UNIVERSITÀ DEGLI STUDI
DI TRENTO

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Crack Paths (CP 2018)

# Crack path and notch fatigue strength of Ti-6Al-4V ELI additively manufactured via selective laser melting: Defect sensitivity

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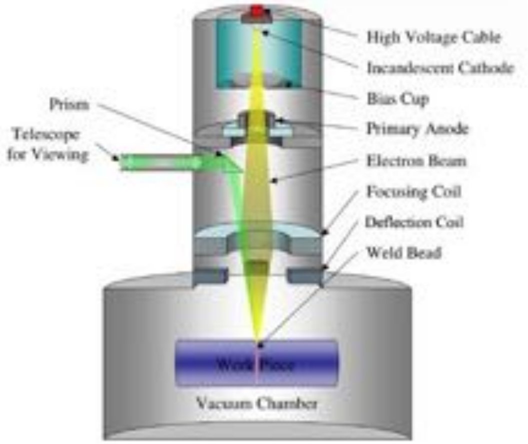
# Introduction

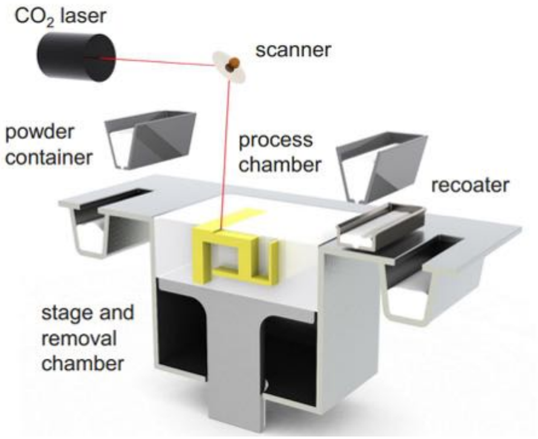
## *Additive manufacturing of metal parts*

- Net-shape production technologies
- Solid object from the sequential superposition of layers.
- The most common AM processes for metals are selective laser melting (SLM) and electron beam melting (EBM).

EBM



SLM

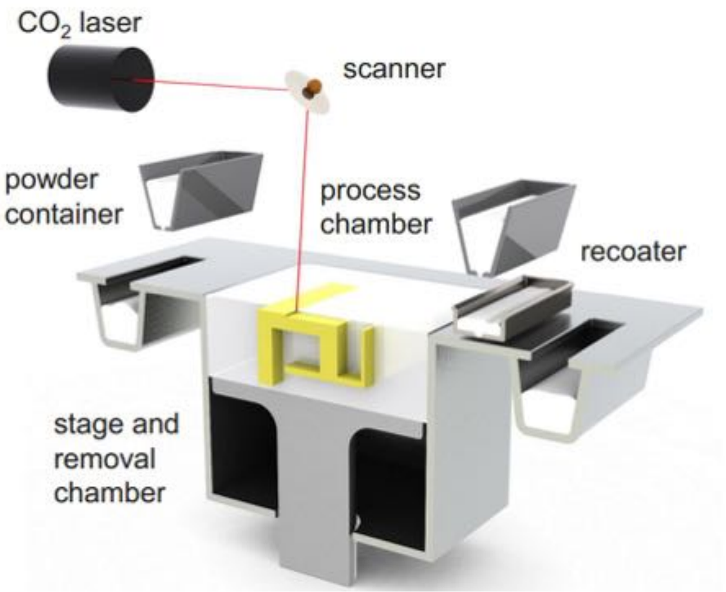


- SLM is well suited to additively manufacture small-to-medium amounts of parts with moderate-to-high surface finish.

# Introduction

## *The SLM process*

- From a rapid prototyping technique to a rapid manufacturing process.
- It can be applied to many different powders but for many mechanical and biomedical applications the most interesting materials are Ti-6Al-4V (Grade 5) and Ti-6Al4V ELI (Grade 23).



Defects in SLM components that can affect the fatigue life:

✓ Residual stresses due to the melting and solidification process

✓ Internal porosity

✓ Surface roughness due to the presence of partially sintered particles

✓ Oxide layer that can be formed during the stress relief heat treatment

# Introduction

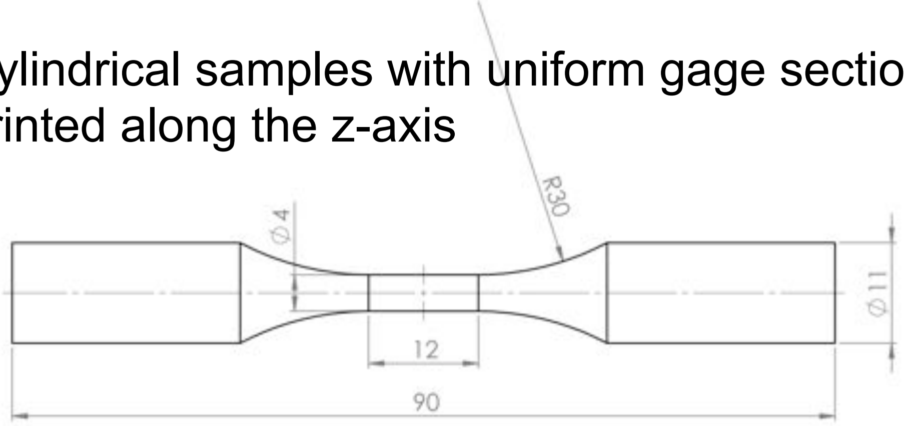
## *Aim and motivation*

- Investigation of the fatigue properties of the biomedical Ti Grade 23 manufactured via SLM.
- Quantitative assessment of the effect of selected post processing treatments on the fatigue response.
- Fatigue tests carried out at different *R*-ratios and microstructural conditions.
- Material characterization complemented with computed tomography (CT) scans, metallographic and fractographic analyses.
- Analysis of **defect sensitivity**.
- **Notch effect and defects: is TCD a viable fatigue calculation approach?**

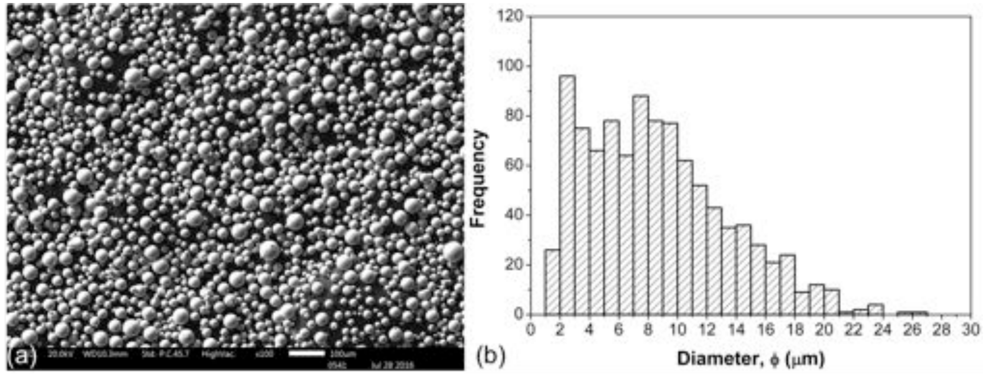
# Experimental material and procedures

## *Specimens preparation*

Cylindrical samples with uniform gage section printed along the z-axis



Atomized powder of biomedical Titanium Grade 23



Mean powder diameter: ≈9 μm

| 3D System ProX DMP 300 | |
|---|---|
| Build Envelope Capacity | 250 x 250 x 300 mm |
| Layer thikness | 5 ÷ 100 μm |
| Repeatibility | x = y = z = 20 μm |
| Min. feature size | x = 100 μm, y = 100 μm, z = 20 μm |
| Min. wall thickness | 150 μm |
| Accuracy | ± 0,1%-0,2% with ± 50 μm |

