

# Fatigue strength of additively manufactured metals

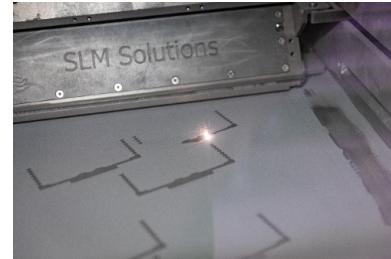
Antti Järvenpää  
Research director, FMT-group

[Antti.jarvenpaa@oulu.fi](mailto:Antti.jarvenpaa@oulu.fi)  
2.12.2020



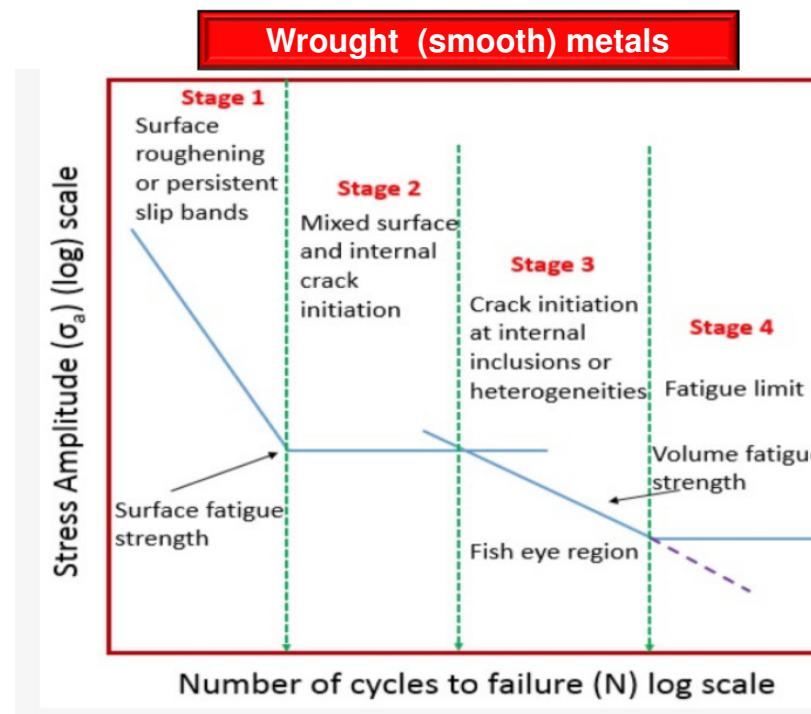
# Content

1. Introduction
2. Fatigue testing
3. Fatigue strength
4. Post-treatments to optimize fatigue properties

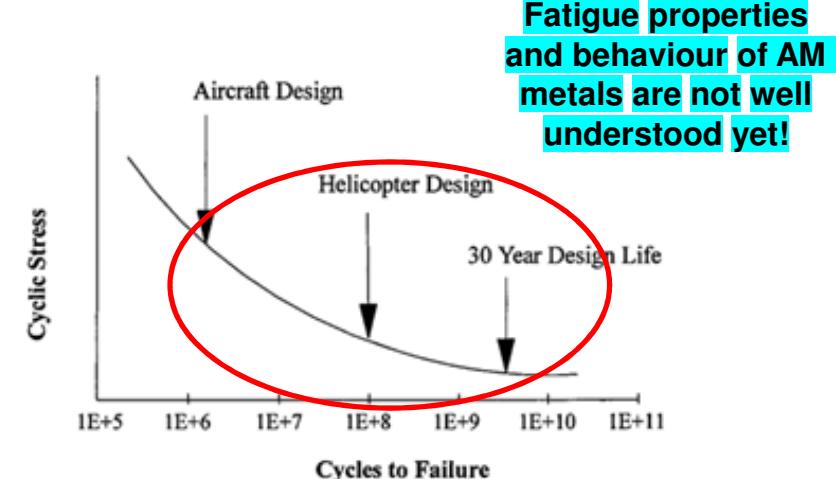




# Introduction: Fatigue principles



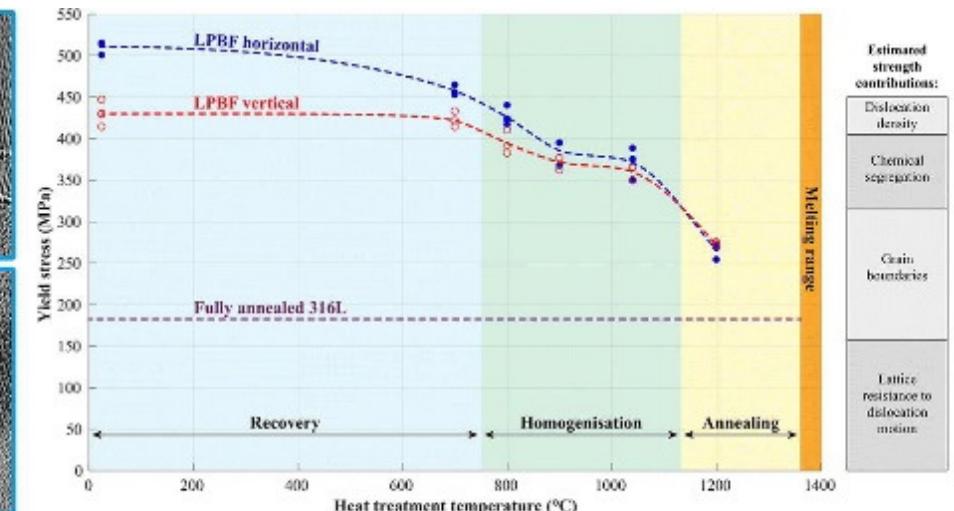
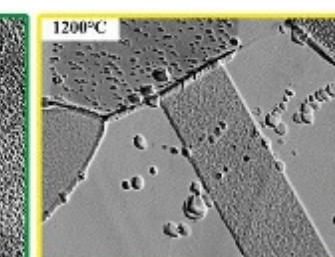
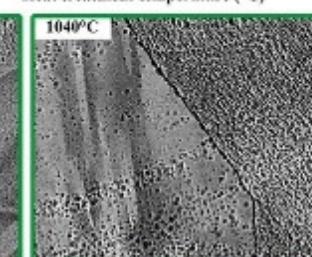
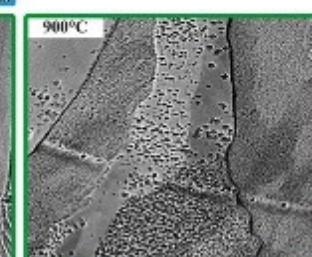
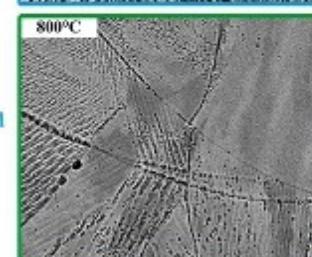
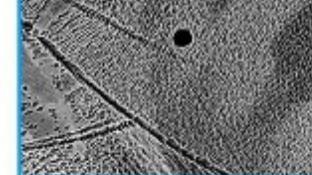
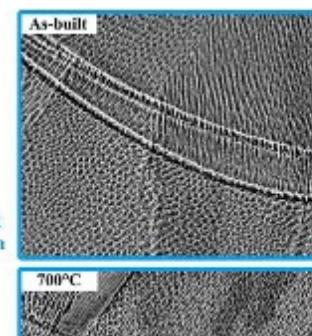
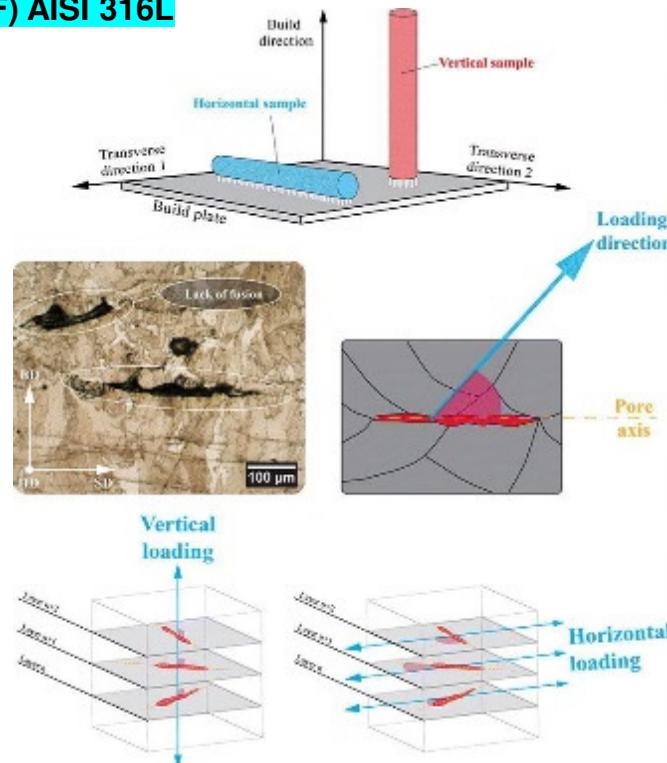
B. Pytel et al. Very high cycle fatigue—Is there a fatigue limit?





