

RESEARCH AND DEVELOPMENT OF ADDITIVELY MANUFACTURED LATTICE STRUCTURES

Jan Jaroš, Ing.

Institute of Machine and Industrial Design
Faculty of Mechanical Engineering
Brno University of Technology

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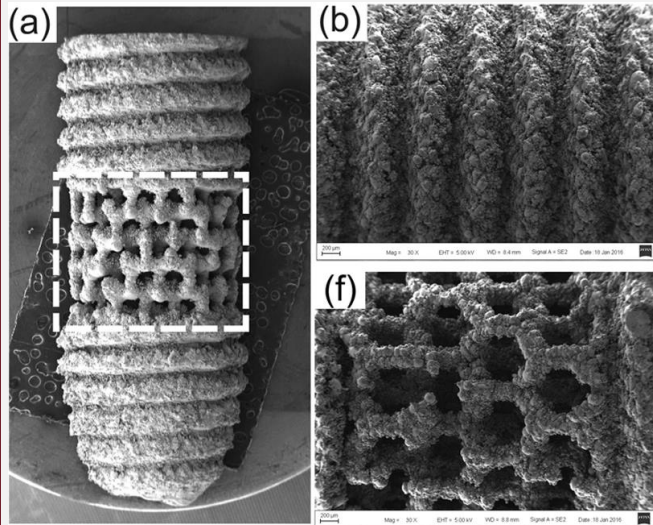
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AND INDUSTRIAL DESIGN

CONTENT

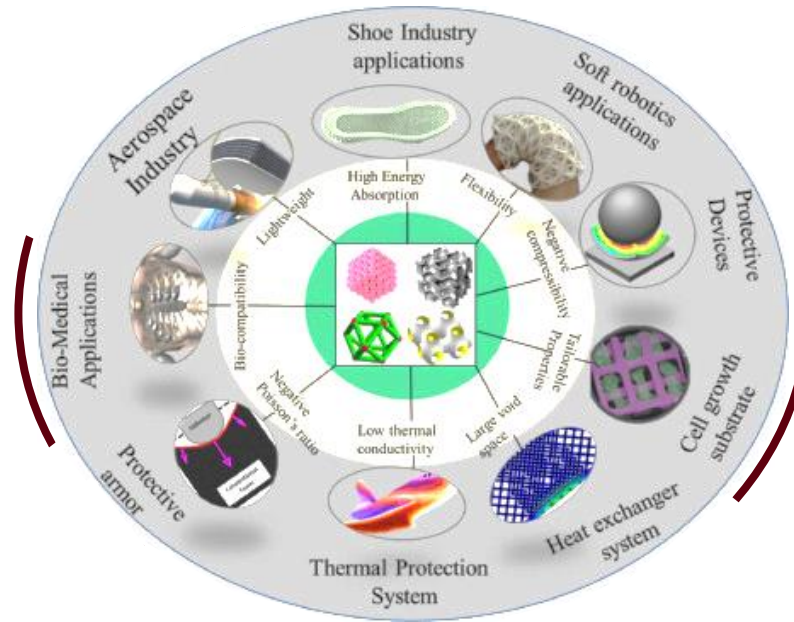
- ❖ Introduction and Motivation
- ❖ State of the Art
- ❖ Summary of Literature Review
- ❖ Aim of the PhD Thesis
- ❖ Materials and Methods
- ❖ Results and Discussion
- ❖ Conclusions

Introduction and Motivation

Structured implant

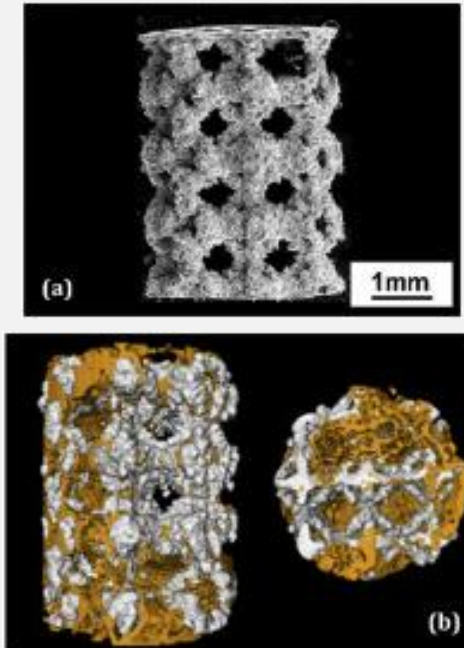


Yang et al. 2017



Ali et al. 2022

Bone cells growth



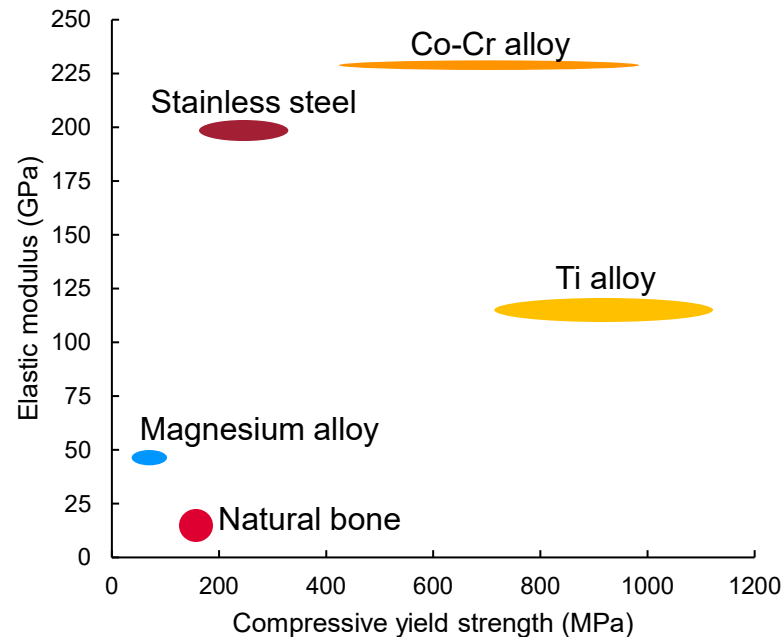
■ Cell tissue

Ataollahi 2023

Introduction and Motivation

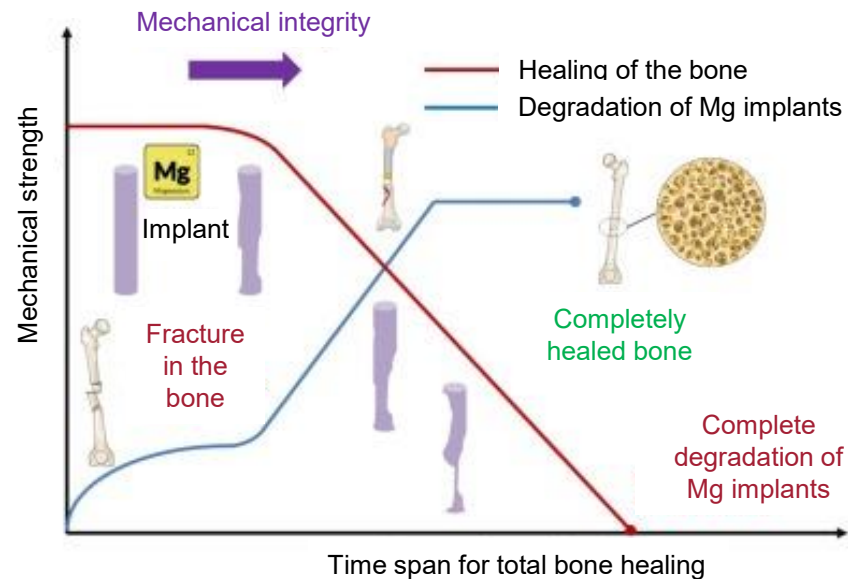
Magnesium alloy implants

- ❖ Mechanical properties close to those of natural bone



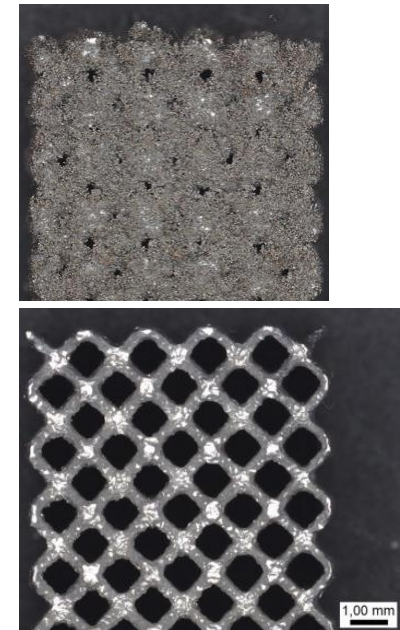
Staiger et al. 2006

- ❖ Replacement of the implant with bone tissue



Singh et al. 2024

- ⚡ Challenging processing requirements
- ⚡ Minimum of imperfections



Kopp et al. 2019

State of the Art – Lattice structures production

2016

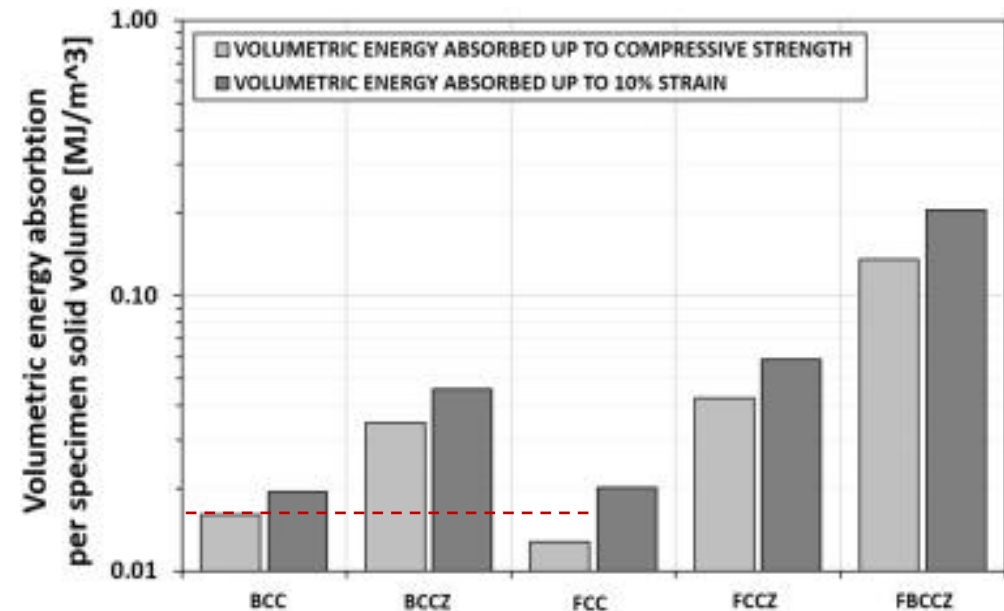
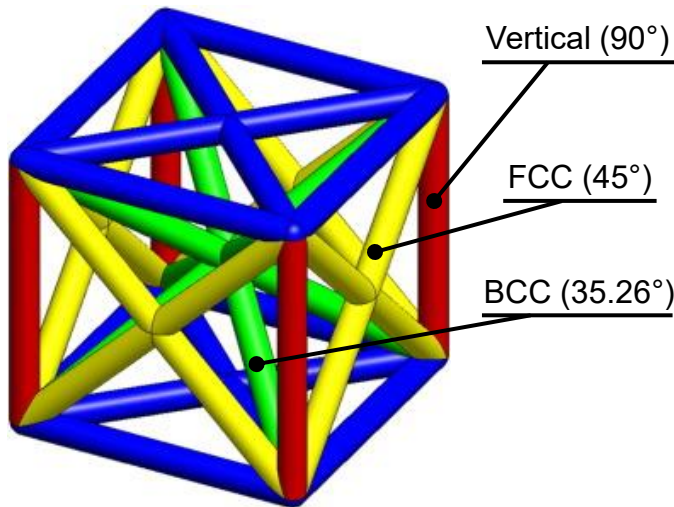
2017

2018 – 2019



Leary, M. et al.

