Fatigue of 3D Printed Parts

FUTURE MANUFACTURING TECHNOLOGIES (FMT) – DAY
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2. Fatigue
3. Equipment and sample preparations
4. Factors contributing to fatigue in 3D printing
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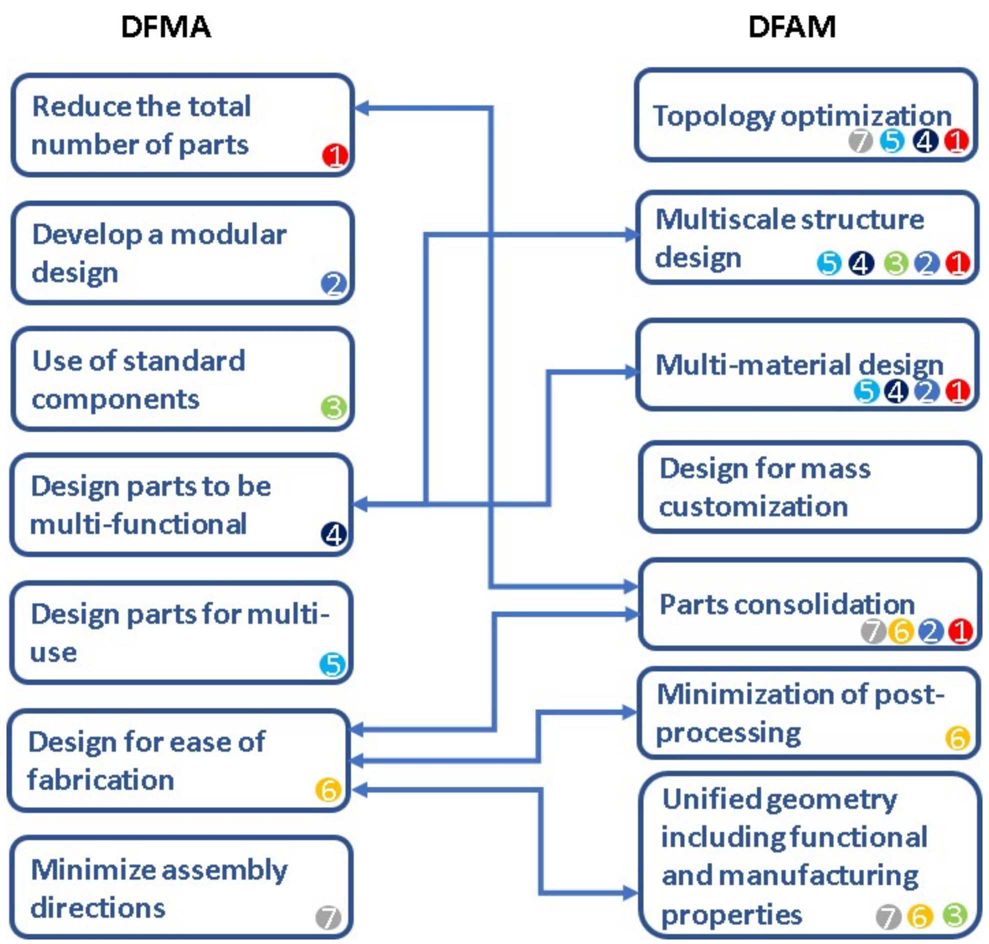
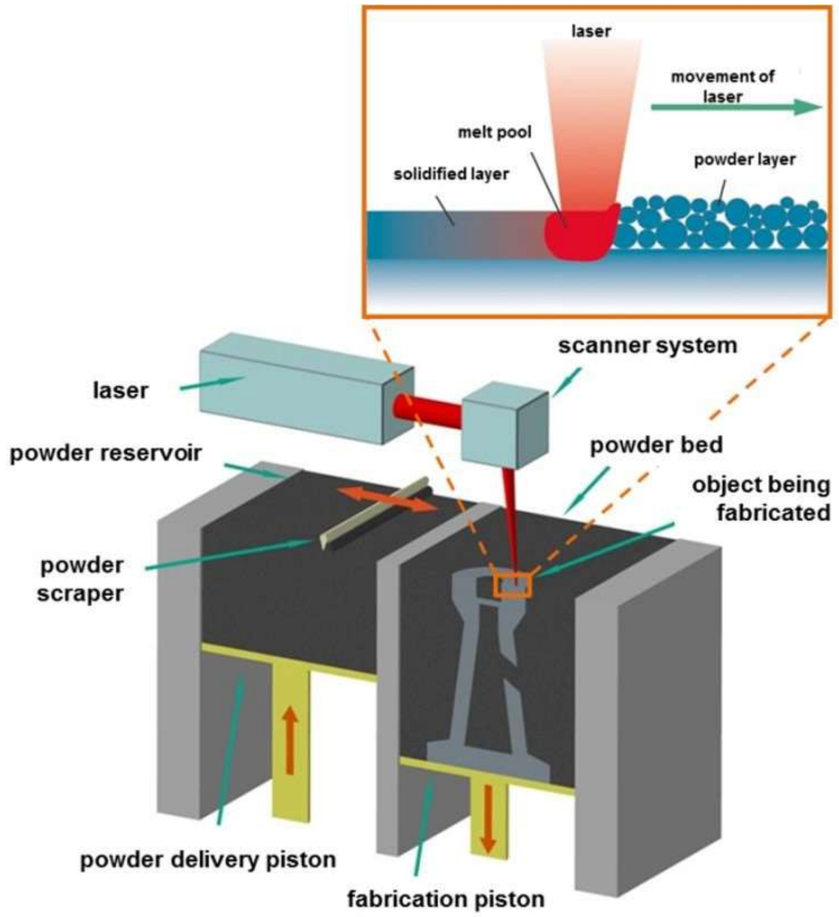
Additive Manufacturing



K. Mäntyjärvi et al., Key Eng. Mater 786, 342-347

- Additive Manufacturing (AM) is a manufacturing method which is becoming more and more common with technological development
- Most common AM method is 3D printing of plastic parts
- With metal AM parts can be manufactured cost-effectively as single pieces or small series
- Parts can be designed directly to AM (DFMA ja DFAM)

SLM



Source: Fraunhofer IWU

- With the SLM method, the metal powder is melted with a laser
- A powder scraper spreads the powder to a pre-heated platform, which the laser melts before adding the next layer → The manufactured part is built layer by layer (similar to plastic printing)
- A significantly smaller porousness is achieved compared to sintering (SLS) (even less than 1%)
- The manufactured part still requires heat treatment (relief annealing) after the printing
- Lots of controllable parameters!