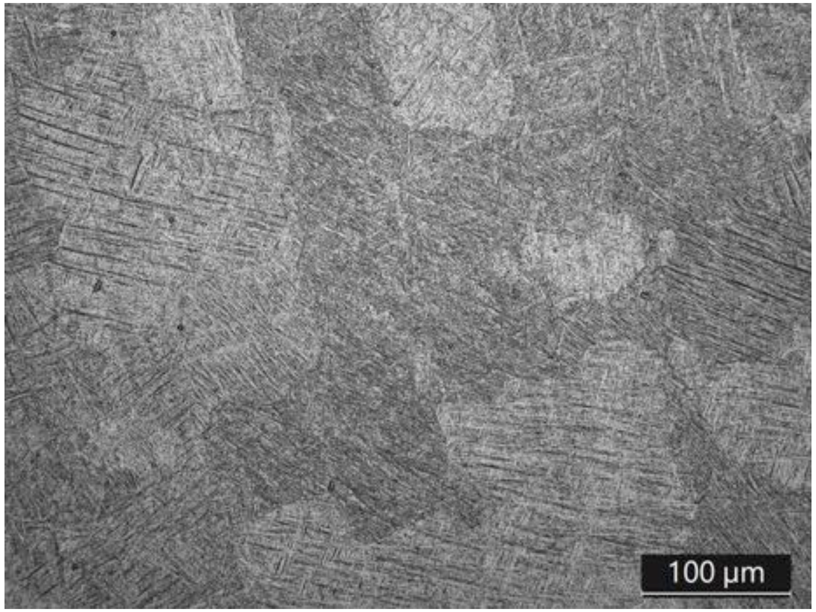
# Experimental material and procedures

## *“As-built” specimens*

Low-temperature stress relief
(5h @ 670°C, Ar)

↓

Fine acicular α’ martensite



Surface finish not altered by post-processing treatments

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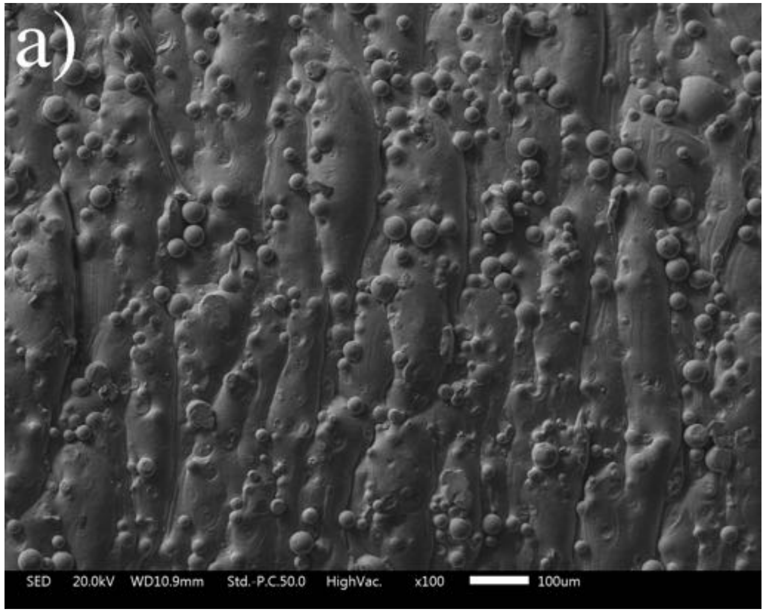
Surface striations + unmolten powder particles (Ra 6.8 µm)



# Experimental material and procedures

## *Fatigue tests*

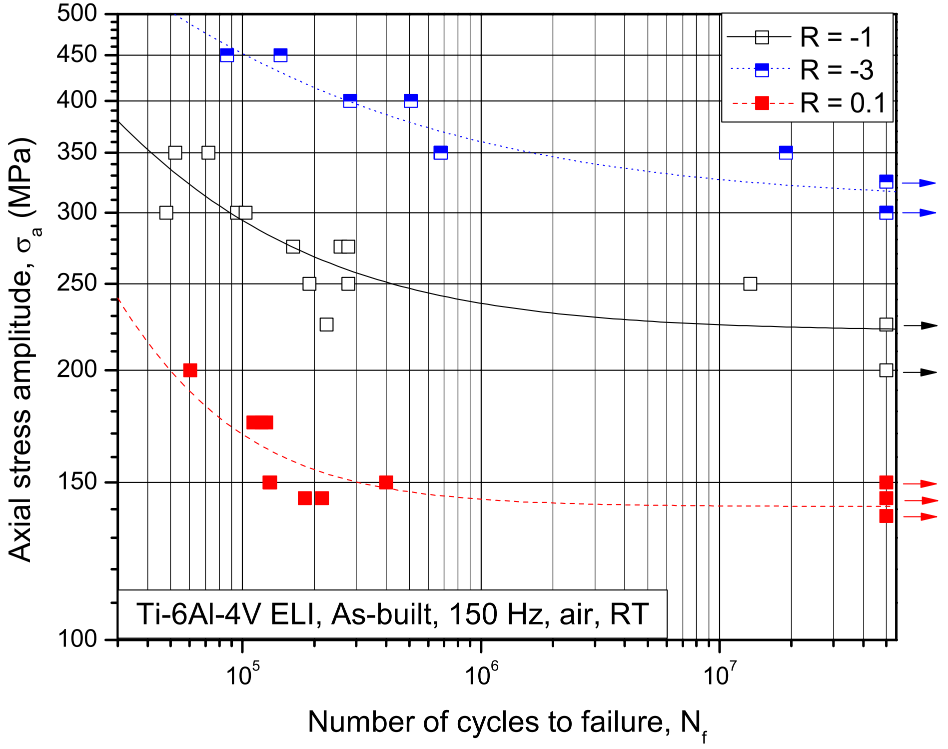
- Load controlled axial fatigue tests
- 150 Hz, laboratory environment
- Load ratios R = -1, R = -3 and R = 0.1
- Explored fatigue lives: between 5×$10^4$ and 5×$10^7$ cycles

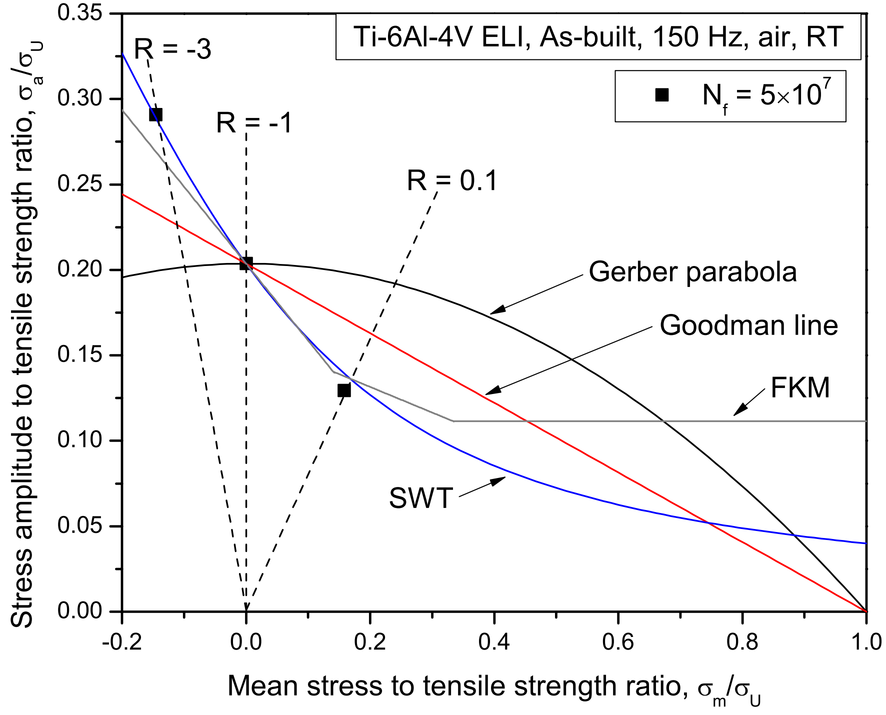
## *Computed tomography (CT) scans*

- Metrological X-ray CT system Nikon X-Tek MCT225
- Central part of the gage length analyzed with volume of ≈ 40 $mm^3$
- Detection of pores in terms of volume, projected area and min. distance from the outer surface

