Additive Manufacturing of Topologically Optimised Parts

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Dissertation defence

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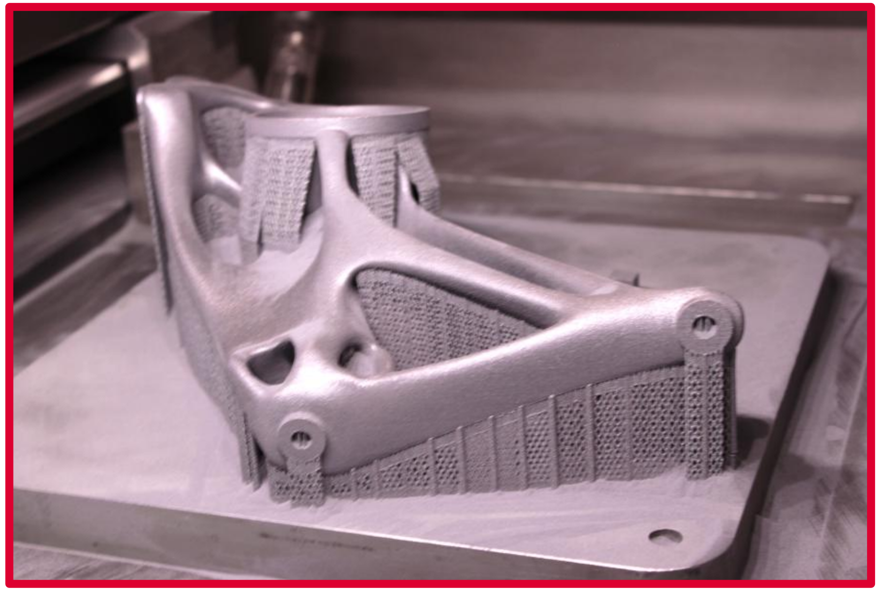
INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

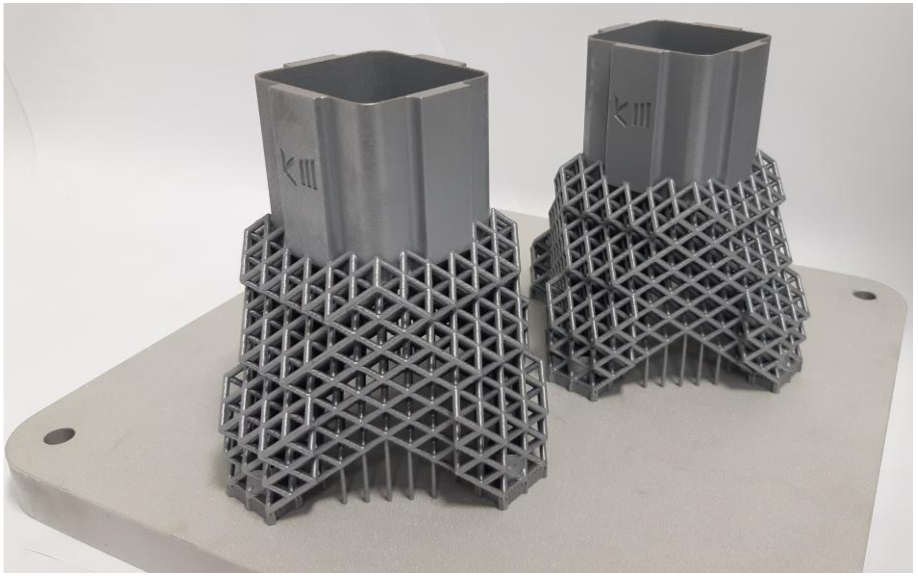
DEPARTMENT OF REVERSE ENGINEERING AND ADDITIVE TECHNOLOGIES

Content

Motivation

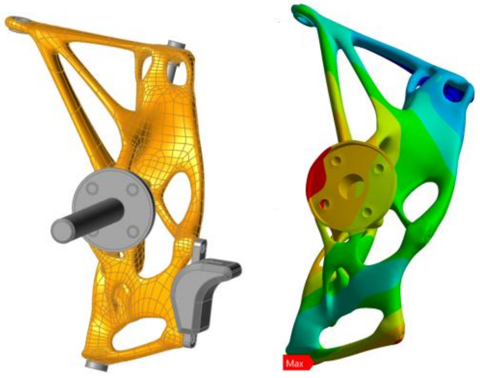
- Topology optimisation ≠ additive manufacturing friendly design
- Need for supports – mechanical stability and heat dissipation
- Residual stresses change the mechanical properties
- Structured material could solve most of the problems



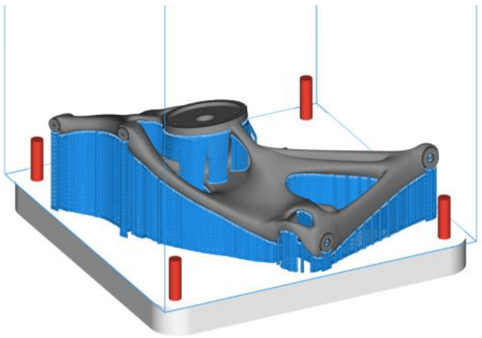


Problems

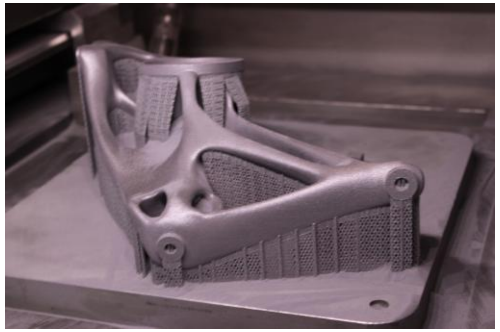
Design stage → Pre-processing → Manufacturing → Post-processing



- Mechanical properties
- Modelling



- Orientation
- Support structures

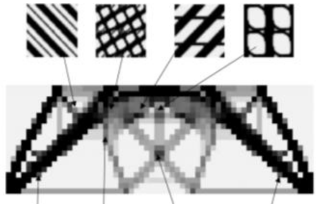
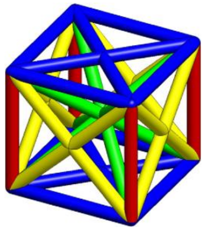
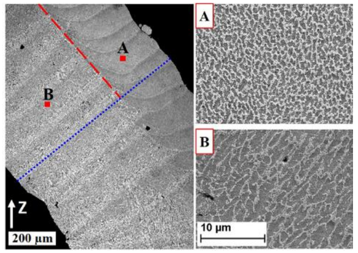


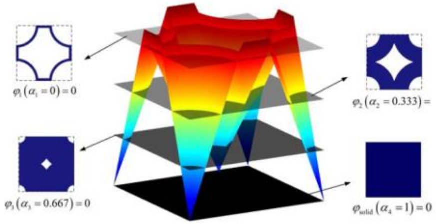
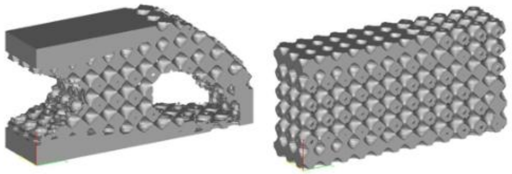
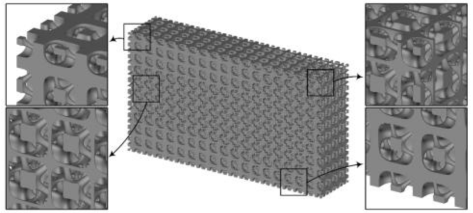
- Inner stress

- Residual stress
- Support structures

Analysis of the Literature Review

State of the art	Research gap
Multi-scale design should provide superior performance	Multi-scale approaches are often not feasible
Geometry consisting of solid material, lattice material and voids	
Functionally graded lattice structure or multiple lattice cells	
Heat treatment is the best way to eliminate residual stresses	Complex view on heat treatment is missing
Ideal lattice cell should be able to rotate according to the loading	Lattice structures are not tested in more directions
Lattice structures are extensively studied	Lattice structures with relative density less than 0.3 are studied

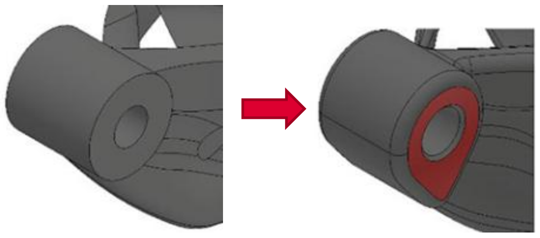




Rodriguez, et al., 2002 | Leary, et al., 2016 | Delroisse, et al., 2017 | Wang, et al., 2018 | Panesar, et al., 2018 | Zhao, et al., 2023

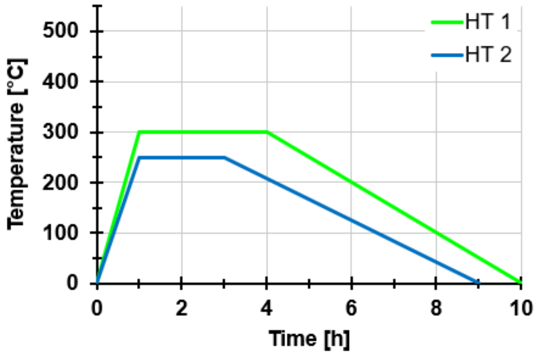
Aim of the Thesis

The aim of this thesis is to define an effective way to design and manufacture topologically optimised Al-Si alloy components using LPBF.