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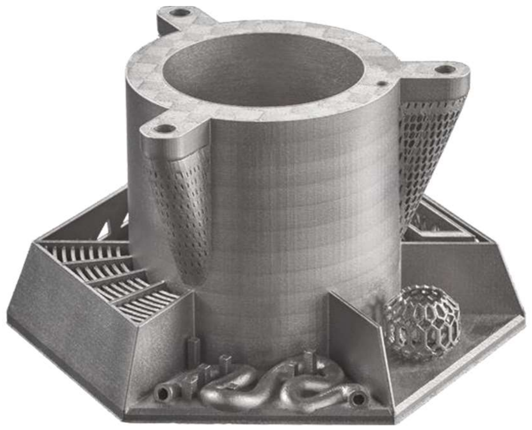
Why Fatigue Testing?



- AM parts are often designed to targets, where dynamic strain takes place
- Stress amplitudes leading to fracture significantly lower than yield strength!
- Material can get fatigued even if plastic deformation doesn't happen! (almost completely elastic load)

- **Even though the process in AM materials is the same as in sheet material, the factors are different/there are more of them!**
  →Manufacturing process affects this significantly!

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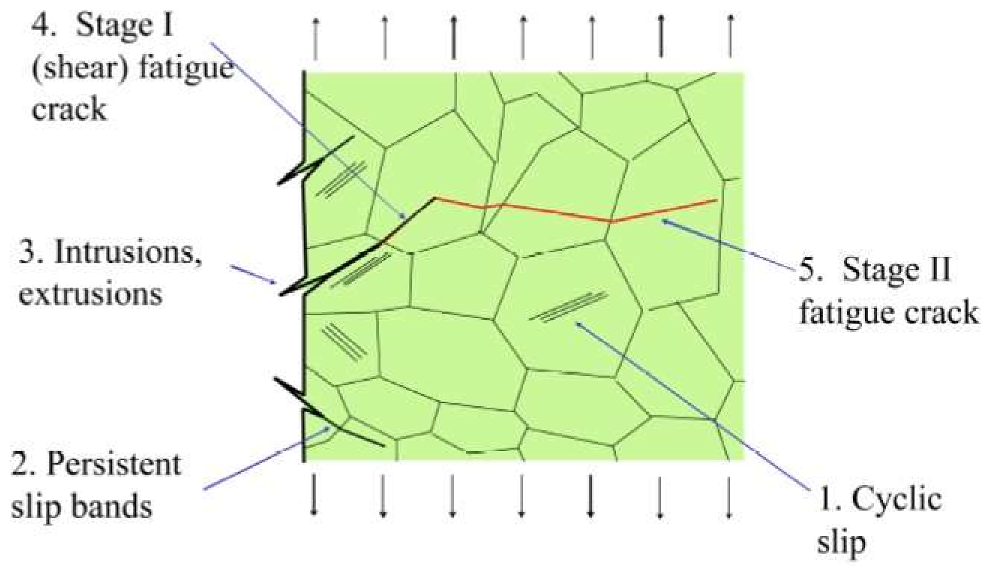
Phases of Fatigue



Kuva 27. Väsymisen vaiheet. /15/.

1. Cyclic strengthening / softening
2. Creation of slip bands
3. Distortion nucleation into discontinuities
4. Stage 1 fatigue crack (shear stress)
5. Stage 2 fatigue crack (vertically to the main tension level)
6. Final fracture

Source: http://fcp.mechse.uiuc.edu/media/pdfs/02_fundamentals.pdf

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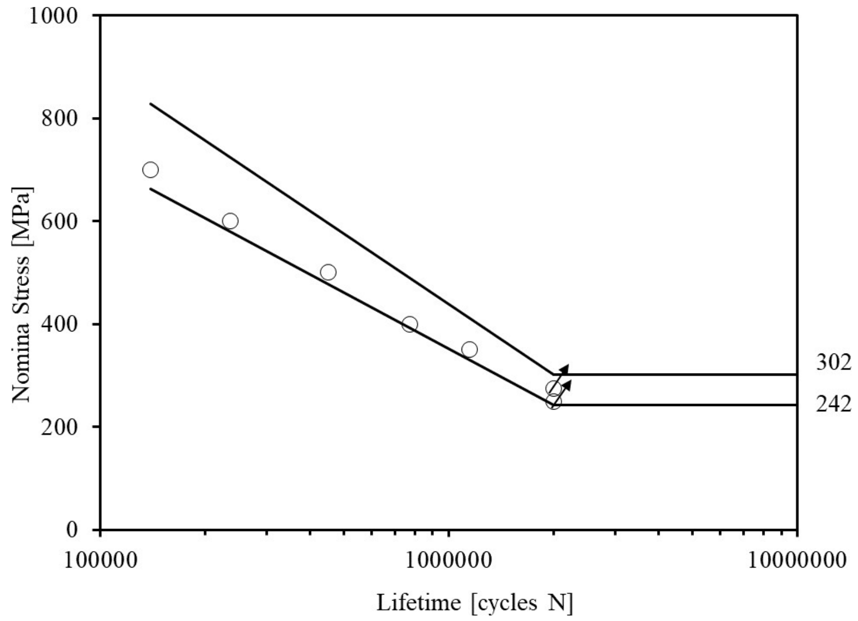
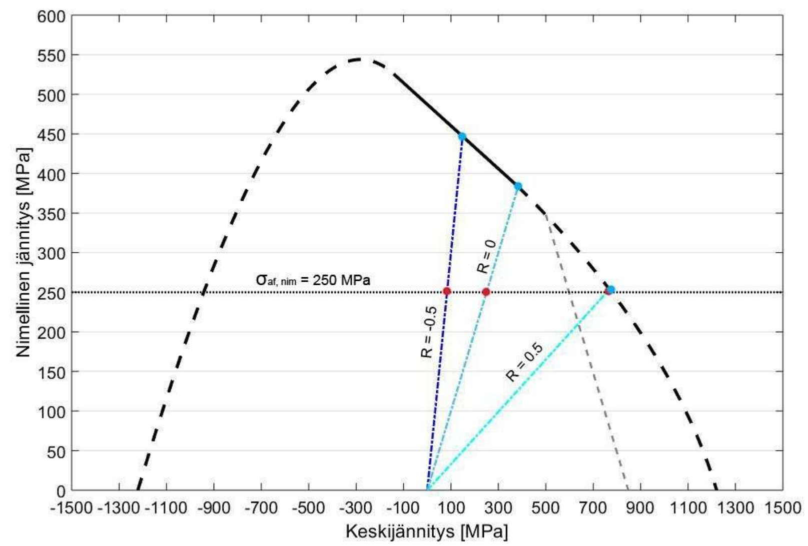
Fatigue



