PBF-LB of Large-Area Magnesium WE43 Structures Surface-Enhanced by Plasma Electrolytic Oxidation

Arvid Abel[1] · Anutsek Sharma[2] · Hannes Holländer[1] · Dawn Zheng[1] · Nicole Emminghaus[1] · Anna Buling[2] · Jörg Hermsdorf[1] · Jörg Zerrer[2] · Stefan Kaierle[1,3]

1 Laser Zentrum Hannover e.V.
2 ELB – Helmut Zerrer GmbH
3 Institute of Transport and Automation Technology, Leibniz University Hannover

Motivation

- Magnesium as a lightweight material
  - » Density of 1.8 g/cm^3
  - » High specific strength (rivals aluminum)

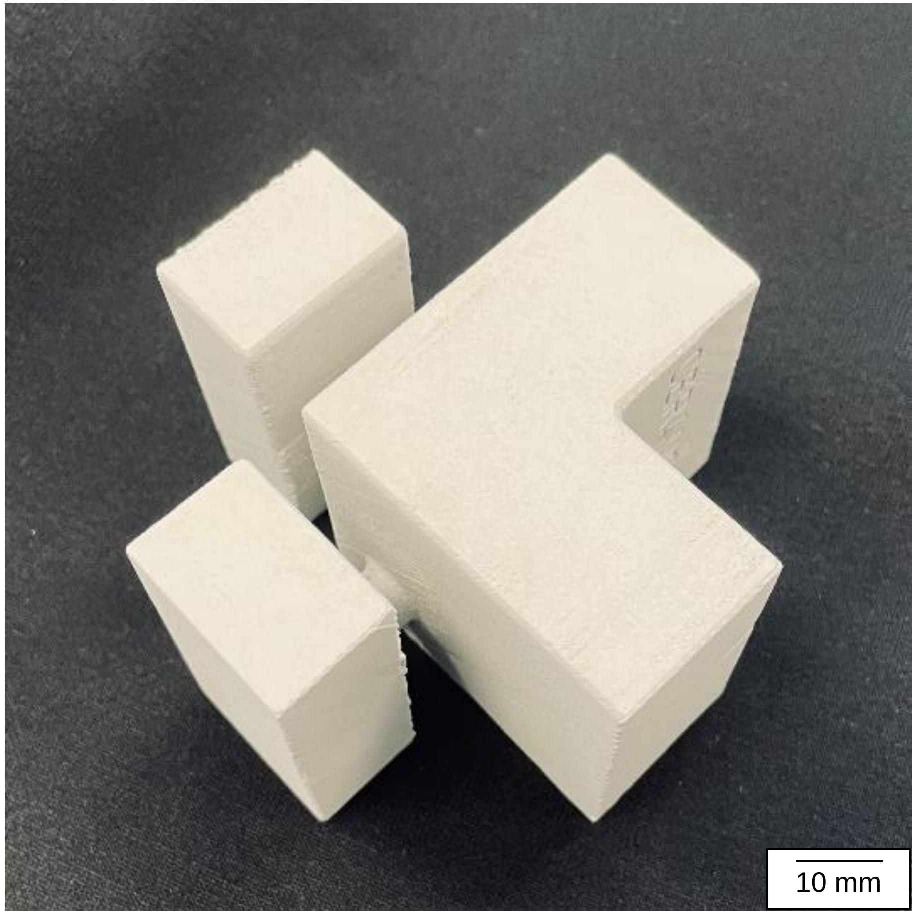
- Main application of additively manufactured magnesium: Biodegradable implants
- More applications in aerospace, motorsports, outdoor, and general lightweight construction

- Challenge:
  - » Strong oxidative behavior
  - » No closed passivating oxide layer

Cranial implant lattice demonstrator

Solution

- Synergy between the PBF-LB/M and the Plasma Electrolytic Oxidation (PEO)
  - » Benefits of AM: Freedom of design and material, functionalization, …
  - » Surface enhancement of the oxide layer with a ceramic
- PBF-LB of large-area parts of Mg WE43
  - » Paving the way for larger geometries
- PEO of ceramic surface
  - » Mitigate oxidation
  - » Protect surfaces from wear



ELB-Logo: Ceramic surface on magnesium part

Ceramic Additively Manufactured Magnesium

LASER ZENTRUM HANNOVER e.V.

- Joined ZIM-Project of
  - » Laser Zentrum Hannover e.V.
  - » ELB – Helmut Zerrer GmbH

Supported by:

Federal Ministry for Economic Affairs and Climate Action

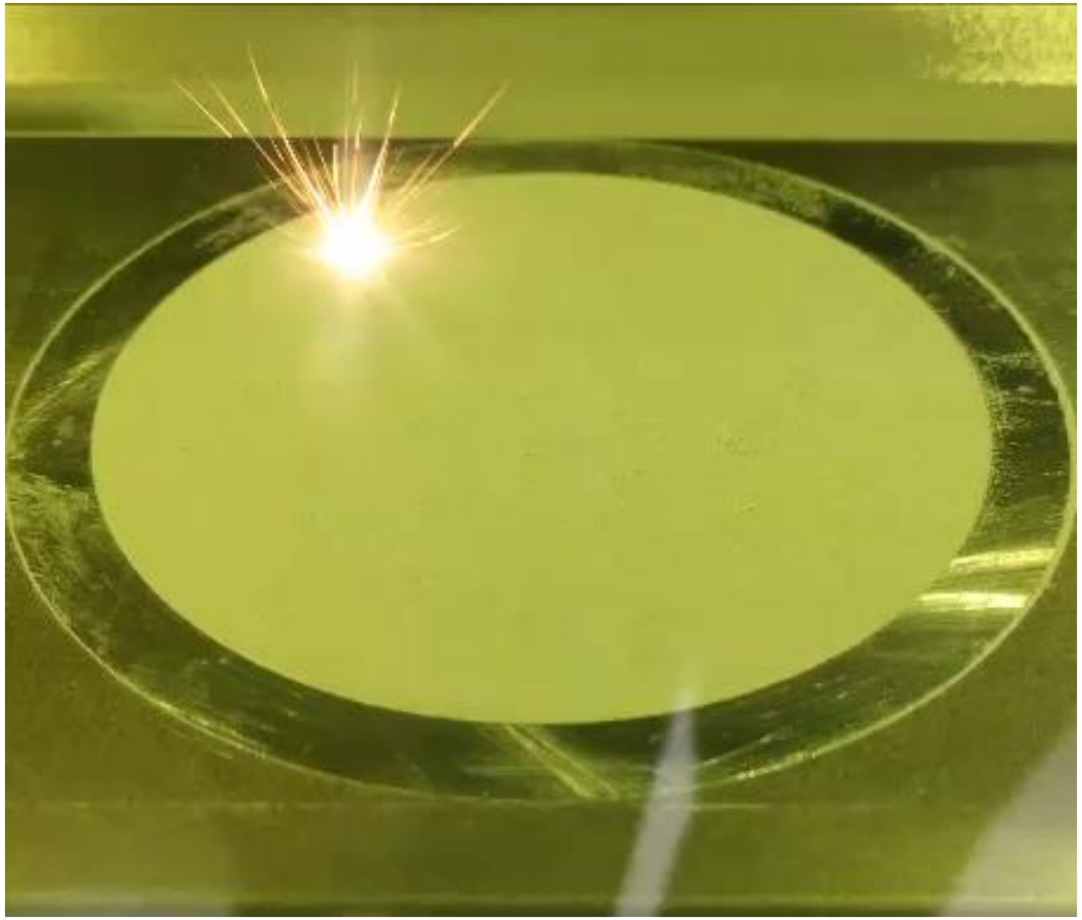
on the basis of a decision by the German Bundestag