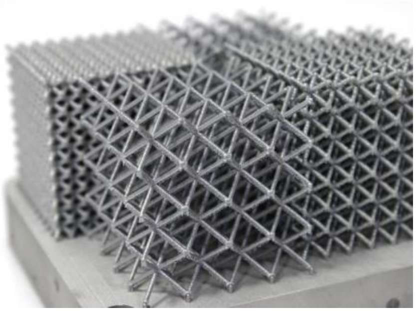
Mono-scale topology optimisation – modification for LPBF technology



Heat treatment of Al-Si alloys produced by LPBF technology



Properties of structured Al-Si alloy material produced by LPBF



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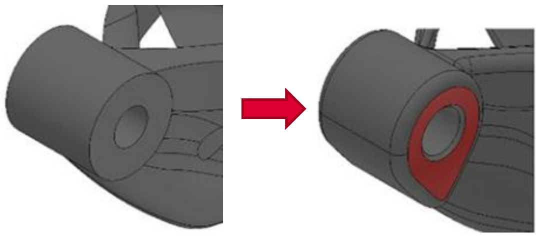

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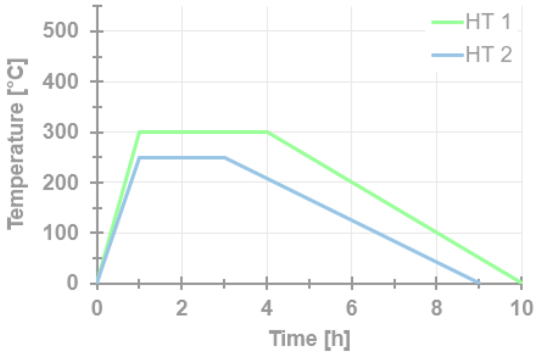

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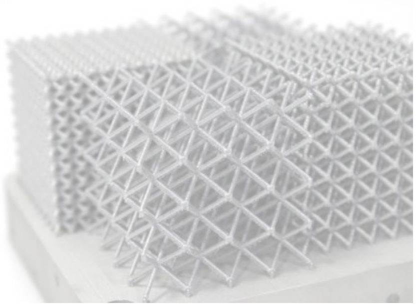

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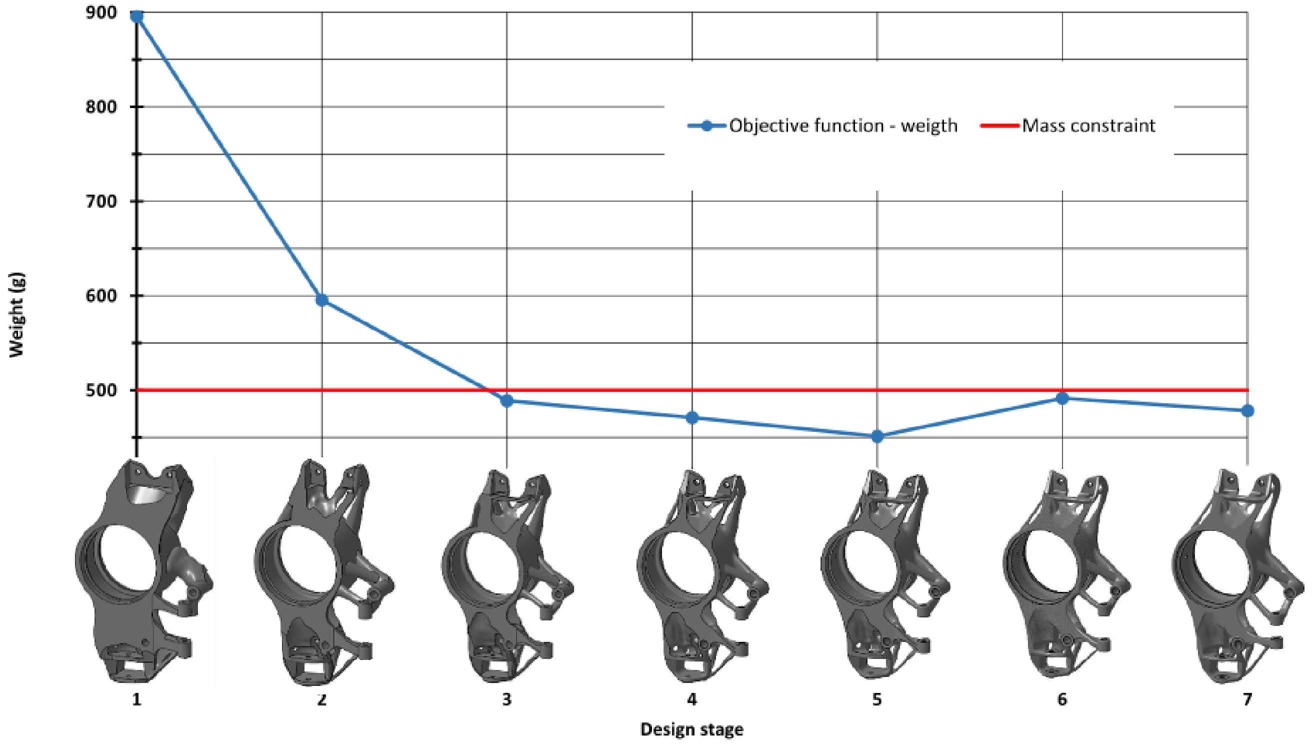
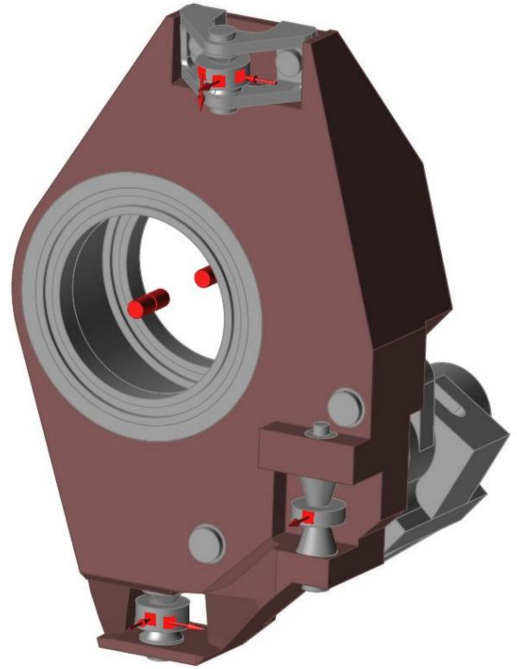
Materials and Methods

Topology optimisation in several iterations

INSPIRE





Materials and Methods

Topology optimisation in several iterations

Surface and volume remodelling

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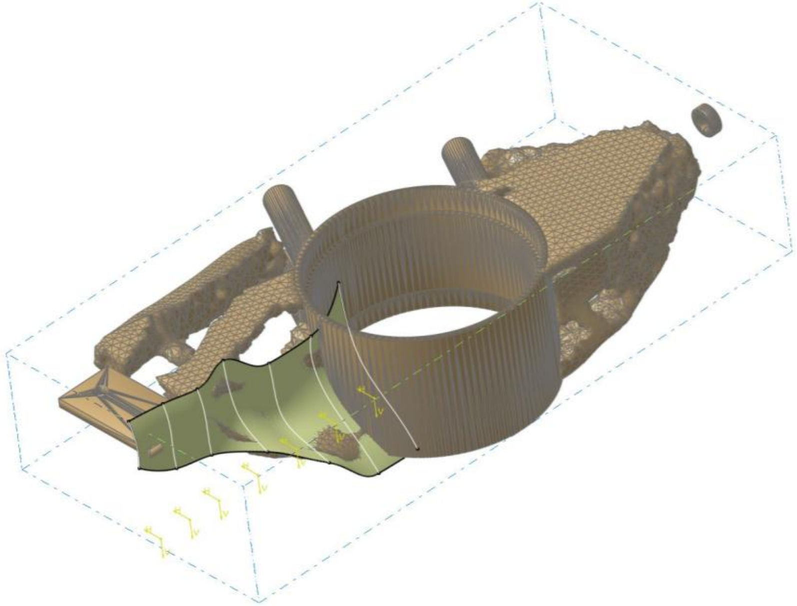

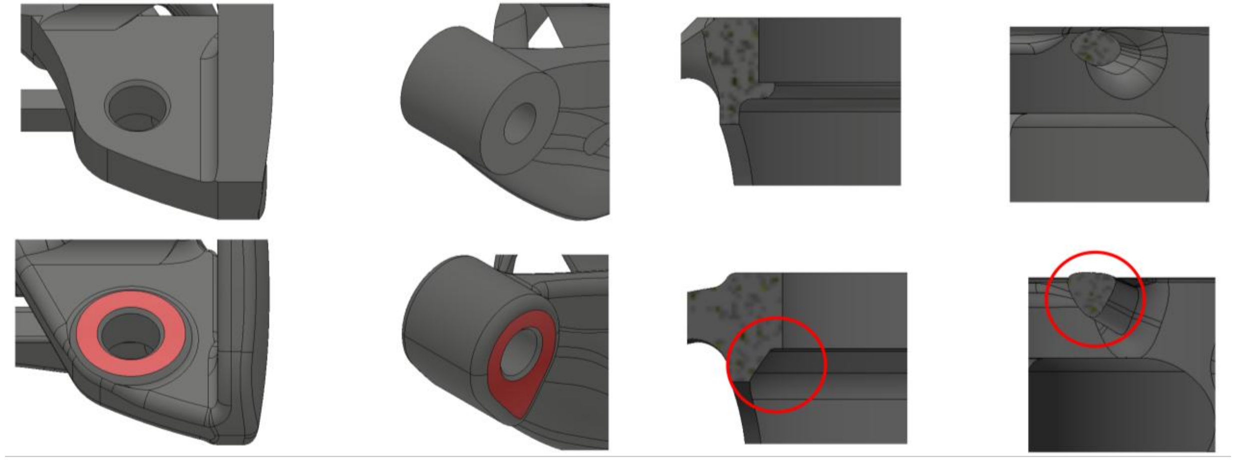

Materials and Methods

Topology optimisation in several iterations

Surface and volume remodelling

Control FEA

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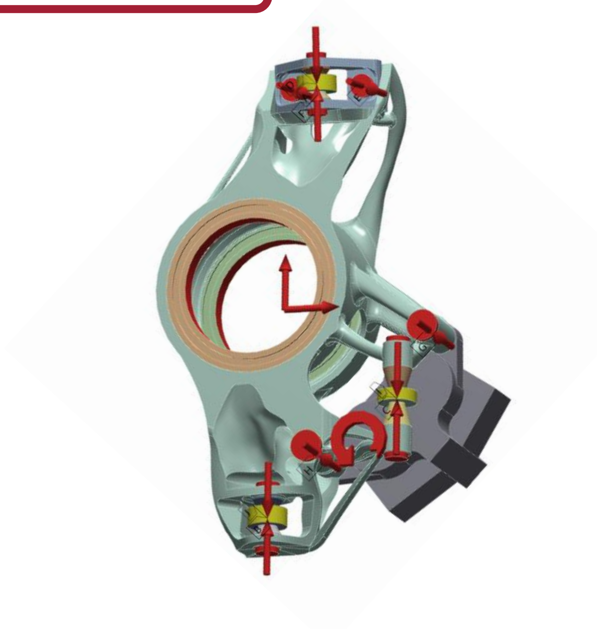