# Experimental results

## *Fatigue tests: mean stress sensitivity*



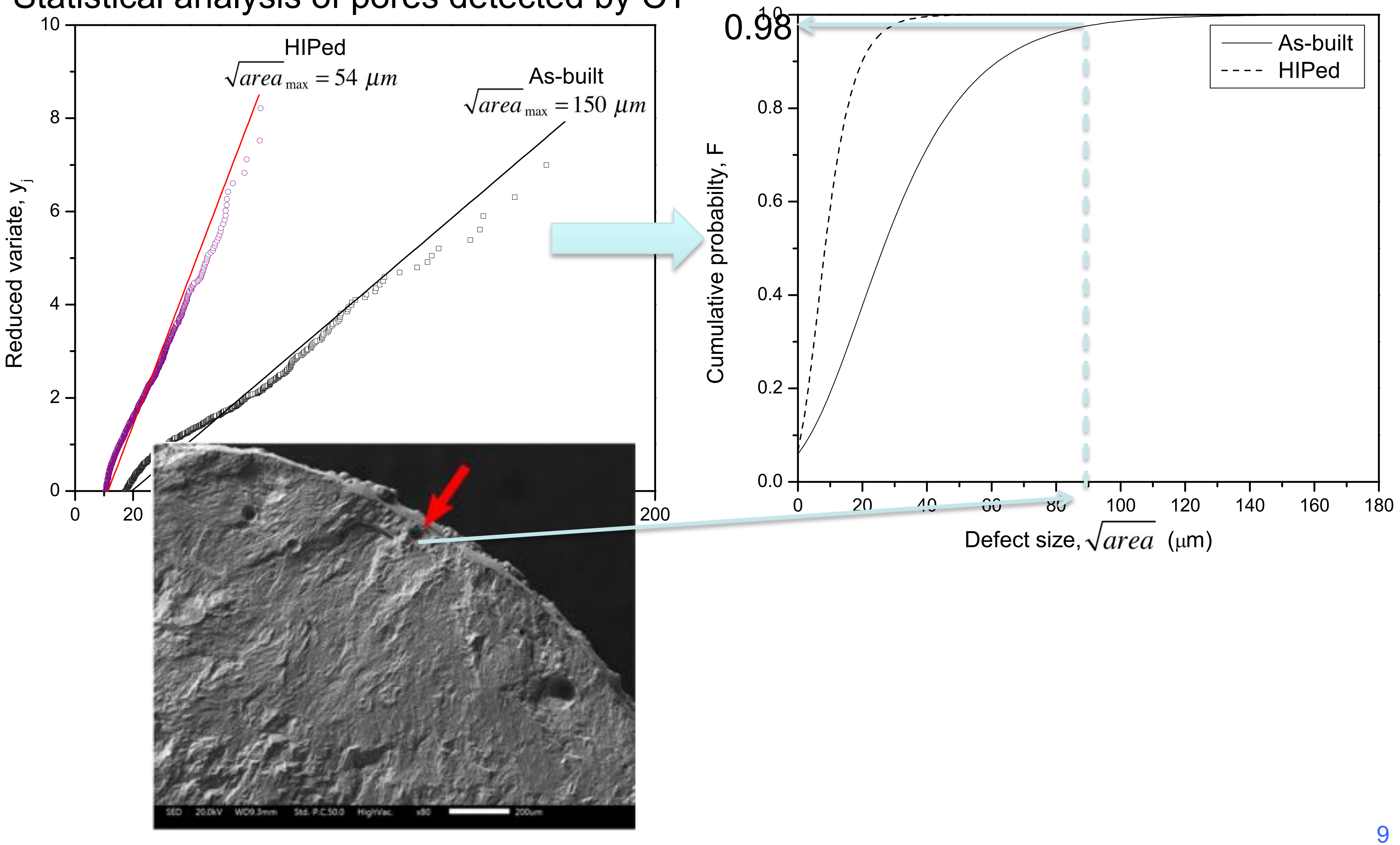


- Low fatigue properties of the as-built condition (20% of UTS)
- Marked mean stress sensitivity, not captured by classical approaches
- Tensile mean stresses are particularly detrimental, while compressive mean stresses induces a remarkable increment in the fatigue strength
- Fatigue strength dictated both by mean and maximum stress