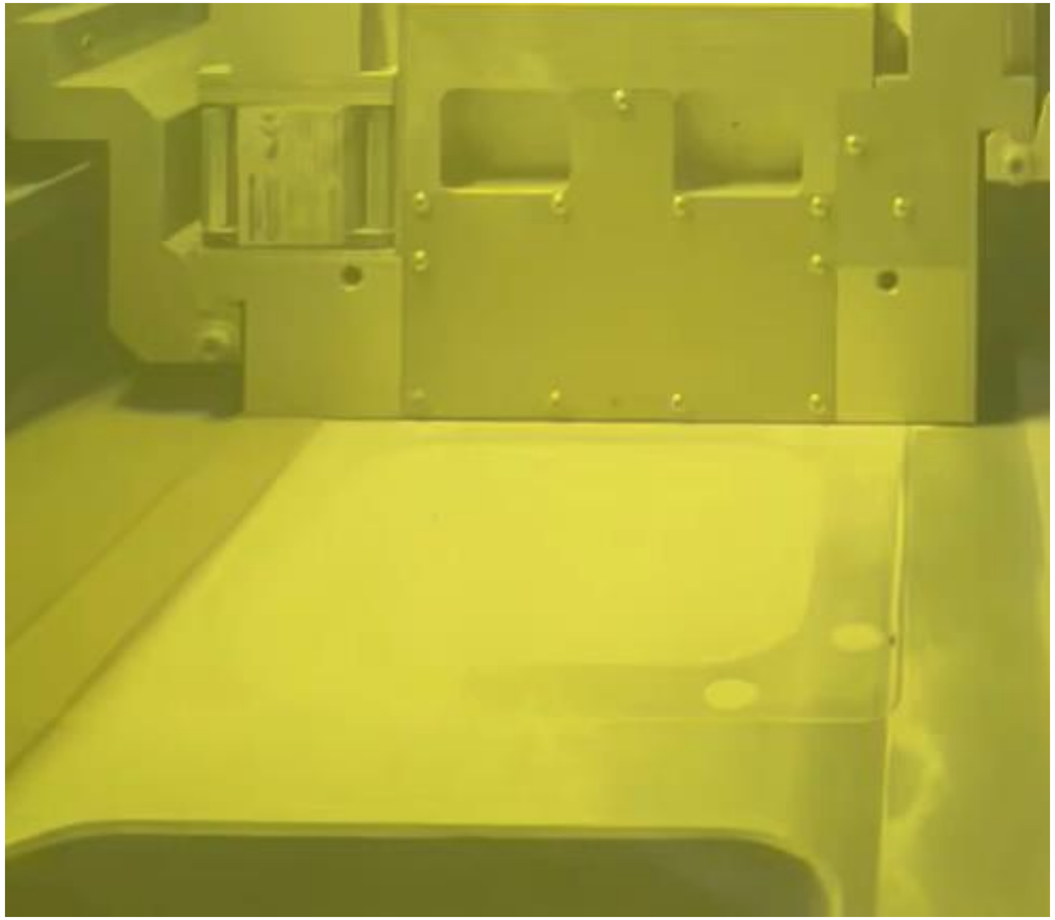
- Expertise in AM:
  - » PBF, DED (Powder & Wire)
  - » Construction of special PBF systems
  - » Entire value chain of lasers (optics, laser, processes)
- Expertise in surface modification
  - » Especially of light metals (Mg, Al, Ti)
  - » (Hard-)Anodizing, Ultraceramics®
  - » Polymer or hybrid coatings

Top: LZH AM area; Bottom: ELB site

Comparison of process videos

- Differences in processing behavior:





Process video: PEO of Magnesium

- Plasma Electrolytic Oxidation of cylindrical specimen
  - » Ceramic in solution of electrolytes:
    - – Potassium hydroxide (KOH)
    - – Sodium metasilicate (Na_2SiO_3)
    - – Sodium Diphosphate ($Na_4P_2O_7$)
  - » Pulsed energy application to generate plasma
  - » Adjusting voltage, duration, concentration

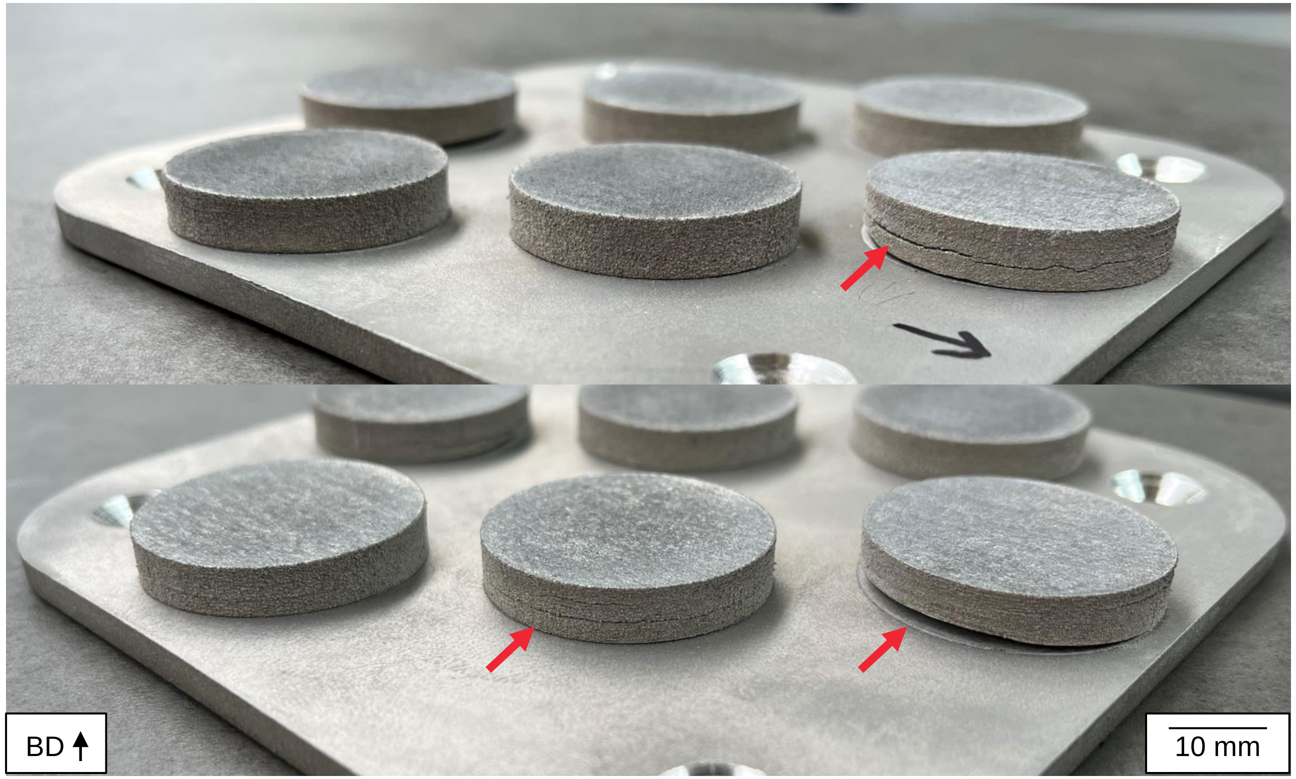
- Aim of PEO:
  - » Using plasma to melt the magnesium oxide layer
  - » Inclusion of ceramics in the outer layer
  - » Closed surface (layer thickness 10 – 40 µm) to mitigate further oxidation
  - » General possibilities: thicknesses from 5 µm to 200 µm