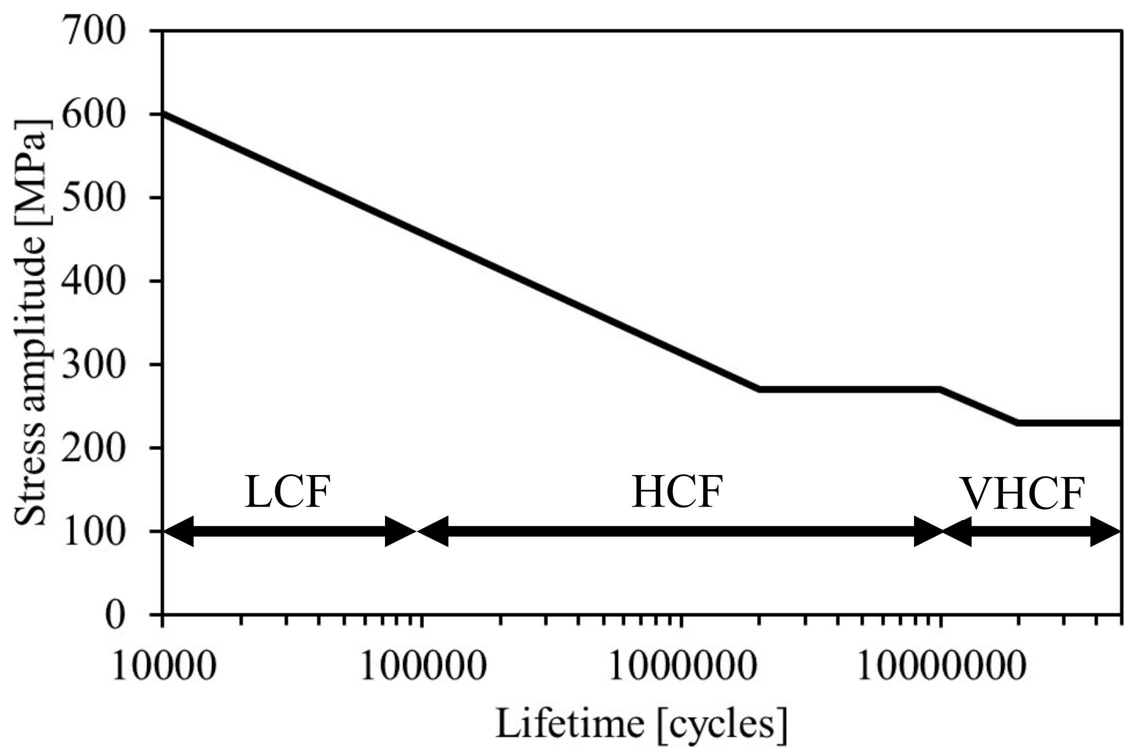
$$FAT50\% = \left(\frac{\hat{C}}{N_f}\right)^{\frac{1}{m}}$$

$$C = \Delta\sigma_i^m \cdot N_i$$

- Fatigue behavior is often expressed with S-N-curves (Stress-Number)
- In addition to statistical examination, fatigue can be studied qualitatively, for example, in terms of microstructure
- Material fatigue limit can be determined with some accuracy → dimension optimization



S-N Curve



- Steels usually have some sort of fatigue limit; below which load changes won't cause fractures.
- For example, aluminum does not have a fatigue limit!

- **LCF in region (N < 100 000) Fatigue follows Coffin-Manson's law**
- **HCF in region (N > 100 000) Basquin's equation**
- **Especially strong materials show a second fatigue limit in the VHCF region!**

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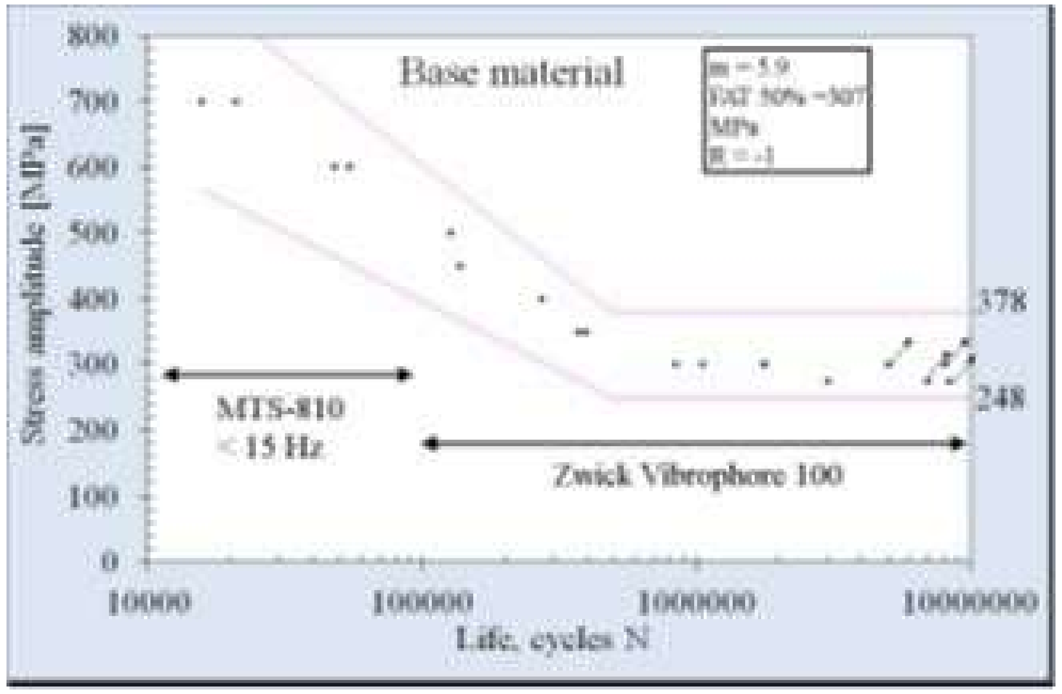
Equipment

Axial



- Zwick Vibrophore
- ± 50 kN
- 45-200 Hz

MTS 810 and Instron

- ± 200 kN
- < 15 Hz

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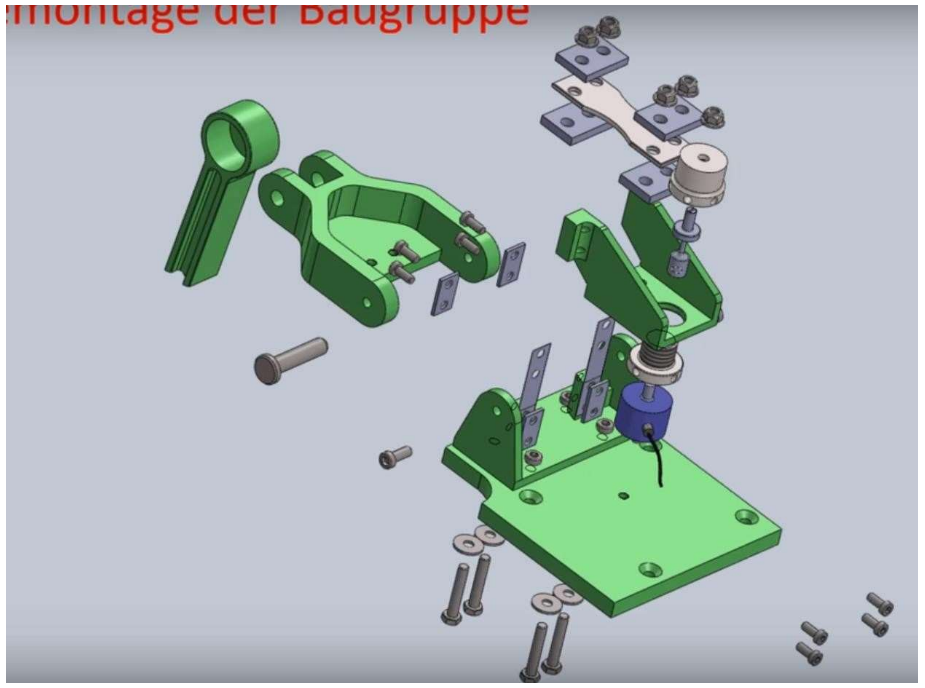
Bending Fatigue