# Introduction: AM special features

## AM (LPBF) AISI 316L



T. Ronneberg, et al. 2020

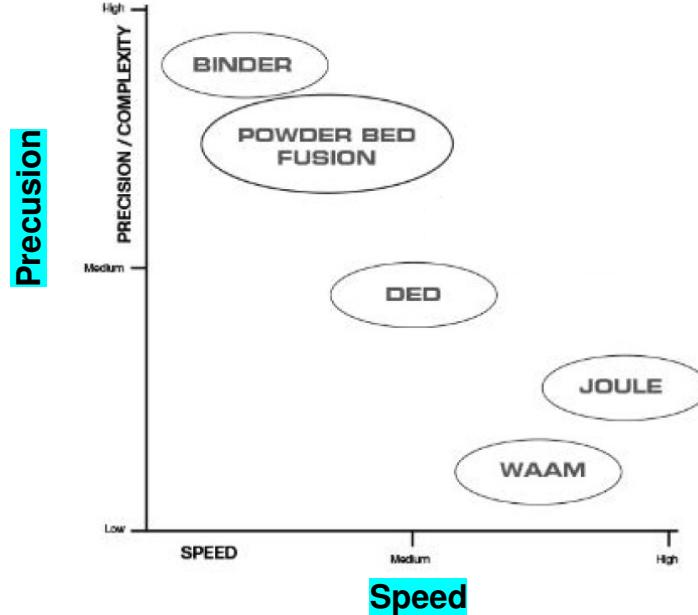
University of Oulu – Kerttu Saalasti Institute – Future Manufacturing Technologies  
Oulun yliopisto – Kerttu Saalasti Instituutti – Tulevaisuuden tuotantoteknologiat (FMT)



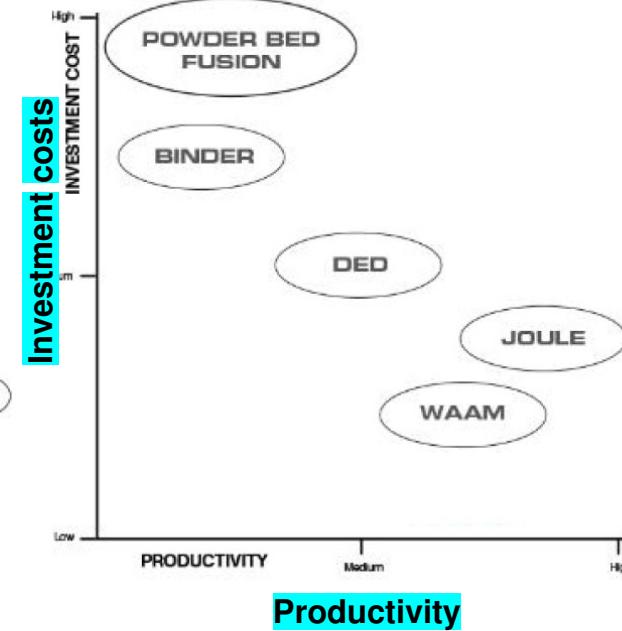
# Introduction: AM special features

Quality ?

## EFFICIENCY



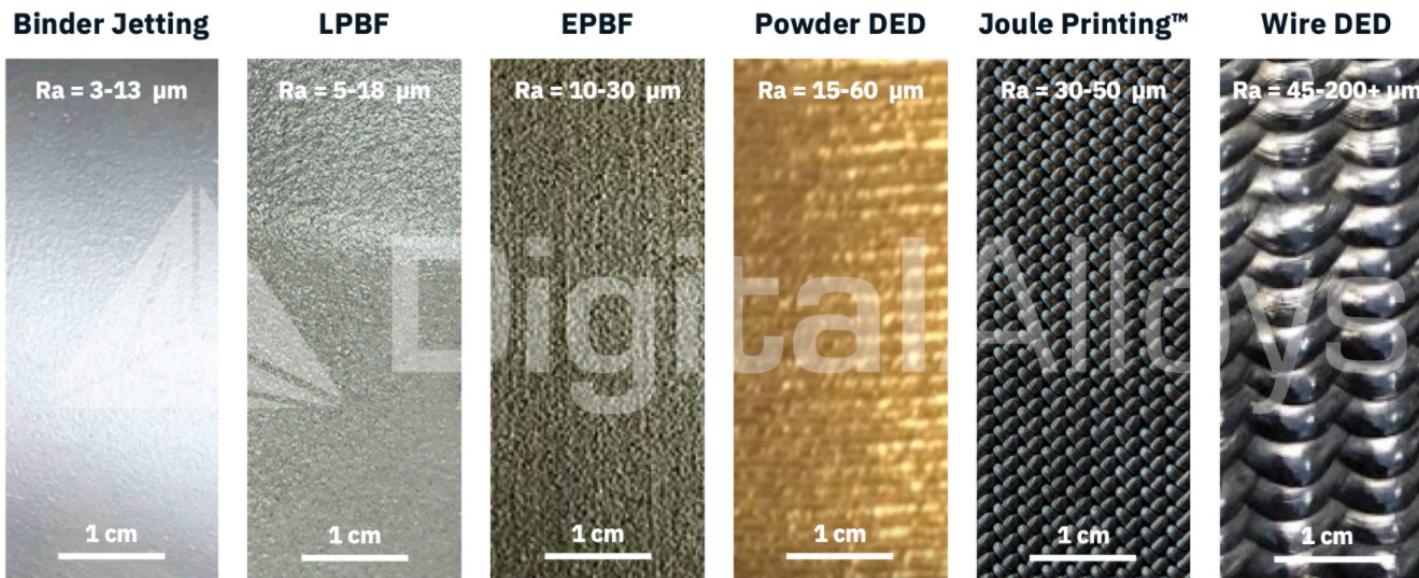
## ROI





# 1. Introduction – AM special features

## Typical Surface Roughness of Metal AM Processes

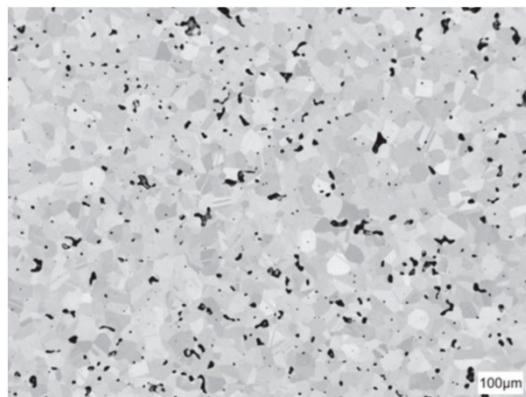


<https://www.digitalalloys.com/blog/surface-roughness/>



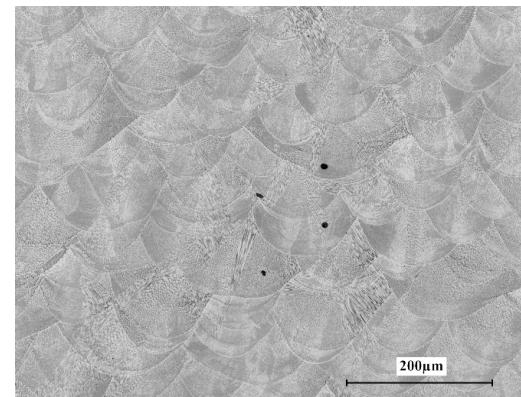
# 1. Introduction: AM special features

**Binder Jet – AISI 316L**



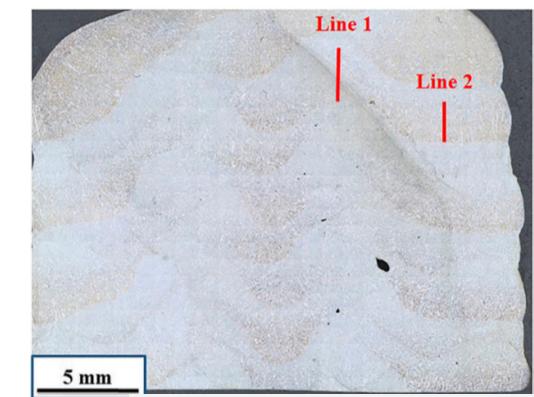
S. Mirzababaei A Review on Binder Jet Additive Manufacturing of 316L Stainless Steel