PEO process video

Source: https://www.youtube.com/watch?v=e2YsTe6Iiiw

Laser-Based Powder Bed Fusion of WE43

- PBF-LB of WE43 processes conducted on modified SLM Solutions SLM125HL
- First experiment with standard parameters
  - » Laser power: 100 W
  - » Scan speed: 400 mm/s
  - » Hatch distance: 60 µm
  - » Layer height: 40 µm
- Results:
  - » Cracks in the sidewalls
  - » Curling of the specimens of the build plate

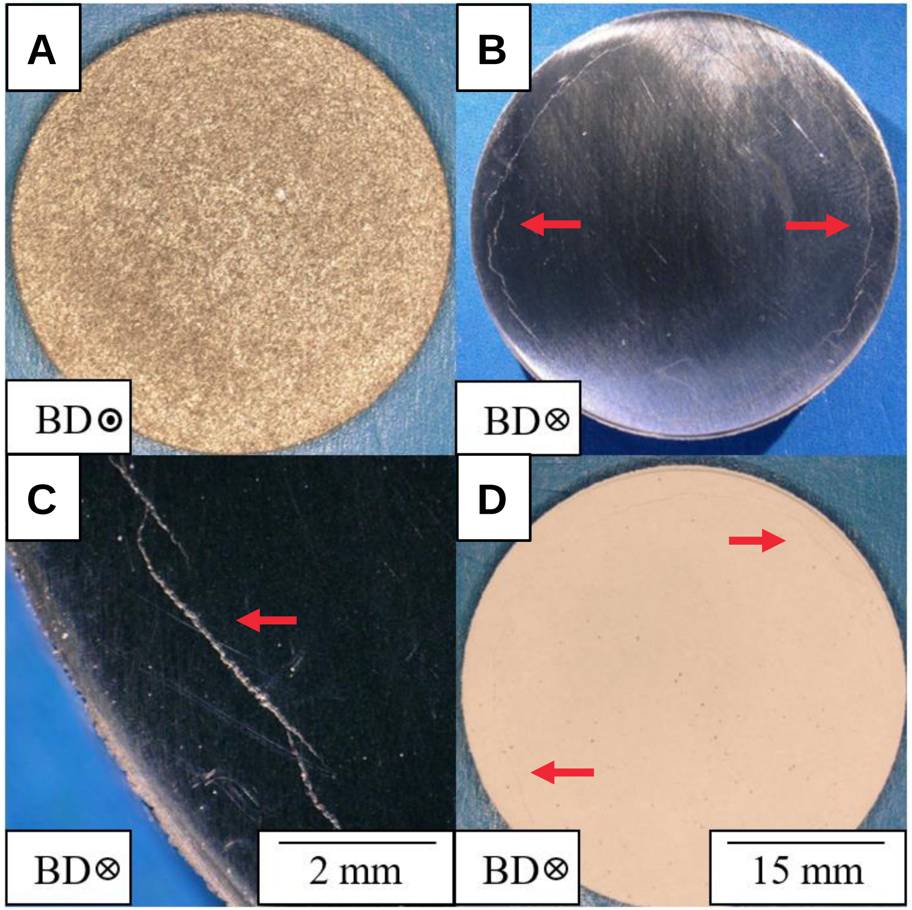


Cylindrical specimen (Ø = 31 mm, h = 6 mm) of first experiment

(BD indicates the build direction)

Laser-Based Powder Bed Fusion of WE43

- Extracted specimen without cracks in sidewall show circular crack on the bottom
- Top surface as-built, bottom surface polished for PEO
- Parts after PEO show beige surface
- Crack is still visible but enclosed
  - » PEO is feasible, further investigation of the surface

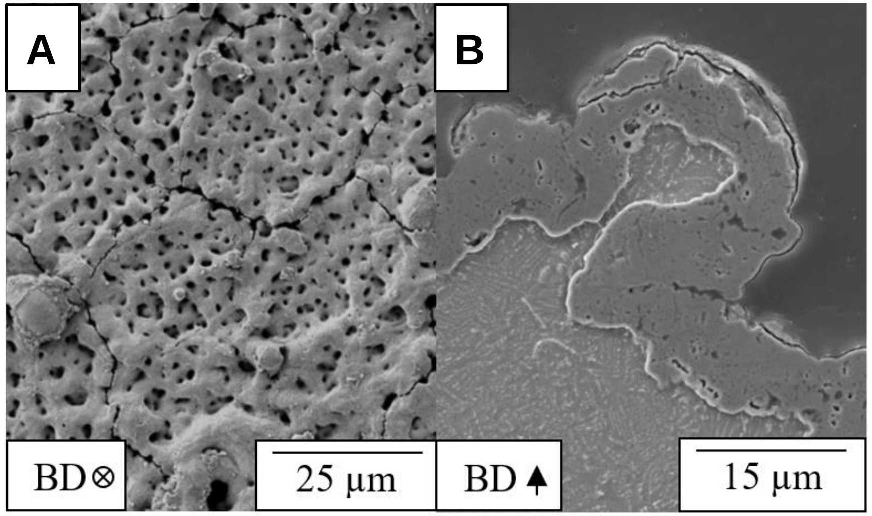


A: Top surface as-built; B: Bottom surface polished.
C: Circular crack; D: Bottom surface after PEO