- ❖ PBF-LB production limitations: strut inclination
- ❖ Relatively high volumetric energy absorption
- ❖ BCC lattice structure: worst-case of inclination for production



State of the Art – Lattice structures production

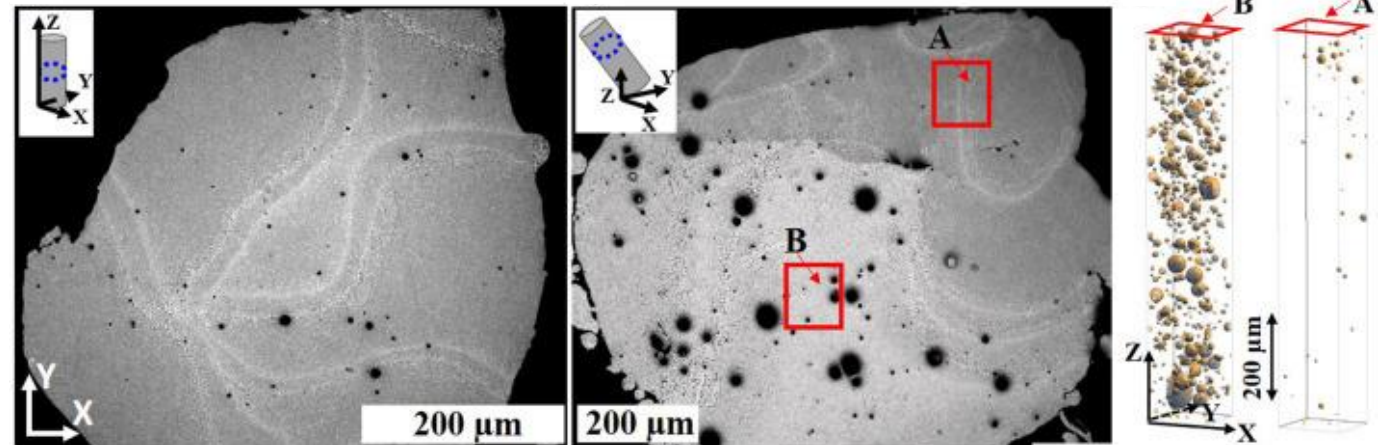
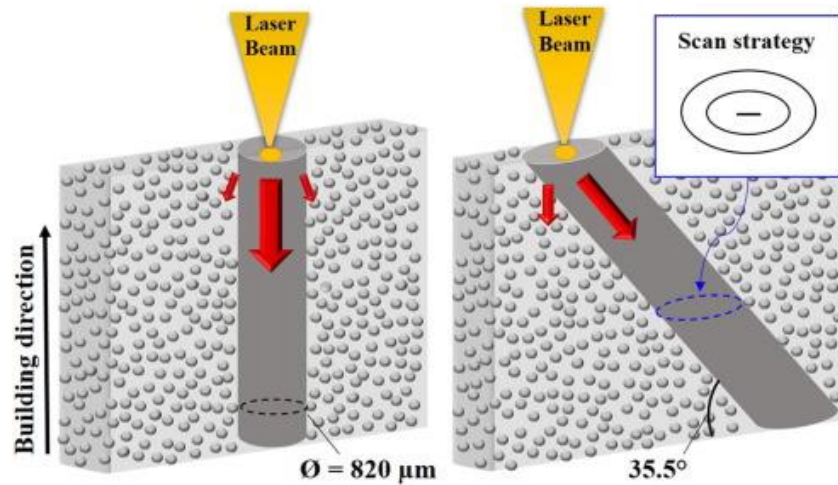
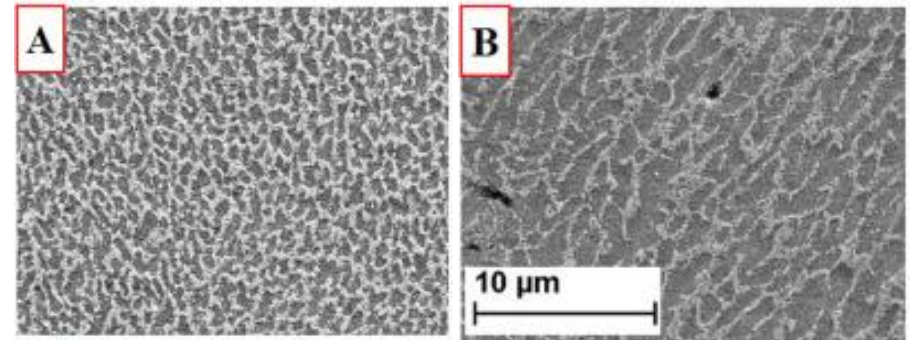
2016 2017

2018 – 2019



Delroisse, P. et al.

- ❖ Thermal flux density and direction
- ❖ Two areas in inclined struts
 - ❖ Difference in pore distribution and volume of porosity
 - ❖ Microstructure



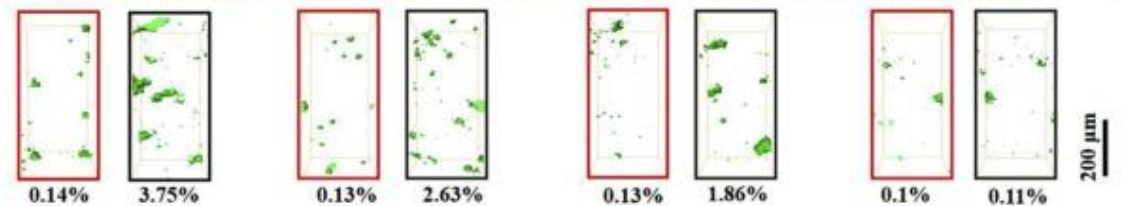
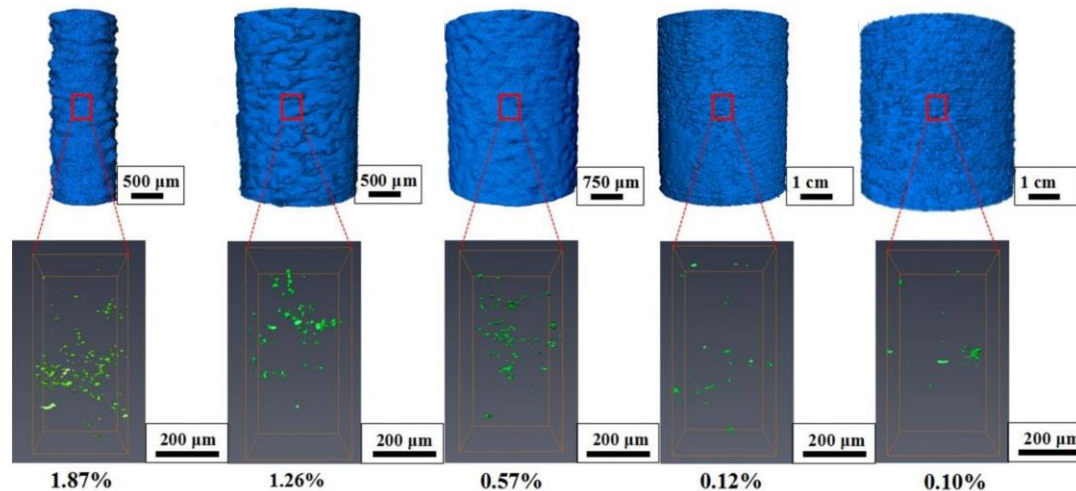
State of the Art – Lattice structures production

2016 2017 2018 – 2019



Dong, Z. et al.

- ❖ Influence of diameter and inclination on Ultimate Tensile Strength (MPa) and Elastic Modulus (GPa)
- ❖ ↓ diameter and ↓ inclination ↓ UTS and ↓ EM



UTS	267.7	315	338	344	349.5	278.4	331.3	335.5	360.7
EM	51.7	60.5	65.4	70.3	70.4	46.4	51.1	53	54.2

State of the Art – Porosity

2014

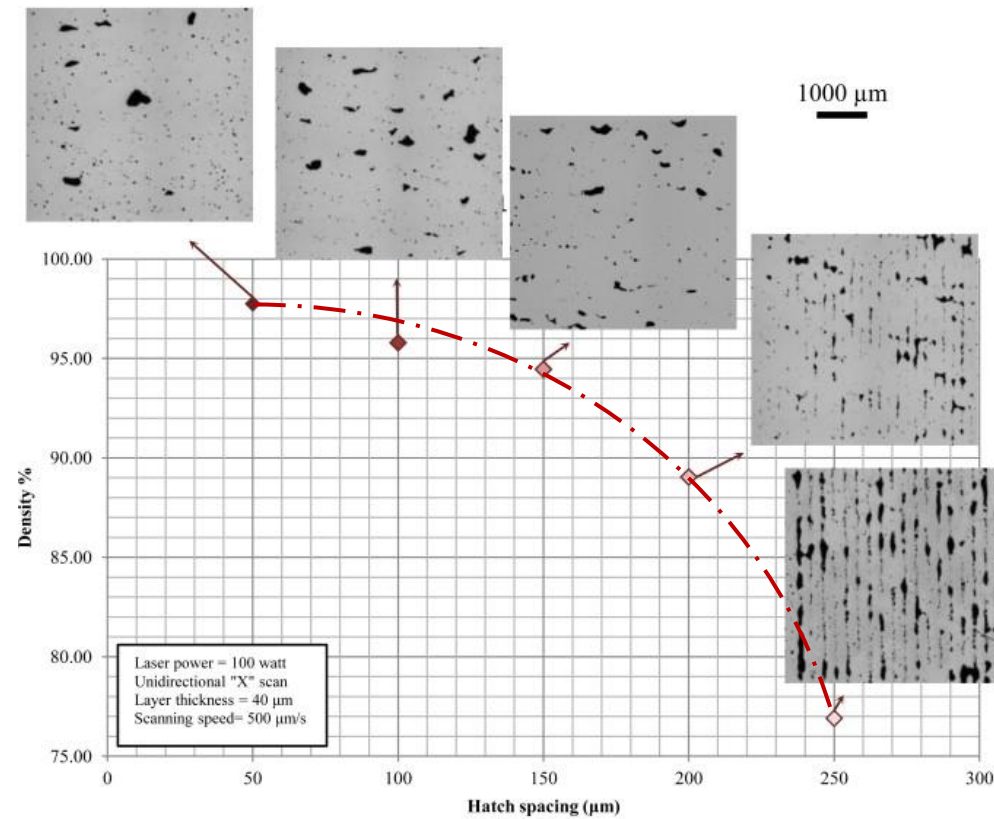
2015

2017



Aboulkhair, N. et al.

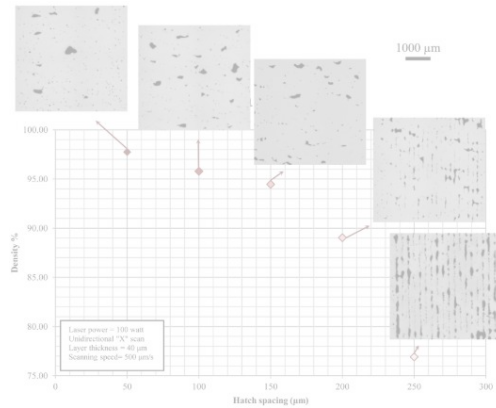
- ❖ Hatch distance
- ❖ Irregular pores



State of the Art – Porosity

2014

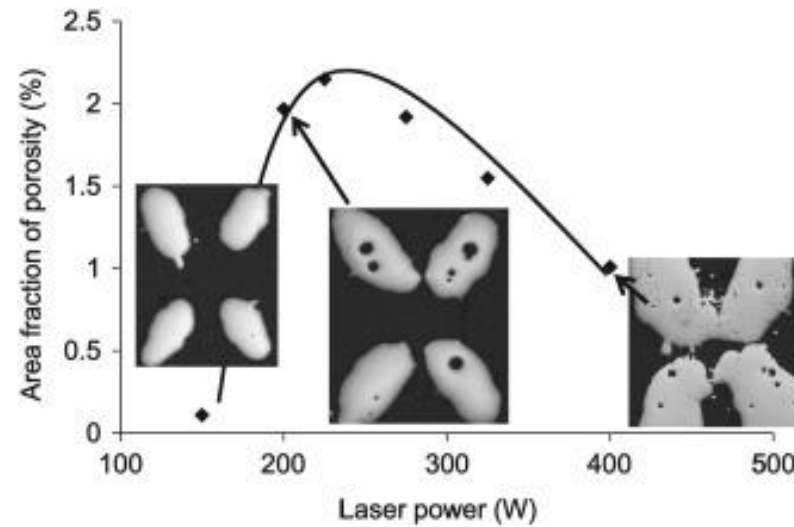
Aboulkhair, N. et al.



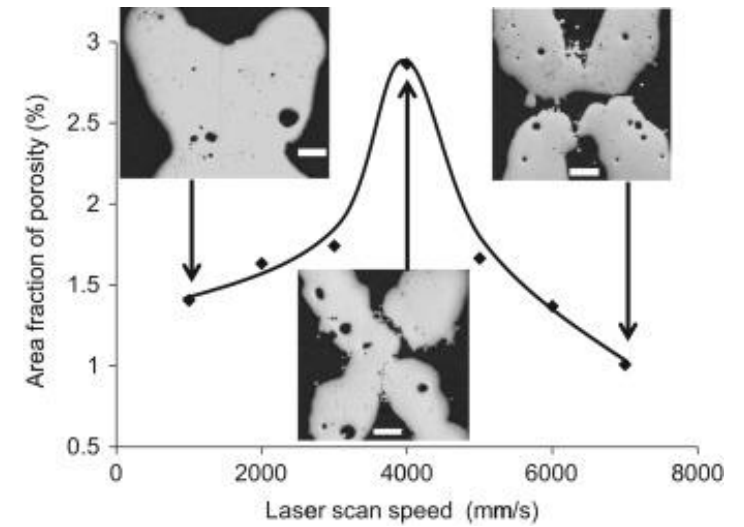
2015

Qiu, Ch. et al.

- ❖ Laser power and Laser speed
- ❖ Regular pores



2017



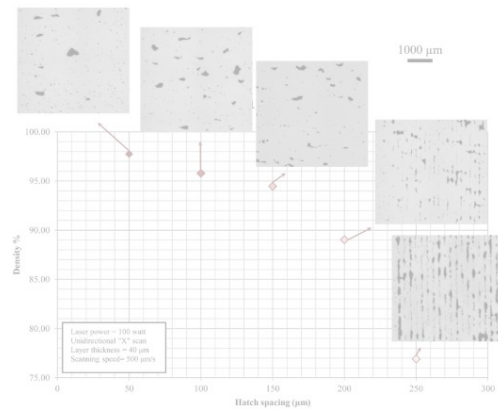
State of the Art – Porosity

2014

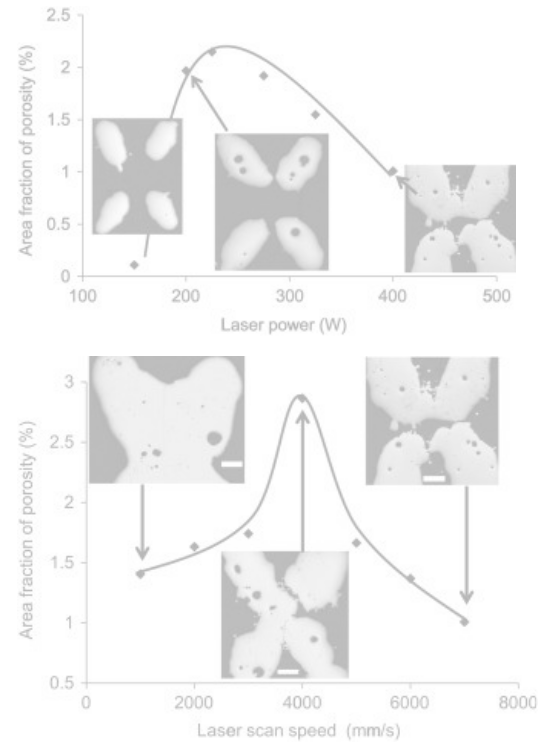
2015

2017

Aboulkhair, N. et al.