**LPBF – AISI 316L**



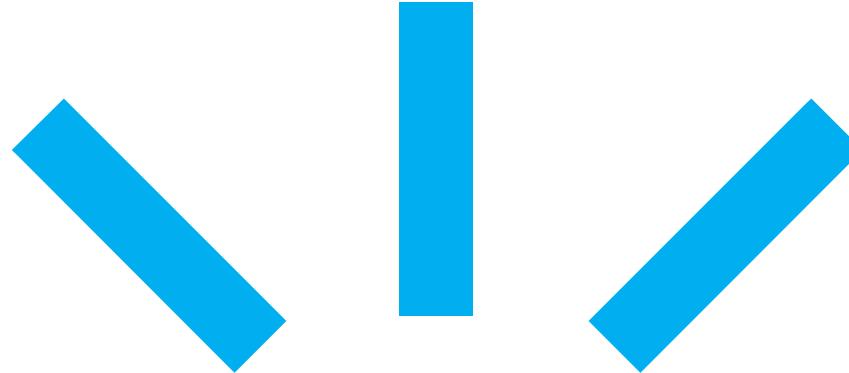
M. Jaskari

**WAAM – AISI 316L**



W. Jin, Wire Arc Additive Manufacturing of Stainless Steels: A Review

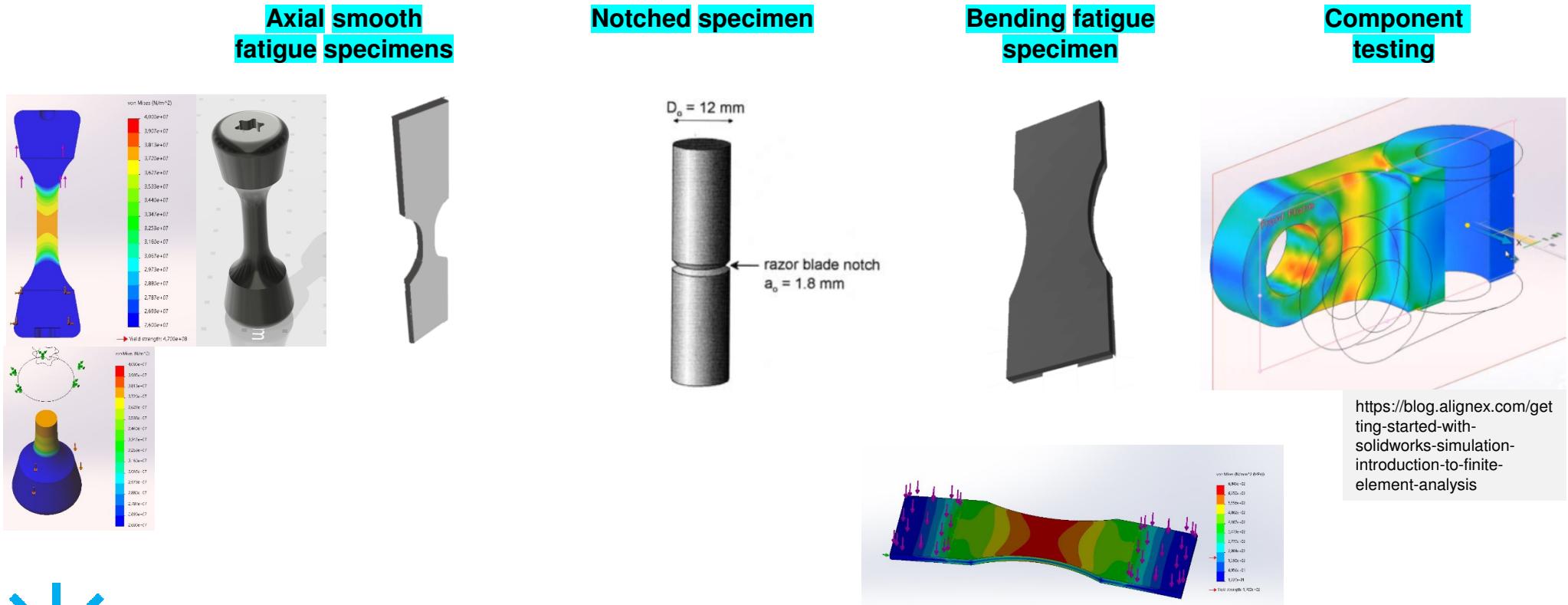




## 2. Fatigue testing



## 2. Fatigue testing – Lab. Scale vs. component scale



<https://blog.alignex.com/getting-started-with-solidworks-simulation-introduction-to-finite-element-analysis>

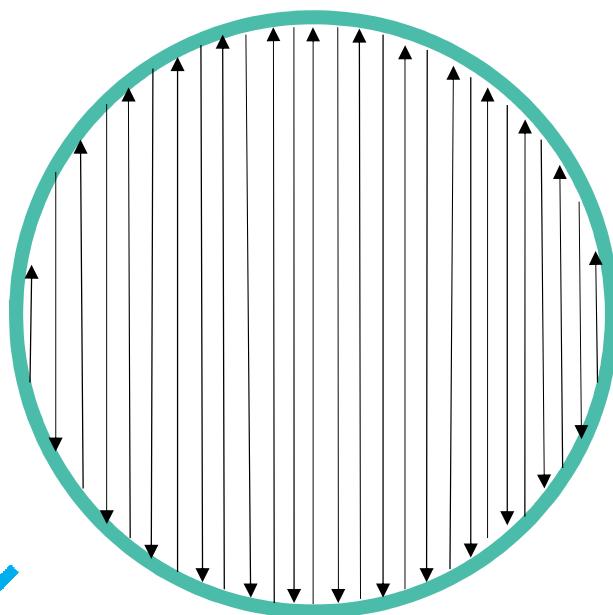




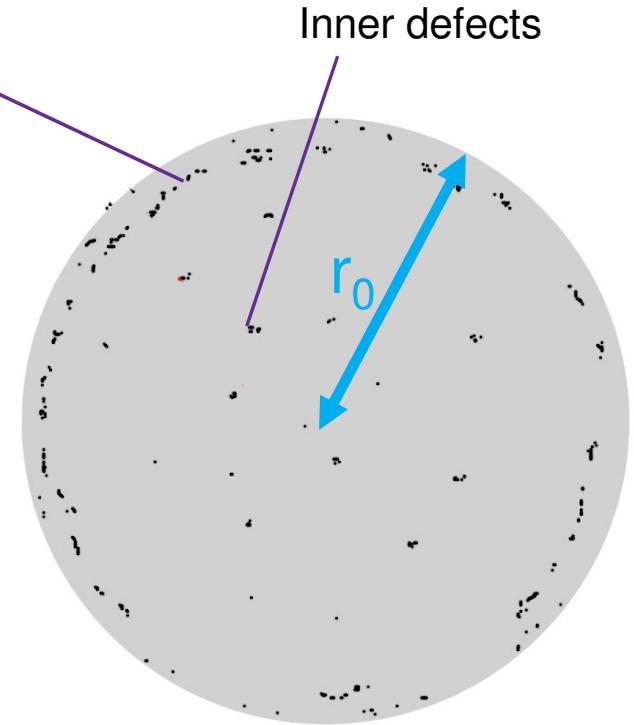
## 2. Fatigue testing – Inner defects (LPBF)