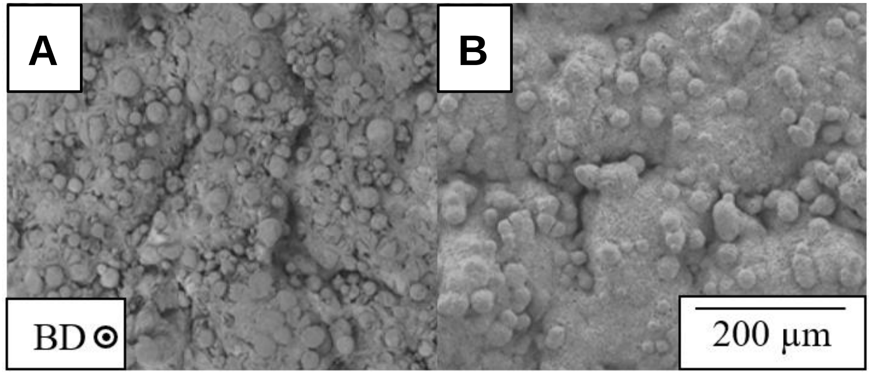
Detailed look into PEO surface

- Detailed analysis of PEO surface
  - » Layer thicknesses of 10 – 40 µm applied
  - » Ceramic layer with open cavities (0.5 – 5 µm) on the outside
  - » Closed at the interface to the WE43 specimen
  - » Fragmentation of the surface with patches of 20 – 30 µm

- Comparing the as-built surface before and after PEO in SEM
  - » Particles enclosed
  - » Ceramic smoothens out the surface
  - » Failure points: sharp cracks in the substrate
    - – Development of the PBF-LB process for crack-free parts is highly important
    - – Further investigation of the process



A: PEO surface on polished specimen
B: Cross section of as-built surface

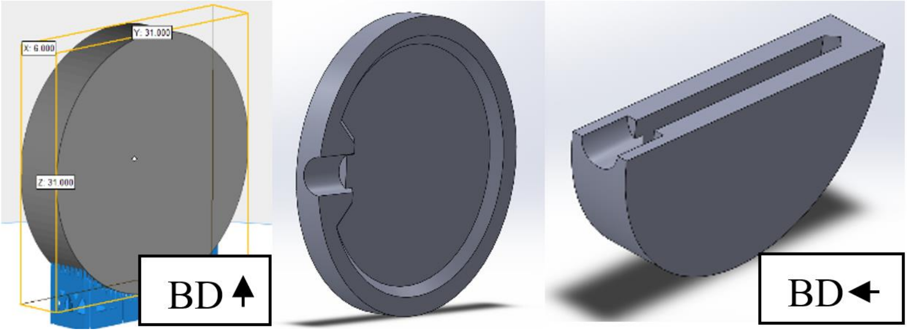


Top surface of specimens. A: as-built; B: After PEO

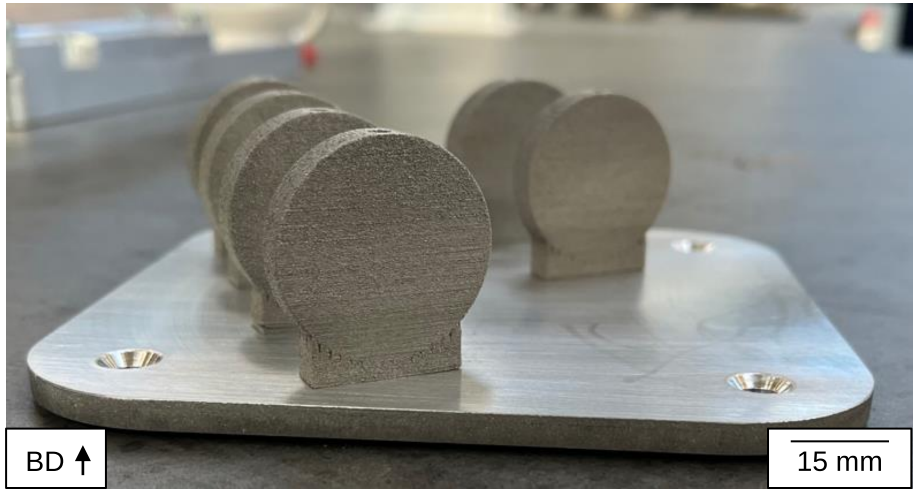
Shortening of scan vectors

- Hypothesis:
  - » Cracks occur due to solidification shrinkage in the PBF process
  - » Shortening of scan vectors should minimize cracking
- Design of cylinders with cavity
- Upright positioning in the build platform
- Variation of parameters with different energy densities

- Results:
  - » Specimens appear to be crack-free
  - » After extraction of the plate and removal of the support, cracks in layer and radial direction appear
  - » Investigating the influence of scan pattern on cracking behavior



