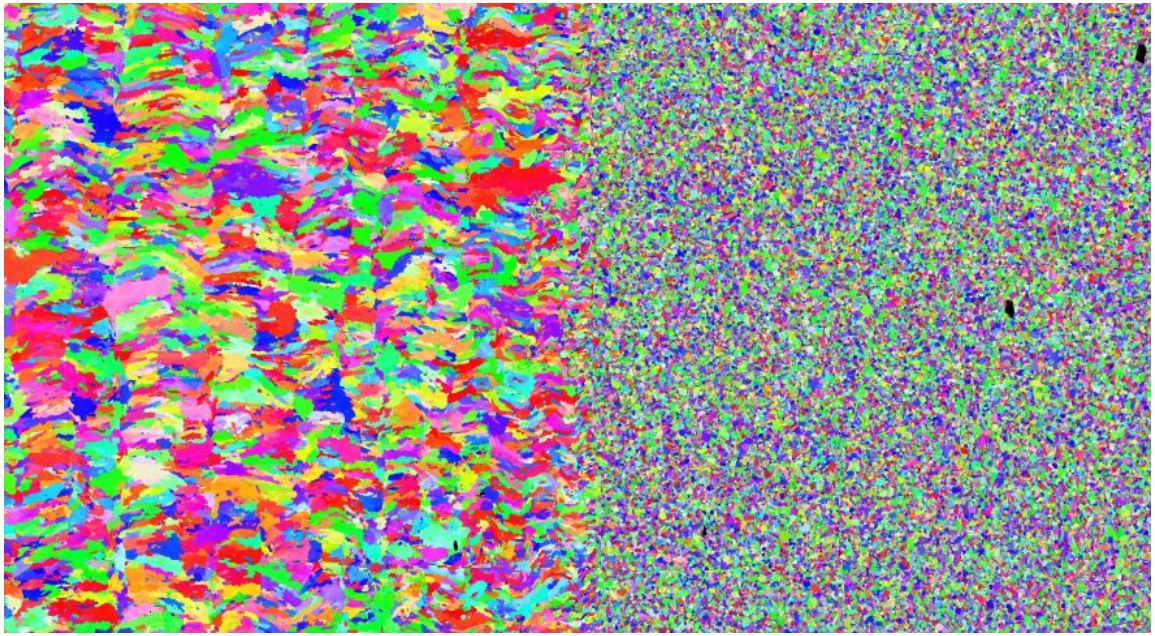
[Charkaluk et al. (2014) *Int. J. Fat.*]

Prospects: repaired structures, multi materials

- Multi-materials, repaired structures:
  - fatigue and **interfaces**?
  - fatigue with **gradient of microstructures**?
  - **fatigue tests**: specimen geometry? Loading?