- Bending fatigue machine Carl- Schenck “WEBI”
- Originated in the 70’s
- Fatigue frequency 23 Hz
- Instrumented by FMT
- Transition measurement
- Automatic cooling
- Datalogging



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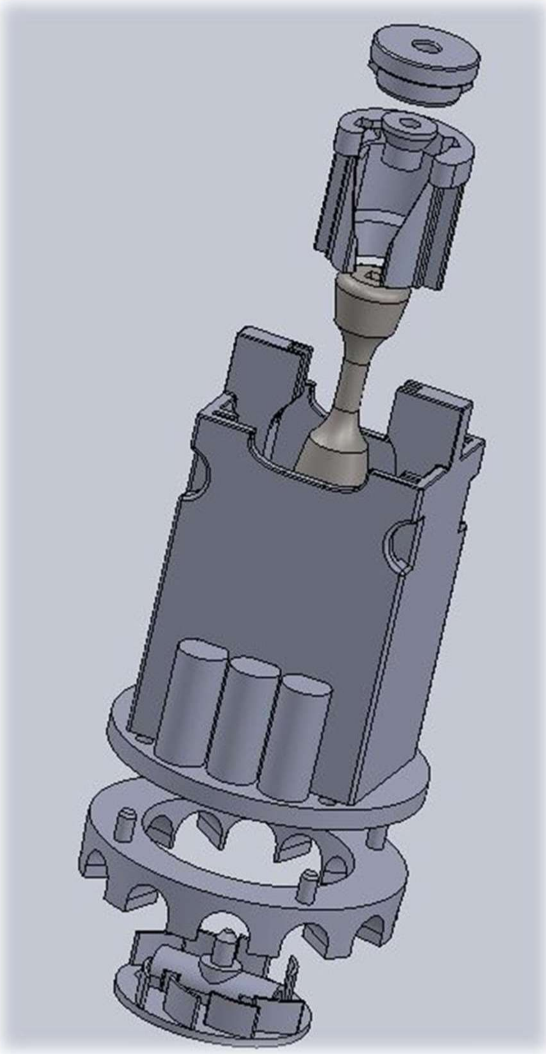
Sample Preparations



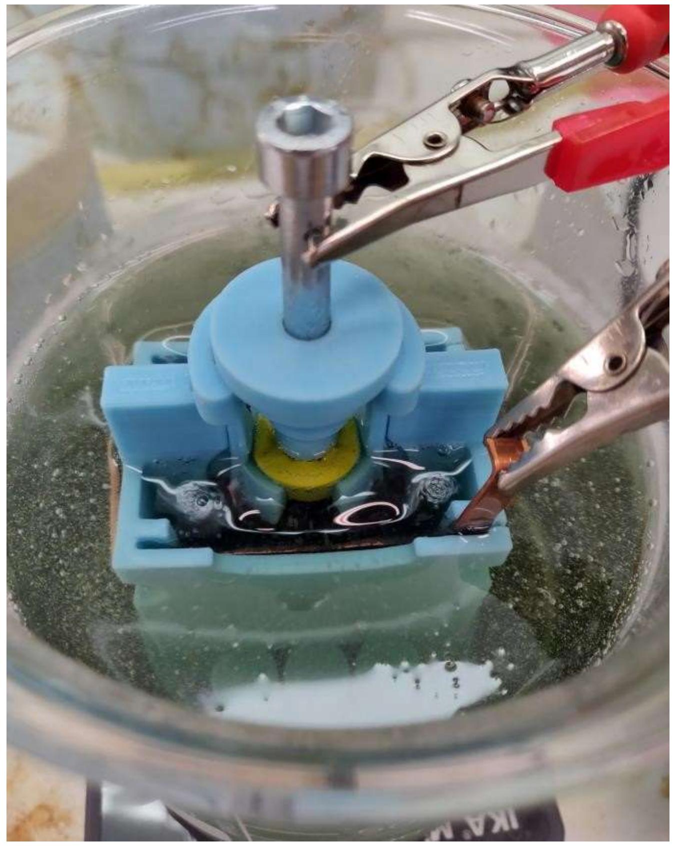
- The quality of the samples needs to be controlled (even surface quality) in order to achieve uniform fatigue tests
- Post-processing procedures should be minimized after the printing
- When studying the effects on microstructure, the sample surface needs to be polished
- Mechanical polishing is slow and difficult on sheet samples → corners and polishing errors

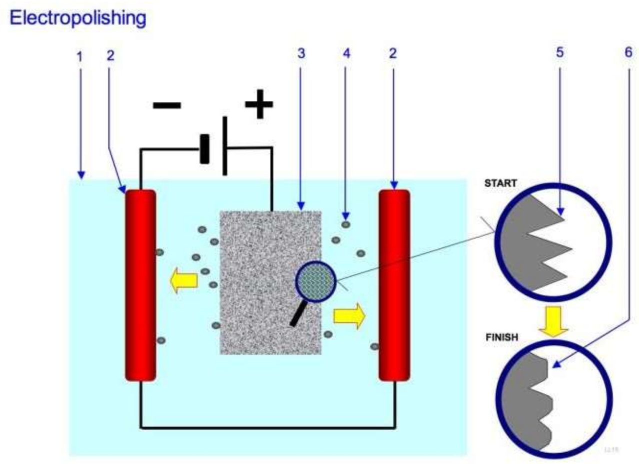
- You can polish the entire sample with electrolyte polishing → Deformation free surface!