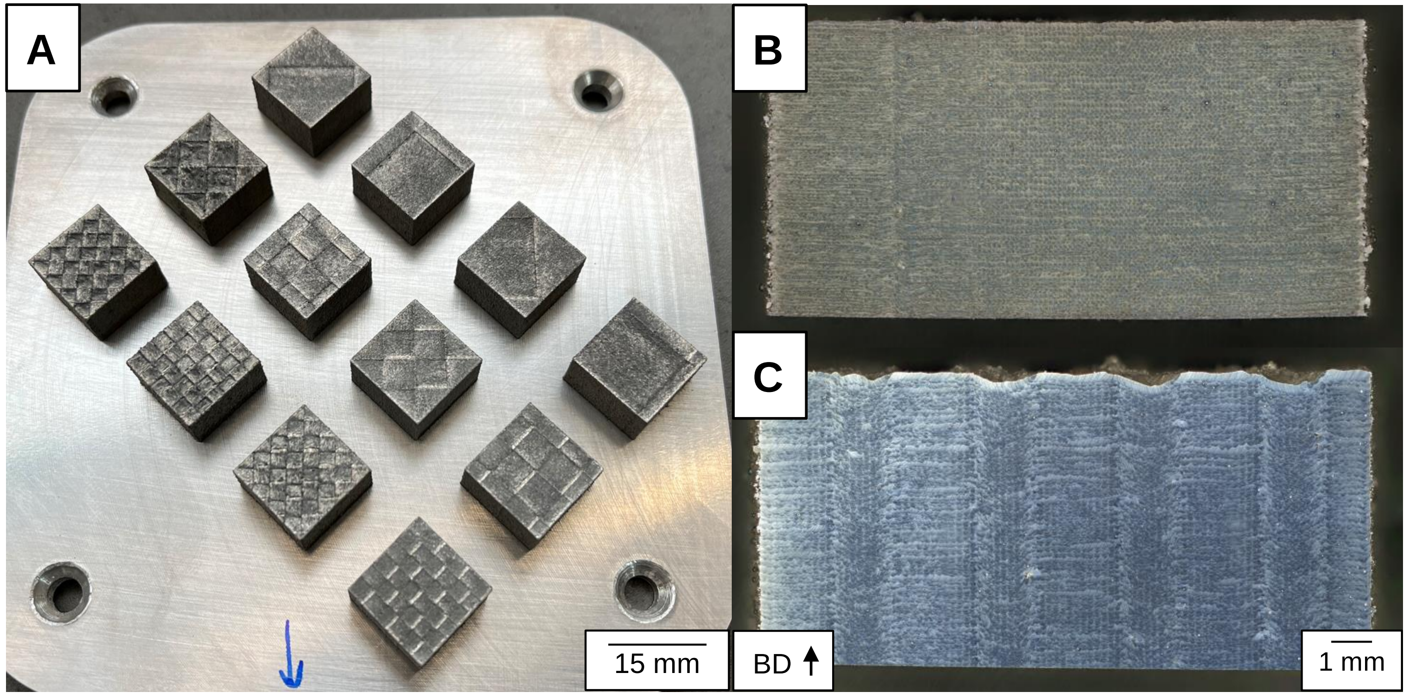
CAD geometry of hollow cylinders



As-built hollow cylinders. Crack-free appearance after PBF

Optimization of the scan strategy

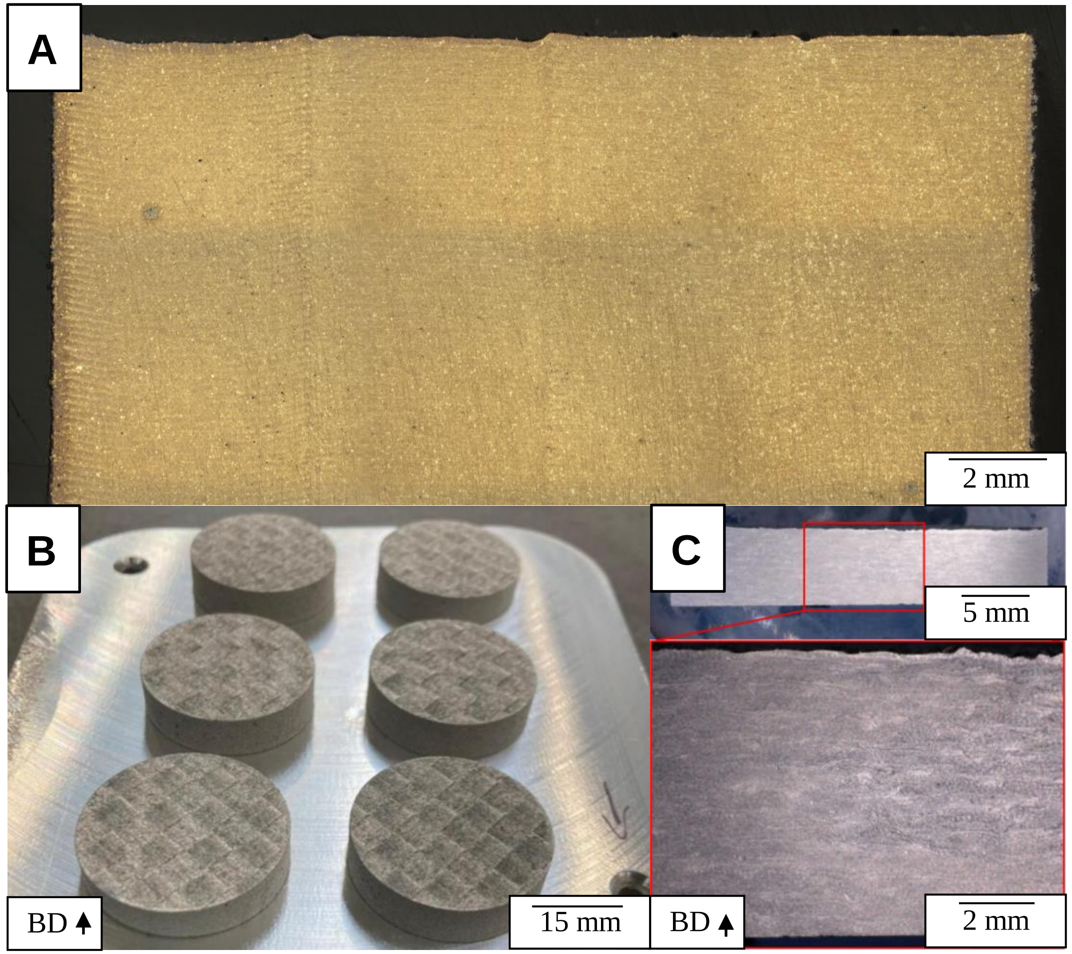
- Investigation of the scan strategy
  - » First test: Cuboids (15 x 15 x 10 mm³)
  - » Variation of field size and orientation, as well as scan orientation
- Results:
  - » Field size below 5 mm leads to strong depression of melt
  - » Field size of 5 or 10 mm showed no cracks and 99.9 % density
  - » Transfer to larger geometries



Adaptation of scan strategy. A: As-Built specimens on build plate; Cross-sections of optimal (B) and suboptimal (C) result