Typical scan track

First the outside layer is made  
Then the inside area is filled



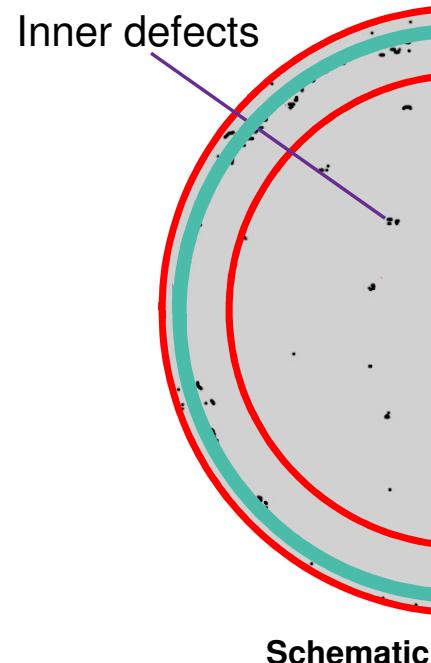
Sub-surface  
defects



Schematic figure: Sample cross-section in the test area



## 2. Fatigue testing – Inner defects

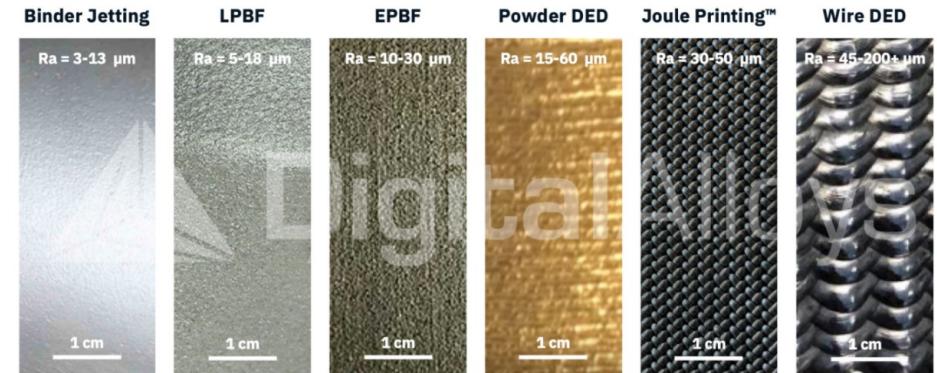


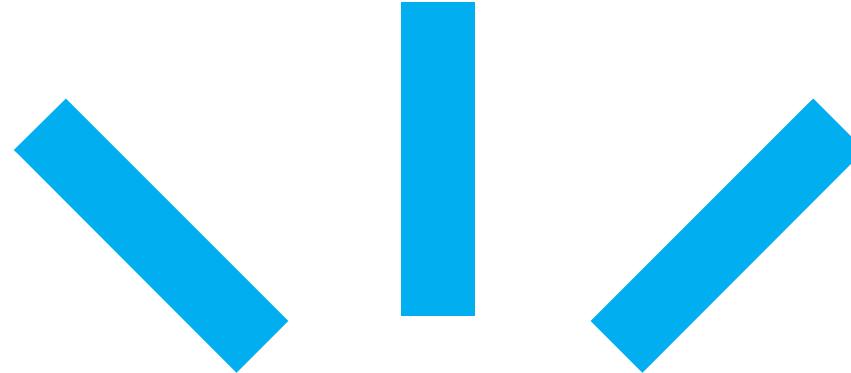
Schematic figure: Sample cross-section in the test area

Machining: Fatigue strength enhanced  
Grinding: Fatigue strength impaired

Hankala valmistaa muotoon muulla kuin LPBF:llä!

### Typical Surface Roughness of Metal AM Processes

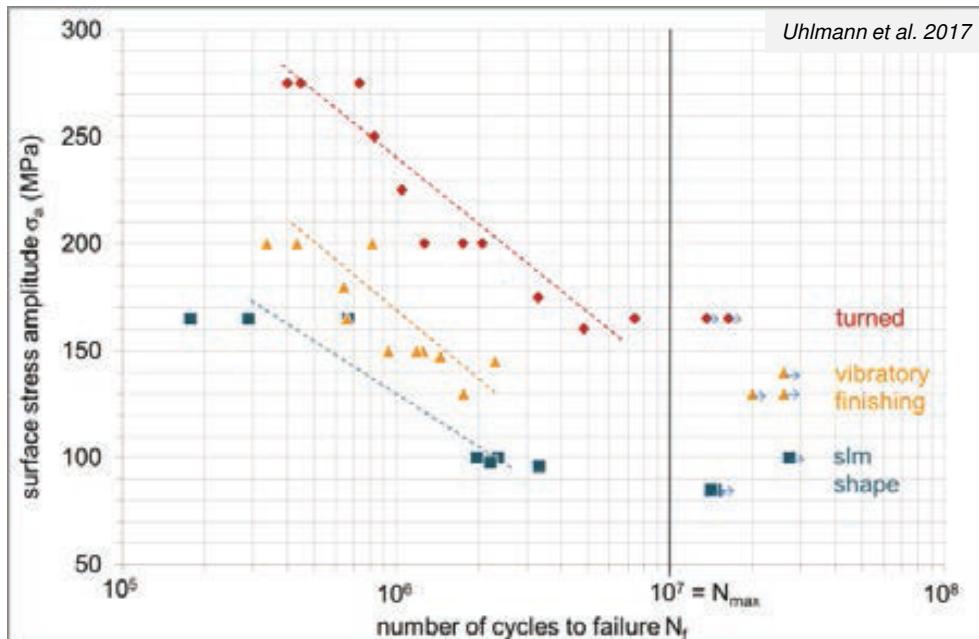




## 3. Fatigue strength



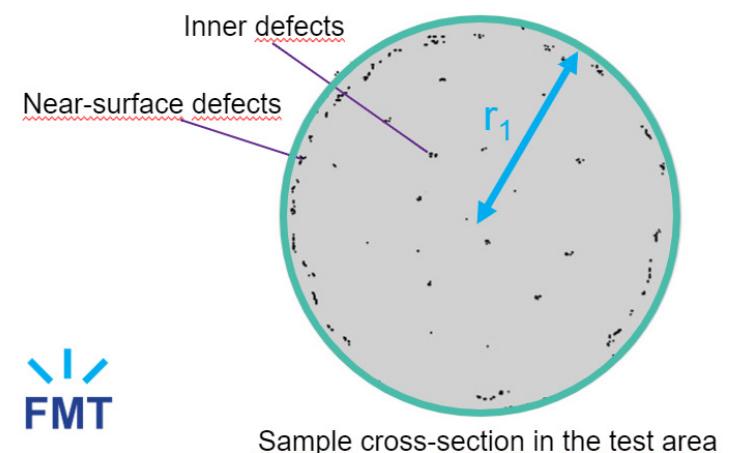
## 3. Fatigue strength LPBF



316L: Effect of surface quality



- Polishing enhances the fatigue strength if near-surface pores are not reached
- Machining is the most effective route to enhance (~50%) the fatigue strength since it removes the near-surface pores