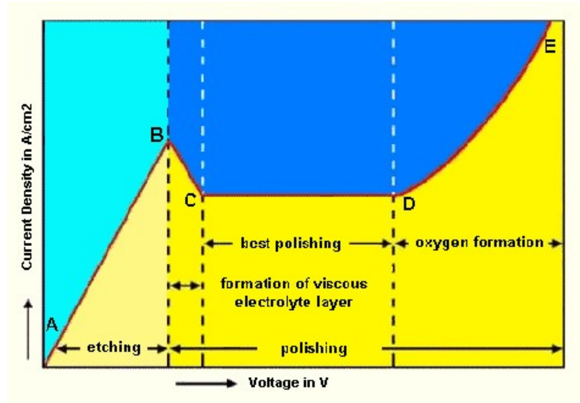
- For flat and round poles
- Almost all metals can be polished

Sample Preparations

- Operation principle: electrochemical cell (anode-cathode), DC and acid mix
- Polished piece
- Temperature dependent

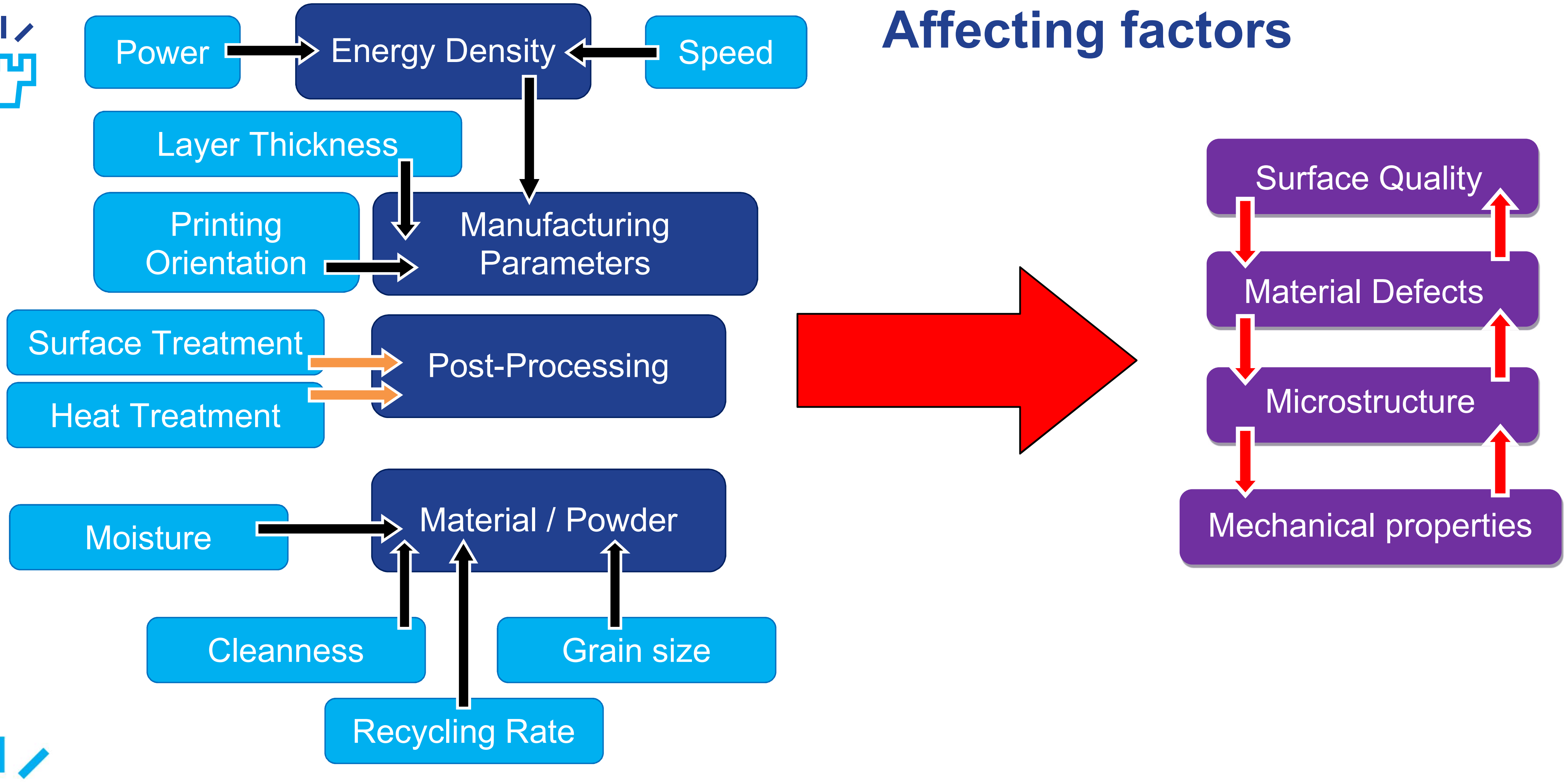






Properties affecting fatigues

Affecting factors



Surface Quality

- Surface quality of the printed parts rough (Ra > 10 µm)
- Pores
- Discontinuities on surfaces cause local stress concentrations (slit effect)
  ➔ fatigue resistance weakens in HCF region

Material Defects

- Inclusion
- Pores
- Cracks
- Material defects above critical size nucleate the premature crack
  → Weaken the fatigue resistance

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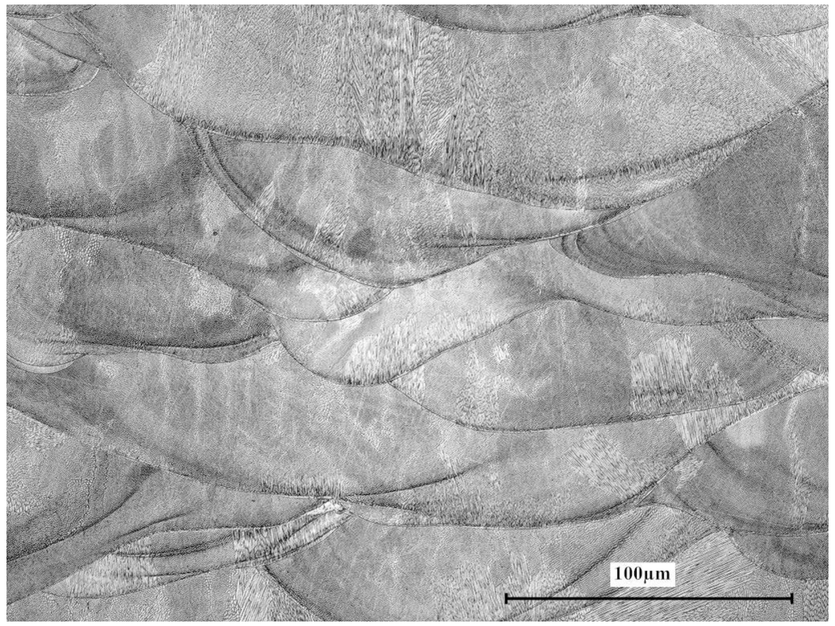
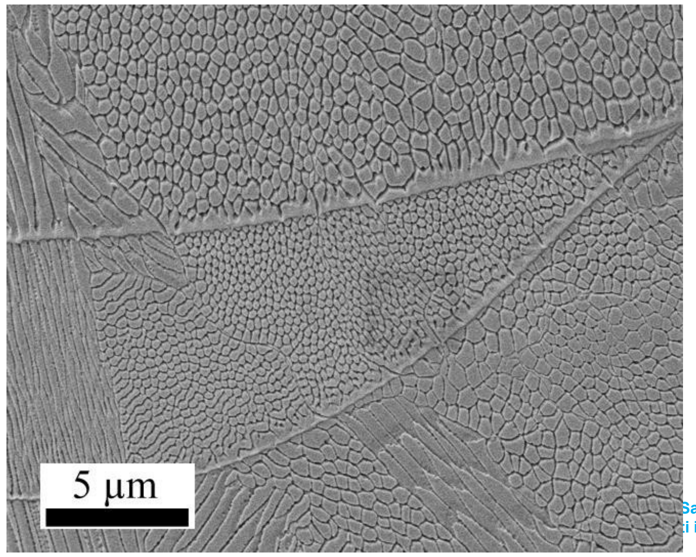
Microstructures