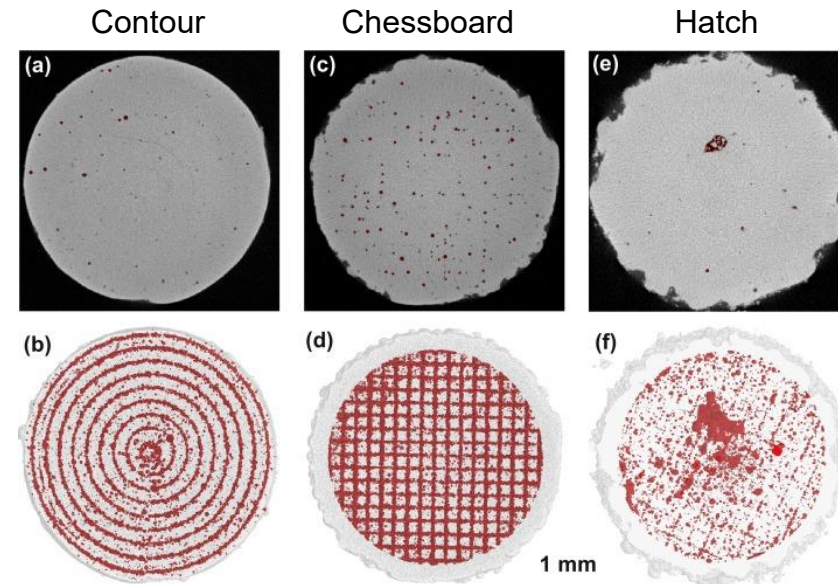


Qiu, Ch. et al.



Pauly, S. et al.

- ❖ Laser strategy
- ❖ Pore morphology



State of the Art – Surface roughness and Dimension

2015

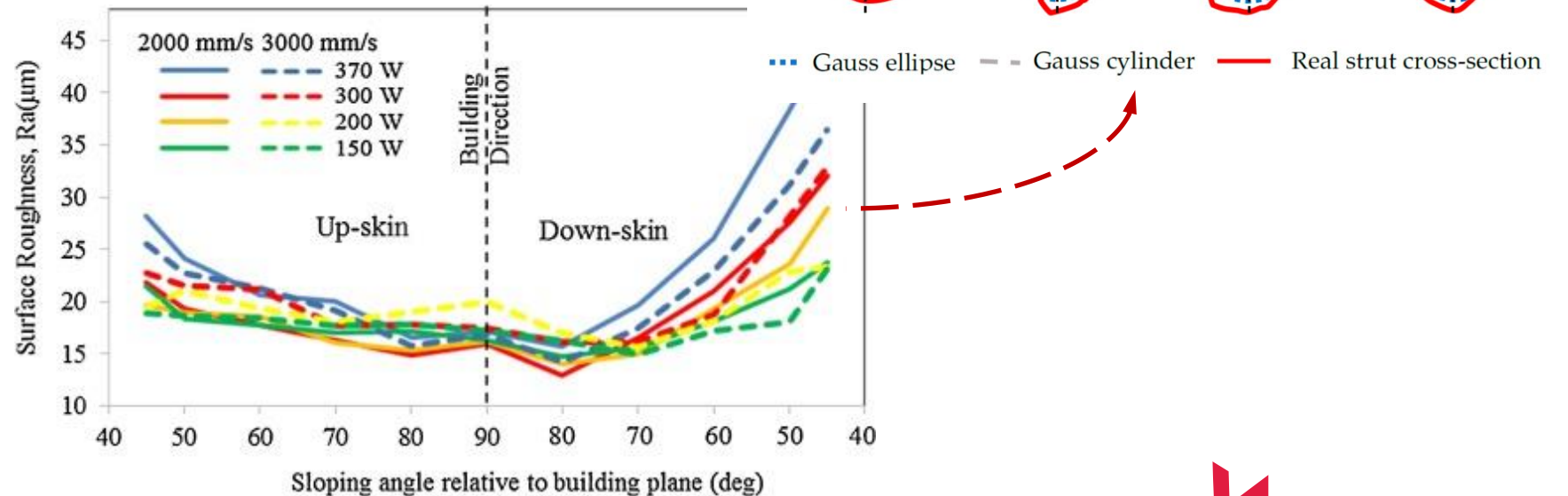
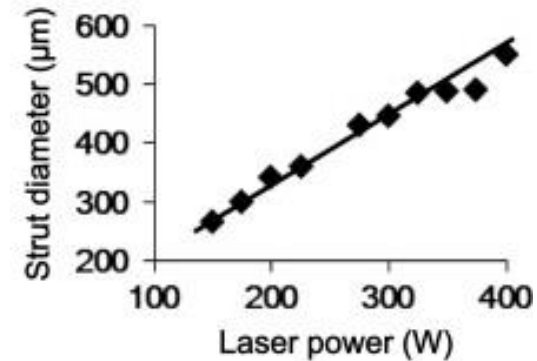
2017

2018



Qiu, Ch. et al.; Tian, Y. et al.; Vrána, R. et al.; Qiu, Ch. et al.

- ❖ Process parameters
- ❖ Strut inclination
 - ❖ Difference in the strut shape



State of the Art – Magnesium alloy

2012

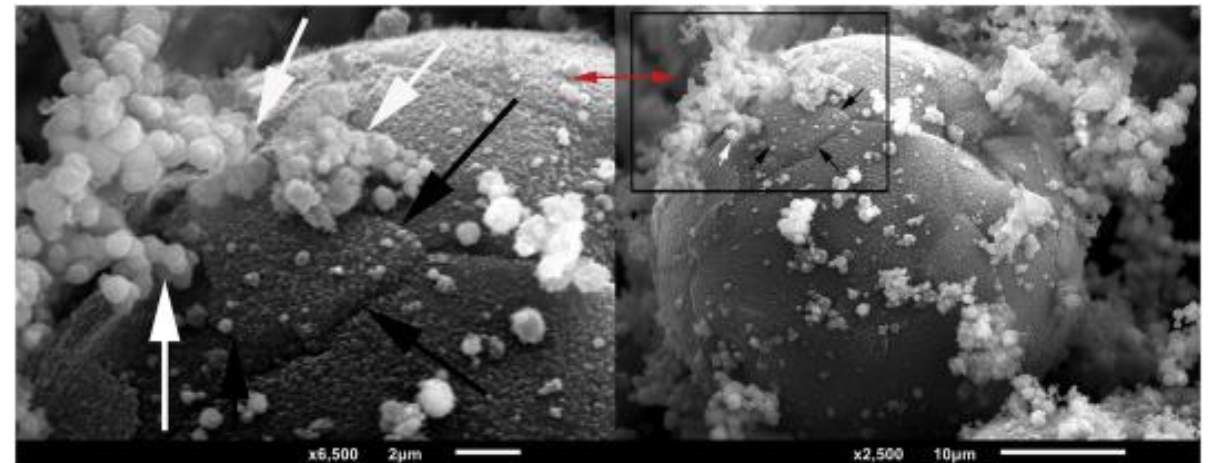
2018



Zhang, B. et al.; Salehi, M. et al. – 2012,2018

- ❖ Process parameters window for bulk material
- ❖ Oxidation of Mg alloys

	10W	15W	20W	30W	60W	90W	110W
0.01 m/s	A	VII. Coarse		II. Much smoke appear and a little of metal remnant	I. Much powder was evaporated		
0.02 m/s	VI. Brittle	B					
0.04 m/s		D	C				
0.08 m/s	V. Loose						
0.16 m/s	IV. Not mechanical strength						
0.3 m/s							
0.5 m/s	III. A little of metal remnant						
1 m/s							

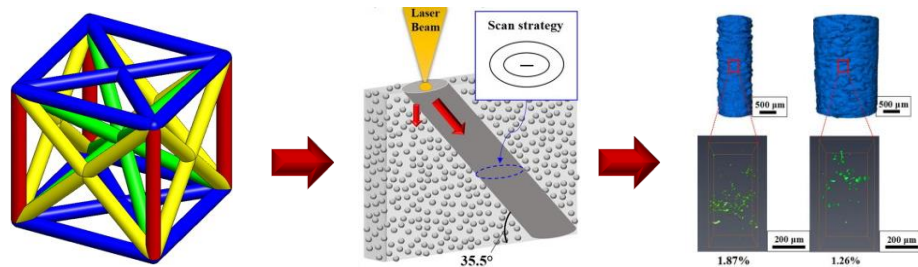


- ❖ Small area of sufficient process parameters
 - ❖ Narrow temperature range (450°C) between boiling point (650°C) and vaporization point (1107°C)
- ❖ Low energy → insufficient mechanical strength
- ❖ High energy → evaporation of Mg

Summary of literature review

Low-volume geometry

- Limitation of lattice structures production
- Heat dissipation
- Effect of strut diameter and inclination

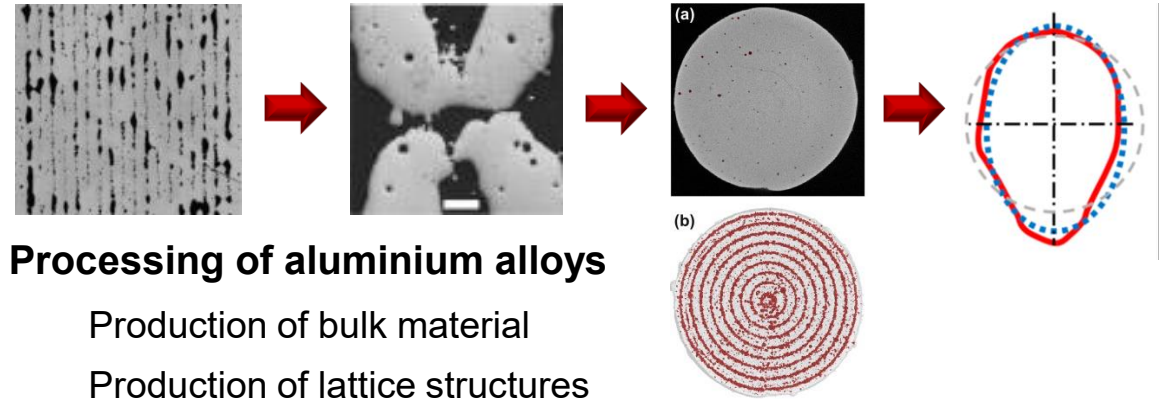


Analysis of unknown aspects

- ⚡ Contour strategy for lattice structures
- ⚡ Lattice structures from Mg alloy
- ⚡ Performance of Mg lattice structures

Influence of process parameters

- Hatch distance
- Laser power and laser speed
- Laser strategy



Processing of aluminium alloys

- Production of bulk material
- Production of lattice structures

Processing of magnesium alloys

- Production of bulk material
- Production of lattice structures

Scientific questions

The main goal of the thesis

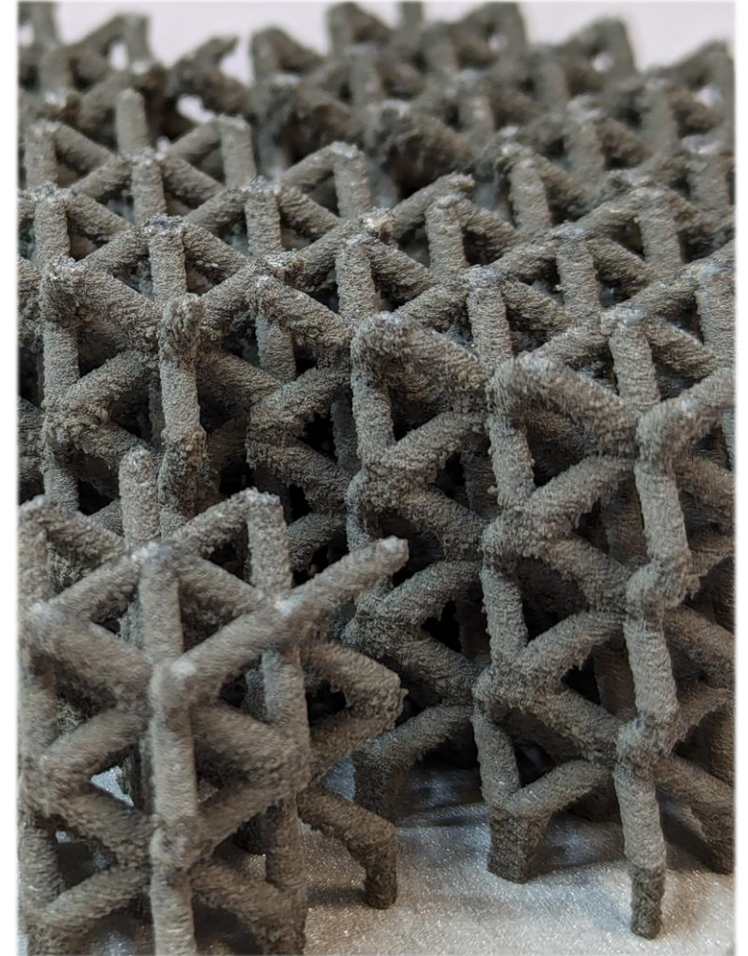
The thesis aims at optimization of PBF-LB process parameters and scanning strategies for producing high-quality lattice structures from aluminum and magnesium alloys.