https://www.mmsonline.com/

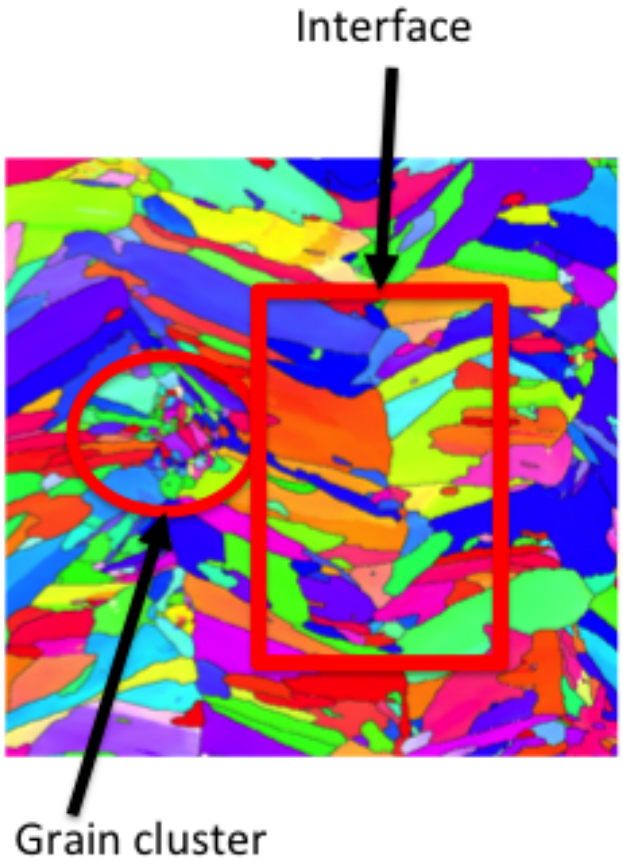


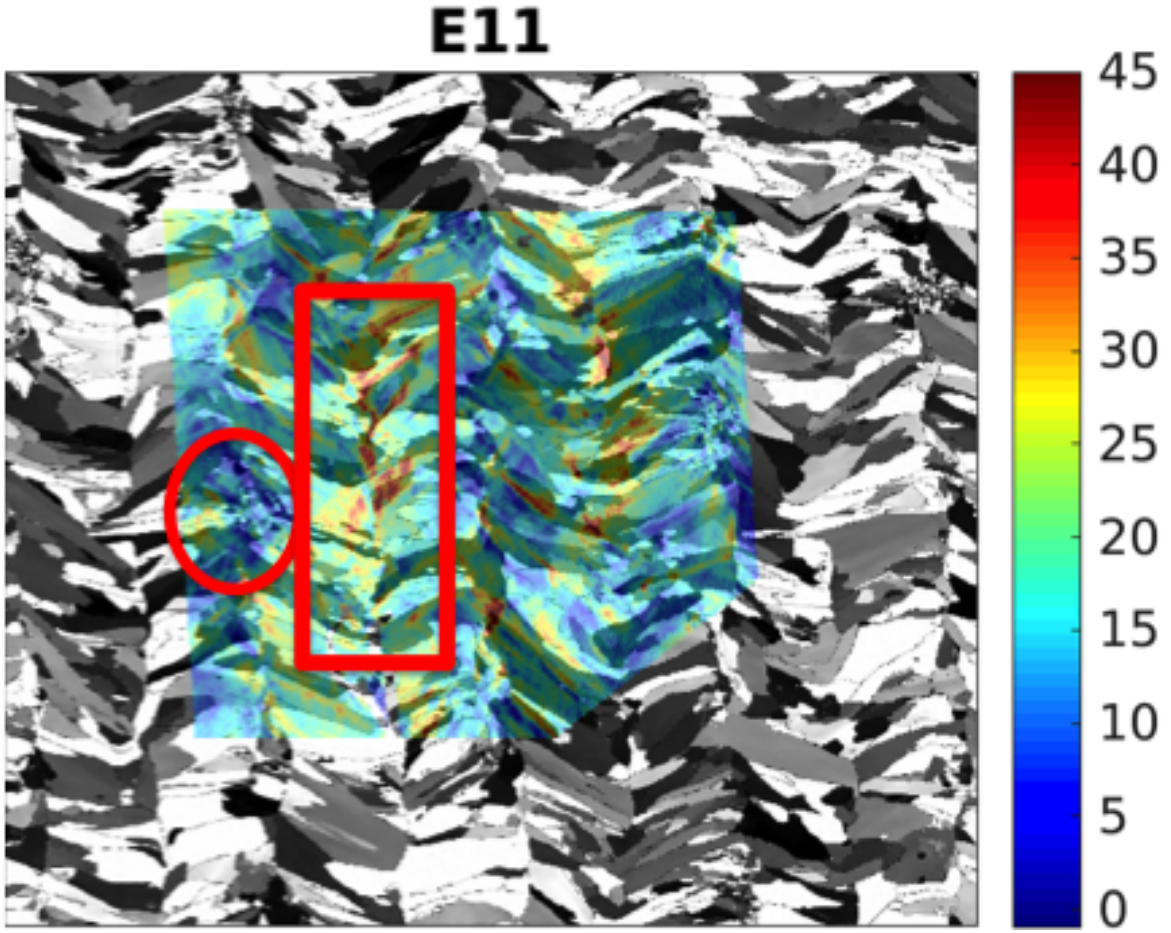
316L by Clad **Wrought 316L**

[PhD Y. Balit, under progress]