# Interpretative model

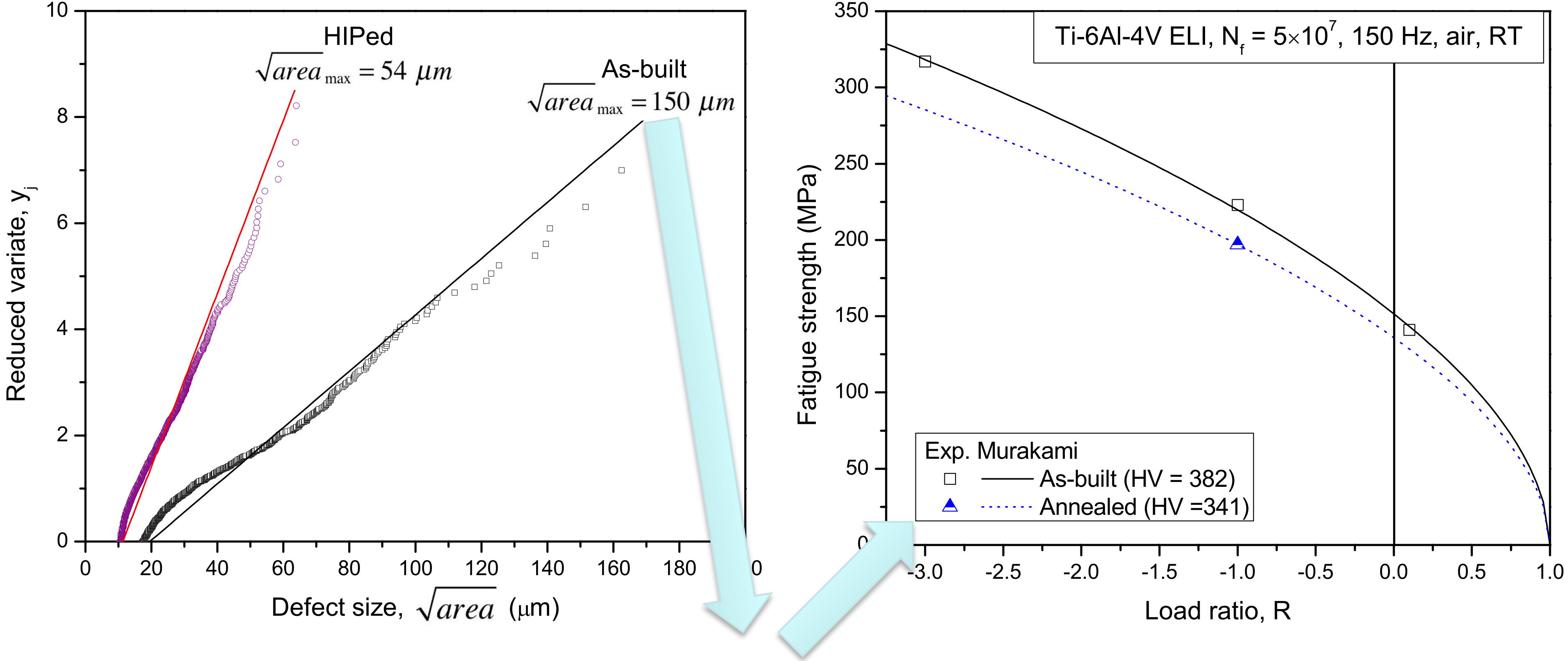
## *Pore size effect on fatigue*

Statistical analysis of pores detected by CT



# Interpretative model

## *Pore size effect on fatigue*



Statistical analysis of pores detected by CT

Murakami model calibration

## Murakami model

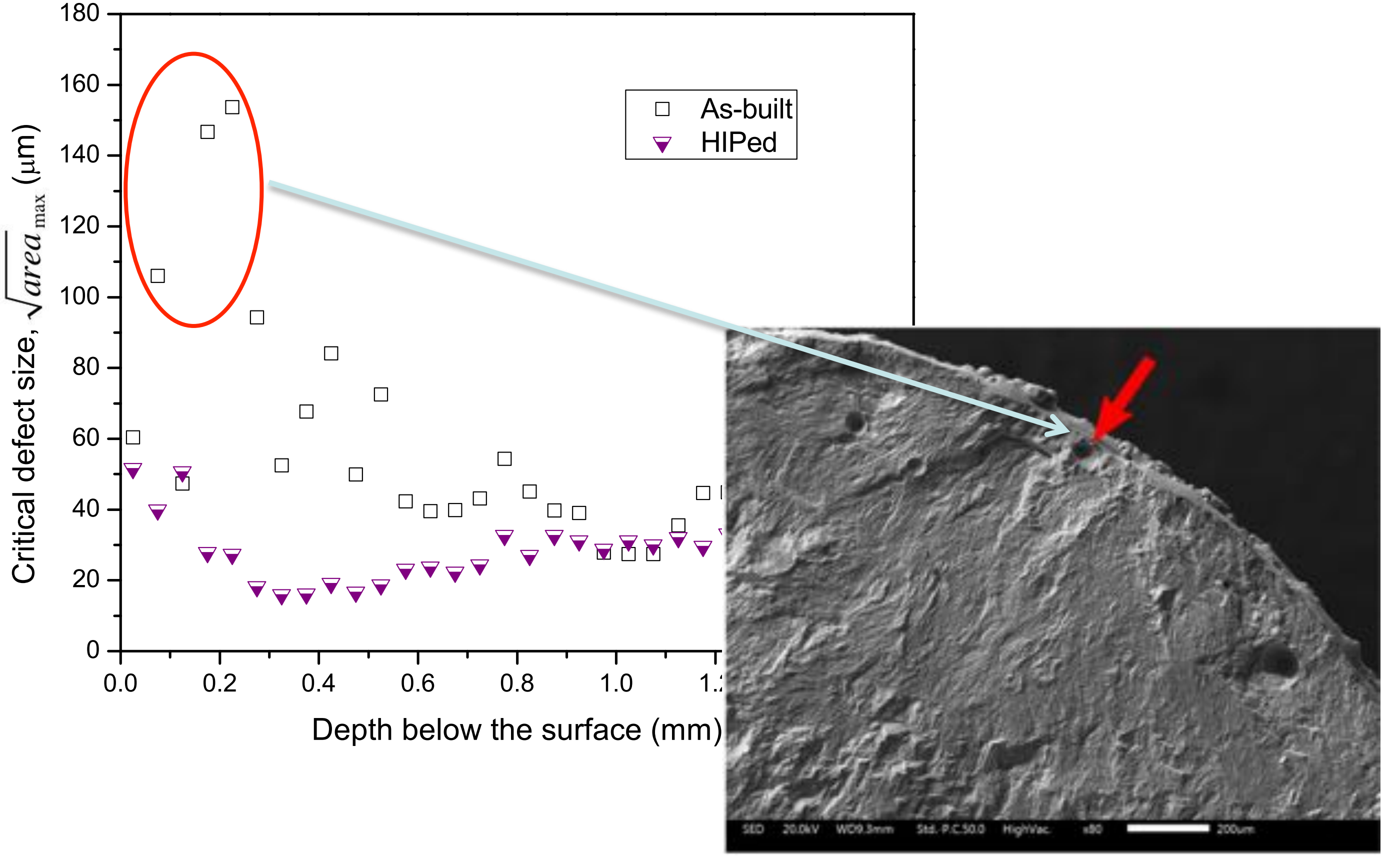
$$\sigma_W = \frac{F_{Loc}F_{HV}}{\left(\sqrt{area}_{\max}\right)^{1/6}}\left(\frac{1-R}{2}\right)^{m}$$

$$F_{HV} = a \cdot HV + b$$

$$F_{Loc} = \begin{cases} 1.43 & \text{Surface defect} \\ 1.41 & \text{Near surface defect} \\ 1.56 & \text{Internal defect} \end{cases}$$

# Interpretative model

## *Critical pore size as a function of depth*[1]



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[1] M. Benedetti et al., Int. J. Fatigue, 2018;107:96-109.

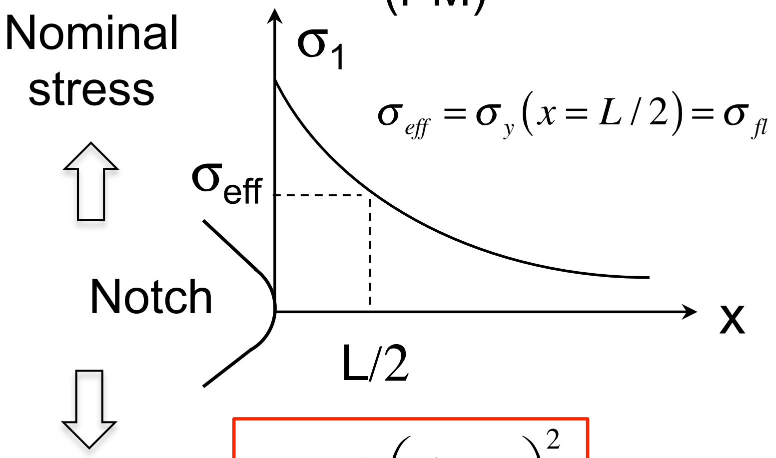
# Motivation

## *Notch fatigue strength of AMed materials: an open issue*

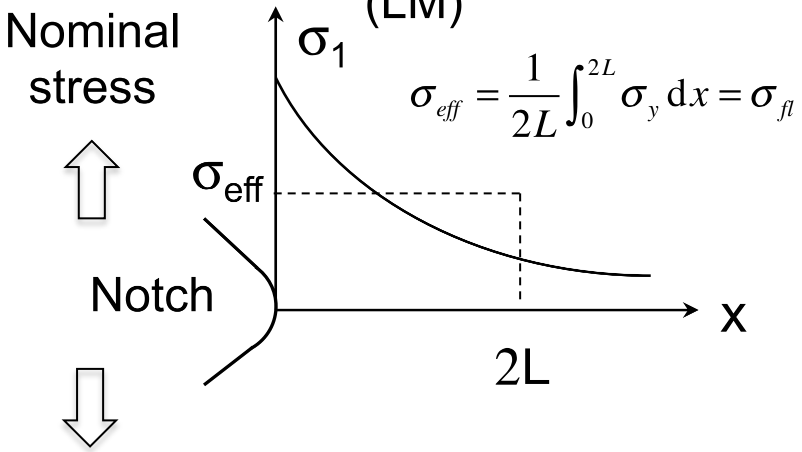
- How does the **concomitant** presence of **notch** effects and **defectiveness** influences the fatigue strength?
- This is of paramount importance, as AM components usually display **intricate** geometry resulting in severe stress concentration effects and therefore necessitate **robust notch** fatigue assessment methods.