- **Microstructure created by the SLM method affects the strength and toughness properties**
- **316L: ”Pod-like” microstructure**
- **Cell-like sub-structure**
- **In addition, e.g. AlSi10Mg creates multiple phases in SLM**
  - →Tougher aluminum phase
  - →Hard and fragile silicon eutectic on grain boundaries (weakens the toughness properties)





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Mechanical Properties

- Strength and toughness properties greatly influence fatigue resistance
- Strengthening ability helps
- On the other hand, great strength and small deformation ability cause the material to soften

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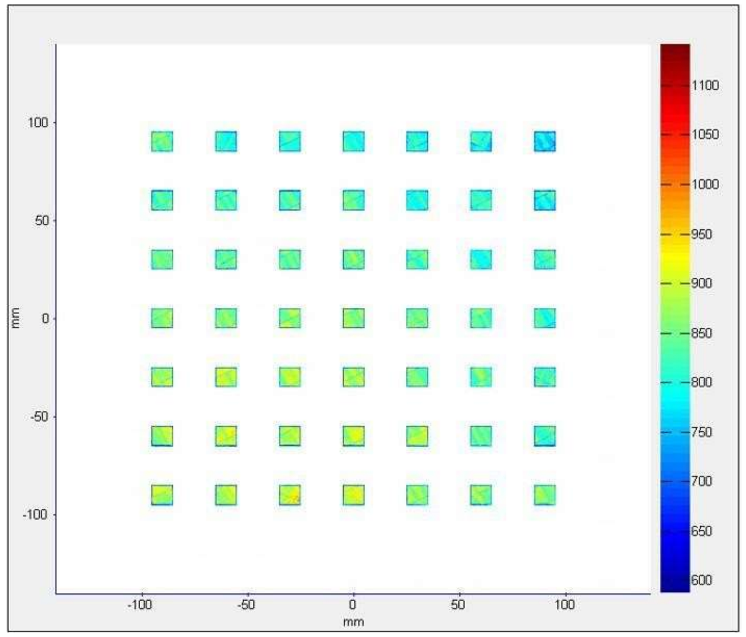
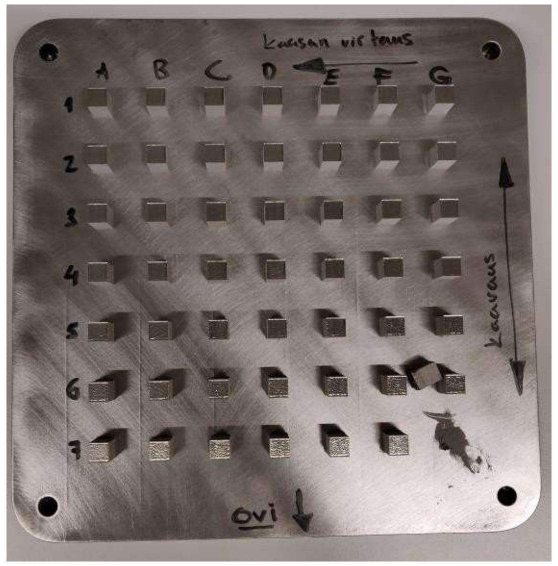
Results

Effects of Printing Parameters





- Printing parameters influence the achieved microstructure and properties
- By increasing the energy density, you can decrease the porosity
- Too high heat input causes gasification and balling
- Too low heat input increases porosity (cf. sintering)
- Test series on parameters effects
- The chosen test series included examples from the extremes, i.e. low and high energy densities

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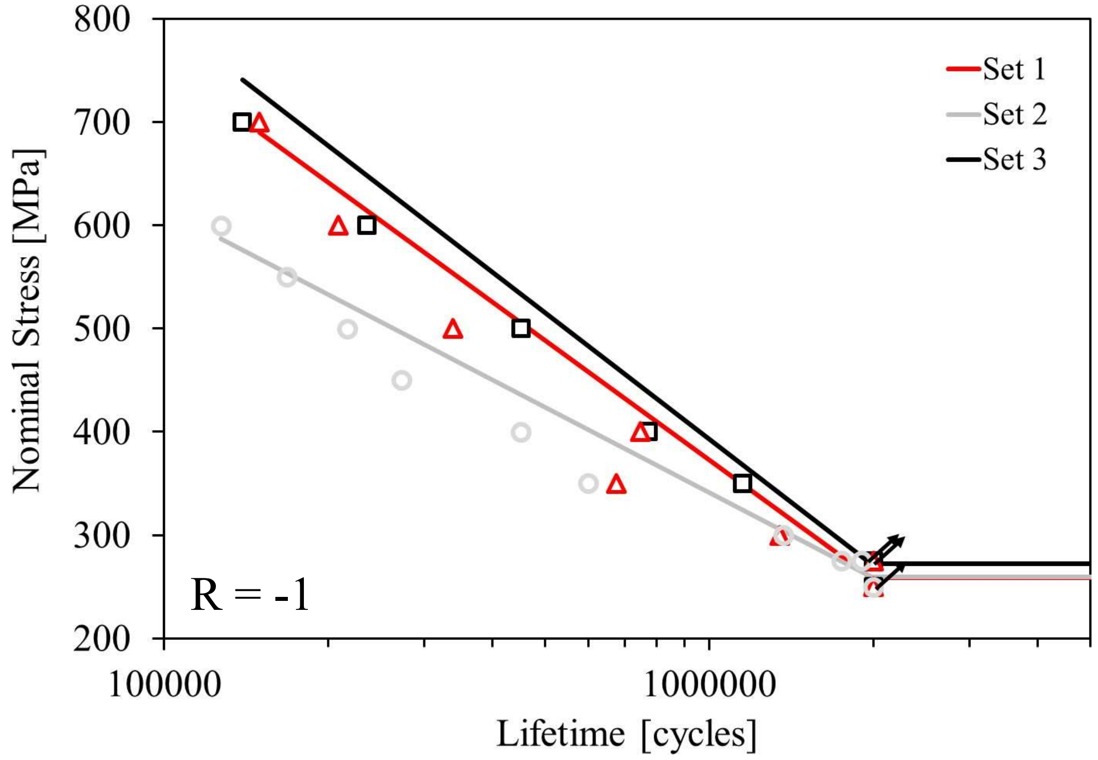
Effects of Printing Parameters



- Control of the state of residual tension (polishing has no effect)
- No HCF advantage (material defects are always found, unlike in sheet or rod material)
- In the LCF region the larger strength improves fatigue resistance
- What are the most cost-effective cost parameters?