Scientific questions

- Q1:** Does the contour strategy reduce imperfections in PBF-LB lattice structures?
- Q2:** Do the lattice structures from WE43 achieve density above 99.5% using contour strategy?
- Q3:** Does the contour strategy improve mechanical performance of WE43 lattice structures compared to the hatch strategy?

Hypotheses

- H1:** Lattice structures require tailored PBF-LB parameters, especially contour strategy, to reduce imperfections caused by limited heat dissipation in low-volume geometry.
- H2:** PBF-LB lattice structures from WE43 require optimization of production and process parameters to minimize defects and achieve high material density.
- H3:** Contour strategy can reduce material imperfections that weaken mechanical performance in lattice structures.



Materials and Methods – Input parameters definition

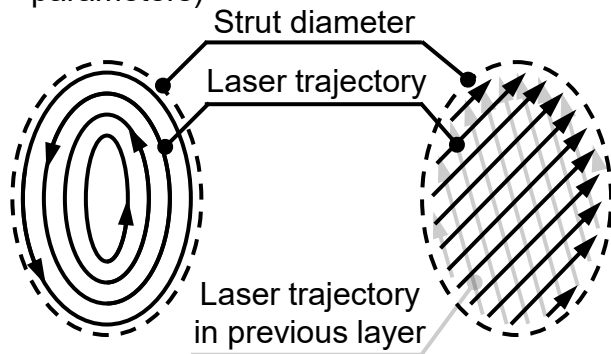
Scientific question 1

Imperfection reduction

- ❖ Aluminum alloy AlSi10Mg
- ❖ Geometry of vertical and inclined struts
- ❖ Diameters of 0.6 – 3 mm



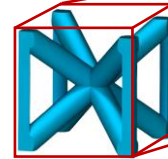
- ❖ Contour vs Hatch strategy (SLM process parameters)



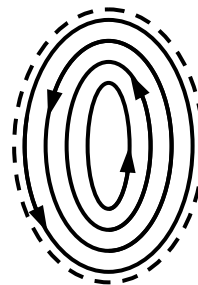
Scientific question 2

Lattice structures

- ❖ Magnesium alloy WE43
- ❖ Geometry of BCC cell + vertical struts
- ❖ Diameters of 0.5 – 3 mm



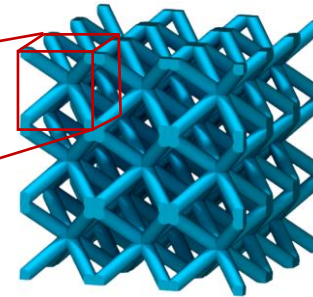
- ❖ Contour strategy



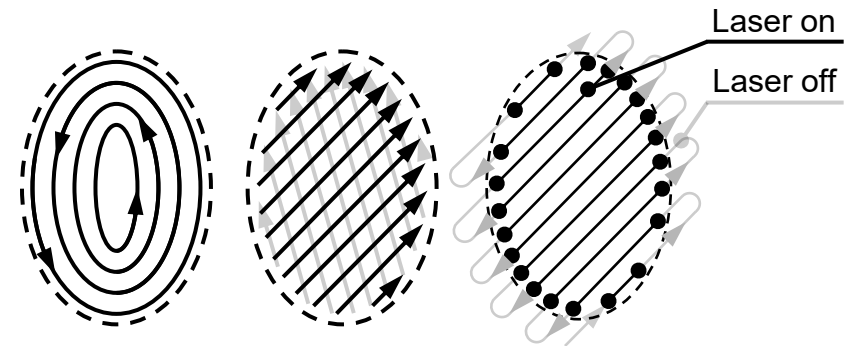
Scientific question 3

Mechanical properties

- ❖ Magnesium alloy WE43
- ❖ Geometry of BCC lattice structure
- ❖ Diameter of 3 mm



- ❖ Contour and Hatch strategy + skywriting



Materials and Methods – Imperfection reduction

Scientific question 1

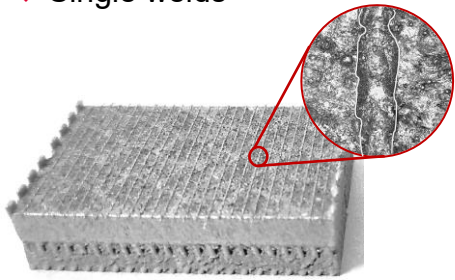
Procedure and Outputs



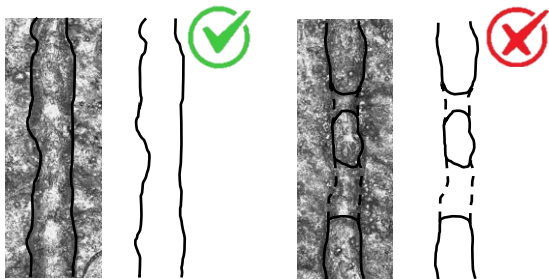
❖ Perspective process parameters



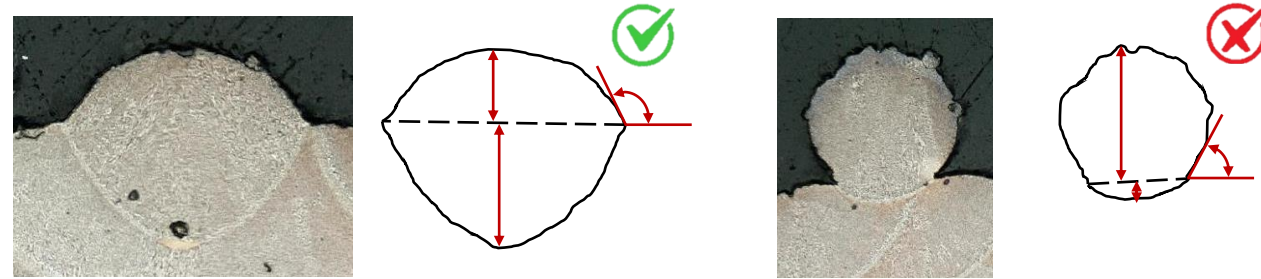
❖ Single welds



❖ Track continuity



❖ Track parameters



Materials and Methods – Imperfection reduction



Scientific question 1

Procedure and Outputs

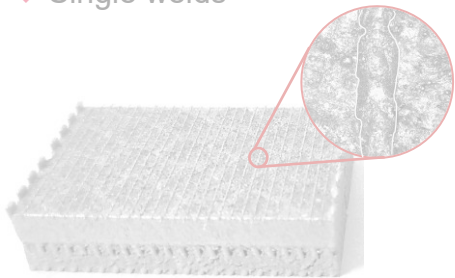


❖ Perspective process parameters

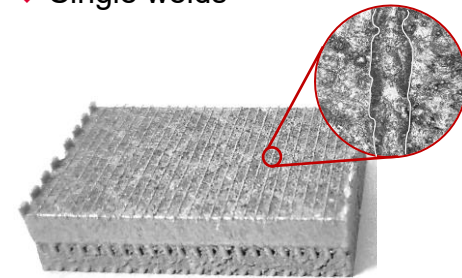
❖ Thickness
❖ For overlap parameter



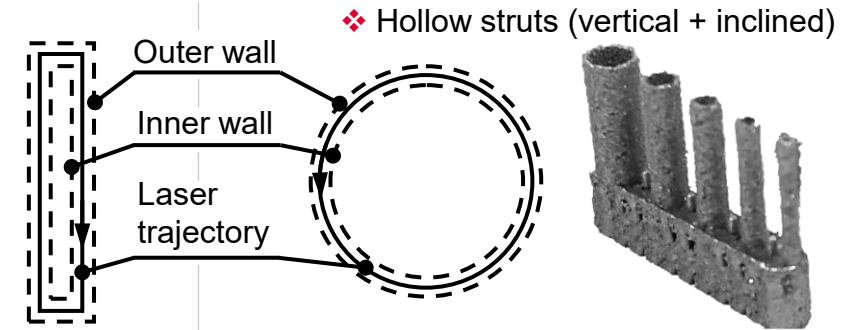
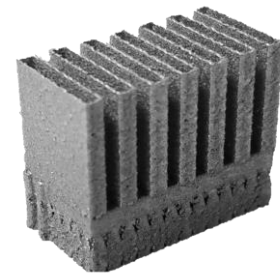
❖ Single welds



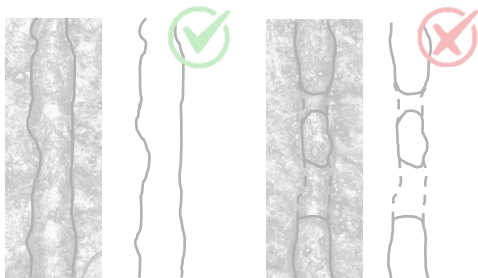
❖ Single welds



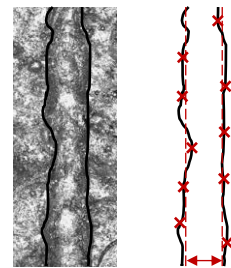
❖ Thin walls



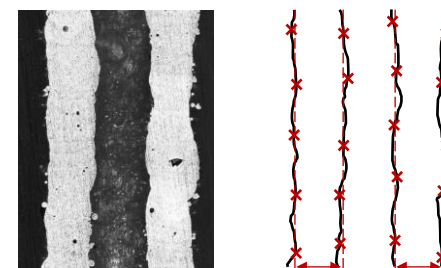
❖ Track continuity



❖ Weld width



❖ Wall and Hollow strut thickness



Materials and Methods – Imperfection reduction



Scientific question 1

Procedure and Outputs



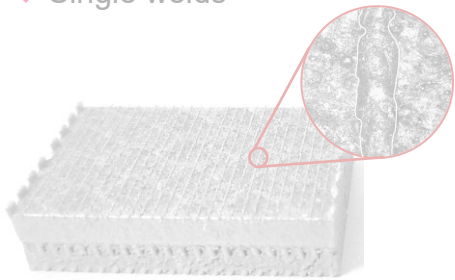
- ❖ Perspective process parameters

- ❖ Thickness
- ❖ For overlap parameter

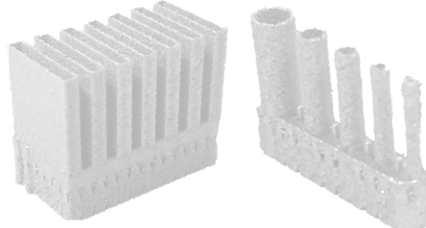
- ❖ Overlap



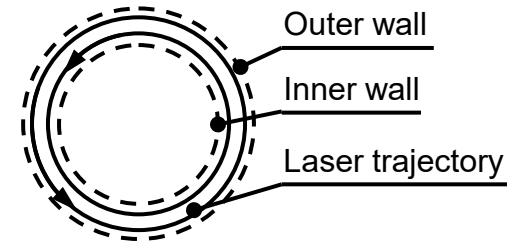
- ❖ Single welds



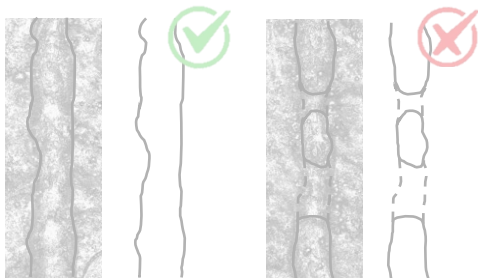
- ❖ Single welds
- ❖ Thin walls
- ❖ Hollow struts



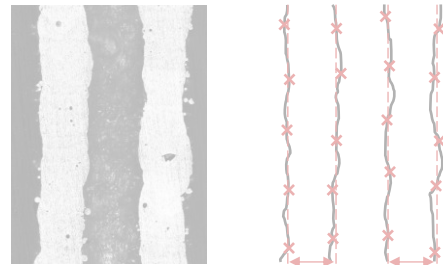
- ❖ Hollow struts with two tracks (vertical and inclined)



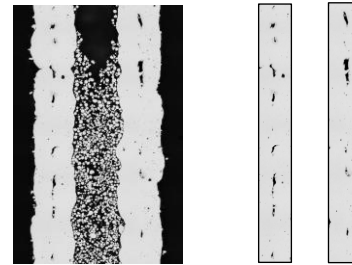
- ❖ Track continuity



- ❖ Weld width
- ❖ Wall and Hollow strut thickness



- ❖ Relative material density between tracks



Materials and Methods – Imperfection reduction



Scientific question 1

Procedure and Outputs



❖ Perspective process parameters

❖ Thickness
❖ For overlap parameter

❖ Overlap

❖ Dimensional accuracy

❖ Surface roughness

❖ Relative material density

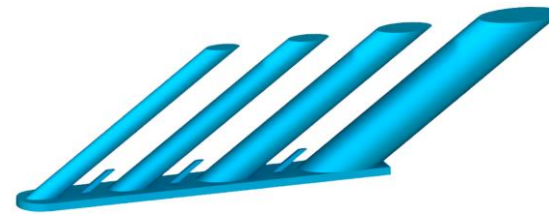
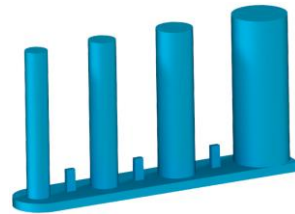
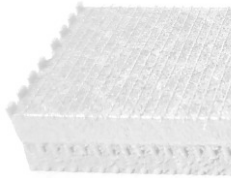


❖ Single welds

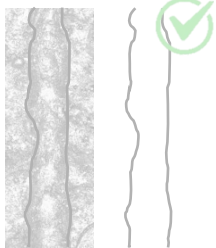
❖ Single welds
❖ Thin walls
❖ Hollow struts