## *The theory of critical distance (TCD)*

The point method
(PM)



The line method
(LM)

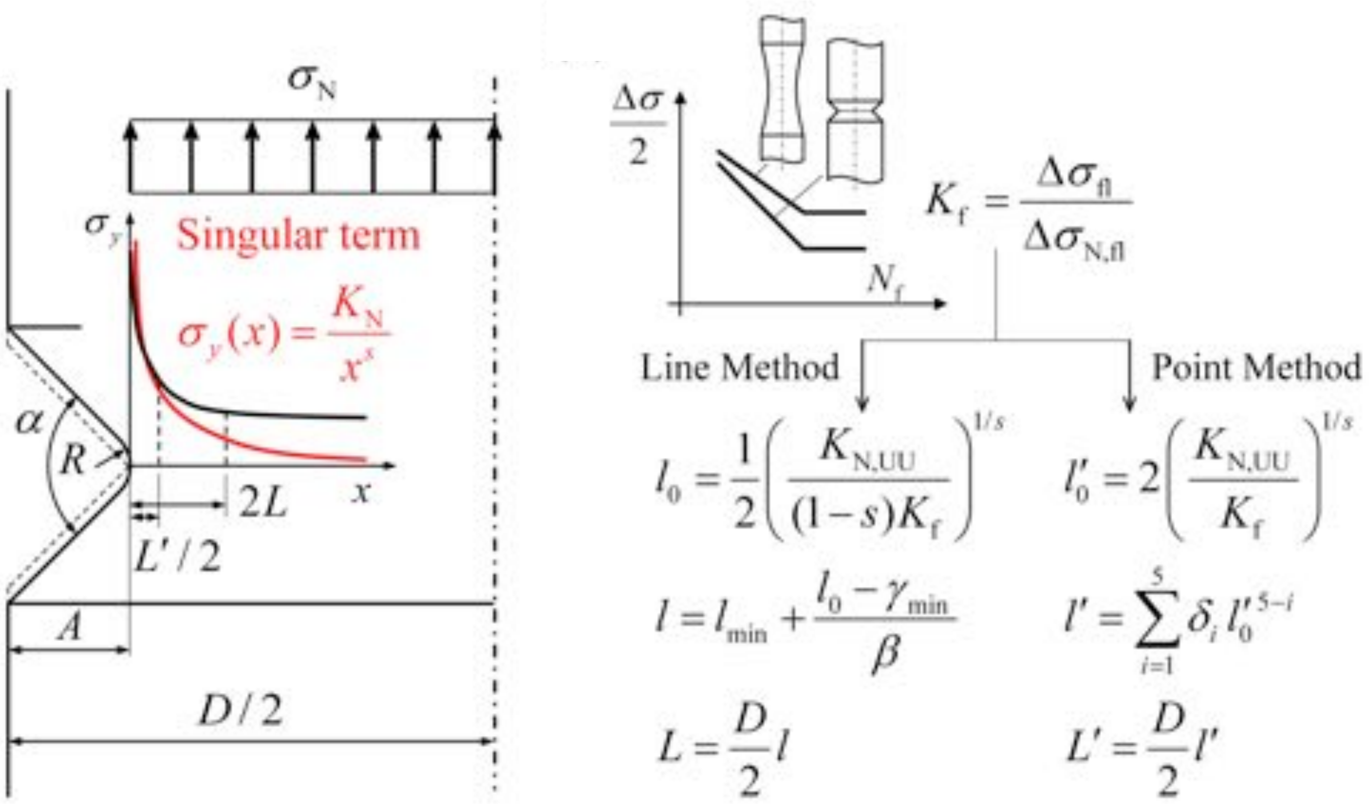


$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta \sigma_{fl}}\right)^2$$

El-Haddad material length

# Motivation

## Alternative critical distance determination[1,2]



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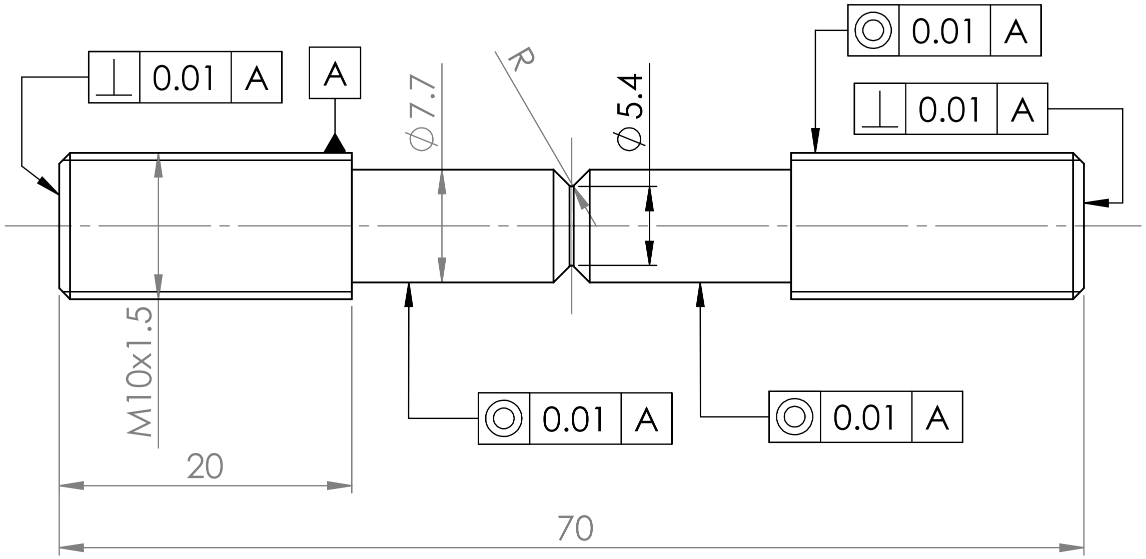
[1] C. Santus et al., Int. J. Fatigue, 2018;106:208-218.

[2] C. Santus et al., Int. J. Fatigue, 2018;113:113-125.