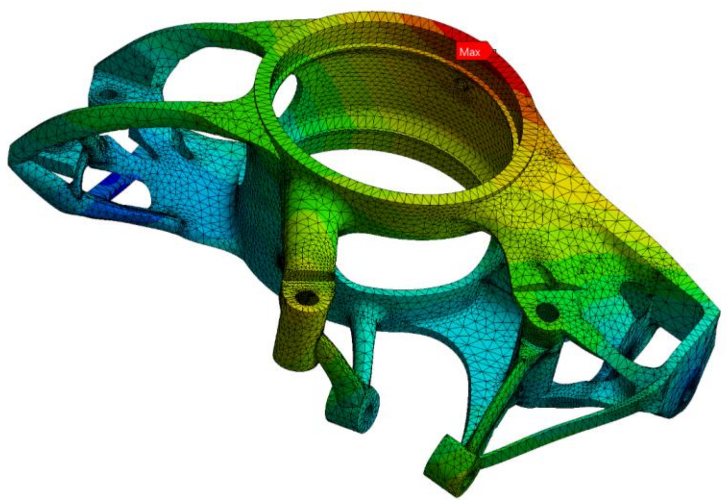

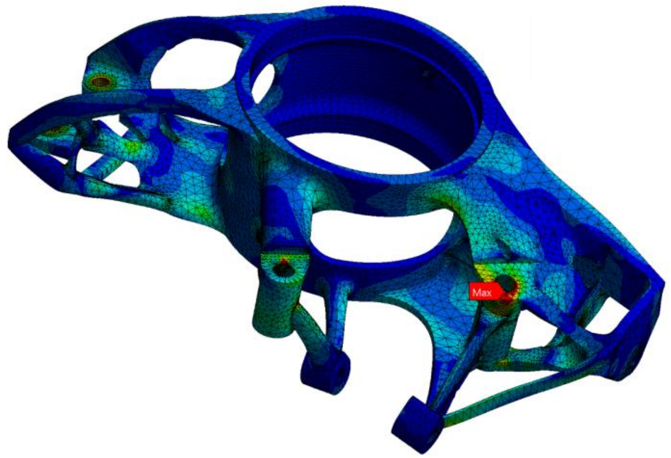

Materials and Methods

- Topology optimisation in several iterations
- Surface and volume remodelling
- Control FEA
- Manufacturing by LPBF from AlSi10Mg

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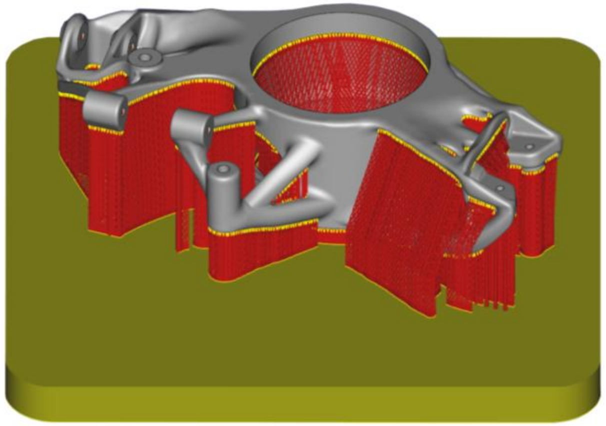
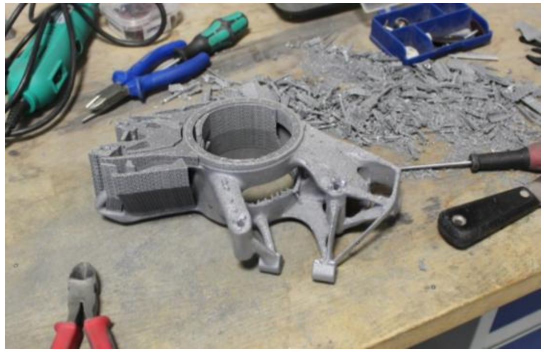
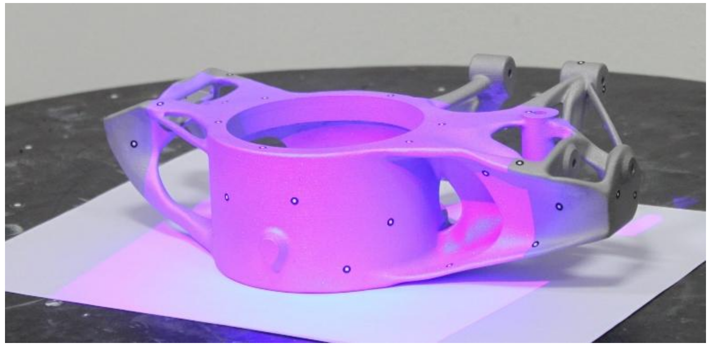
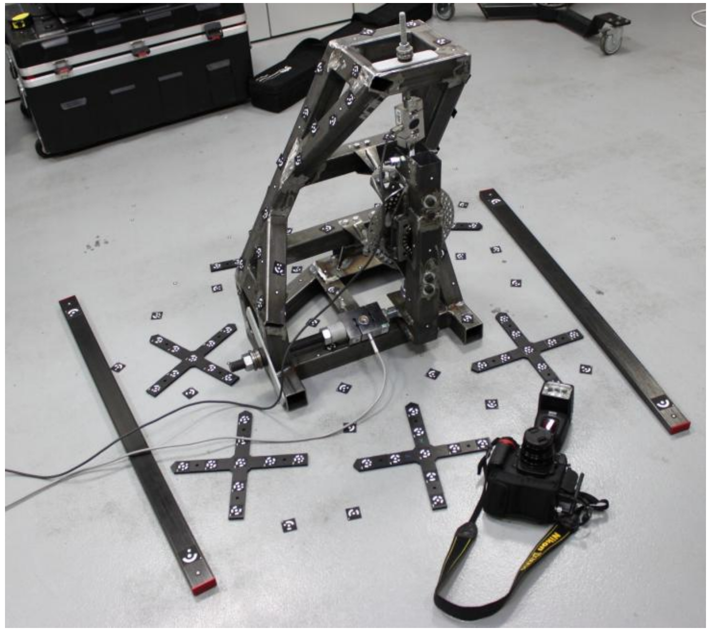




Materials and Methods

- Topology optimisation in several iterations
- Surface and volume remodelling
- Control FEA
- Manufacturing by LPBF from AlSi10Mg
- Quality control and experimental verification





Results

Milled axle carrier

Material:	EN AW 7075 T6 ($R_{p0,2}$ = 500 MPa)
Weight:	485 g
Max. displacement:	0.5 mm

Optimised axle carrier

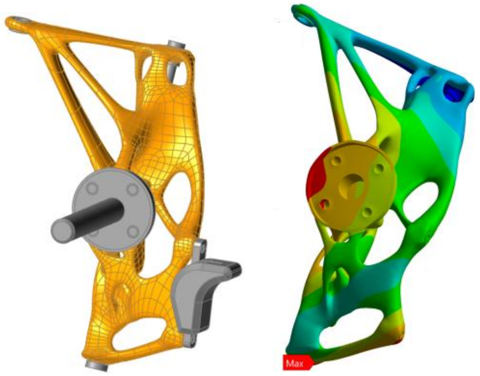
Material:	AlSi10Mg ($R_{p0,2}$ = 240 MPa)
Weight:	485 g
Max. displacement:	0.4 mm

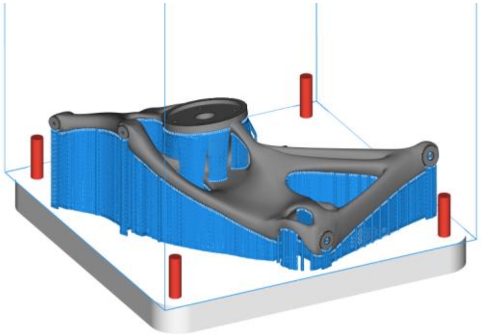
Impact on the Thesis Results

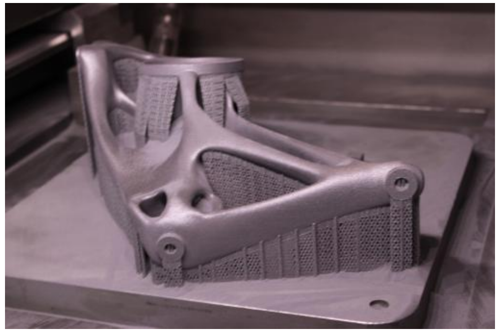
Case study of the design process using mono-scale without the overhang constraint and the manual application of DfAM rules once the manufacturing orientation of the component is known. This process can be further used to create benchmarks for components designed with other TO algorithms, especially for multi-scale geometries.

Solved and Remaining Problems

Design stage → Pre-processing → Manufacturing → Post-processing







Design stage
- Mechanical properties
- Modelling ✓

Pre-processing
- Orientation
- Support structures

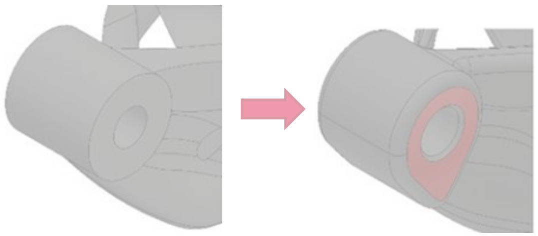
Manufacturing
- Inner stress

Post-processing
- Residual stress
- Support structures ✓

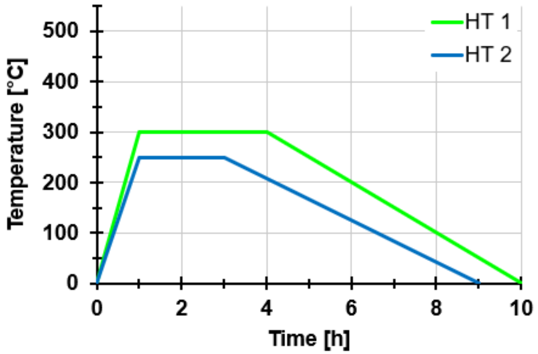
Aim of the Thesis

The aim of this thesis is to define an effective way to design and manufacture topologically optimised Al-Si alloy components using LPBF.

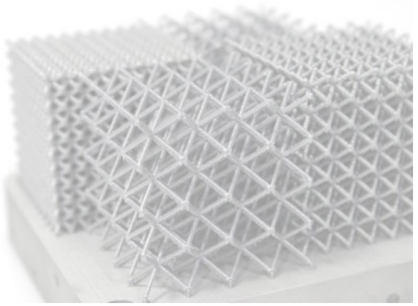
Mono-scale topology optimisation – modification for LPBF technology



Heat treatment of Al-Si alloys produced by LPBF technology



Properties of structured Al-Si alloy material produced by LPBF



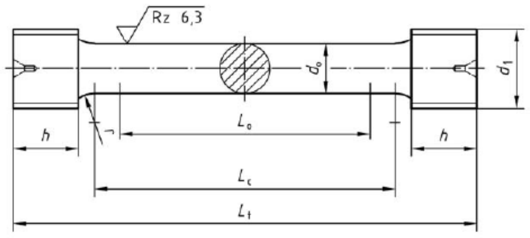
Scientific Questions

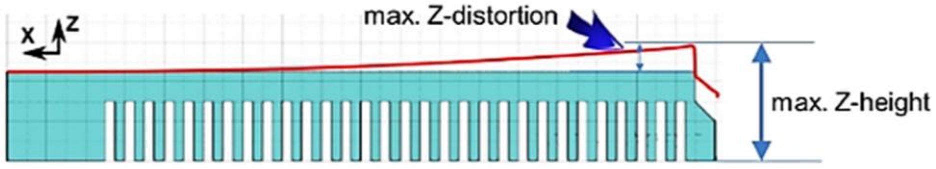
Scientific question no. 1

What is the optimal heat treatment for an additively manufactured Al-Si alloy to reduce residual stresses while maintaining strength properties?