	YS *[MPa]*	UTS *[MPa]*	UE *%*	TE *%*
Set 1	491	645	15.9	30
Set 2	504	660	17.1	31.7
Set 3	538	701	18.6	33.4

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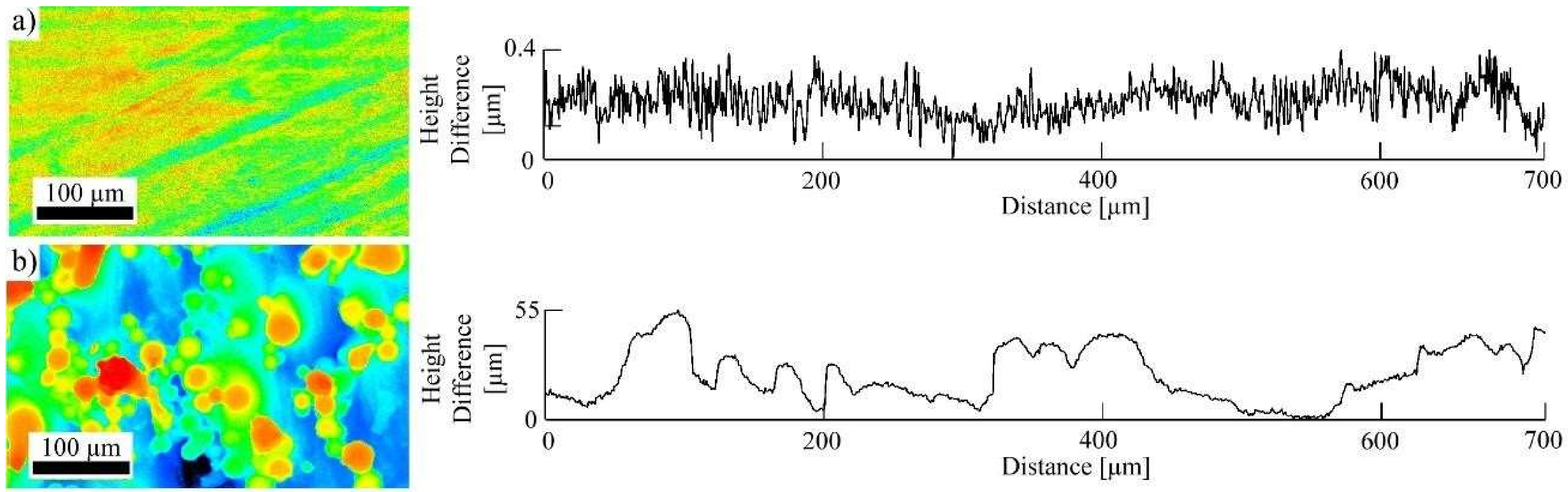
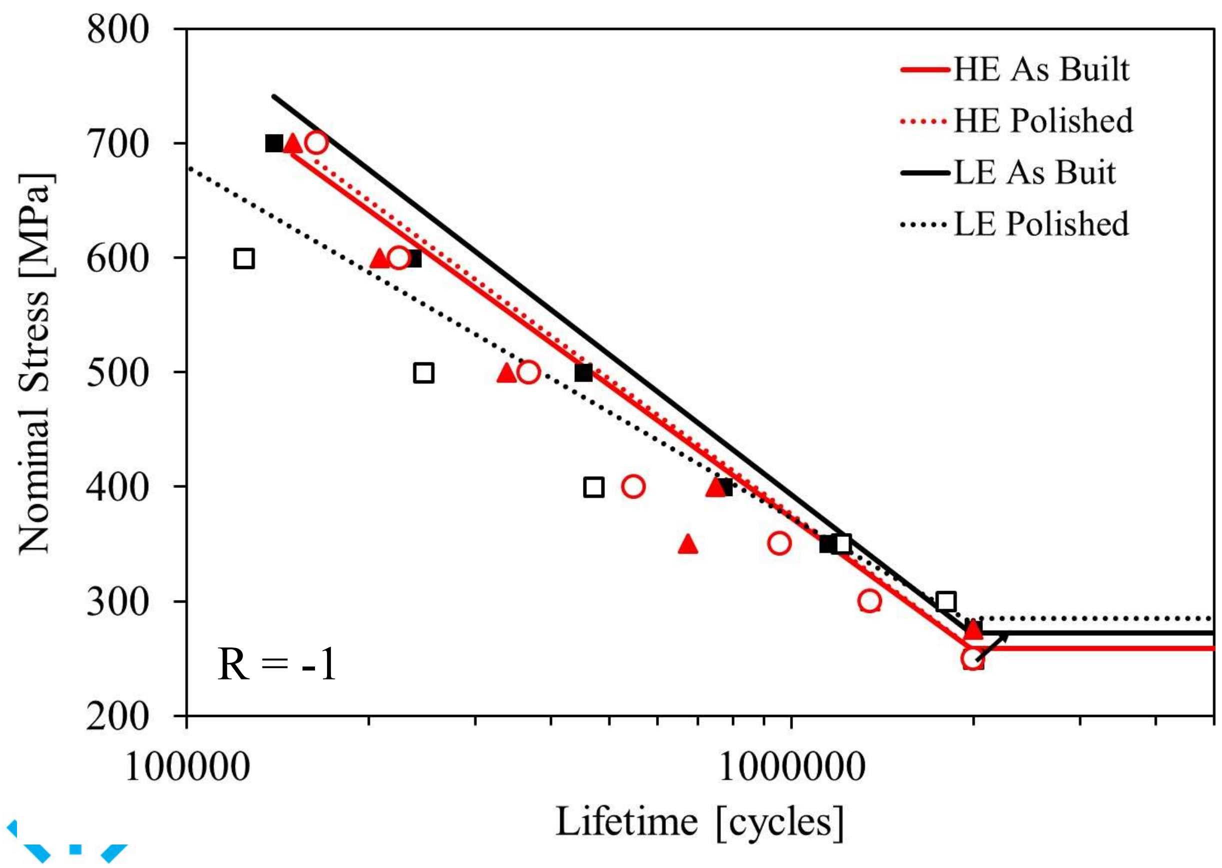
Effects of Surface Quality