Prospects: repaired structures, multi materials

- From structure to **microstructure**

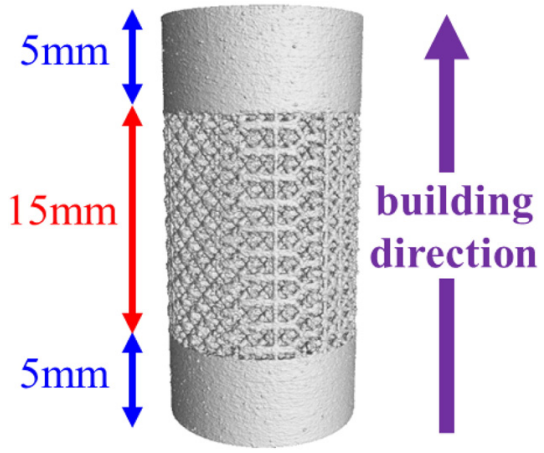




[Balit et al. (2018) *EMMC conference*]

Prospects: fatigue of lattices

- **Fatigue of lattices**: an open-problem!
  - Representative Elementary Volume?
  - Fatigue specimen and loadings?
  - Metrology (strains, stresses, …)
  - **Damage initiation and growth: instabilities?**



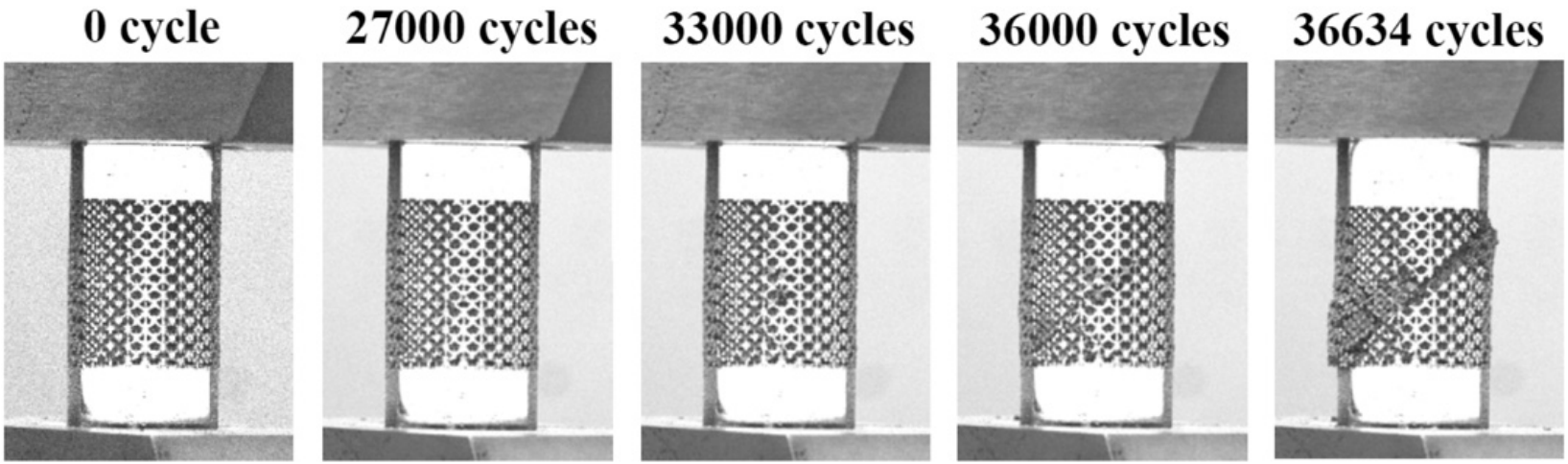
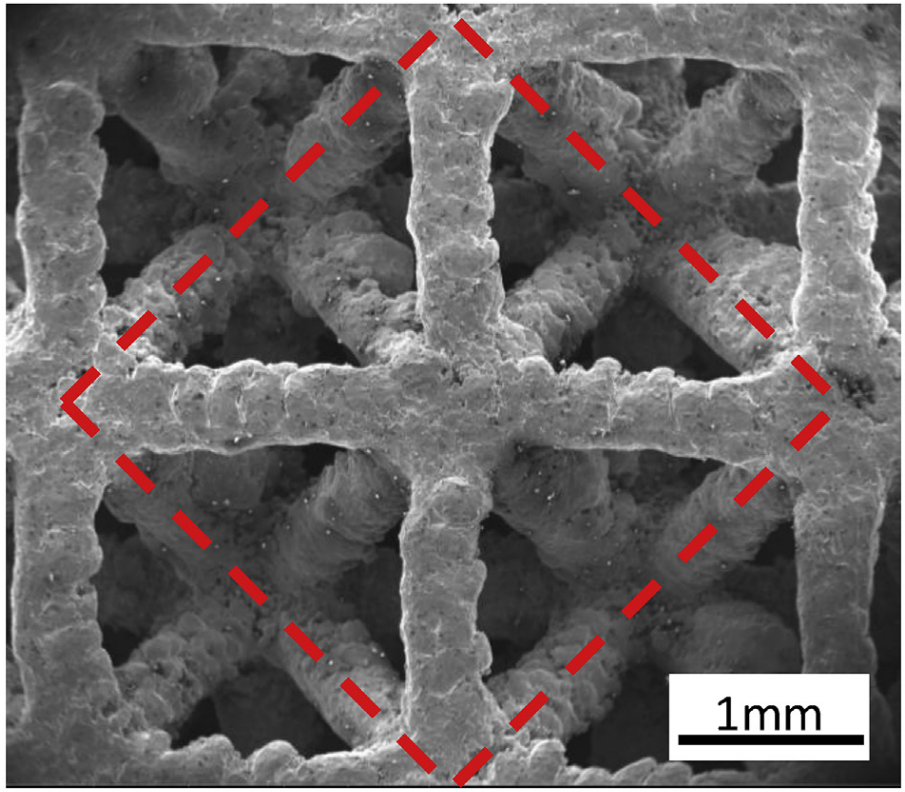