Hypothesis no. 1

When the T6 treatment is applied, the material maintains its strength properties and at the same time residual stresses are sufficiently reduced.





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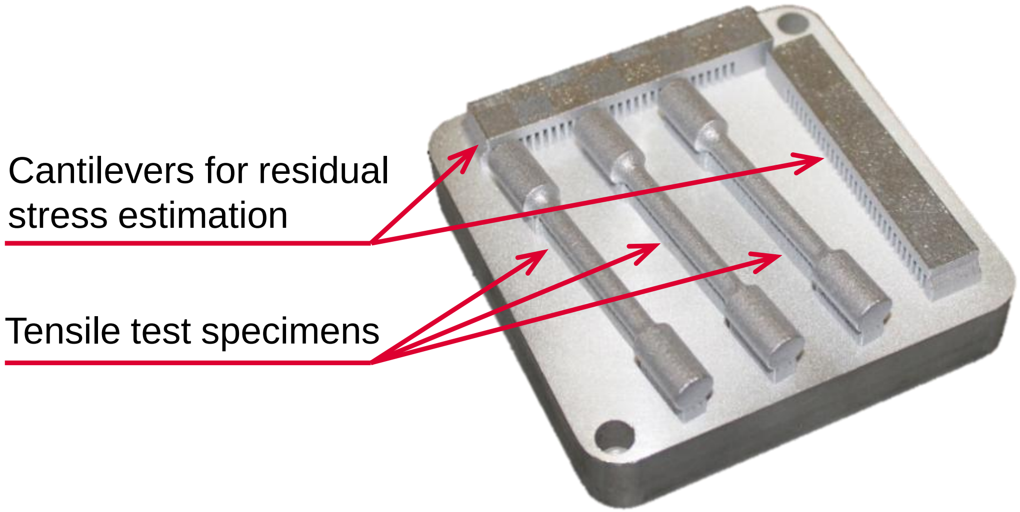
Materials and Methods

- Comparison of stress relieving and T6 treatment
- Different holding times of solution treatment
- Tensile testing
- Cantilever testing (deflection method)

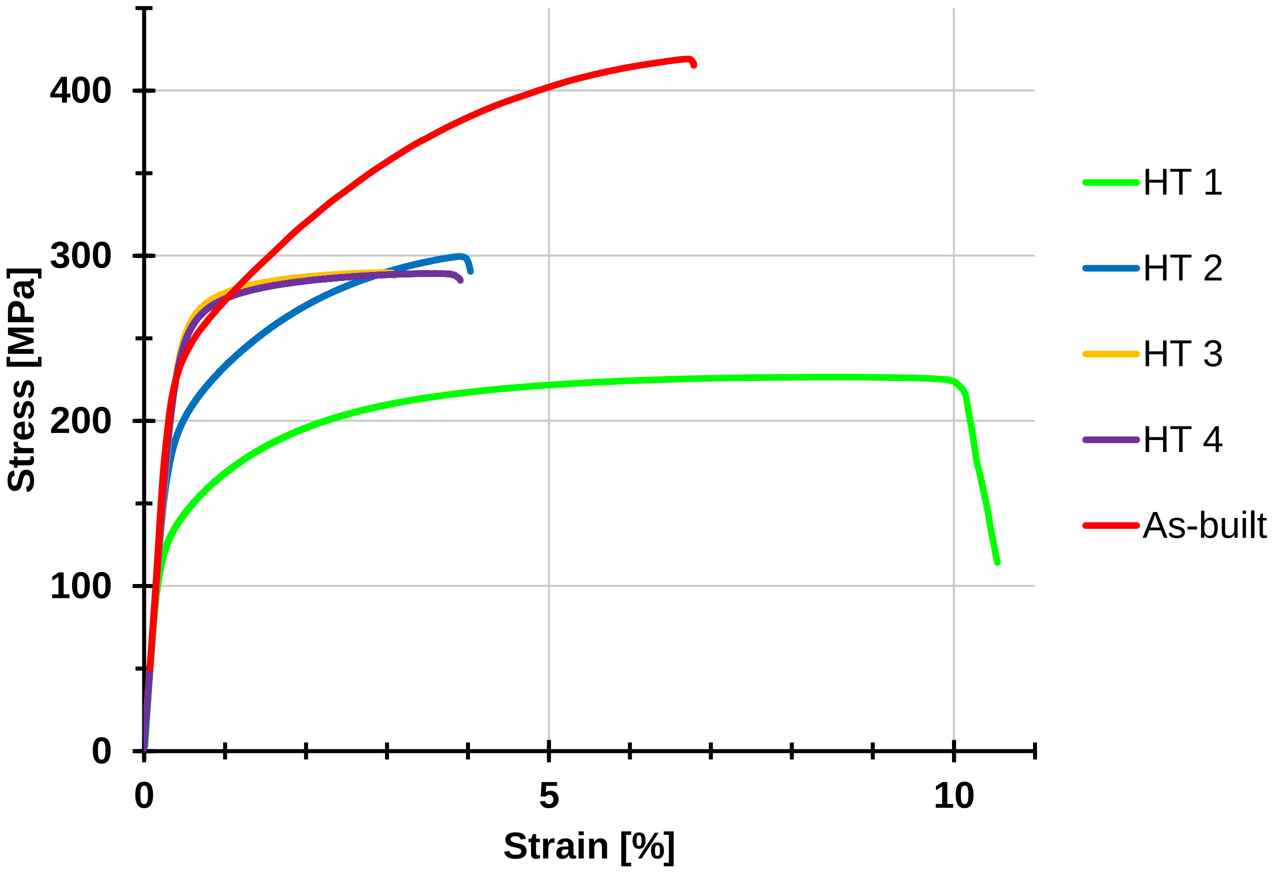


	AlSi10Mg
HT 1	300 °C/ 3 hours
HT 2	250 °C/ 2 hours
HT 3	520 °C/ **6 hours**/ water quench/ 175 °C/ 4 hours
HT 4	510 °C/ **0.1 hour**/ water quench/ 170 °C/ 8 hours
HT 5	As-built

Results

Tensile testing

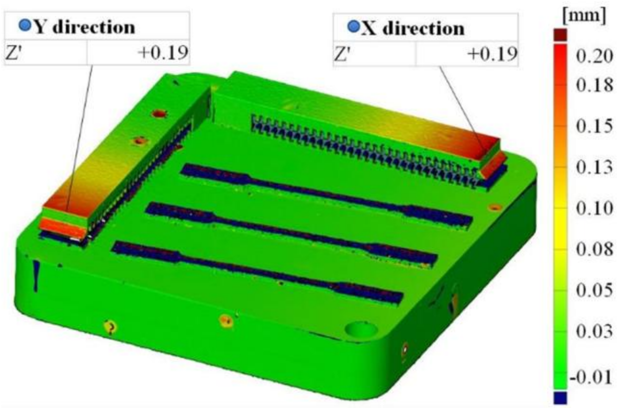
- Highest values in the As-built state
- SR decreases YS with increasing temperature
- SR increases elongation
- T6 increases YS and decreases UTS
- Holding times of solution treatment have no impact

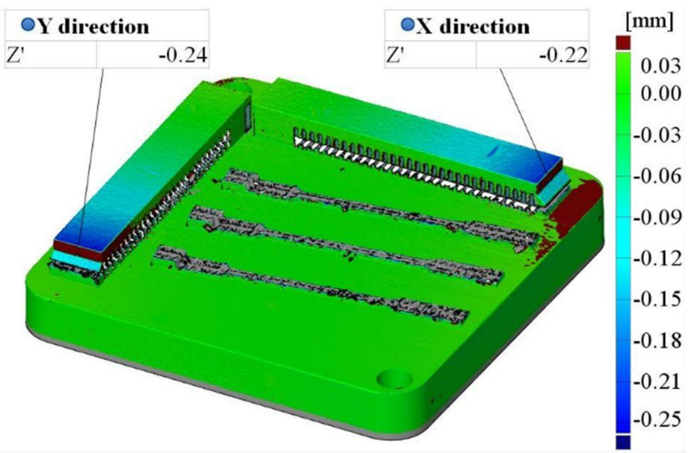


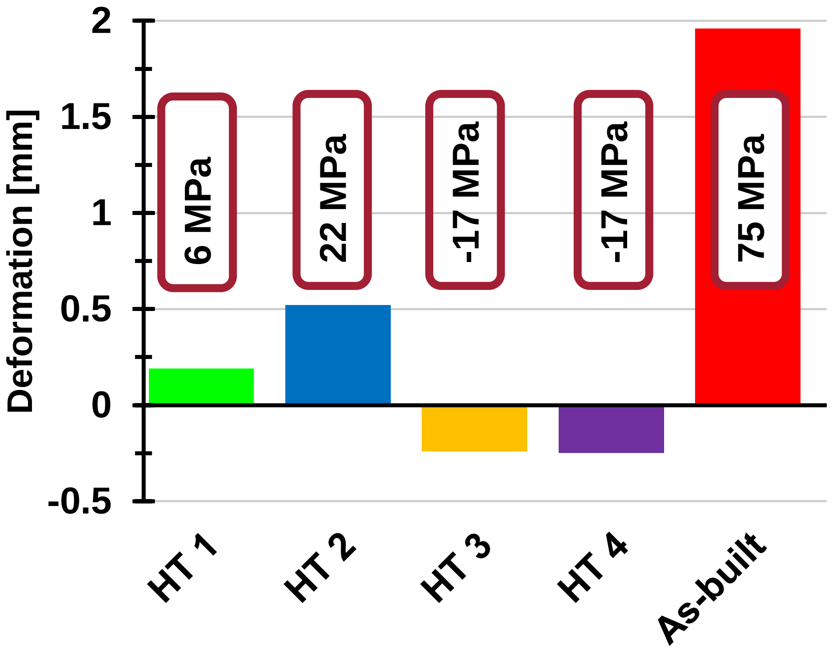
Results

Cantilever testing

- Biggest deformation in the As-built state
- SR decreases deformation with increasing temperature
- T6 causes negative deformation – compressive stress
- Holding times of solution treatment have no impact