Sample cross-section in the test area

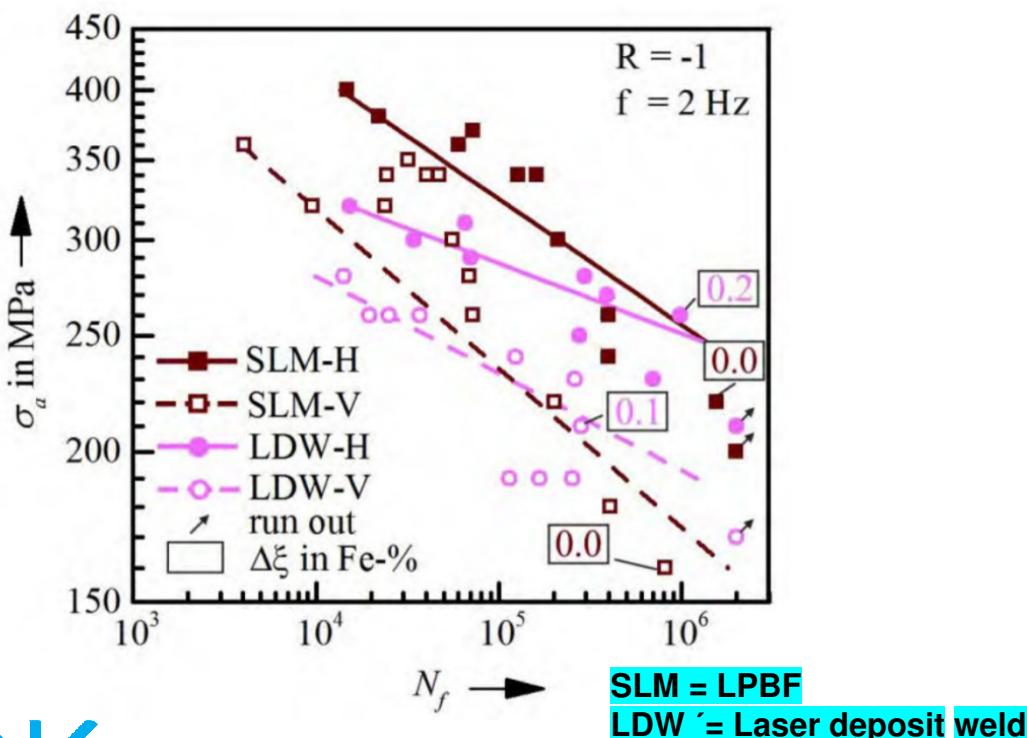




### 3. Fatigue strength LPBF/LDW

316L: Anisotropy

B. Blinn et al. 2018



Axial R = -1, 2 Hz

Load direction = horizontal / vertical direction

Cylindrical specimen

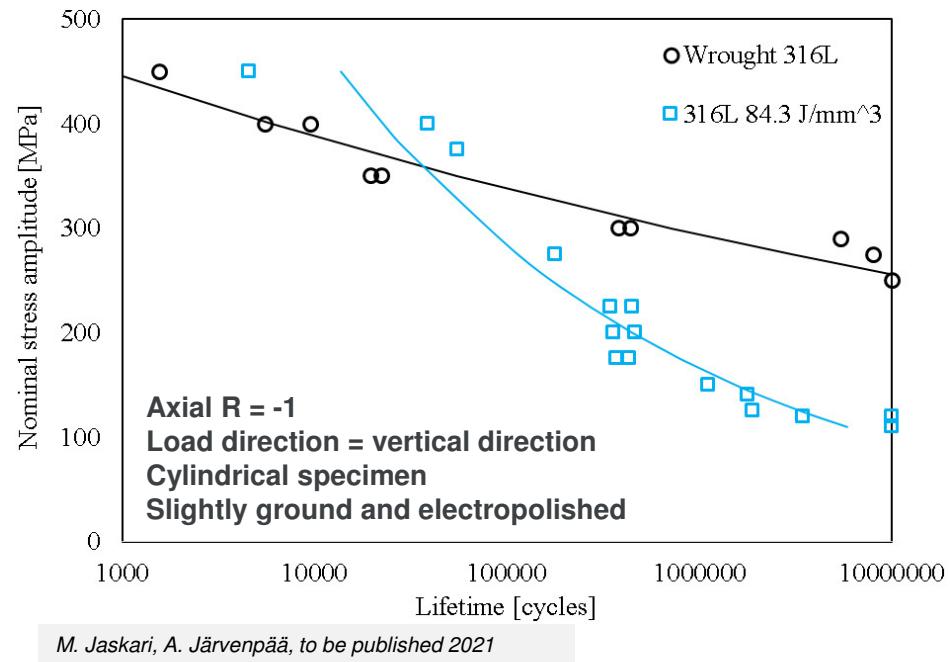
Machined and polished

- Significantly lower in vertical build direction
- Similar fatigue strength between LPBF and larger scale LDW
- Lack of information on very high cycle properties



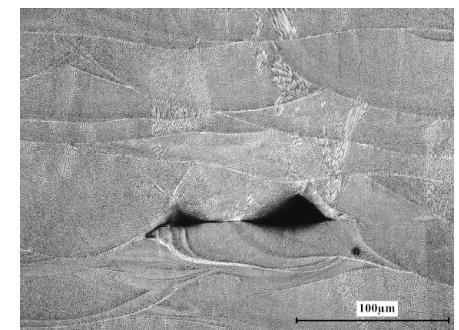
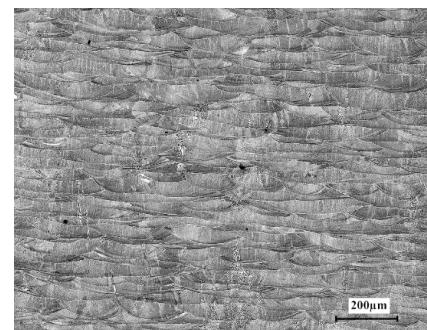


# 3. Fatigue strength LPBF vs. wrought



Energy Density [J/mm <sup>3</sup> ]	R <sub>p</sub> [MPa]	R <sub>m</sub> [MPa]	UE [%]	TE [%]
83.4	452	570	26.3	47.4
Wrought	387	624	36.9	54.0

- LPBF manufactured samples have clearly lower fatigue strength than wrought AISI 316L
  - (Surface quality)
  - Internal defects: density and distribution.
  -