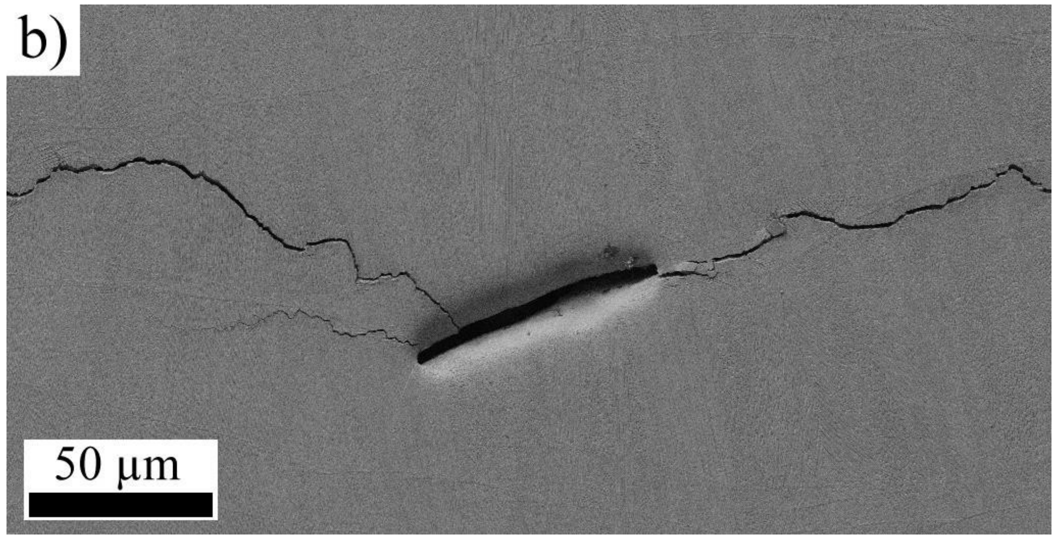
- Surface quality has a significant effect on fatigue resistance in sheet material
- Accentuated with strong materials
- Printed and polished surface
- Ra 13 and 0.2 µm



Effects of Surface Quality



- Despite the lower Ra value there was little improvement in the HCF area
- Fatigue resistance was even weaker in polished samples
- Reason for this was in the material's porosity!



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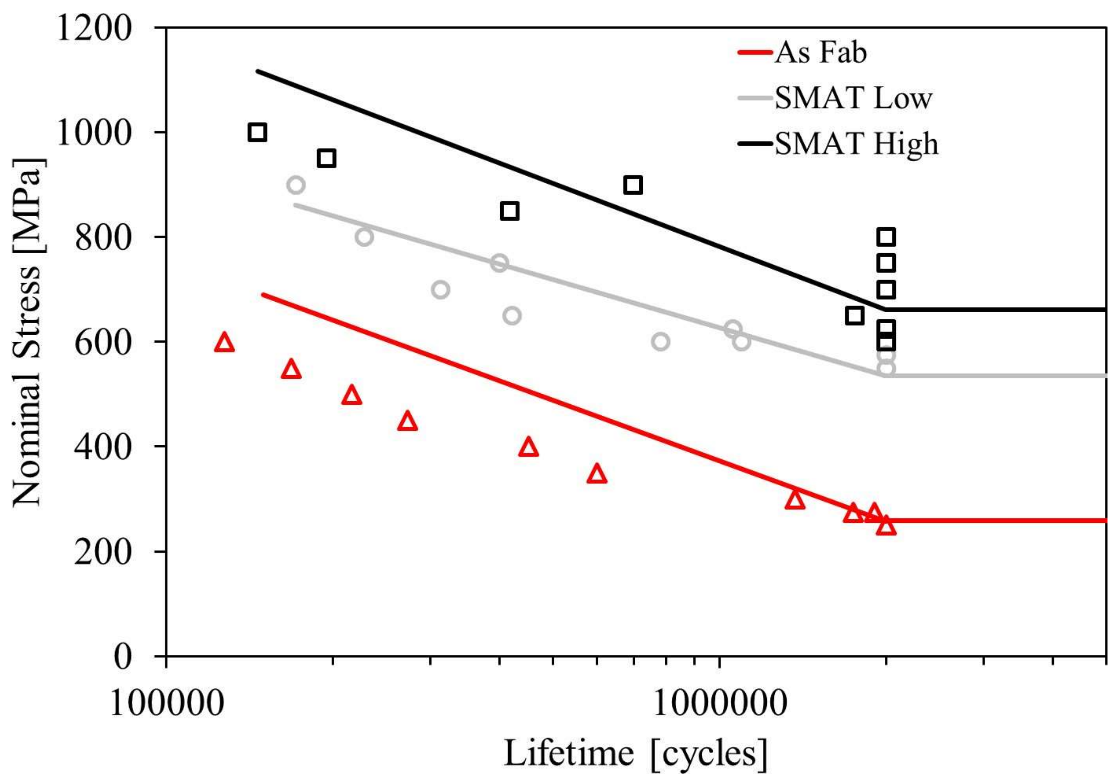
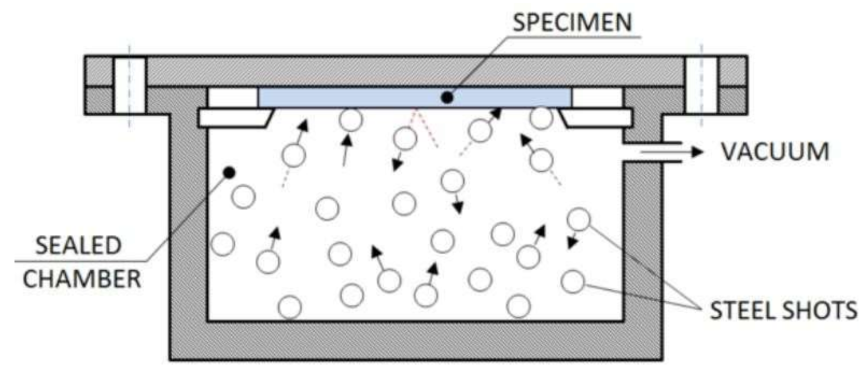
Effects residual tension – SMAT treatment



- Surface Mechanical Attrition Treatment
- The treatment is used to cause high compression stresses on the surface
- Fatigue limit increases with SMAT treatment significantly compared to the basic substance!
- Closes off pores on the surface and improves surface quality



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Further Developments

- ”Cloning” and developing the bending fatigue machine
- Possibility to multiple machines side-by-side → efficient fatigue testing for printed material

- SMAT-treatment developed to larger scale
- Laboratory sized equipment for FMT in Nivala.
- Scaling possibilities?

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Thank you!

Sources

1. *D. Raabe et al. Mater. Sci. Forum 157–162 (1994) 597–610*
2. *V. Massadier et al., Metall. Mater. Trans. A 43A (2012) 2012–2225*
3. *K. Matsudo et al., Texture of Crystalline Solids 3 (1978) 53–72*
4. *C.W. Sinclair et al, Adv. Eng. Mater. 5 (2003) 570–574*

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