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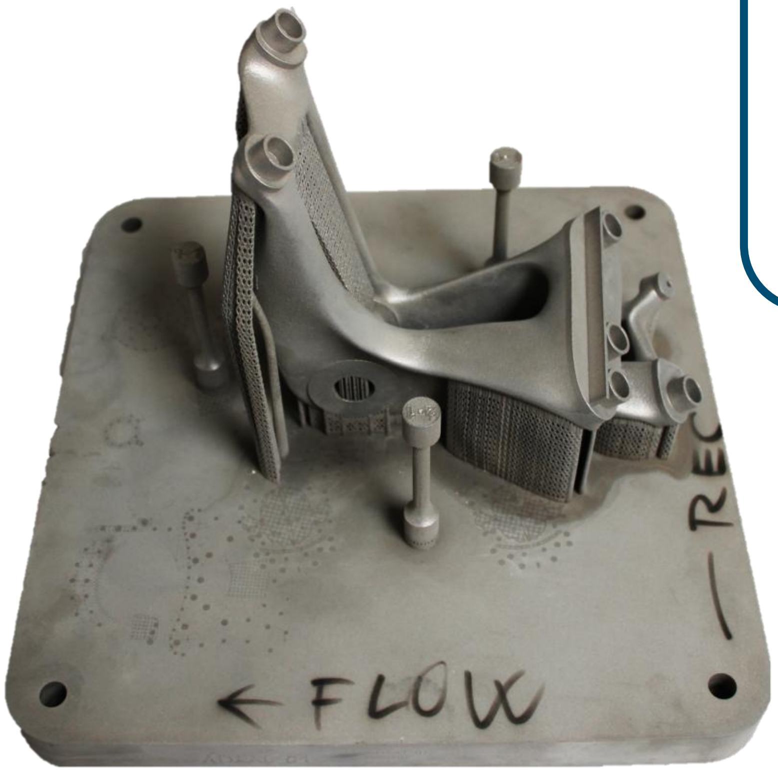
Impact on the Thesis Results



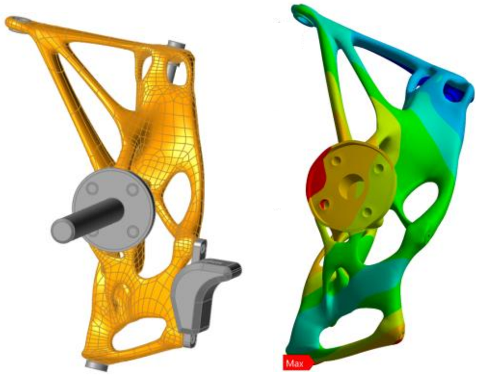
Answer to Scientific question no.1

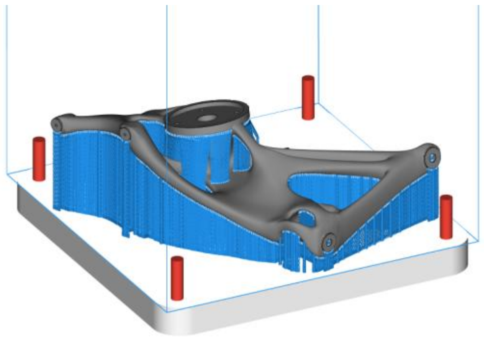
The T6 treatment offers the best compromise between strength properties and residual stress relief. However, water cooling leads to compressive stresses in the part, which can cause undesirable deformations. This must be taken into account during pre-processing and choose the correct orientation on the platform and create sufficient support structures.

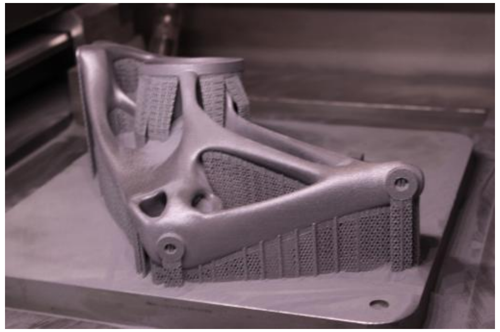
(Hypothesis confirmed)

Solved and Remaining Problems

Design stage → Pre-processing → Manufacturing → Post-processing







- Mechanical properties ✓
- Modelling

- Orientation
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- Inner stress

- Residual stress ✓
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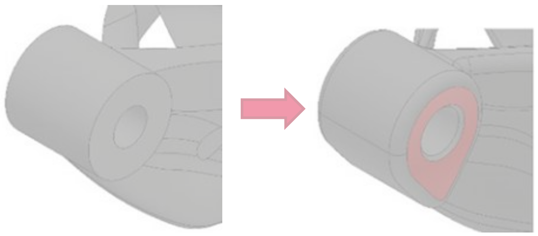
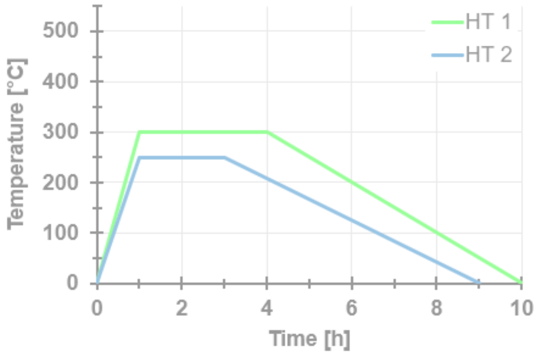
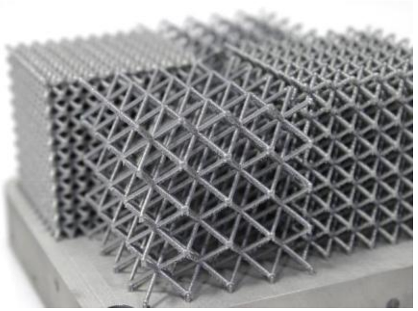


Heat treatment of Al-Si alloys produced by LPBF technology



Properties of structured Al-Si alloy material produced by LPBF



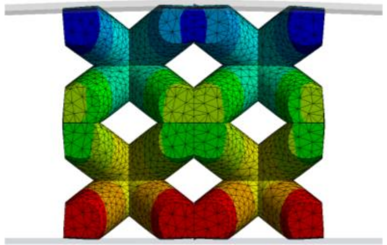
Scientific Questions

Scientific question no. 2

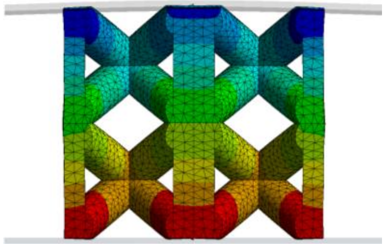
How does the weight of the part change when the correct lattice cell topology is used to create the component?

Hypothesis no. 2

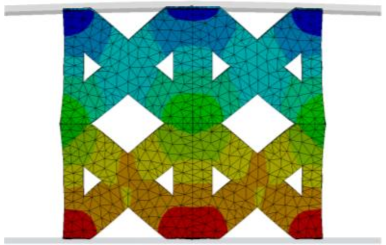
The result of multi-scale topology optimisation can be improved by changing the lattice topology and reducing the weight by more than 30% while maintaining the stiffness.



Displacement: 0,04 mm
Weight: 11.9 g



Displacement: 0,04 mm
Weight: 9.2 g (-23%)



Displacement: 0,04 mm
Weight: 6.9 g (-42%)

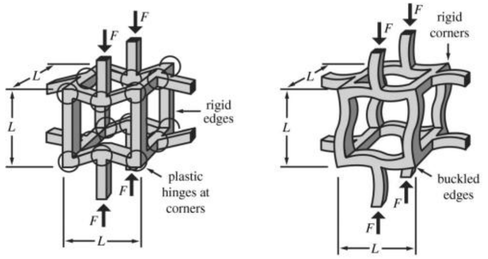
Scientific Questions

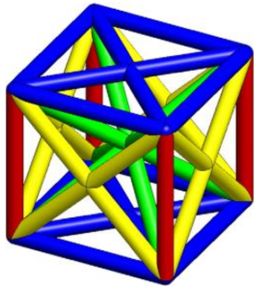
Scientific question no. 3

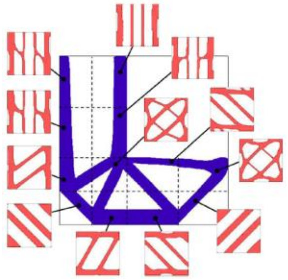
How can the geometric anisotropy of the lattice cell affect its stiffness in the direction parallel and perpendicular to the build plate?

Hypothesis no. 3

Loading lattice structures in the direction perpendicular to the build direction is always disadvantageous because there are no struts aligned with the load. So, if the manufacturing orientation of the entire component is changed properly, it should save the mass while maintaining stiffness.