❖ Hollow struts with two tracks

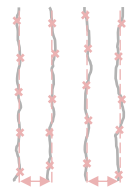
❖ Vertical and inclined struts



❖ Track continuity



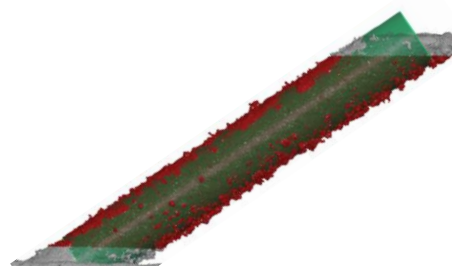
❖ Weld width
❖ Wall and Hollow strut thickness



❖ Relative material density between tracks

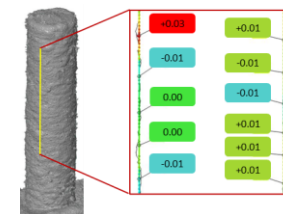


❖ Diameter deviation
❖ Gaussian fit cylinder

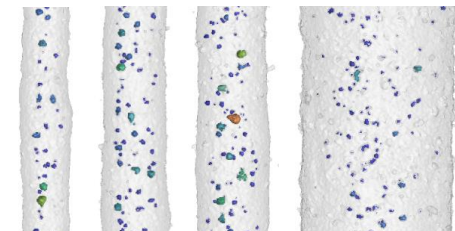


❖ Ra surface roughness

$$R_a = \frac{1}{N} \sum_{i=1}^N |y_i| (\mu\text{m})$$



❖ μCT analysis



Materials and Methods – WE43 lattice structure



Scientific question 2

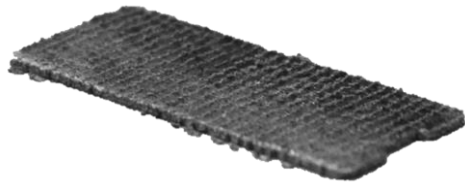
Procedure and Outputs



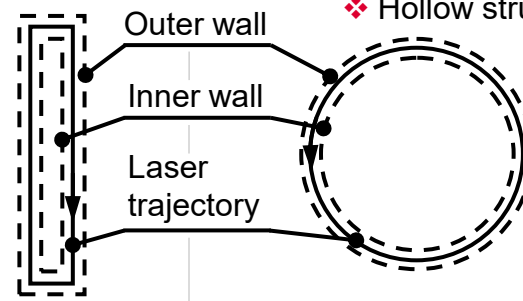
- ❖ Thickness
- ❖ For overlap parameter



- ❖ Single welds



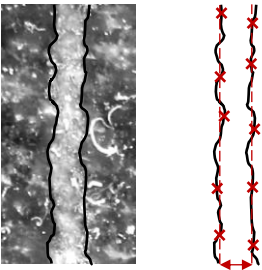
- ❖ Thin walls



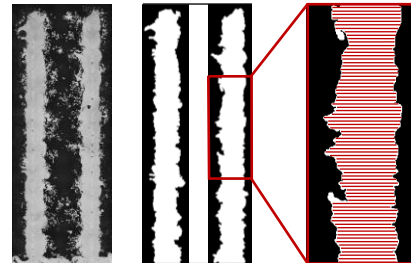
- ❖ Hollow struts (vertical)



- ❖ Weld width



- ❖ Wall and Hollow strut thickness



Materials and Methods – WE43 lattice structure



Scientific question 2

Procedure and Outputs

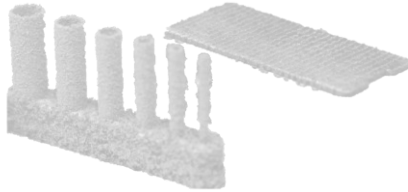


- ❖ Thickness
- ❖ For overlap parameter

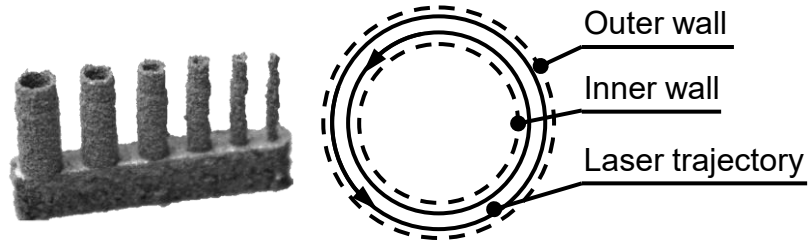
- ❖ Overlap



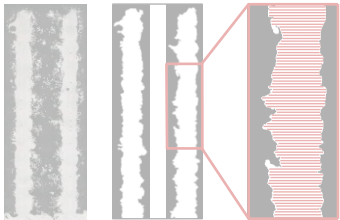
- ❖ Single welds
- ❖ Thin walls
- ❖ Hollow struts



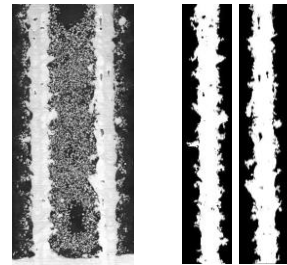
- ❖ Hollow struts with two tracks (vertical)



- ❖ Weld width
- ❖ Wall and Hollow strut thickness



- ❖ Relative material density between tracks



Materials and Methods – WE43 lattice structure



Scientific question 2

Procedure and Outputs



- ❖ Thickness
- ❖ For overlap parameter

- ❖ Overlap

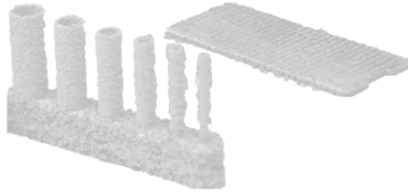
- ❖ Dimensional accuracy

- ❖ Surface roughness

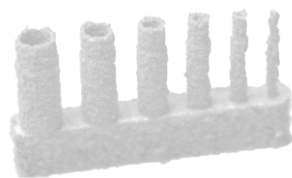
- ❖ Relative material density



- ❖ Single welds
- ❖ Thin walls
- ❖ Hollow struts



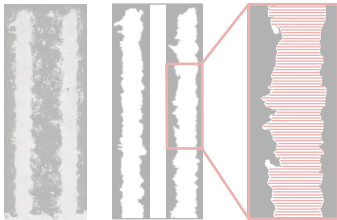
- ❖ Hollow struts with two tracks



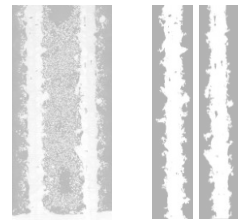
- ❖ Vertical and inclined struts
- ❖ BCCZ cells



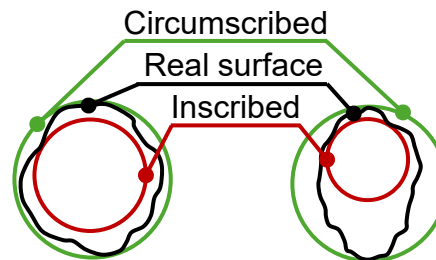
- ❖ Weld width
- ❖ Wall and Hollow strut thickness



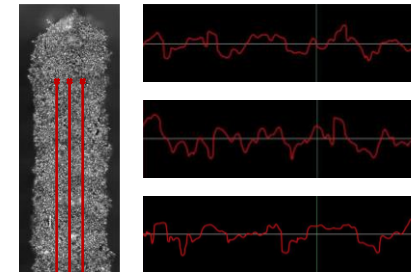
- ❖ Relative material density between tracks



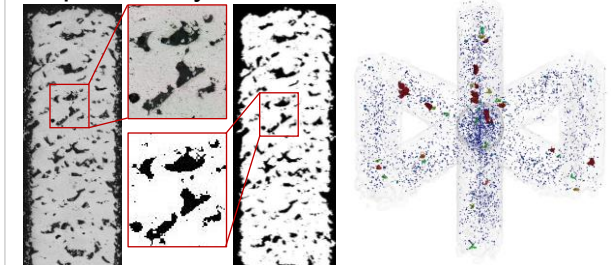
- ❖ Diameter deviation



- ❖ Ra surface roughness



- ❖ Metallographic sections
- ❖ μ CT analysis



Materials and Methods – Mechanical properties



Scientific question 3

Procedure and Outputs



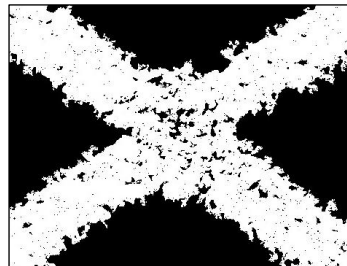
- ❖ Perspective process parameters
- ❖ Contour and Hatch strategies



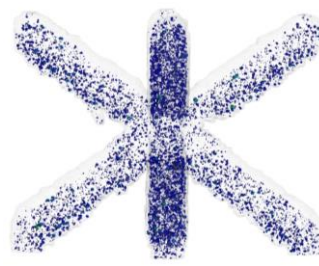
- ❖ BCC cells



- ❖ Metallographic section



- ❖ μ CT analysis



Materials and Methods – Mechanical properties



Scientific question 3

Procedure and Outputs

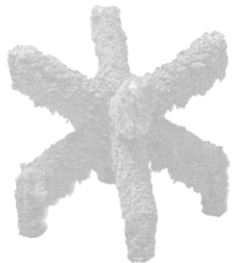


- ❖ Perspective process parameters

- ❖ Perspective laser strategies



- ❖ BCC cells



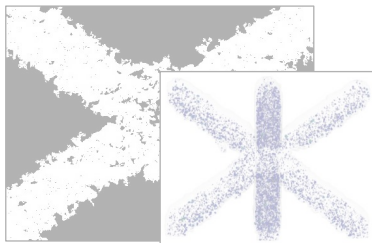
- ❖ BCC cells
- ❖ 5 laser strategies



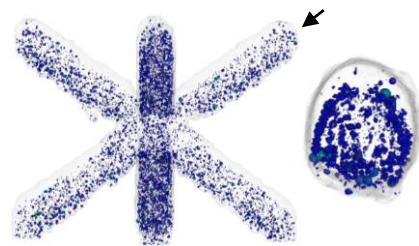
- ❖ Contour strategy
- ❖ Hatch strategy
- ❖ Contour + Hatch strategy
- ❖ Hatch strategy with skywriting
- ❖ Contour + Hatch strategy with skywriting



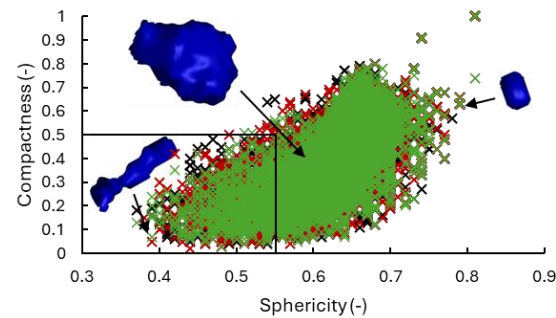
- ❖ Metallographic section
- ❖ μ CT analysis



- ❖ μ CT analysis
- ❖ Pore distribution



- ❖ Pore clarification



Materials and Methods – Mechanical properties



Scientific question 3

Procedure and Outputs



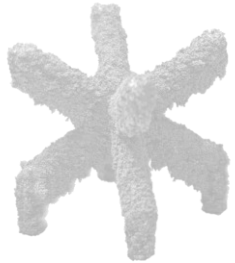
- ❖ Perspective process parameters

- ❖ Perspective laser strategies

- ❖ Melt pool morphology and Material microstructure



- ❖ BCC cells



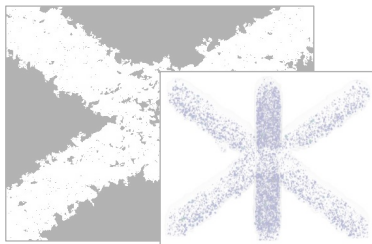
- ❖ BCC cells
- ❖ 5 laser strategies



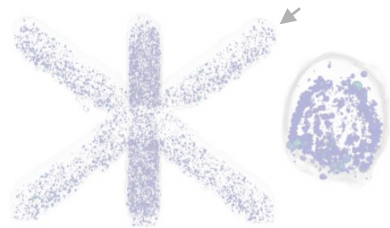
- ❖ BCC cells



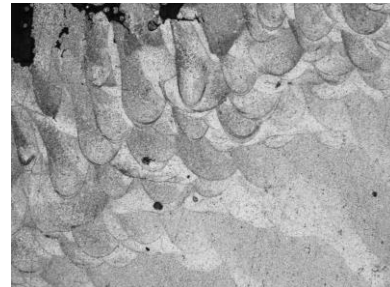
- ❖ Metallographic section
- ❖ μ CT analysis



- ❖ μ CT analysis
- ❖ Pore distribution
- ❖ Pore clarification



- ❖ Clarification of melt pool boundaries



- ❖ SEM-BSE



Materials and Methods – Mechanical properties



Scientific question 3

Procedure and Outputs



- ❖ Perspective process parameters

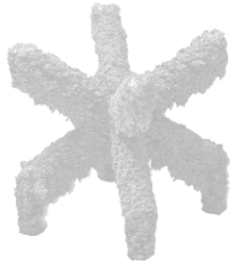
- ❖ Perspective laser strategies

- ❖ Melt pool morphology and Material microstructure

- ❖ Mechanical properties and deformation behavior



- ❖ BCC cells



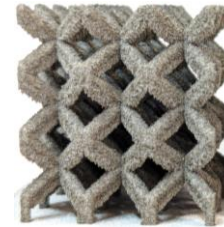
- ❖ BCC cells
- ❖ 5 laser strategies



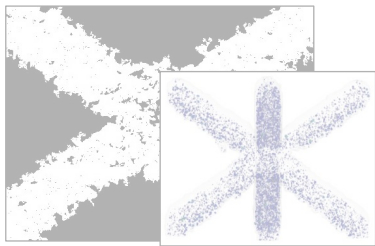
- ❖ BCC cells



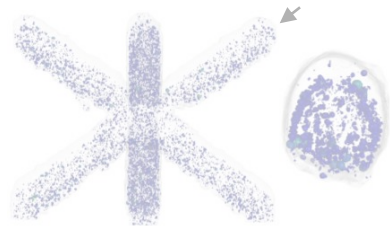
- ❖ BCC lattice structures



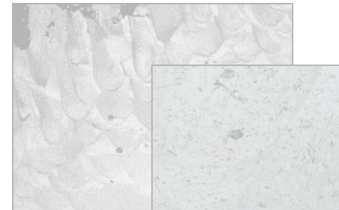
- ❖ Metallographic section
- ❖ μ CT analysis