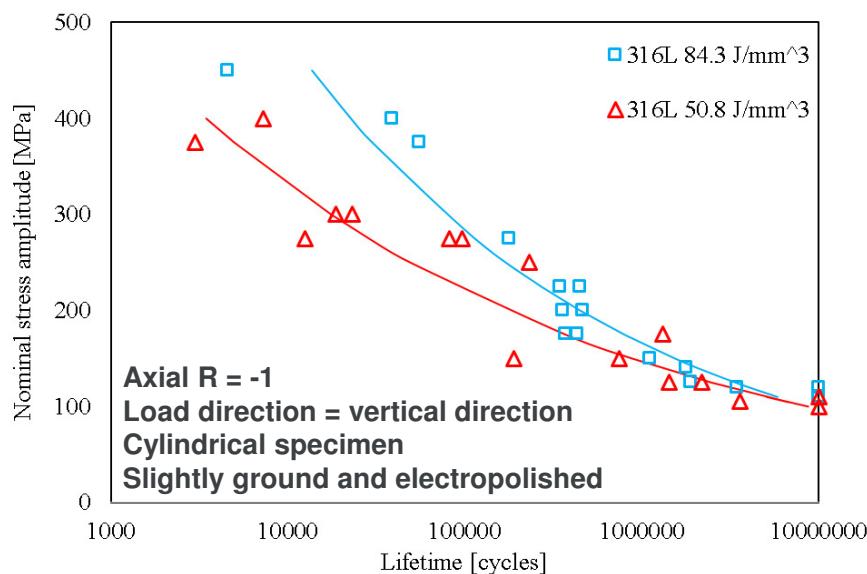


LPBF 83.4 J/mm<sup>3</sup>





## 3. Fatigue strength: LPBF

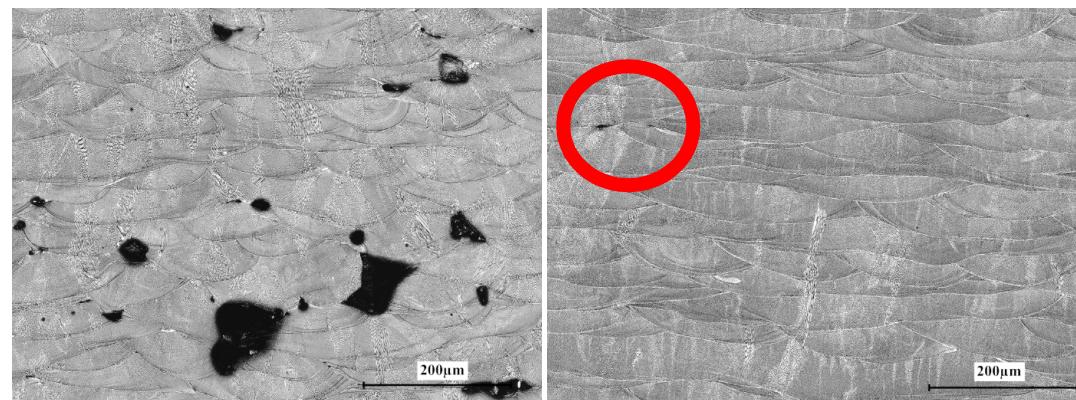


M. Jaskari, A. Järvenpää, to be published 2021



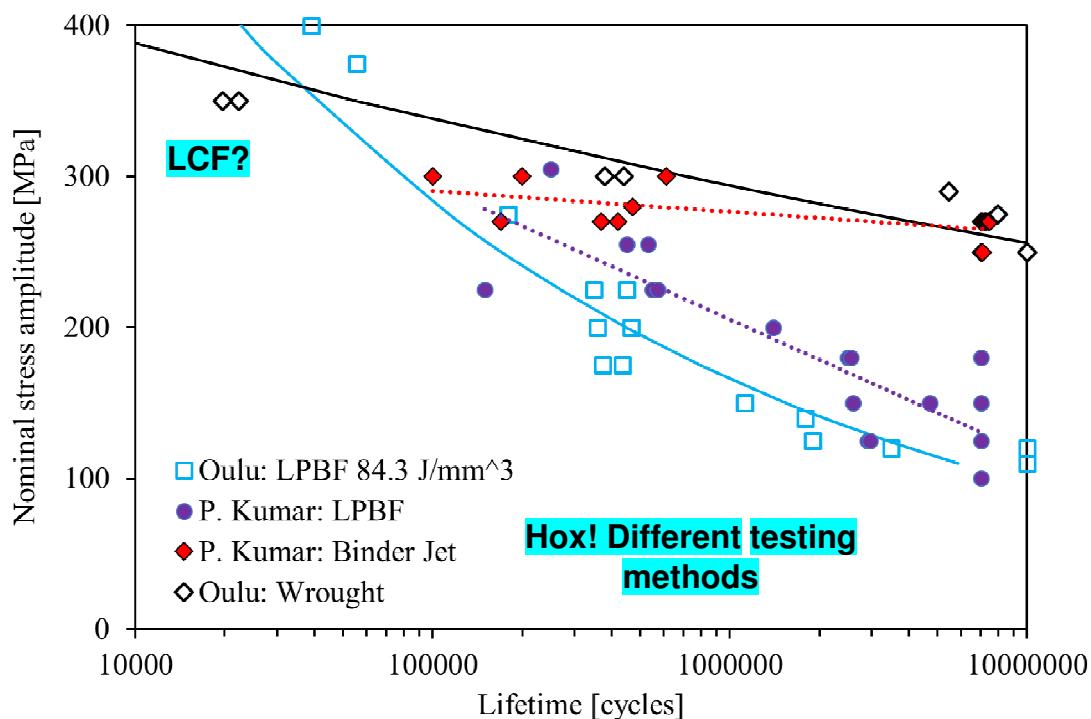
Energy Density [J/mm <sup>3</sup> ]	R <sub>p</sub> [MPa]	R <sub>m</sub> [MPa]	UE [%]	TE [%]
50.8	458	610	22.6	33.2
83.4	452	570	26.3	47.4

- In z-orientation, the HCF fatigue resistance is very sensitive to lack of fusion defects
- Porous structure has poorer LCF strength
- What is the VHCF strength ?
- Is it possible to optimize the structure ?





### 3. Comparison between LPBF and Binder Jet

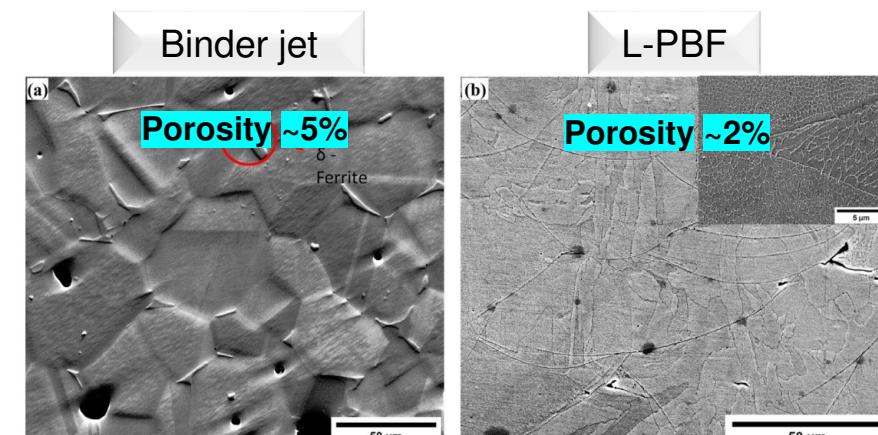


P. Kumar et al.  
experiments

Rotating bending R = -1  
Flat bone specimen  
Polished  
No comparison with wrought material

Oulu experiments

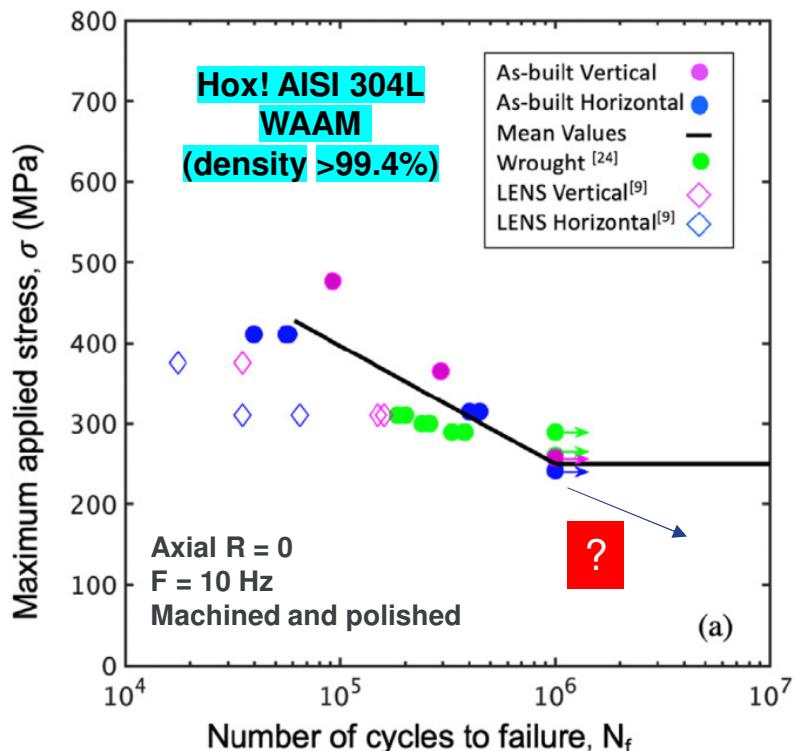
Axial R = -1  
Load direction = vertical direction  
Cylindrical specimen  
Slightly ground and electropolished



P. Kumar et al. 2020



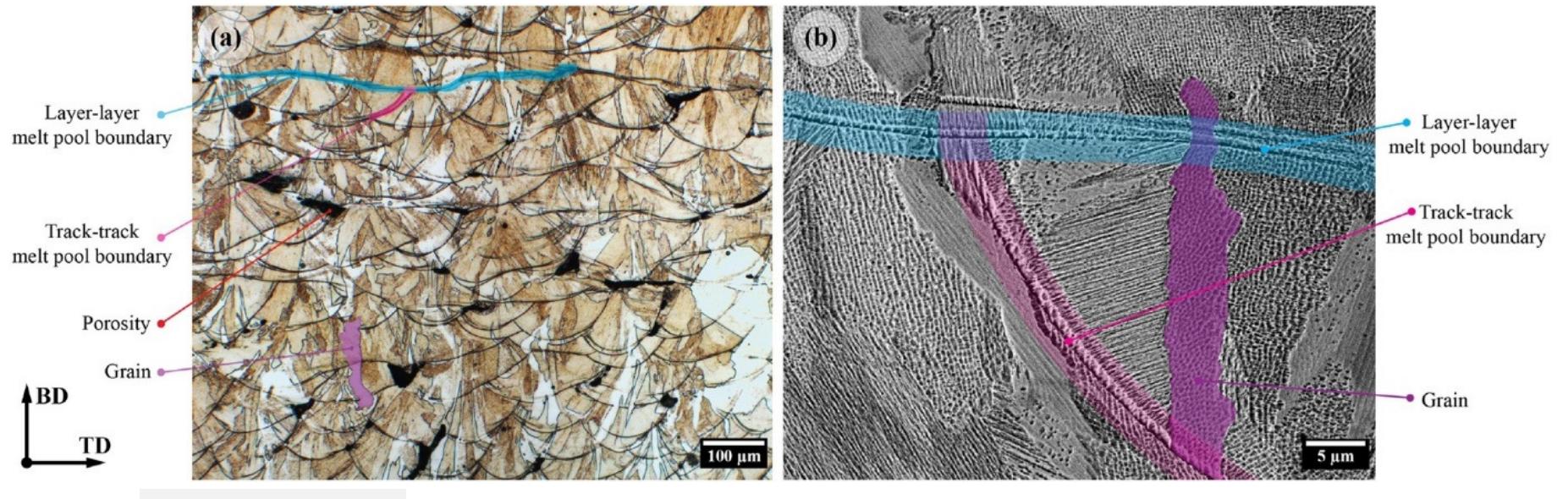
### 3. Comparison between WAAM and wrought