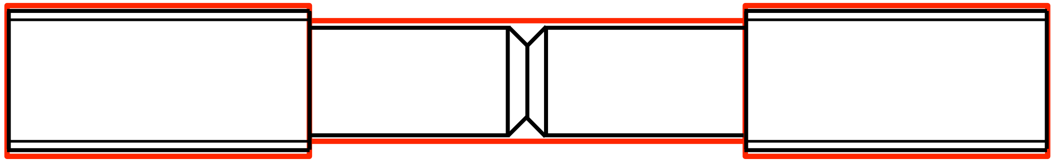
# Experimental material and procedures

## *Notched specimens*

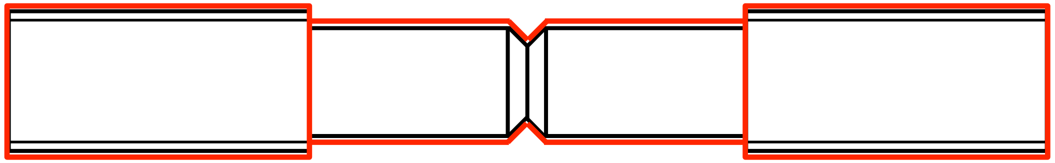


Notch root radius R:

- **R0.2**: **sharp** notch
- **R1**: **blunt** notch



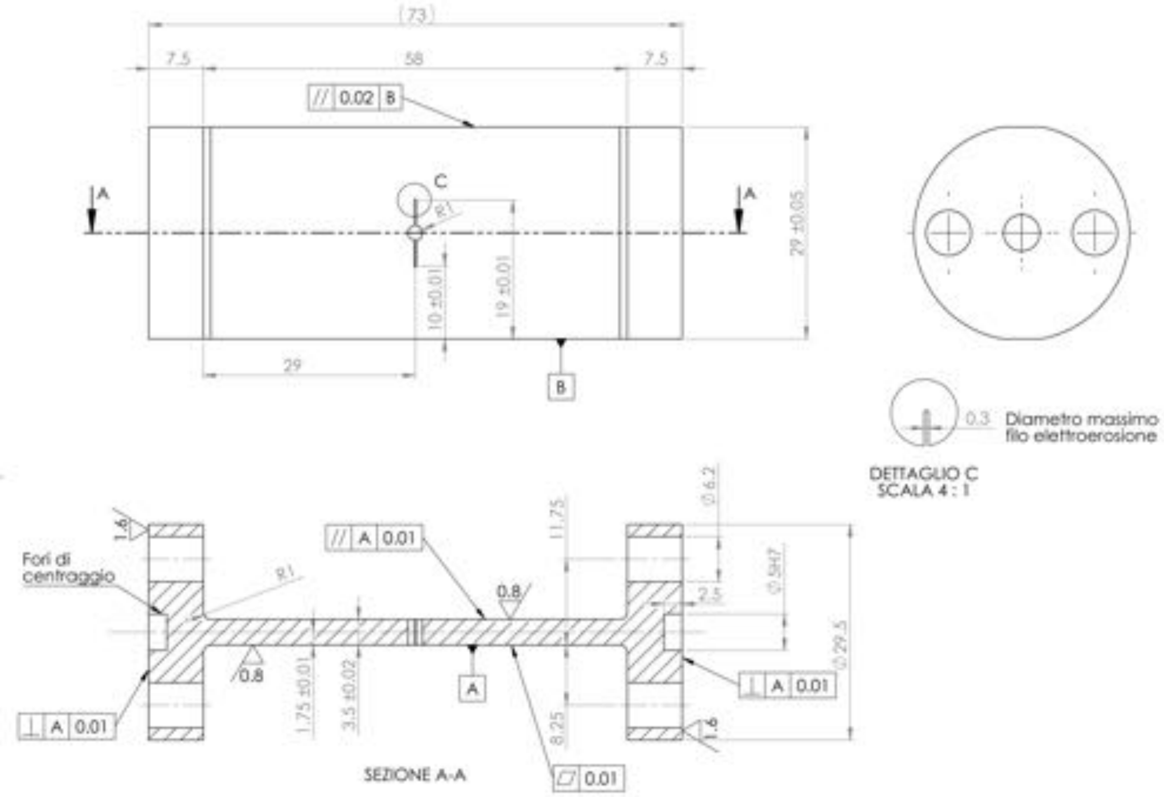
**Turned** notch



**SLM** notch

# Experimental material and procedures

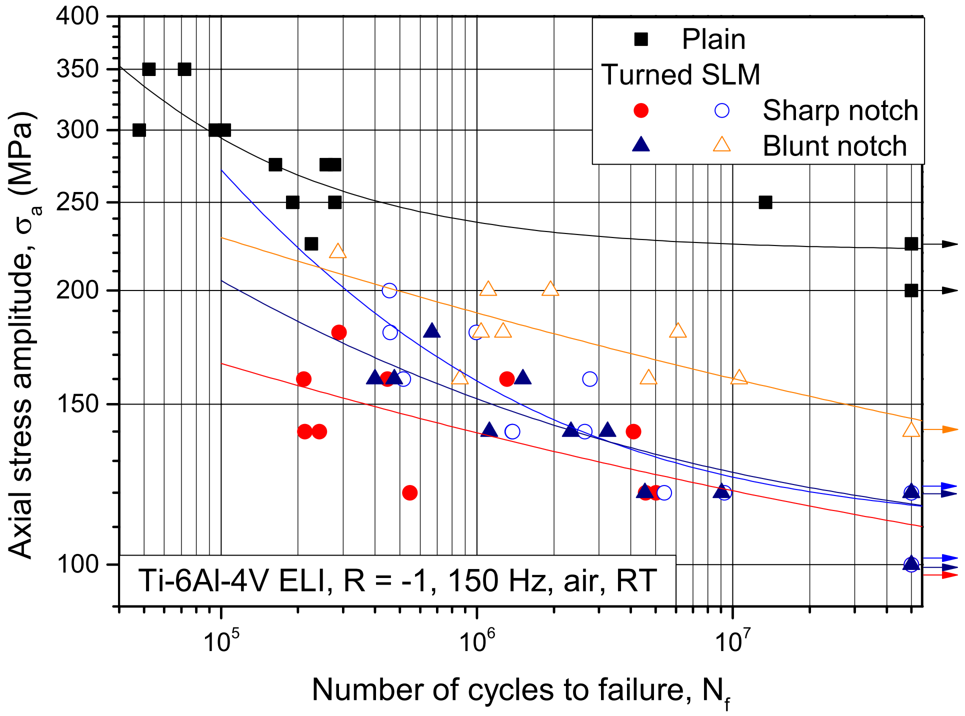
## *Fracture mechanics tests: M(T) specimen*



- Indirect potential drop method (Krak gage) to measure the crack length.
- R = -1
- Force shedding + constant load amplitude FCG

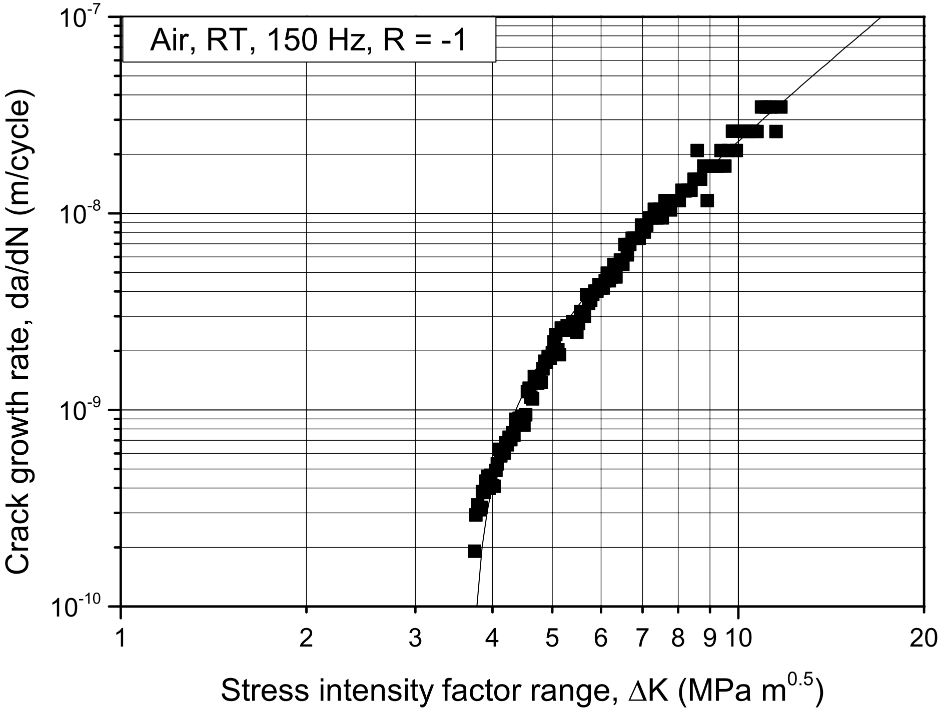
# Experimental results

## *SN curves*



- Fatigue strength of Turned-notched (solid symbols) is lower than that of the SLM-notched (open symbols) variant.
- Large scatter.