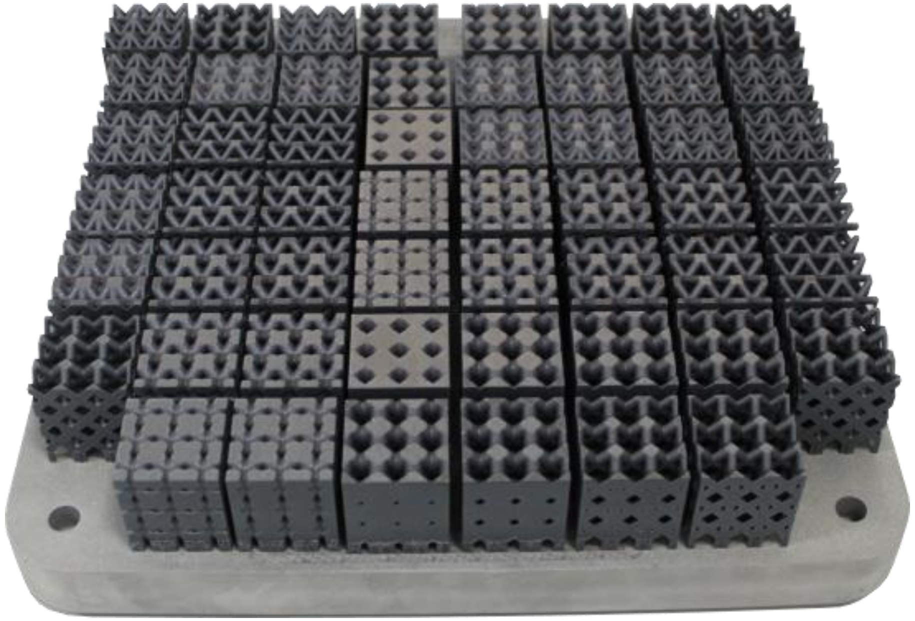


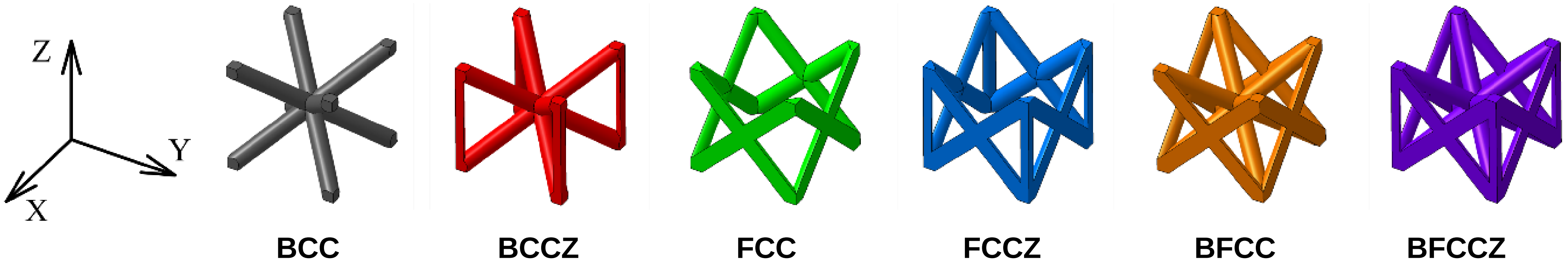




Materials and Methods

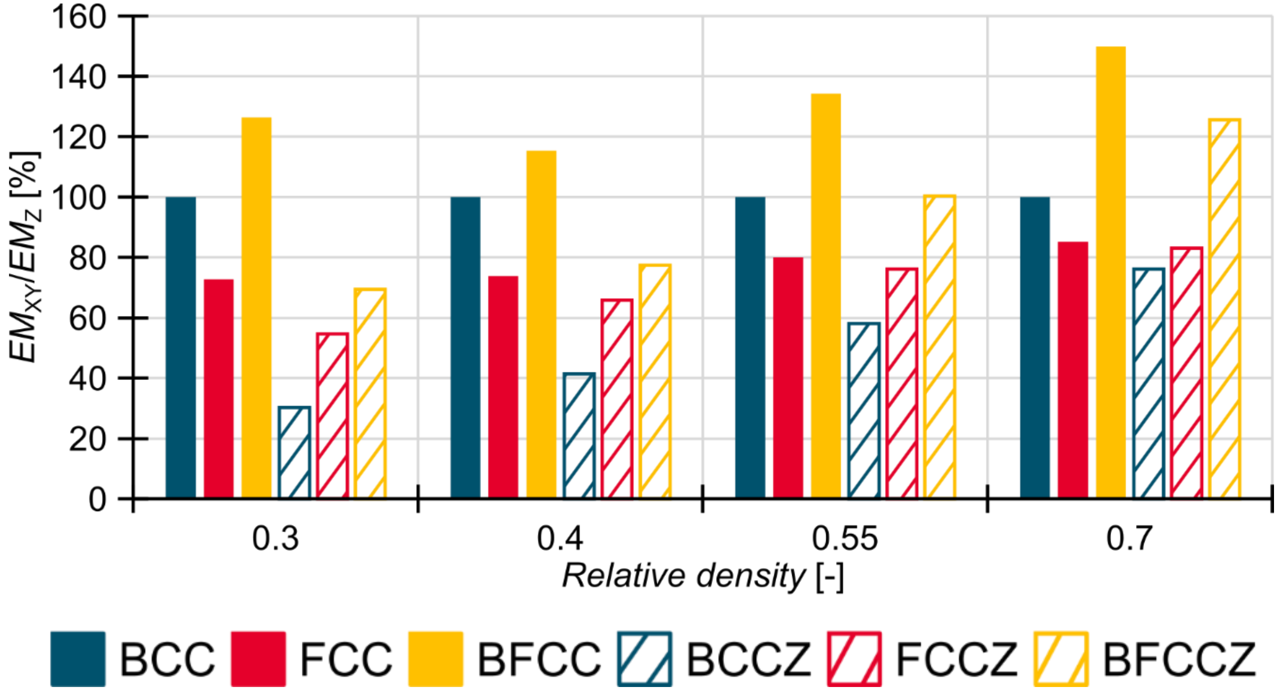
- 6 lattice topologies
- Cell sizes of 10 mm, 3×3×3 cells
- Relative densities 0.3, 0.4, 0.55, 0.7
- Two testing orientations
- T6 heat treatment
- FEA and experimental testing

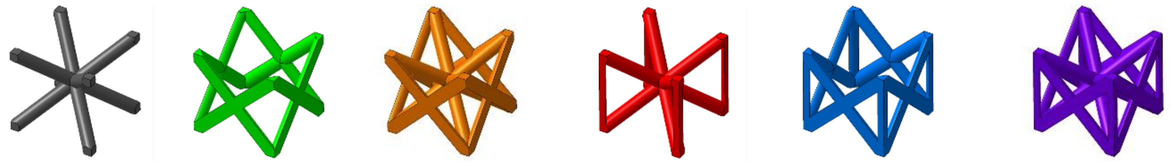




Results

- FCC, BCCZ, FCCZ – higher EM in Z-direction
- BFCC – higher EM in XY-direction
- BFCCZ – varies with relative density





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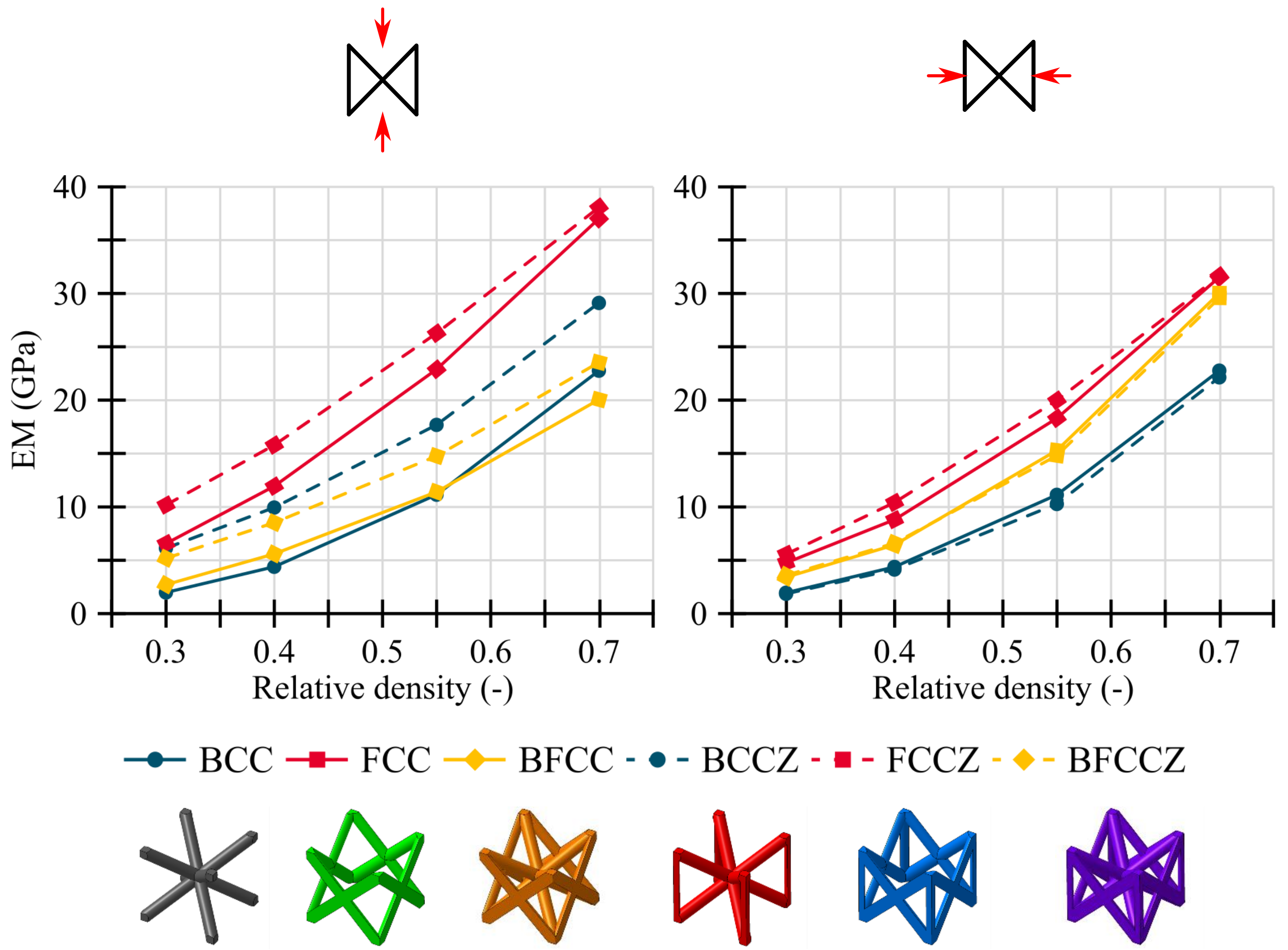
Results