- Mig/Mag WAAM manufactured has similar fatigue strength than wrought at HCF
- Anisotropy lower than with LPBF
- Available literature is limited



### 3. Challenge with LPBF

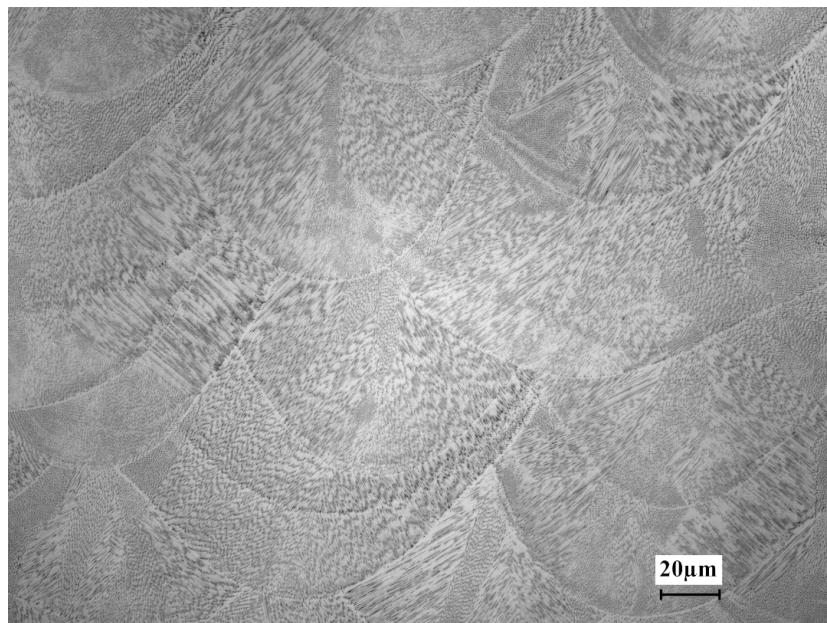


Defect size or  
shape ?

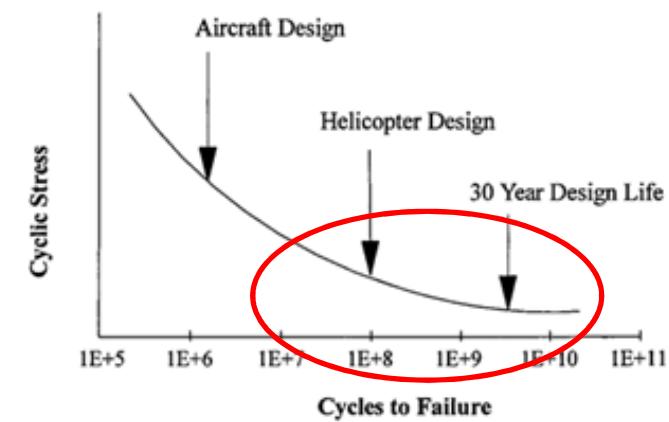


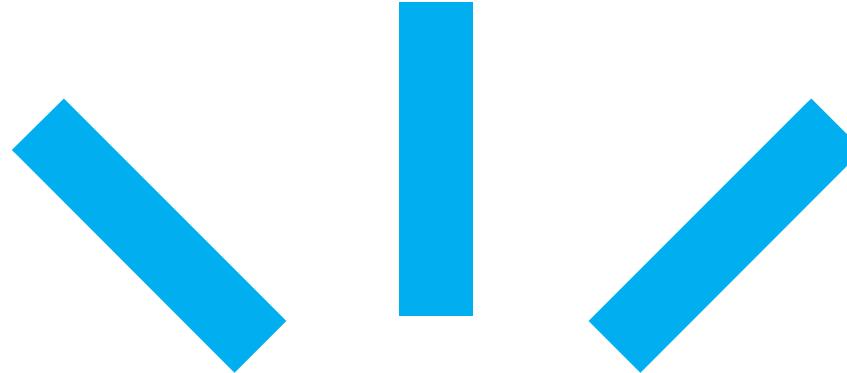


## 3. Optimization



What is the critical  
defect shape and  
size ?

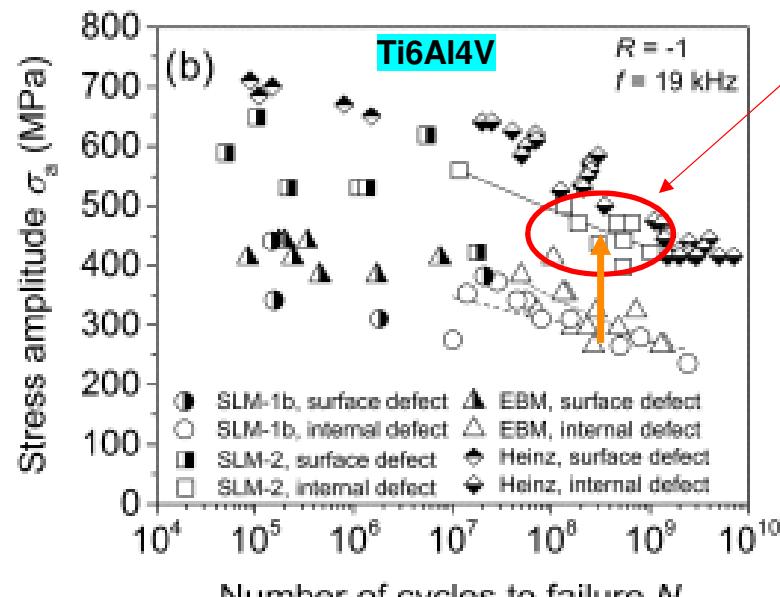




## 4. Post-treatments to optimize fatigue properties



## 4. Hot Isostatic Pressing (HIP)



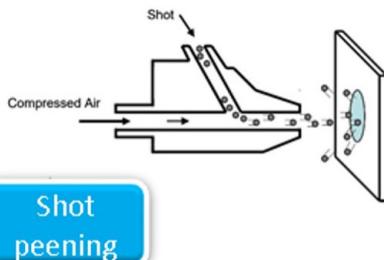
HIP treatment increases the fatigue strength of AM nearly to same level that measured with the wrought metal

The difference between Ti6AL4V AM and wrought is smaller than with AISI 316L

- Only a few study published on VHCF of AM metals
- Wrought metal seems to have saturated fatigue limit at e9 – e10 cycles
- Fatigue limit of AM does not saturate, decreases all the time ?



# 4. Surface deformation – Shot peening

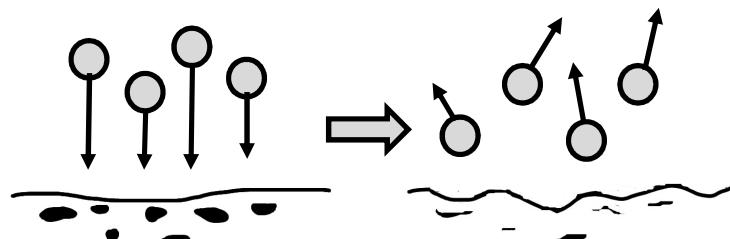


**Shot peening: Traditional surface finishing technology**

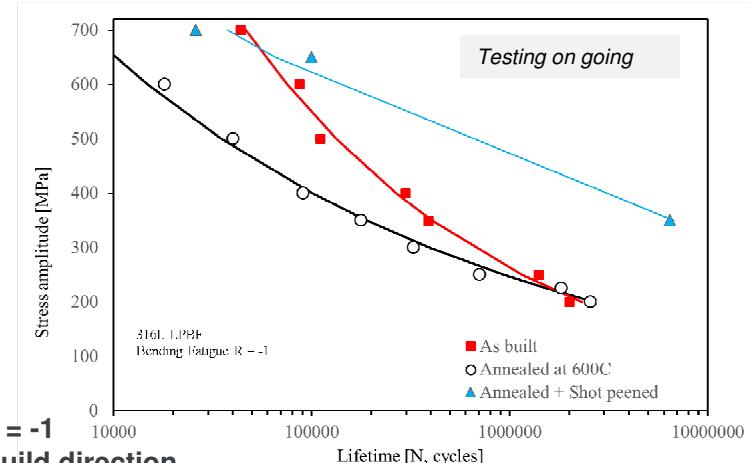
- Round steel / ceramics balls (< 0.5 mm)
- Industrially well-known and available technic