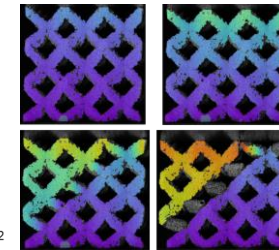
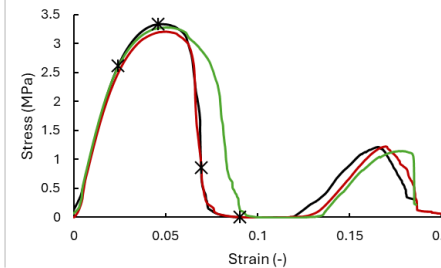
- ❖ μ CT analysis
- ❖ Pore distribution
- ❖ Pore clarification



- ❖ Clarification of melt pool boundaries
- ❖ SEM-BSE



- ❖ Quasi-static test
- ❖ DIC



Materials and Methods – Mechanical properties



Scientific question 3

Procedure and Outputs



- ❖ Perspective process parameters

- ❖ Perspective laser strategies

- ❖ Meltpool morphology and Material microstructure

- ❖ Mechanical properties and deformation behavior

- ❖ Material Young's modulus



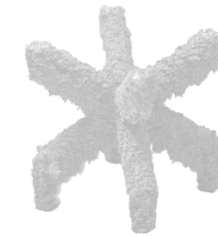
- ❖ BCC cells



- ❖ BCC cells
- ❖ 5 laser strategies



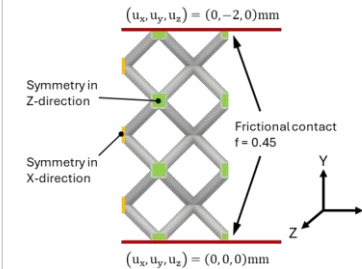
- ❖ BCC cells



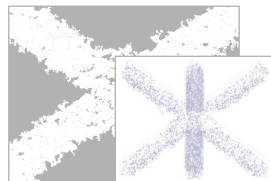
- ❖ BCC lattice structures



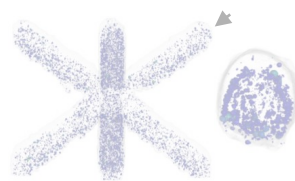
- ❖ FEA – 1/4 BCC lattice structure



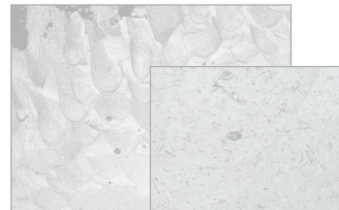
- ❖ Metallographic section
- ❖ μ CT analysis



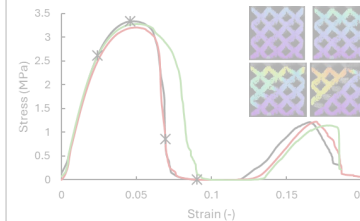
- ❖ μ CT analysis
- ❖ Pore distribution
- ❖ Pore clarification



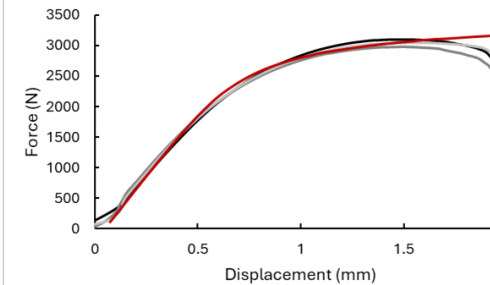
- ❖ Clarification of meltpool boundaries
- ❖ SEM-BSE



- ❖ Quasi-static test
- ❖ DIC



- ❖ FEA vs Quasi-static test



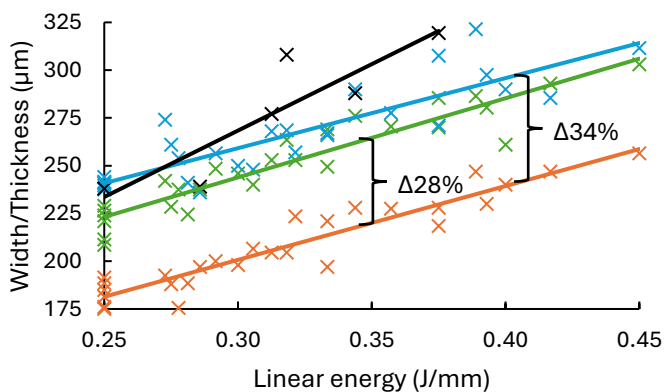
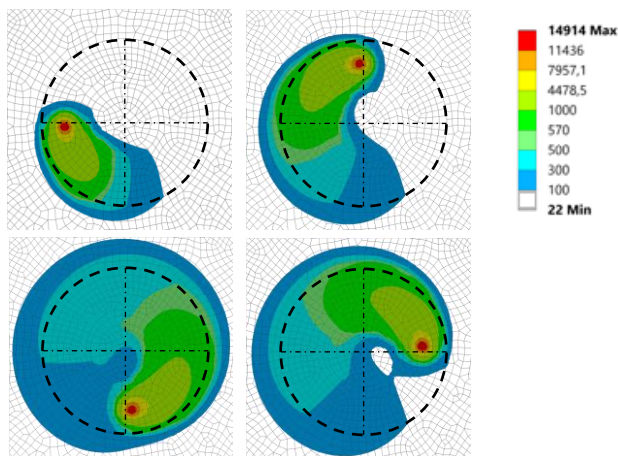
Results and Discussion

Scientific question 1 - Imperfection reduction

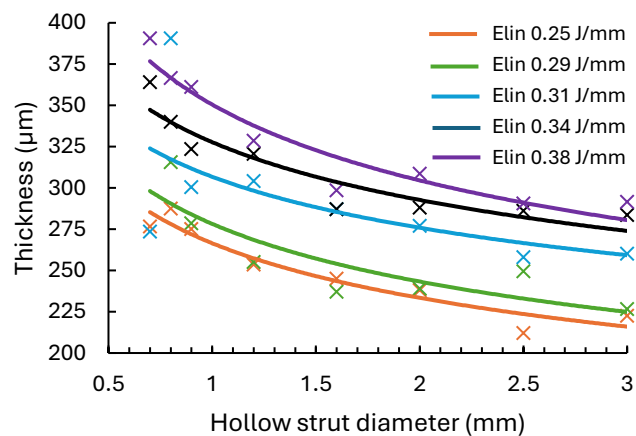
Contour strategy input parameters

- ❖ Linear Energy = 0.27-0.4 J/mm
 - ❖ Continuity and welds parameters

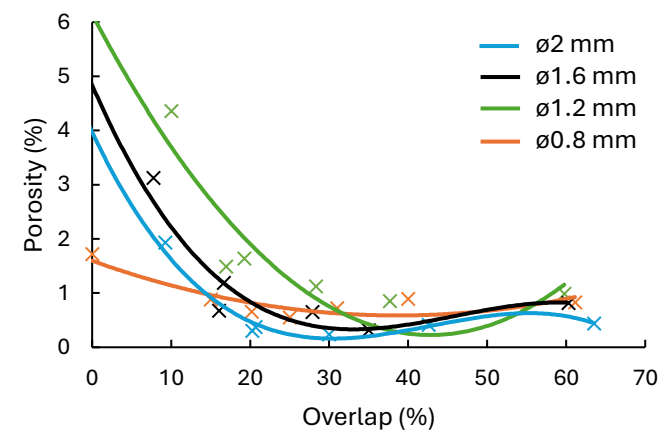
- ❖ Vertical thin walls ↑28%
- ❖ Inclined thin walls ↑34%
- ❖ Hollow struts ↑↑



x Single welds
 x Thin walls - ver.
 x Thin walls - incl.
 x Hollow struts



- ❖ Overlap 30-40%

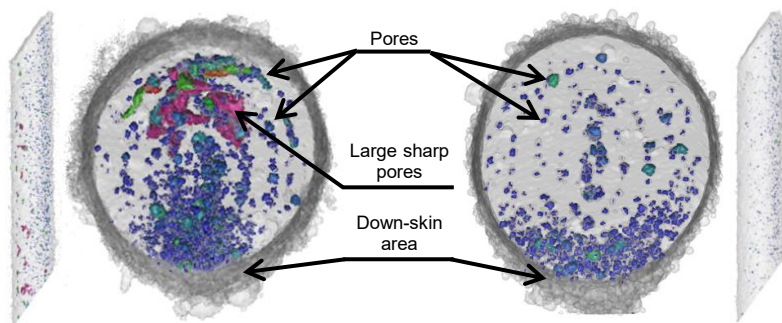


Results and Discussion

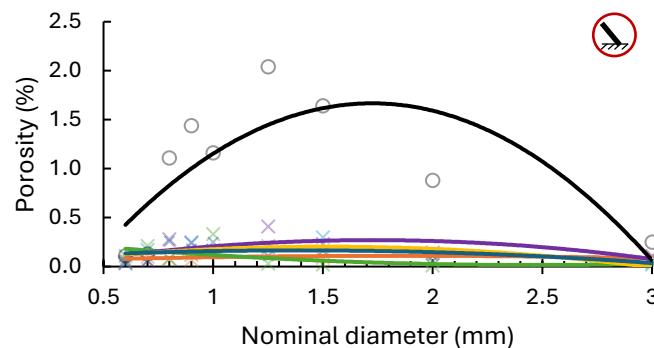
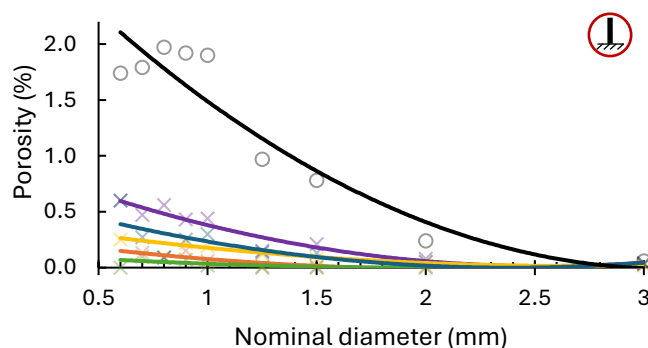
Scientific question 1 - Imperfection reduction

Material quality

- ❖ Out-In vs In-Out laser track order

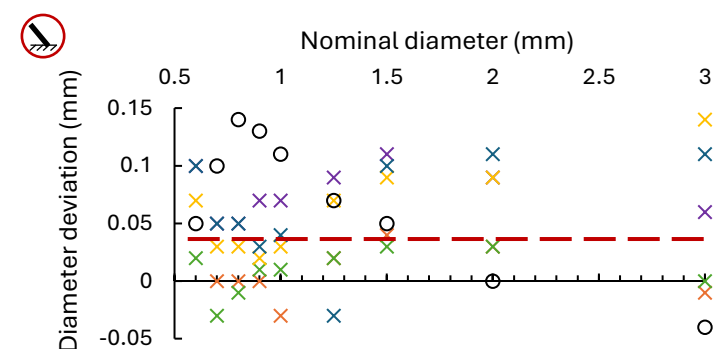


- ❖ Porosity reduction – energy dependent

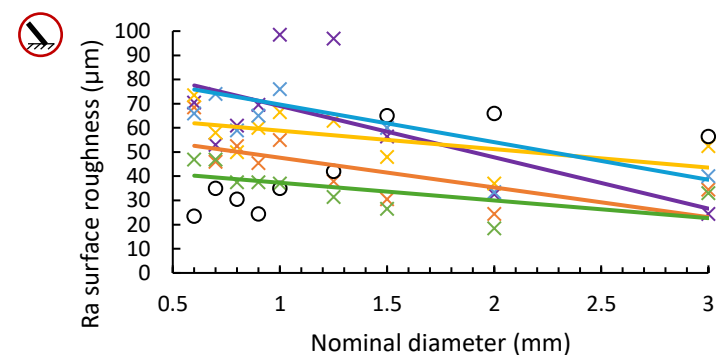


— Elin=0.25 J/mm — Elin=0.29 J/mm — Elin=0.32 J/mm
 — Elin=0.34 J/mm — Elin=0.38 J/mm — Default