Optimization of the scan strategy

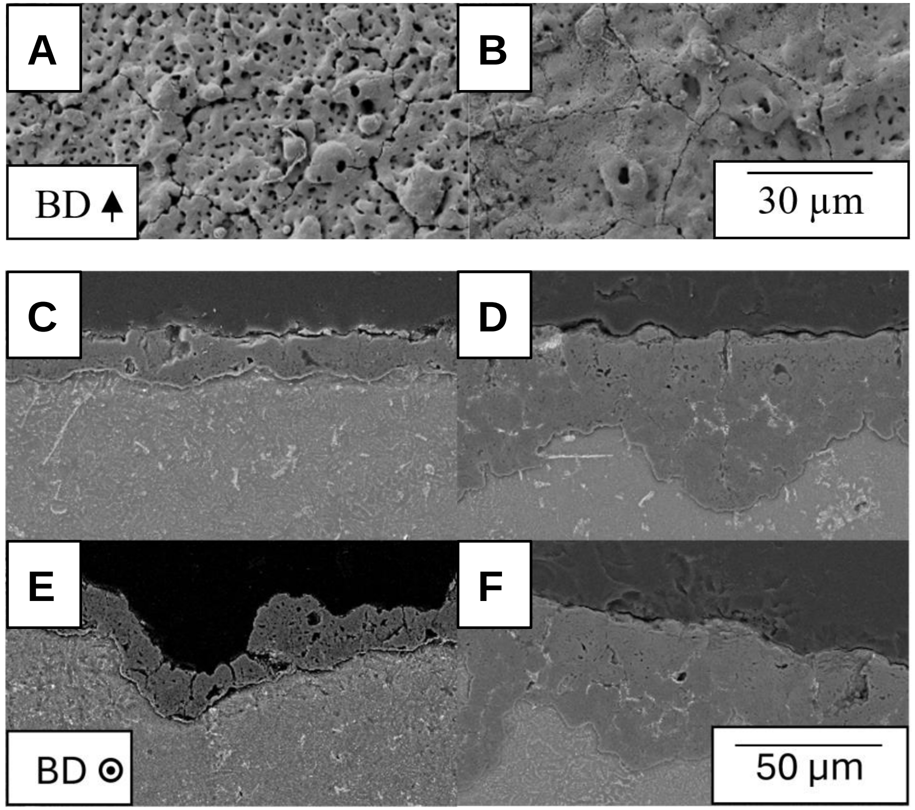
- Investigation of the scan strategy
  - Second test: Cubes (20 x 20 x 20 mm³)
  - Variation of field size and distance
- Results:
  - Large specimen without cracks or porosity feasible
  - Only 5 mm field size showed crack-free results
  - Transfer to cylinders (Ø = 31 mm) successful



A: Cube without cracks or porosity; B: Transfer of optimized strategy to cylinders; C: Cross-section of cylinders

Analysis of PEO surface – Tribological testing – Setup

- The PEO layer for tribological and corrosive testing was applied one the standing hollow cylinders
- For this work, two surfaces are compared:
  - » A thinner surface with 10 µm
  - » A thicker surface with 40 µm
- Pin-on-disc measurements were carried out at different loads with a Tungsten-Carbide ball as counter partner (Ø = 6 mm)
  - » Normal force: 5 & 10 N
  - » Linear reciprocal mode, track length 10 mm
  - » Total tested distance 70 m
  - » Wear volume was evaluated

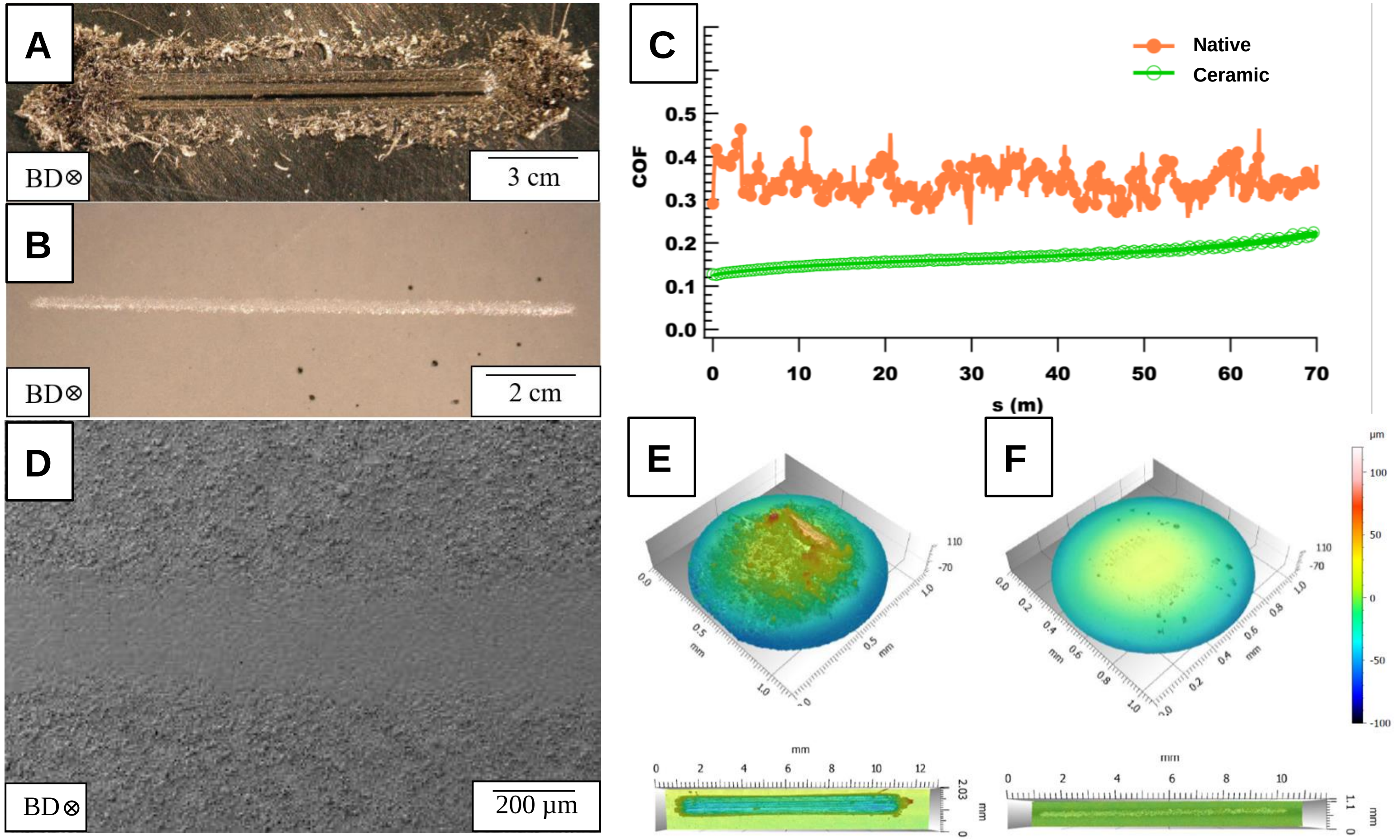


A,B: Surfaces after PEO; C-F: Cross-sections on polished and as-built surfaces; A,C,E: 10 µm layer; B,D,F: 40 µm layer

Analysis of PEO surface – Tribological testing – Results

Results:

- Strong surface wear on native (polished) specimens
  - » Deep tracks after testing
  - » Mg abrasions from the substrate on the pin
  - » Instable coefficient of friction (COF)
- The ceramic dramatically decreases the surface wear
  - » Almost no wear and adhesion on the ball after testing
  - » After a running-in phase, the COF remains stable