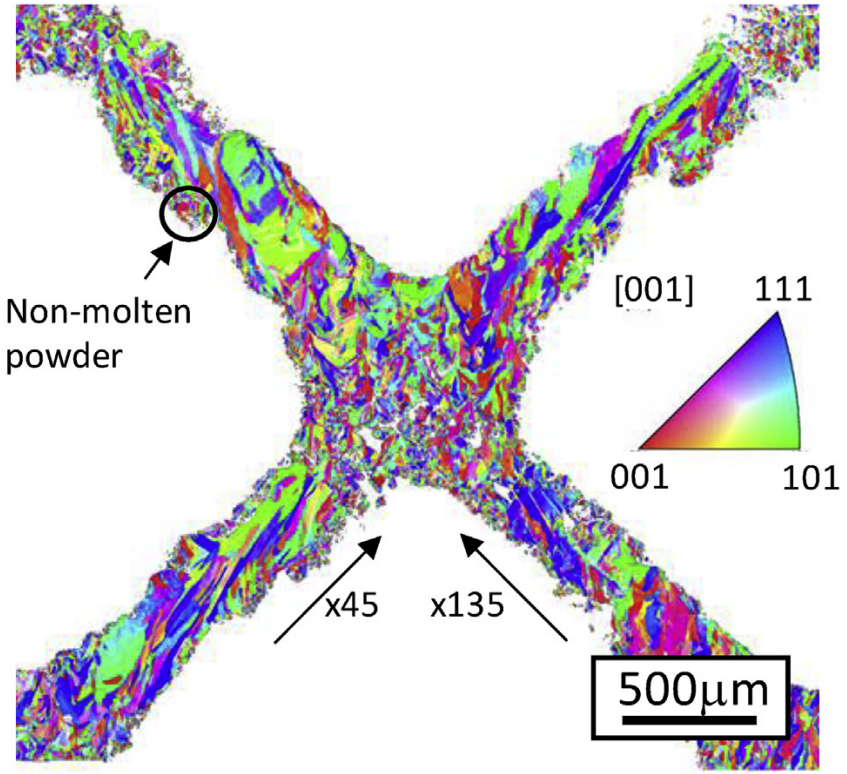
Fig. 7. The progress of fatigue failure in the SLM Ti-6Al-4V lattice under a maximum fatigue stress of 50% yield strength.

[Wu et al. (2017) *Mat Design*]

Prospects: fatigue of lattices

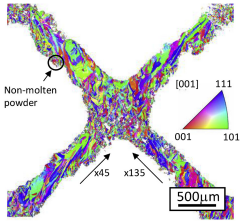
- **Fatigue of lattices**: an open-problem!
  - **Microstructure? Roughness?**





[Tancogne et al. (2016) *Acta Mat*]

Thank you for your attention



eric.charkaluk@polytechnique.edu