- ❖ Median diameter deviation 0.04 mm
- ❖ Median diameter deviation -0.03 mm



- ❖ Surface roughness – energy dependent

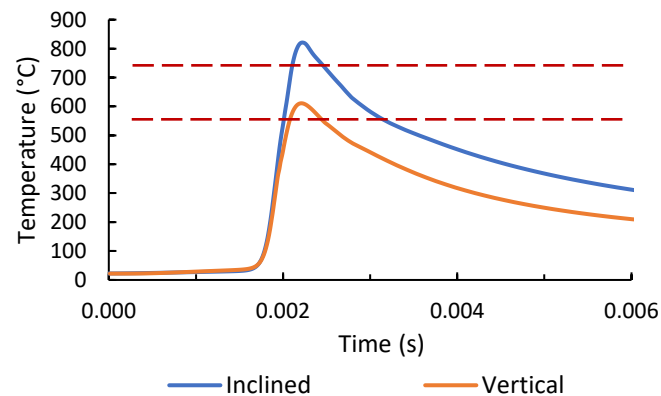
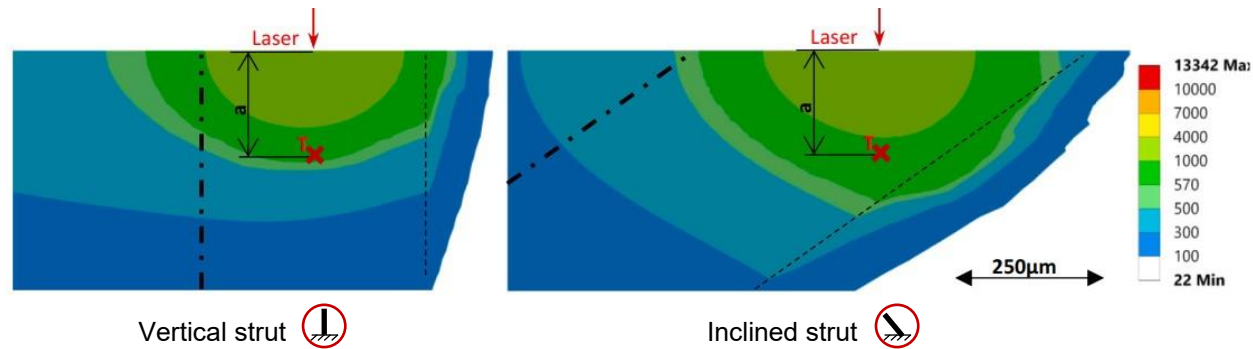


Results and Discussion

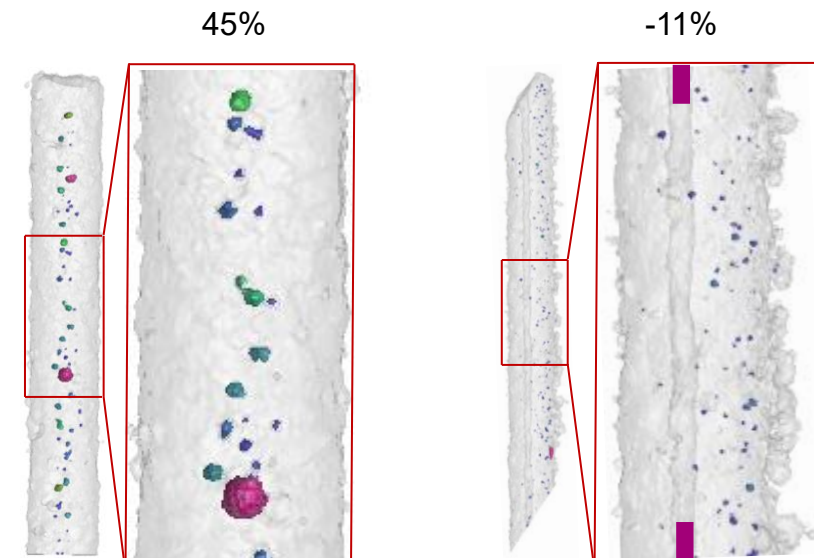
Scientific question 1 - Imperfection reduction

Contour strategy possible issues

- ❖ Heat gradient in inclined struts
- ❖ Increase in diameter and surface roughness



- ❖ Overlap of the center track
- ❖ High center overlap – circular pores
- ❖ Low center overlap – gap

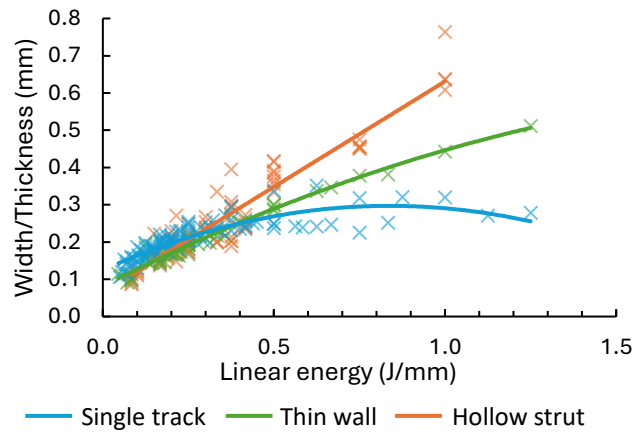


Results and Discussion

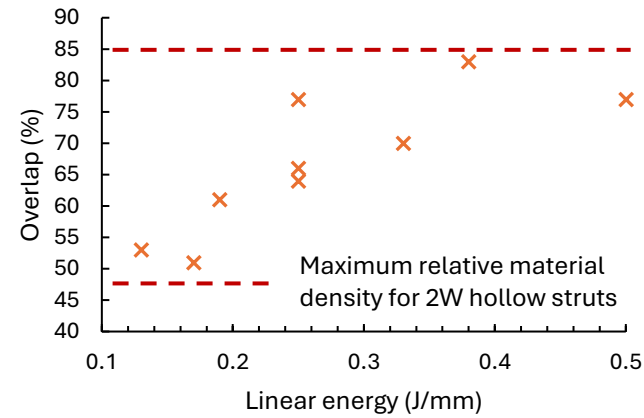
Scientific question 2 – WE43 lattice structures

Contour strategy input parameters

- ❖ Linear energy = 0.05-0.8 J/mm
 - ❖ Higher energy led to large weld's depth
- ❖ Similar weld's width/thickness up to 0.5 J/mm
- ❖ Linear energy greater than 0.5 J/mm
 - ↑↑↑ Hollow struts ↑↑ Thin walls ↑ Single welds



❖ Overlap 45-85%



Results and Discussion

Scientific question 2 – WE43 lattice structures

Material quality

- ❖ Area energy including hatch distance

$$\text{Area energy} = \frac{\text{Laser power}}{\text{Laser speed} \cdot \text{Hatch distance}} \text{ (J/mm}^2\text{)}$$

Relative material density:

99.96%

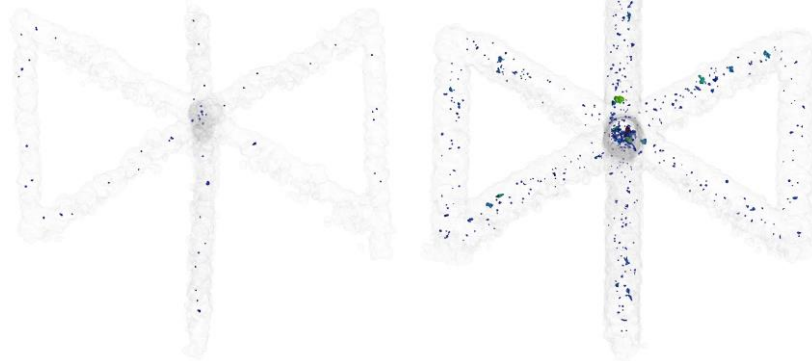
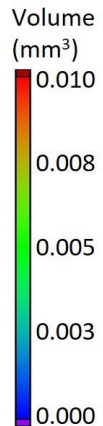
99.83%

Area energy:

1.34

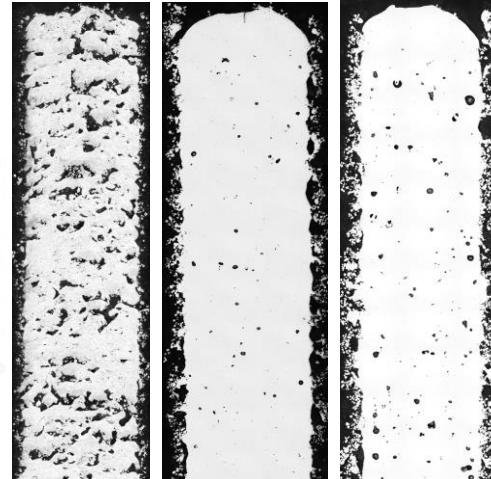
3.26

3.99



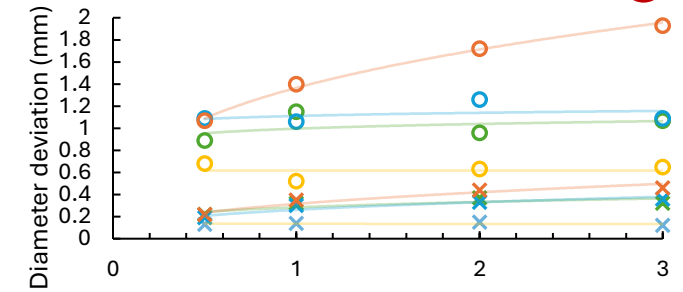
Diameter: 0.5 mm

1 mm

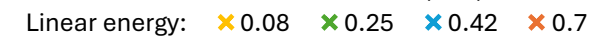
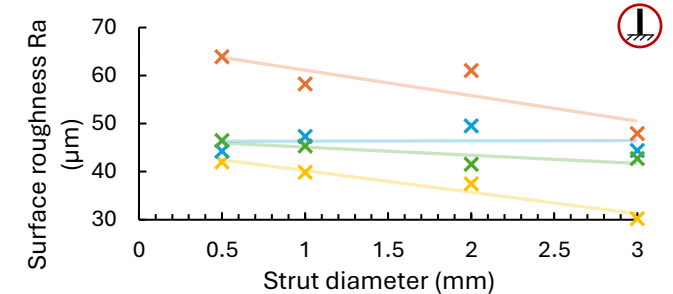


- ❖ Inscribed diameter up to 1.5x

- ❖ Circumscribed diameter up to 3.5x



- ❖ Surface roughness – side of the strut

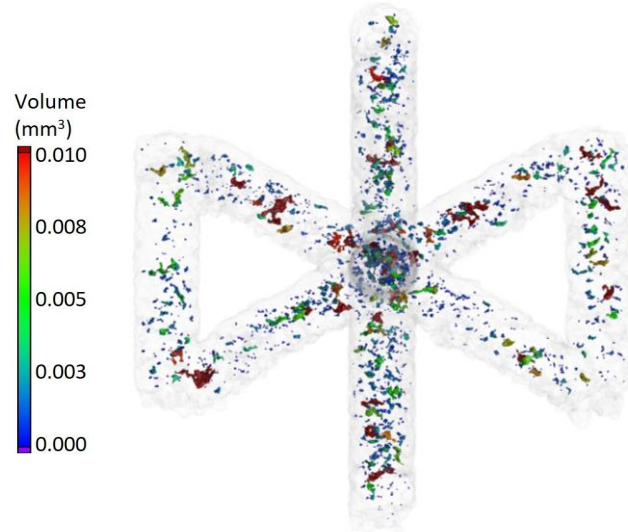


Results and Discussion

Scientific question 2 – WE43 lattice structures

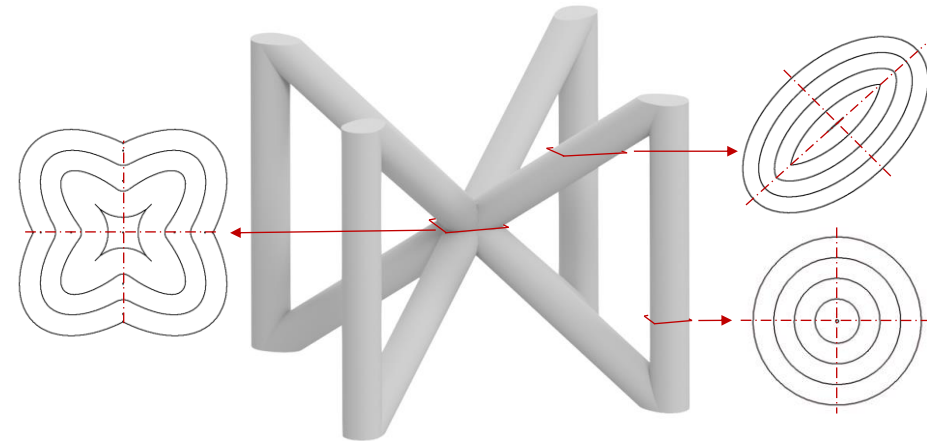
Contour strategy possible issues

- ❖ Irregular pores when BCCZ cells were produced
 - ❖ Diameter of 2 and 3 mm

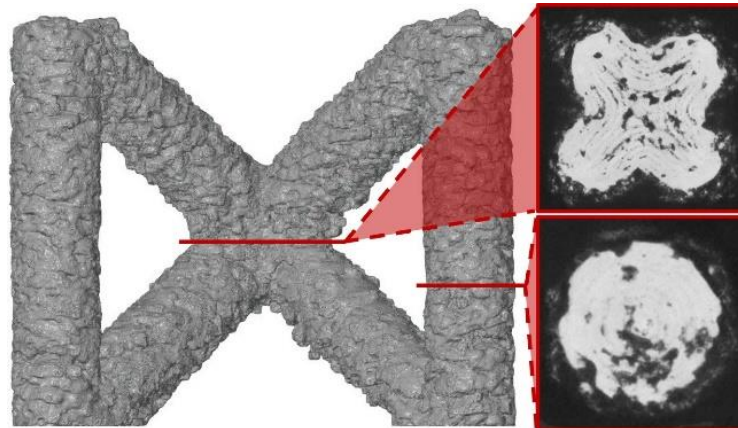
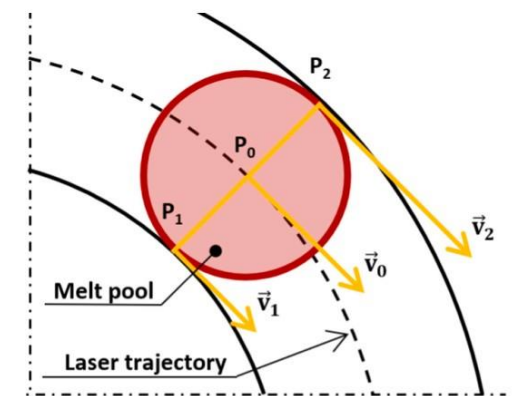