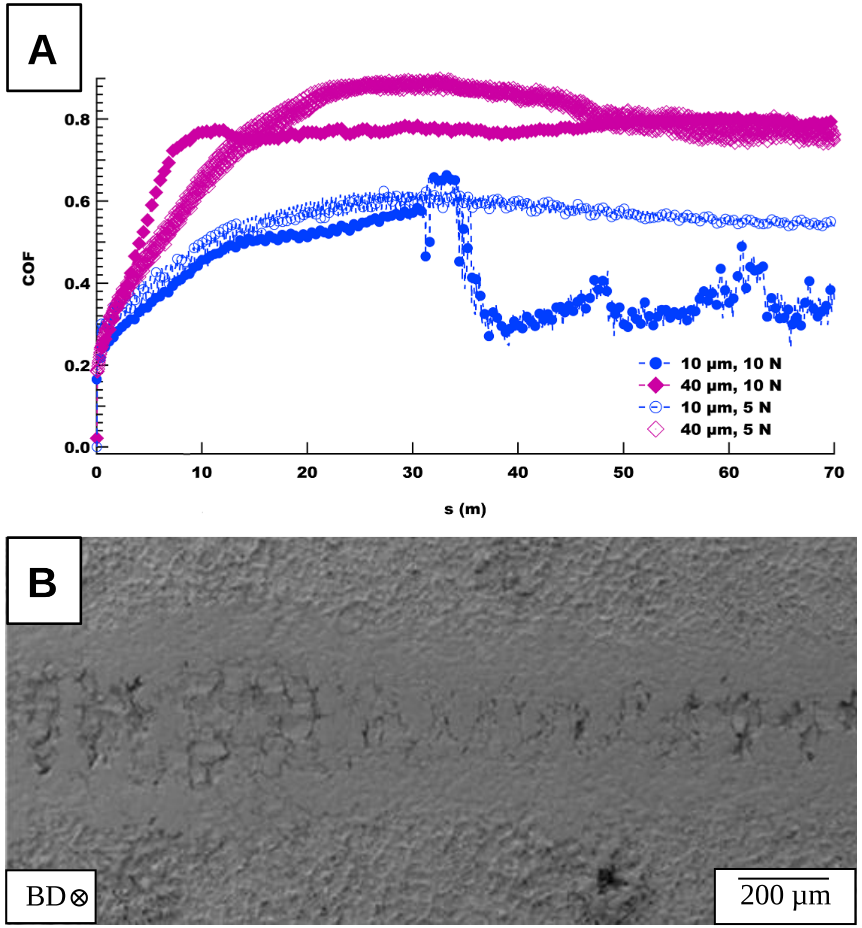


A,B: Surfaces after tribological testing, wear only on native specimens (B); C: COF over the testing distance of native (orange) and ceramic (green) specimens. D: PEO surface after testing. E,F: Display of wear volume on pin and tested tracks, native (E) and ceramic (F) surface

Analysis of PEO surface – Tribological testing – Results

Results:

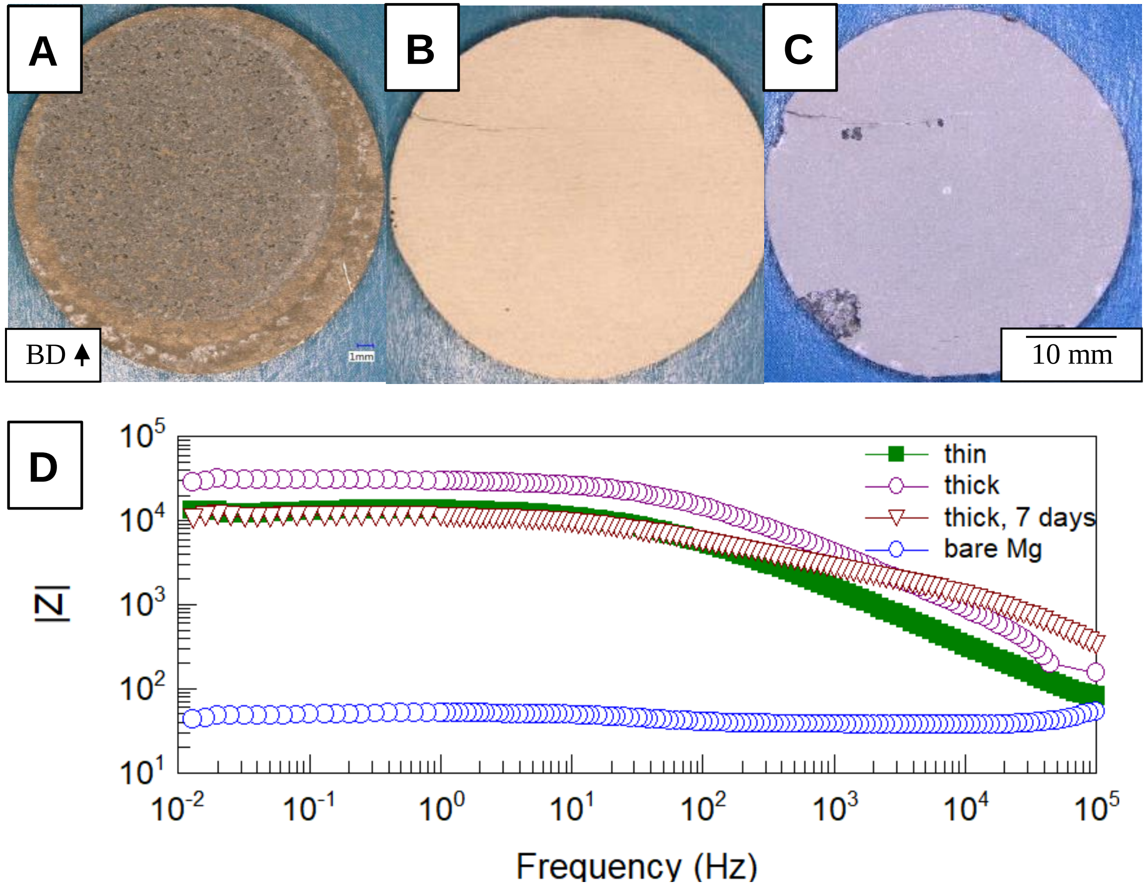
- The thicker ceramic layer leads to a higher COF due to increased surface roughness
- The thinner ceramic layer could not withstand the high load (of 10 N) in testing
- At 5 N load, no wear could be detected for both surfaces
- At 10 N load, (Compared to the native surface) the wear volume was decreased to 10^{-10} %



A: Progression of COF for different load cases on different ceramic surface thicknesses; B: 40 µm Surface after high load testing

Analysis of PEO surface – Corrosive testing

- Measurement of resistance against corrosion with electrochemical impedance spectroscopy (EIS)
  - Immersion of specimen in 0.1 M NaCl solution for 24 hours and 7 days
- Results after 24h:
  - Bare specimens showed strong corrosion
  - Thinnest ceramic layer showed minor corrosion
  - Thick ceramic layer showed no sign of corrosion
- Results after 7 days:
  - Cracks lead to corrosion, no sign of corrosion on even surfaces
  - At $2.9*10^4$ Ohm*cm² the ceramic surface showed a 658x increase in resistance against corrosion compared to as-built surfaces