- Highest EM provided by FCCZ cell
- Lowest EM provided by BCC



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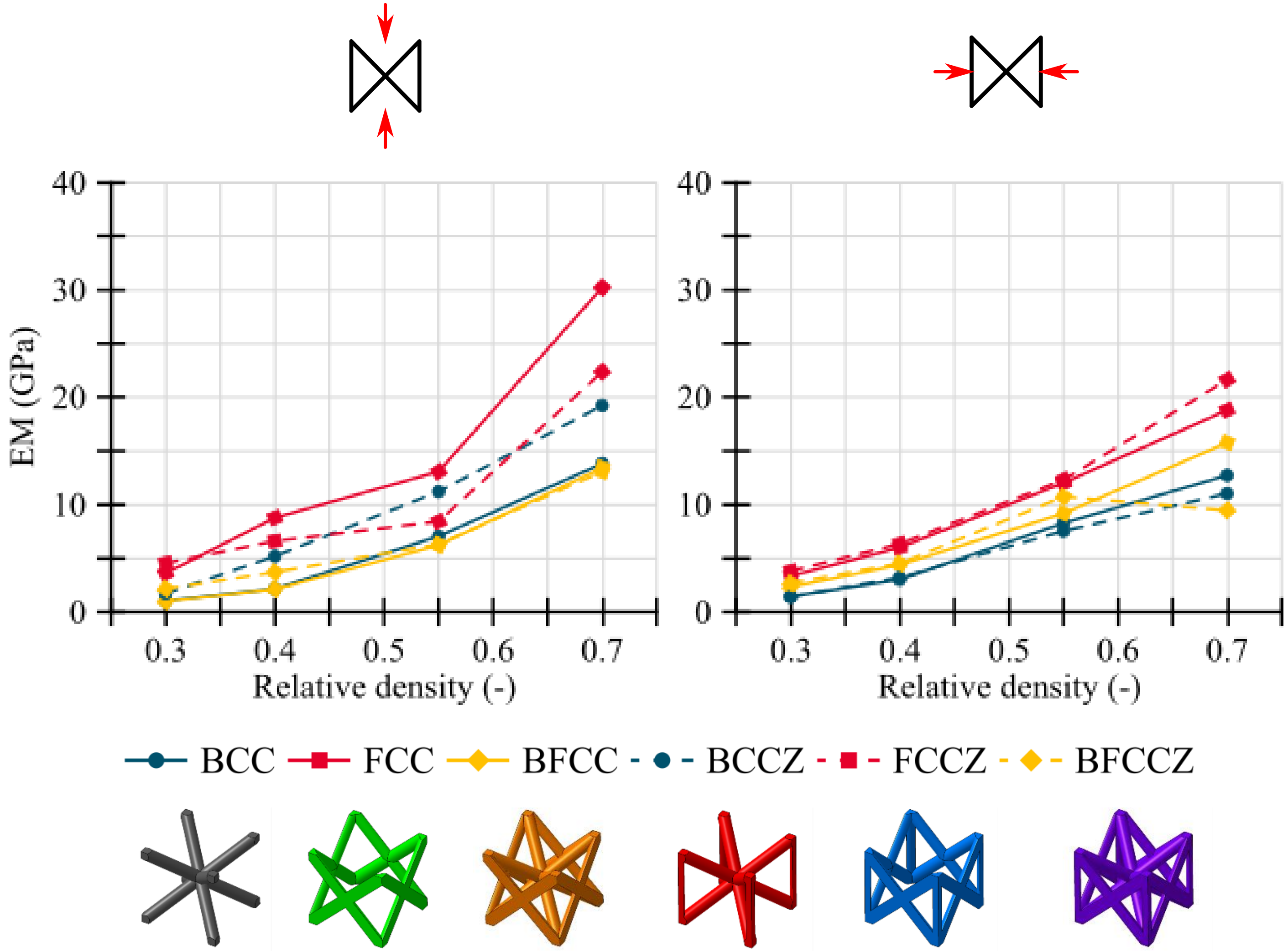
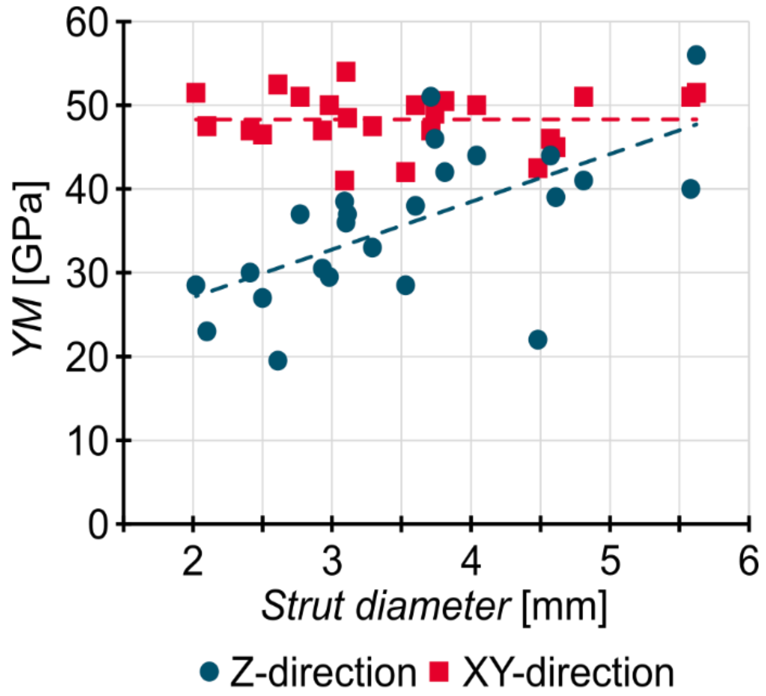


Results

- Tuning FEA to meet experimental results
- Big variation of YM, increasing with decreasing strut diameter
- Relation with loading direction
- Caused by T6 heat treatment
- True *YM* based on strut diameter when loaded in Z-direction



Specimen	EM (experiment) [GPa]	Error of EM (nominal material) [%]	Error of EM [%]
BCC (Ø 4.3 mm)	7.32	+108	**+23**
FCC (Ø 3.9 mm)	7.59	+100	**+12**
BFCC (Ø 3.4 mm)	8.33	+130	**+20**
BCCZ (Ø 3.5 mm)	8.31	+83	**-3**
FCCZ (Ø 3.4 mm)	7.67	+99	**+3**
BFCCZ (Ø 3.0 mm)	6.10	+174	**+34**

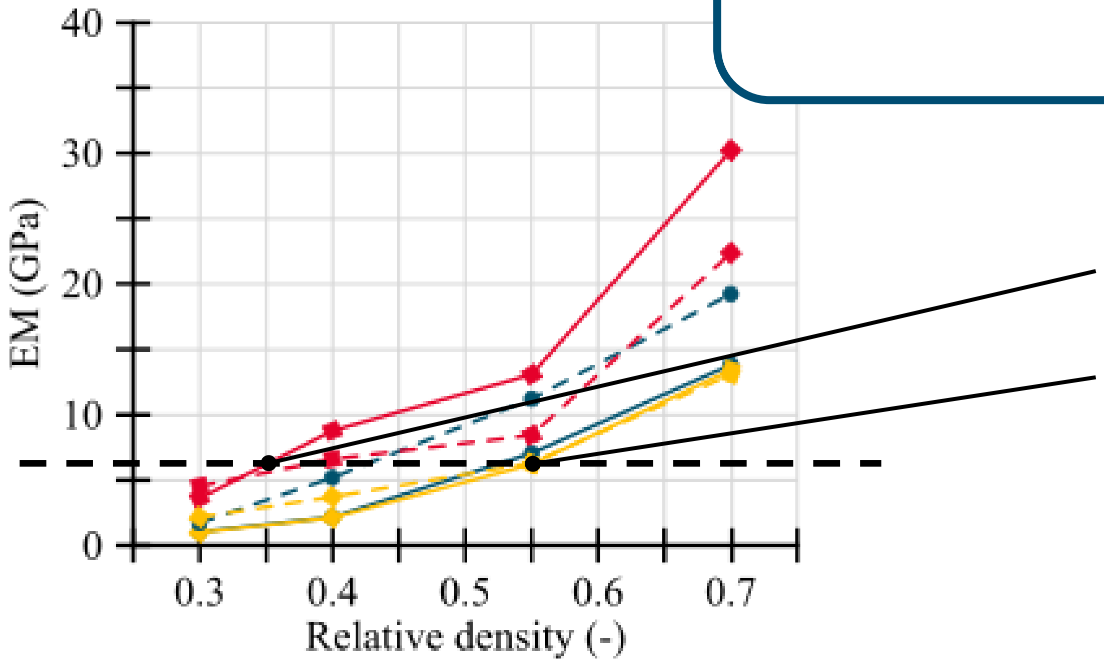
$$YM\ [\mathrm{GPa}] = 5.7\ D[\mathrm{mm}] + 16.1$$

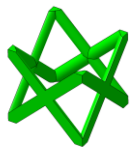
Impact on the Thesis results

Answer to Scientific question no.2

The FCCZ lattice cell has the highest effective modulus of elasticity in compression, regardless of orientation. The difference between FCCZ and the lowest performing lattice cell reaches up to **36%** when loaded in the Z-direction and **22%** when loaded in the XY-direction.

(Hypothesis falsified)





≈ 0.35 **(-36%)**

0.55

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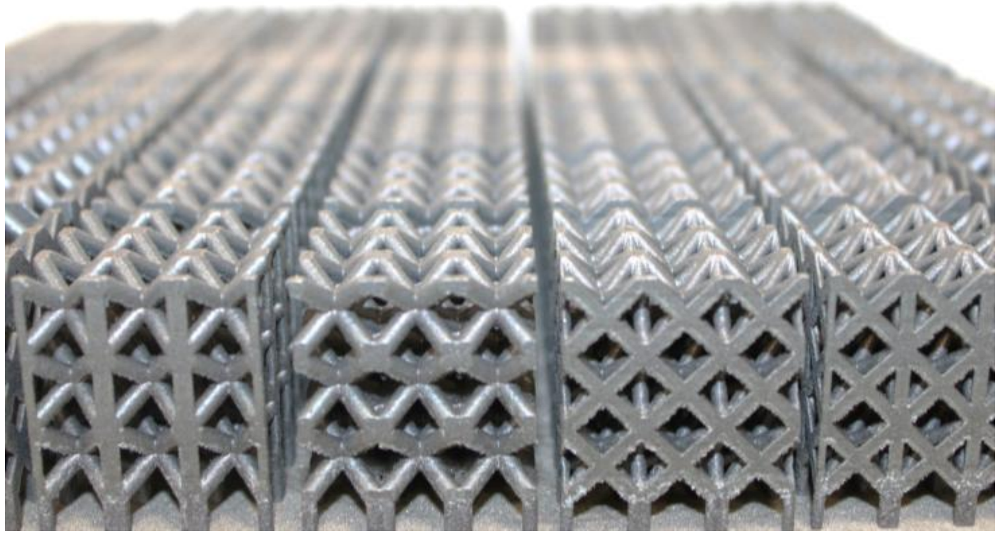
Impact on the Thesis results

Answer to Scientific question no.3

The geometric anisotropy of basic truss-based lattice cells without horizontal struts does not generally provide lower stiffness in the XY-direction. The advantage of struts aligned with the load direction varies with the relative density or is not present at all in some lattice topologies.

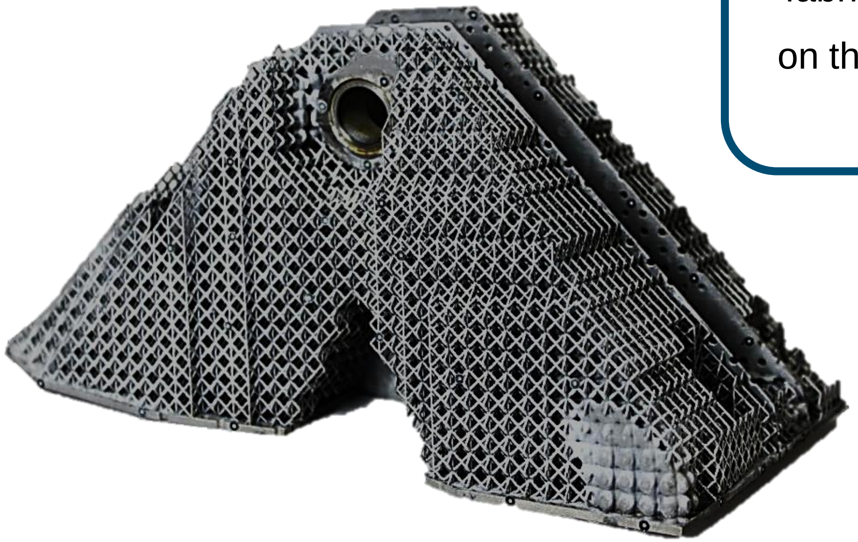
(Hypothesis falsified)



Impact on the Thesis results

The T6 treatment induces residual stresses also in the structured material with high relative density. No deformation is visible, but the mechanical properties are strongly affected, mainly in the Z-direction.