## *da/dN-ΔK curves*

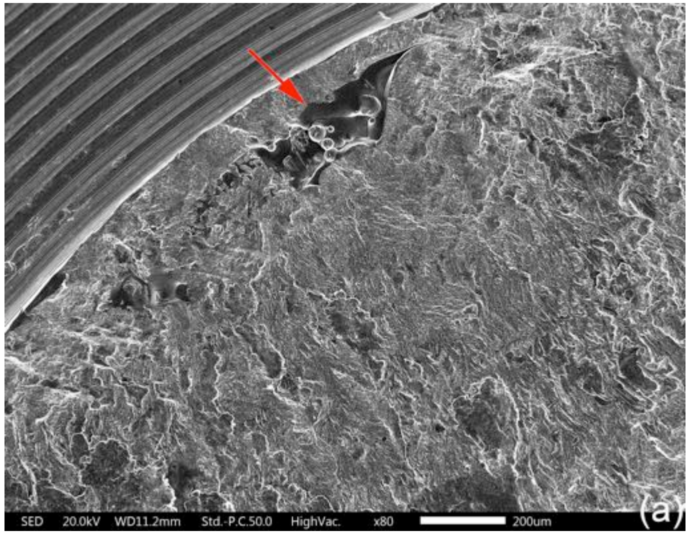


- Low FCG resistance as a consequence of the fine martensitic microstructure.
- $\Delta K_{th}$ = 3.7 MPa $m^{0.5}$

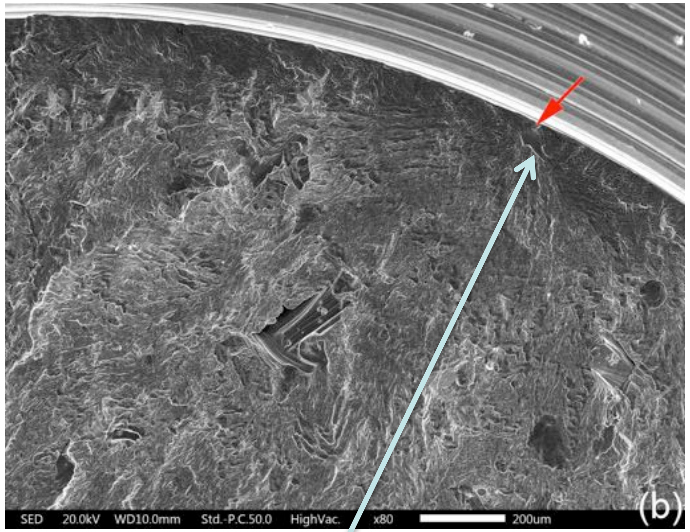
# Experimental results

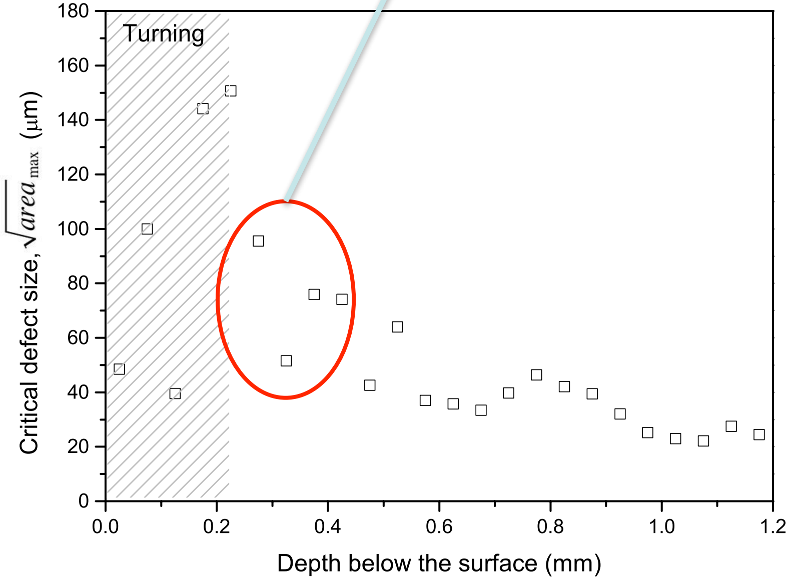
## *SEM fractographic analysis*

Turned notch



SLM notch



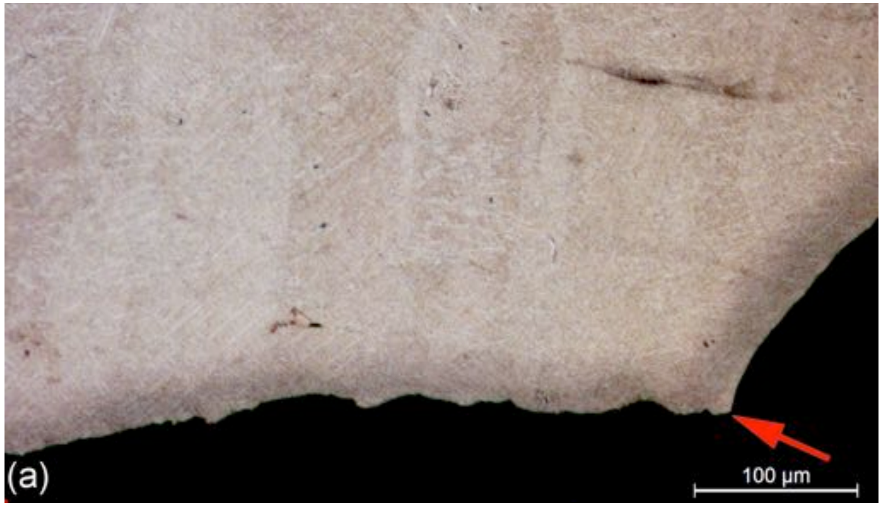


- Crack initiation starts from a defect in the immediate vicinity of the notch tip.
- Critical defect is larger in the turned than in the SLM-notch.
- Sample batches with different size of defects ahead of the notch