Bare specimen after 1h (A), Ceramic surface after 24h (B) and 7 days (C) of immersion; D: Plot of EIS measurement; Drastic increase of impedance at lower frequency border

Conclusions:

→ This work successfully showed the potential of the PBF-LB for large area parts and the surface modification by PEO

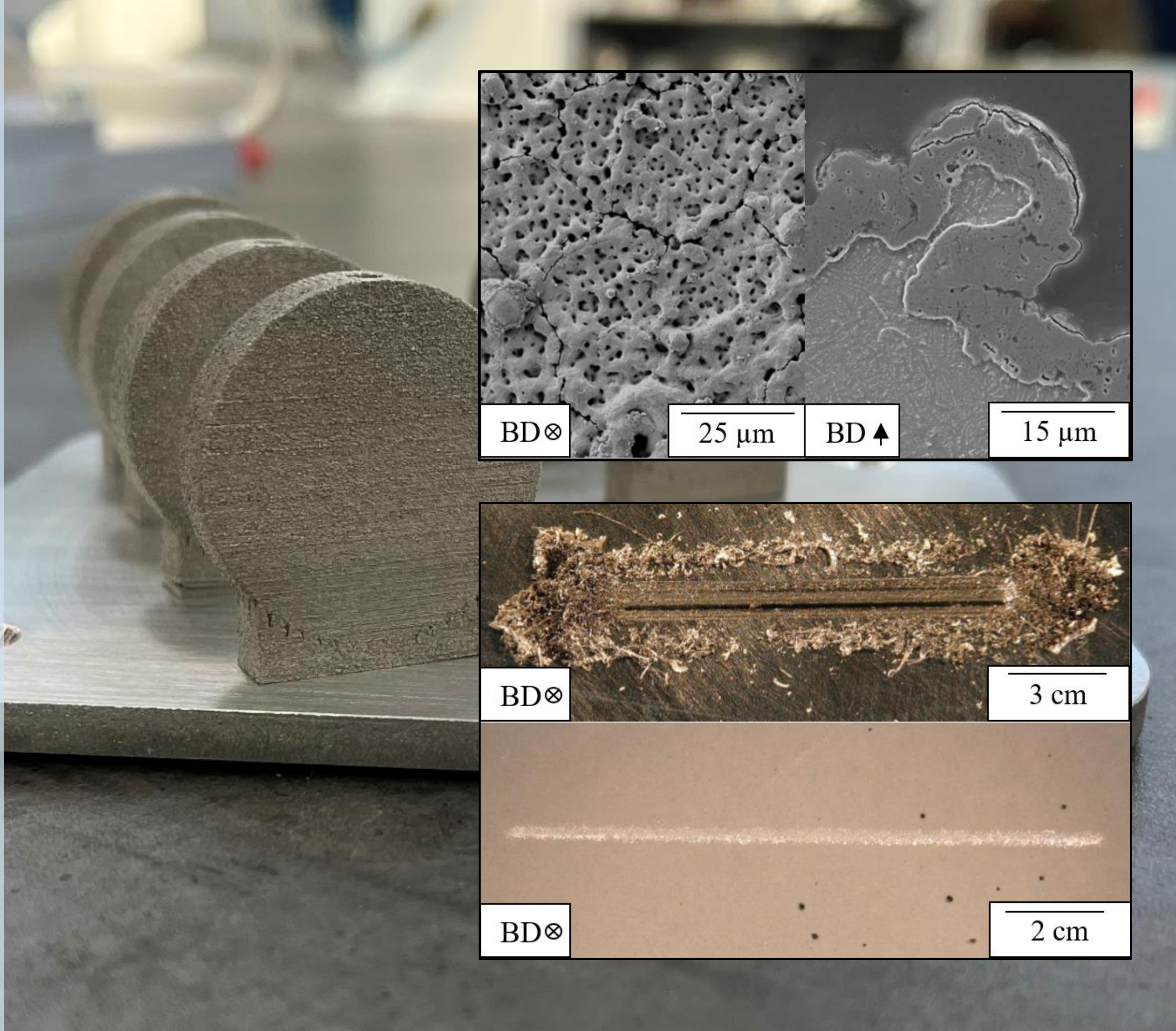
→ Large-area parts (Ø = 31mm) were fabricated without porosity or cracks

→ The oxidation and tribological wear could be drastically minimized

Next Steps:

→ Transfer to complex lattice structures

→Investigated the correlations between the microstructure of the PBF parts and the oxidative behavior



Thank you for your attention!

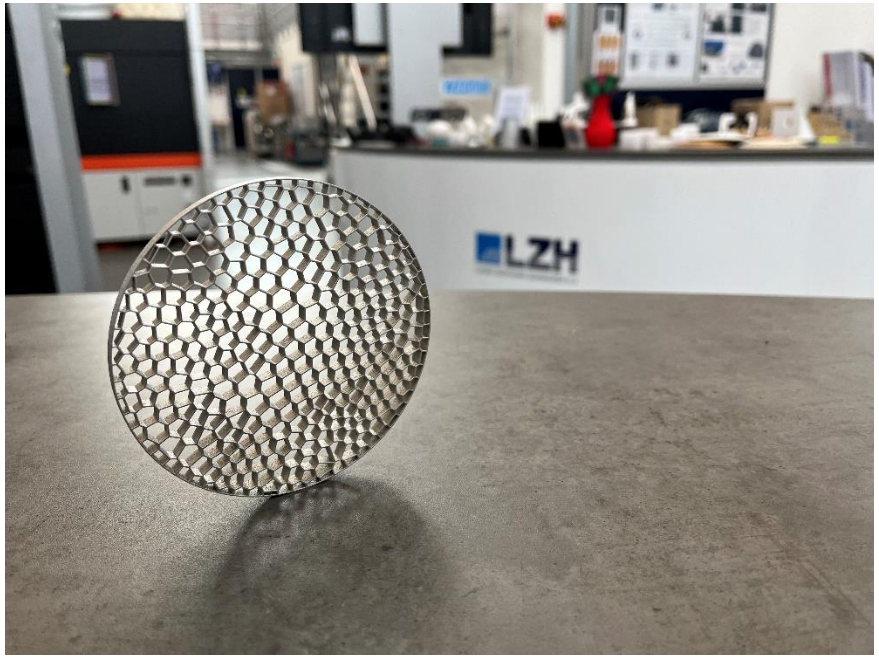
LASER ZENTRUM HANNOVER e.V.

M.Sc. Arvid Abel

Additive Manufacturing of Metals

a.abel@lzh.de

+49 511 2788 482



www.lzh.de

www.linkedin.com/company/lzh/