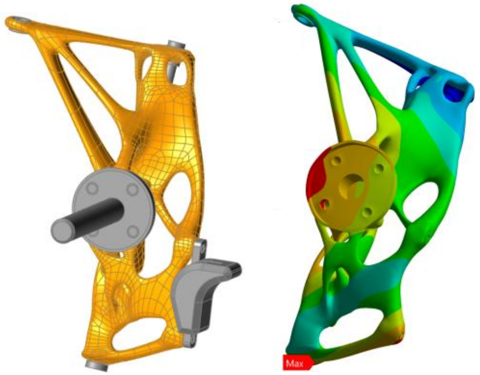
Material interpolation in density-based multi-scale TO should take into account the effects of fabrication (residual stresses, different shape of struts, reduced Young's modulus of elasticity) on the resulting effective modulus of elasticity of the structured material under different loading conditions.



Solved problems

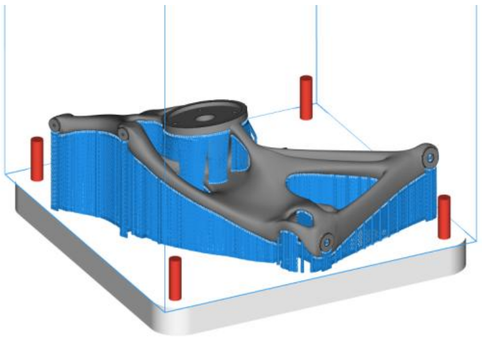
Design stage → Pre-processing → Manufacturing → Post-processing

Design stage



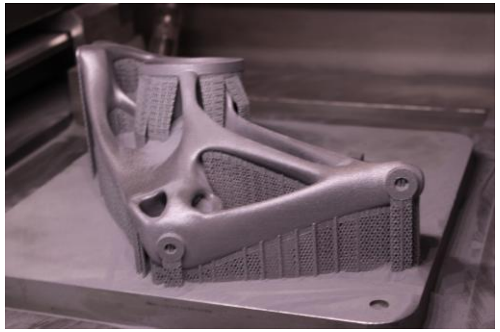
- Mechanical properties ✓
- Modelling ✓

Pre-processing



- Orientation ✓
- Support structures ✓

Manufacturing



- Inner stress ✓

Post-processing

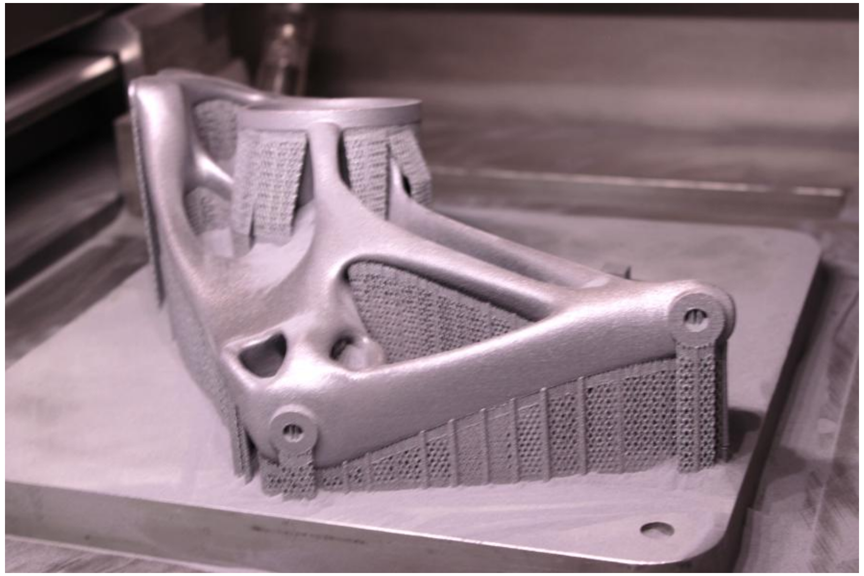
- Residual stress ✓
- Support structures ✓

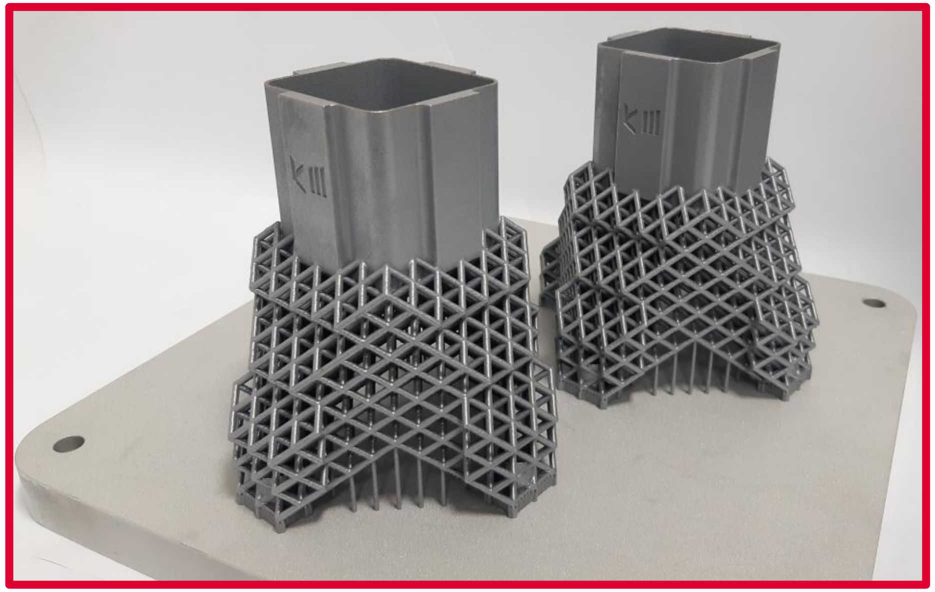
Concluding Remarks

- TO with DfAM does not solve all problems
- Real mechanical properties after HT must be always considered in design
- Structured material with high relative density was studied

T6 eliminates residual stresses, but induces new compressive stress in part — **Key finding, new in literature**

The influence of T6 HT on mechanical performance of structured material in two directions — **Key finding, new in literature**





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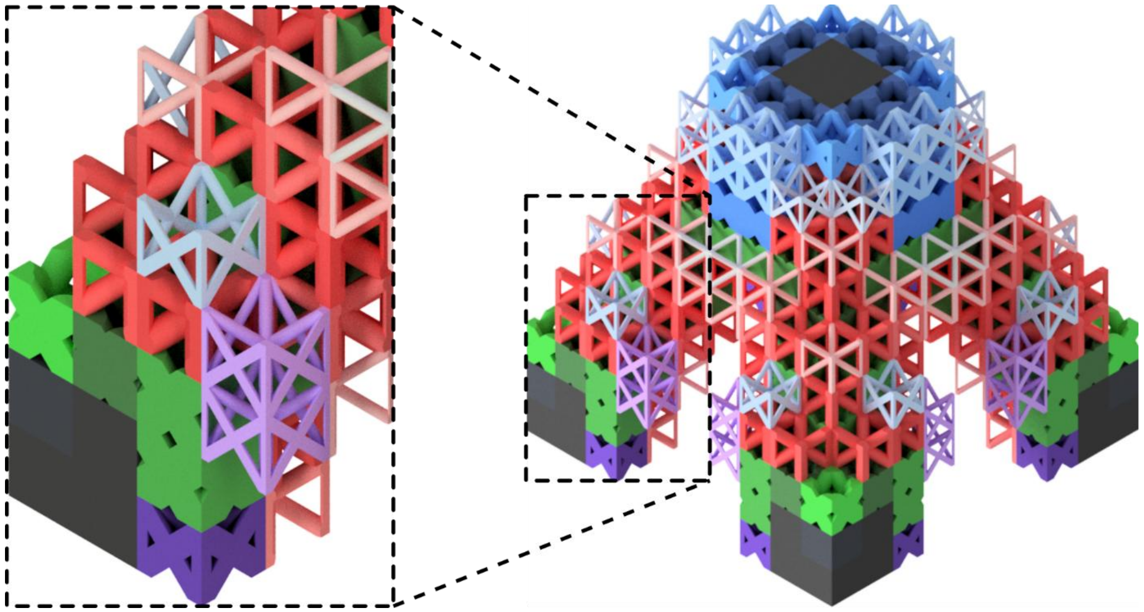
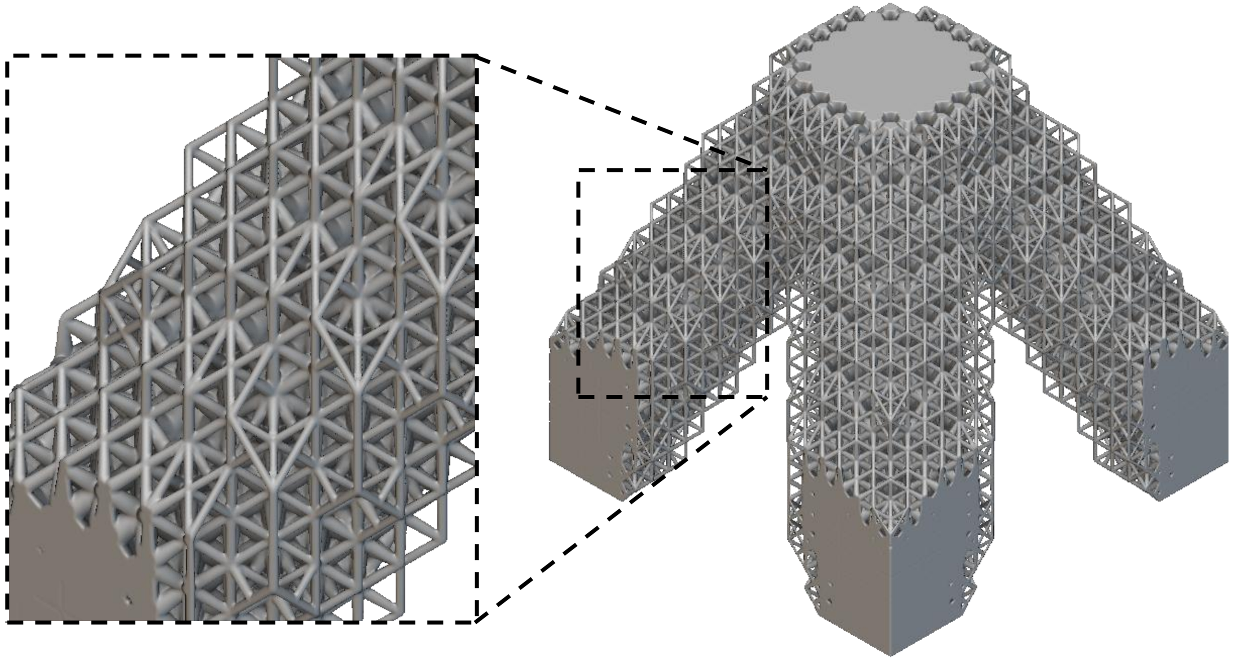
Current and Future Work





Thank You for your attention!

BRNO UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING

INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

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