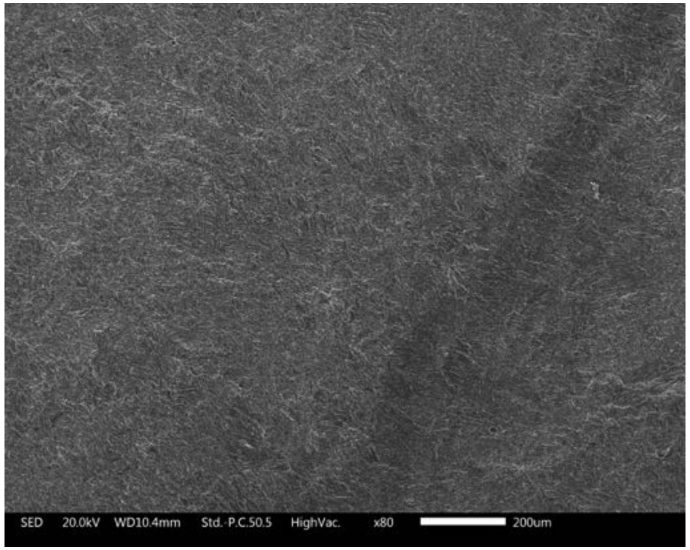
# Experimental results

## *Crack path from crack initiation site*

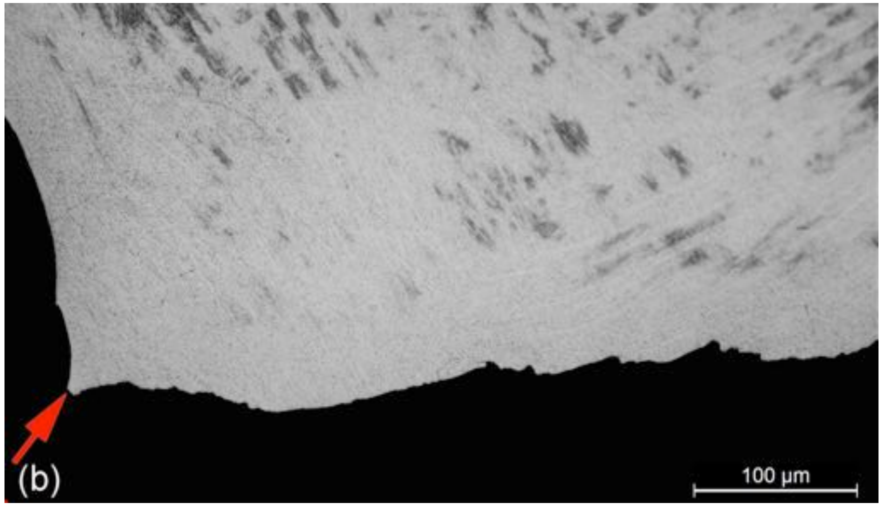
Turned notch



M(T) specimen



SLM notch



- The early crack propagation stage is approximately **straight** and fairly **orthogonal** to the loading direction.
- Subsequently, the crack exhibits, an **erratic** zigzagging path to **interconnect** the **nearest** defects encountered during its propagation.

# Interpretative model

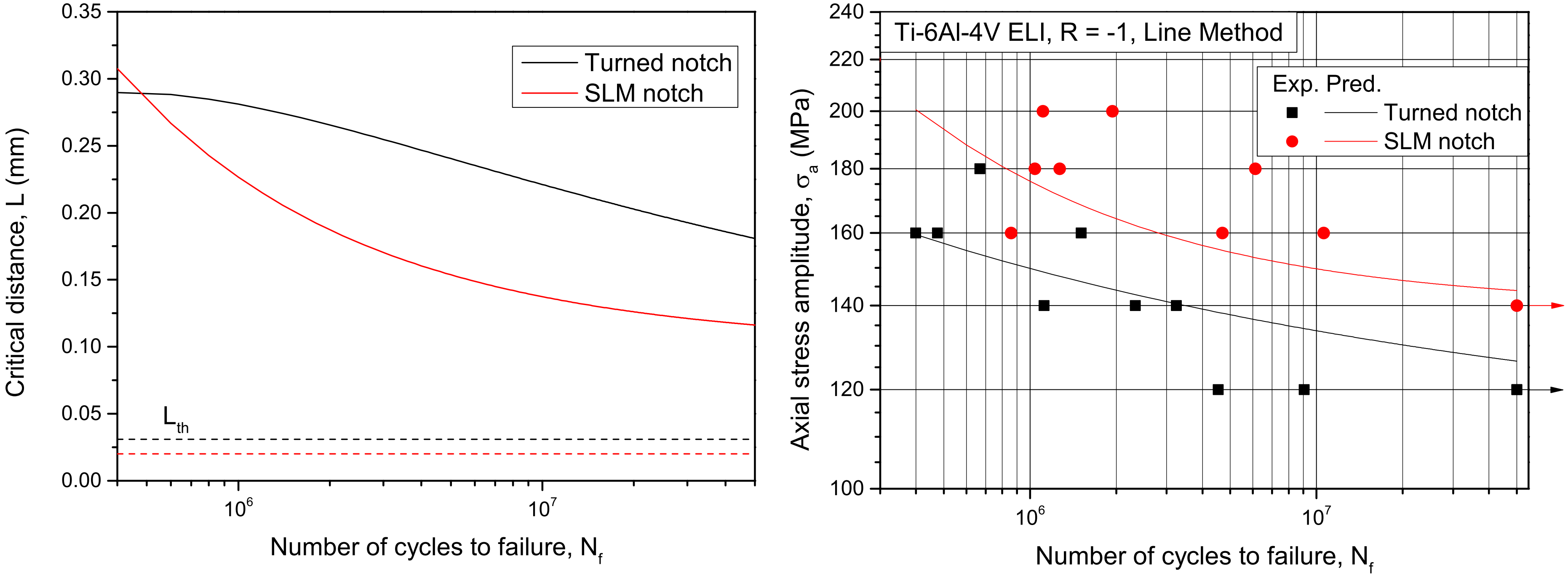
## *TCD predictions*

| **Sample geometry** | **Critical defect size $\sqrt{area}$ (µm)** | **$\sigma_w$ (MPa)** | **$K_f$** | **L (mm)** | **L' (mm)** | **$L_{th}$ (mm)** |
|---|---|---|---|---|---|---|
| Plain | 150 | 225 | - | - | - | |
| Turned sharp notch | 210 | 190 | 1.73 | 0.180 | 0.260 | 0.031 |
| SLM sharp notch | 60 | 230 | 1.98 | 0.115 | 0.180 | 0.020 |

| **Sample geometry** | **Fatigue strength @ 5×$10^7$ cycles (MPa)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Exp. | L, L' from Sharp notch | | | | $L_{th}$ from M(T) | | | |
| | | LM | | PM | | LM | | PM | |
| | | Pred. | Err. (%) | Pred. | Err. (%) | Pred. | Err. (%) | Pred. | Err. (%) |
| Turned blunt notch | 116.6 | 125.9 | 8.0 | 119.9 | 2.8 | 100.9 | -13.5 | 97.9 | -16.0 |
| SLM blunt notch | 144.8 | 143.5 | -0.9 | 139.3 | -3.8 | 122.4 | -15.5 | 119.9 | -17.2 |

# Interpretative model

## *TCD predictions: medium-to-high cycle fatigue*



- Critical length decreases with increasing fatigue life $N_f$.
- L derived from sharp notched samples is 3-4 times larger than $L_{th}$ and depends upon material defectiveness.
- Accurate predictions of the blunt-notched samples, also in view of the large scatter of the experimental data.

# Concluding remarks

1. Fatigue properties of Ti64 additively manufactured via SLM are mainly dictated by defectiveness.
2. Defectiveness sensitivity is well represented by the Murakami $\sqrt{area}$ model.
3. Notch fatigue strength is controlled by the largest defect in the immediate vicinity of the notch root.
4. Large scatter in notch fatigue results.
5. The size of the critical defects strongly depends upon the notch-manufacturing route (SLM vs. turned notch!).
6. The critical distance length increases with increasing size of the critical defect.
7. Defectiveness influences much the crack path of micro-cracks, little that of macro-cracks. Fracture mechanics tests not indicated for determining L.
8. Accurate prediction obtained by TCD in combination with the proposed critical distance inverse search procedure, especially if the actual defectiveness of the sample is known.

# Crack path and notch fatigue strength of Ti-6Al-4V ELI additively manufactured via selective laser melting: Defect sensitivity

THANK YOU FOR YOUR ATTENTION!

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