- ❖ Located in the struts and in the center of cell

❖ Different shape of laser trajectories



❖ Different velocities

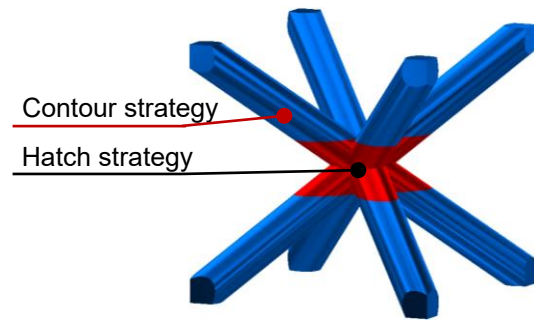


Results and Discussion

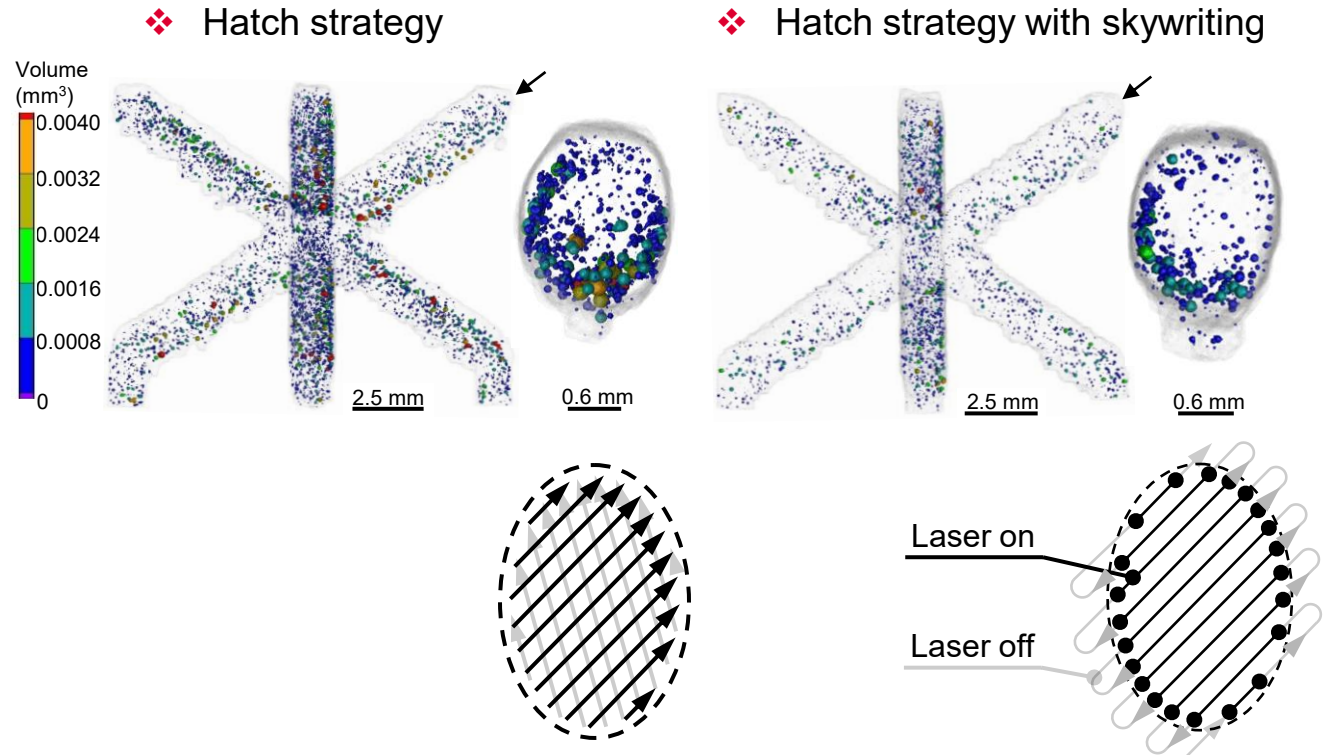
Scientific question 3 – Mechanical properties

Comparison of Contour and Hatch strategies

- ❖ Process parameters selection based on the BCC cell relative material density
- ❖ Three perspective laser strategies (relative material density above 99.11%)
 - ❖ Contour strategy
 - ❖ Hatch strategy with skywriting
 - ❖ Combination of contour and hatch strategies



- ❖ Skywriting reduced pores in the subsurface areas

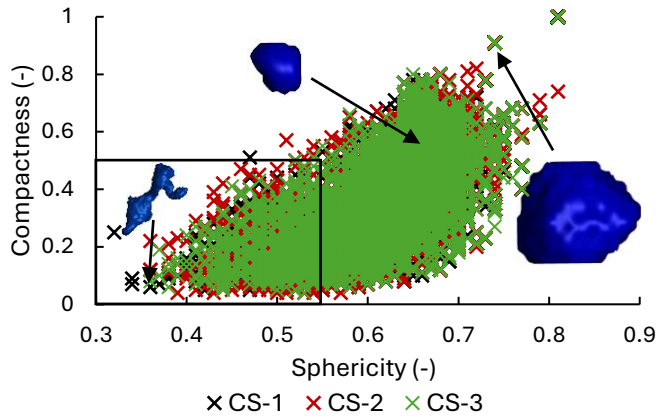


Results and Discussion

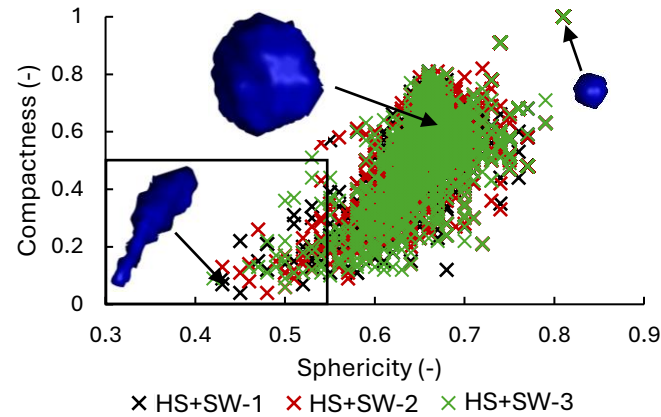
Scientific question 3 – Mechanical properties

Comparison of Contour and Hatch strategies

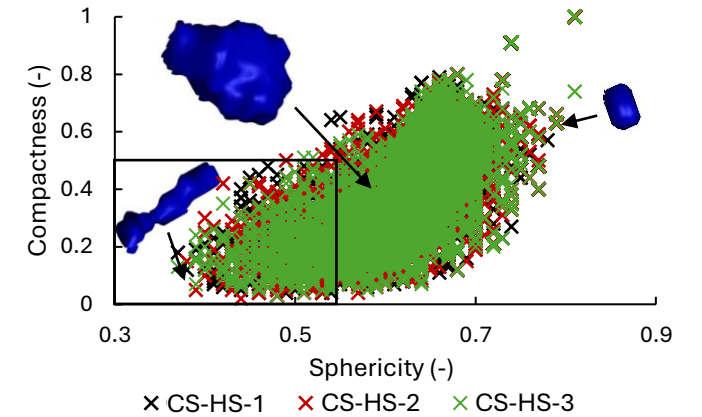
- ❖ Identification of dangerous pores
- ❖ Melt pool morphology
- ❖ Contour strategy



❖ Hatch strategy with skywriting



❖ Combination of strategies



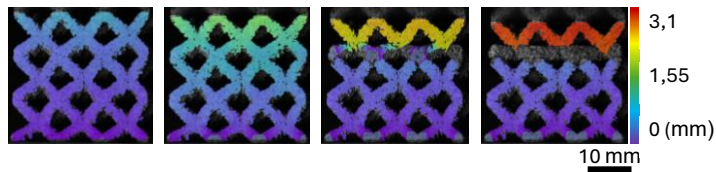
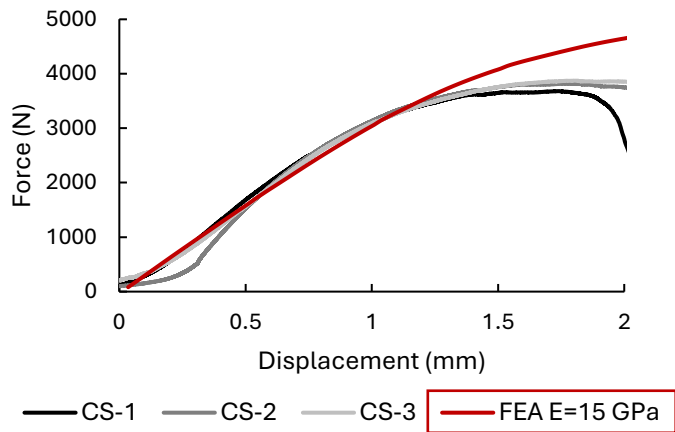
Results and Discussion

Scientific question 3 – Mechanical properties

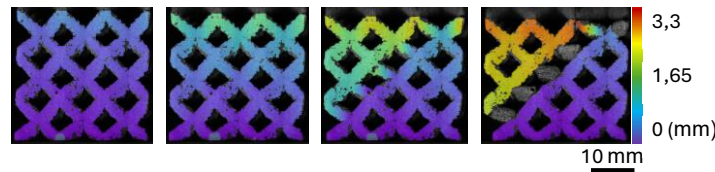
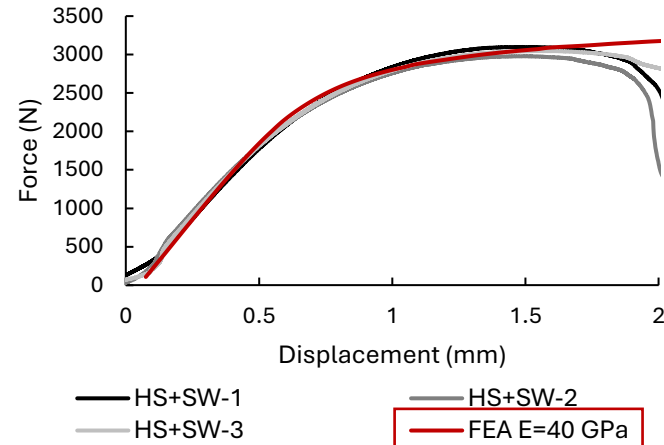
Comparison of Contour and Hatch strategies

- ❖ Mechanical properties and deformation behaviour
- ❖ WE43 Young's modulus 45 GPa

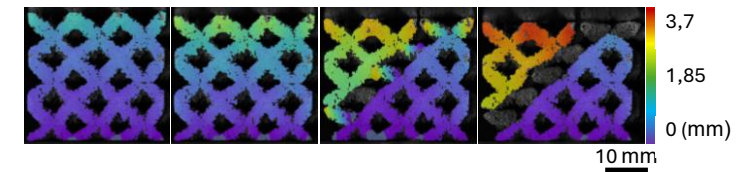
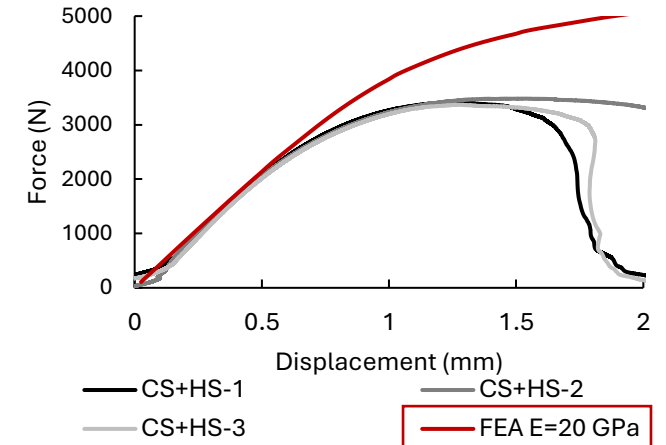
❖ Contour strategy



❖ Hatch strategy with skywriting



❖ Combination of strategies



Conclusions

Evaluation of scientific questions

Q1: Does the contour strategy reduce imperfections in PBF-LB lattice structures?

- ❖ The contour strategy led to **significant increase** of relative material density
- ❖ Surface roughness **strongly depends** on energy of process parameters strut diameter
- ❖ Dimensional accuracy **strongly depends** on weld width

1st hypothesis

Not falsified

Q2: Does the lattice structures from WE43 achieve density above 99.5% using contour strategy?

- ❖ The diameters up to 1 mm led to relative material density above 99.8%
- ❖ The relative material density **significantly decreased** with diameters above 1 mm
- ❖ The quality of specimens is **strongly affected** by low melting point of magnesium alloy

2nd hypothesis

Not falsified

Q3: Does the contour strategy improve mechanical performance of WE43 lattice structures compared to hatch strategy ?

- ❖ Higher mechanical performance was observed for hatch strategy with skywriting
- ❖ The contour strategy exhibited a **significantly higher** number of dangerous pores
- ❖ The contour strategy exhibited **no clear** boundaries for meltpools
- ❖ The brittle deformation behavior was observed for contour strategy

3rd hypothesis

Falsified

List of publications

Dissertation	❖ VRÁNA, R.; JAROŠ, J.; KOUTNÝ, D.; NOSEK, J.; ZIKMUND, T.; KAISER, J.; PALOUŠEK, D. Contour laser strategy and its benefits for lattice structure manufacturing by selective laser melting technology. <i>Journal of Manufacturing Processes</i> , 2022, vol. 74, no. 1, p. 640-657. ISSN: 1526-6125.
	❖ JAROŠ, J.; VAVERKA, O.; SENCK, S.; KOUTNÝ, D. Influence of Process Energy on the Formation of Imperfections in Body-Centered Cubic Cells with Struts in the Vertical Orientation Produced by Laser Powder Bed Fusion from the Magnesium Alloy WE43. <i>Micromachines</i> , 2024, vol. 15, no. 2, p. 1-16. ISSN: 2072-666X.
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Jan Jaroš, Ing.

Jan.Jaros2@vut.cz



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