**Severe surface plastic deformation:**

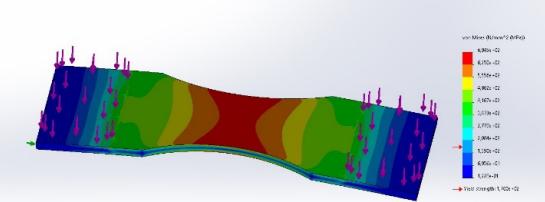
- Round steel balls (0.2–10 mm)
- Increased impact velocity / repeated process



Bending fatigue  $R = -1$   
Load direction = build direction  
Flatbone specimen  
As built + Shot peened



T. Rautio, A. Järvenpää, to be published 2021

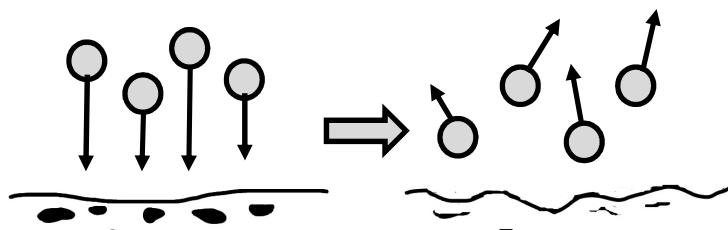
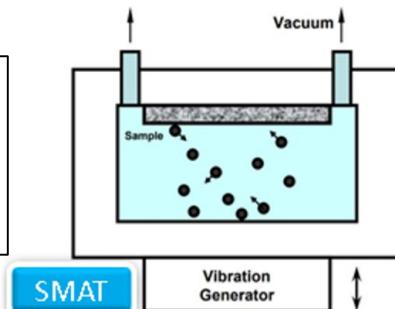




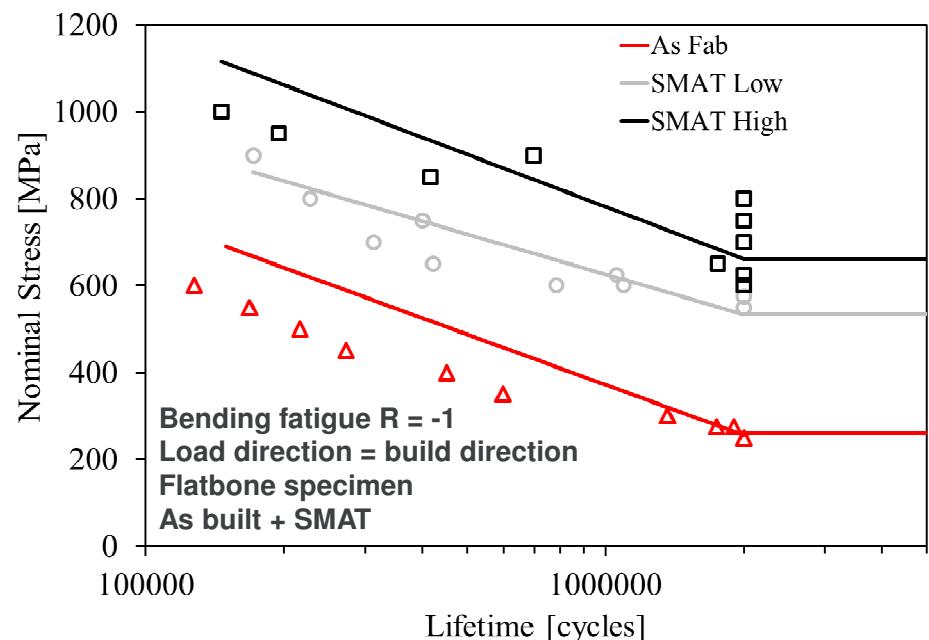
## 4. Surface deformation

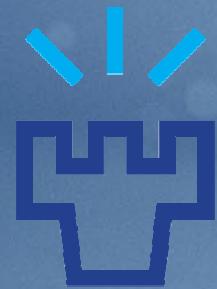
Troyes University

**Severe mechanical attrition treatment (SMAT): Novel technic**  
- Round steel balls  
- Significant plastic deformation



Similar effect can be achieved with optimized shot peening treatment ?

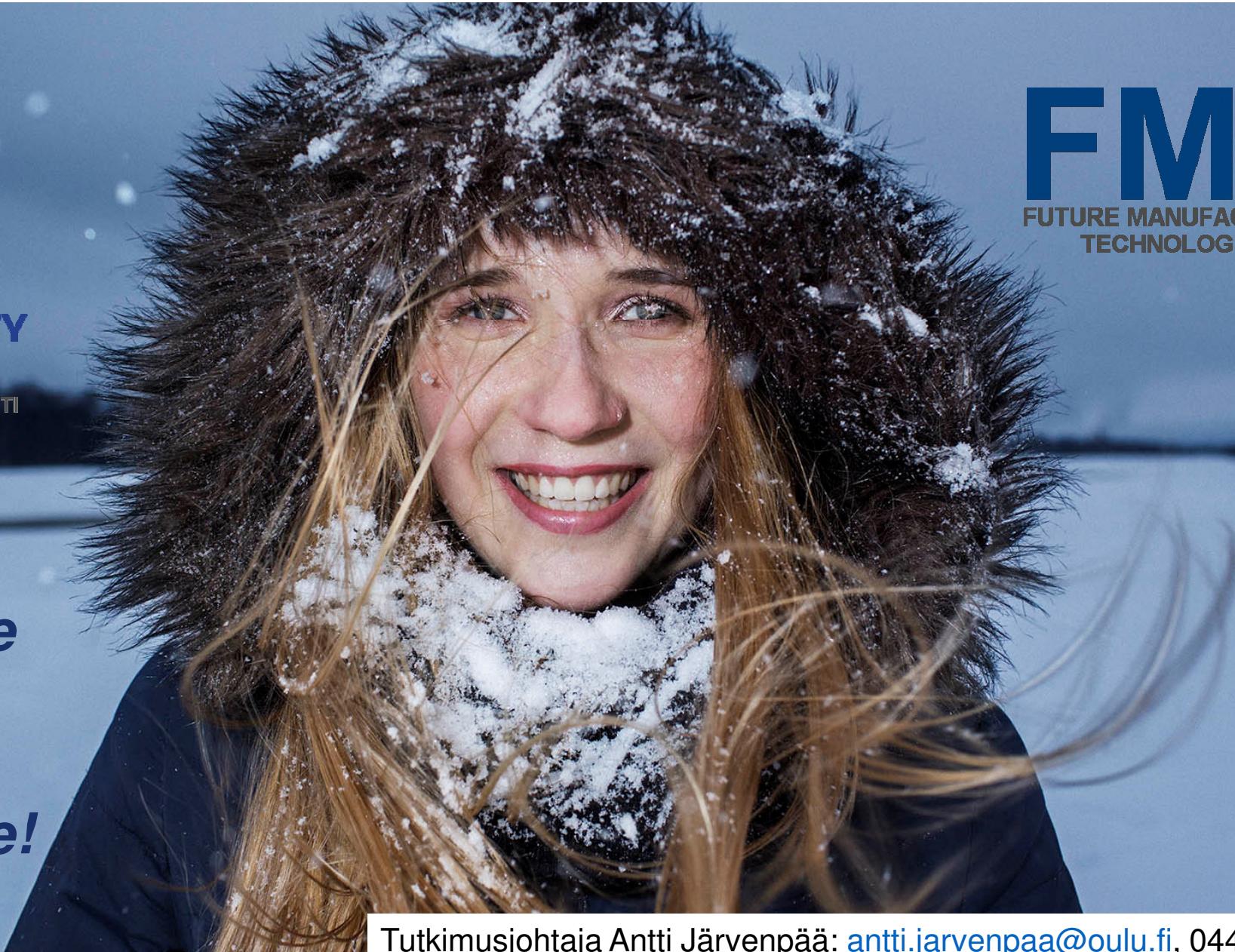




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KERTTU SAALASTI  
INSTITUTE

*Science  
With  
Arctic  
Attitude!*



**FMT**  
FUTURE MANUFACTURING  
TECHNOLOGIES

Tutkimusjohtaja Antti Järvenpää: [antti.jarvenpaa@oulu.fi](mailto:antti.jarvenpaa@oulu.fi), 0445551633