Additive manufacturing of tungsten by means of laser powder bed fusion for plasma-facing component applications

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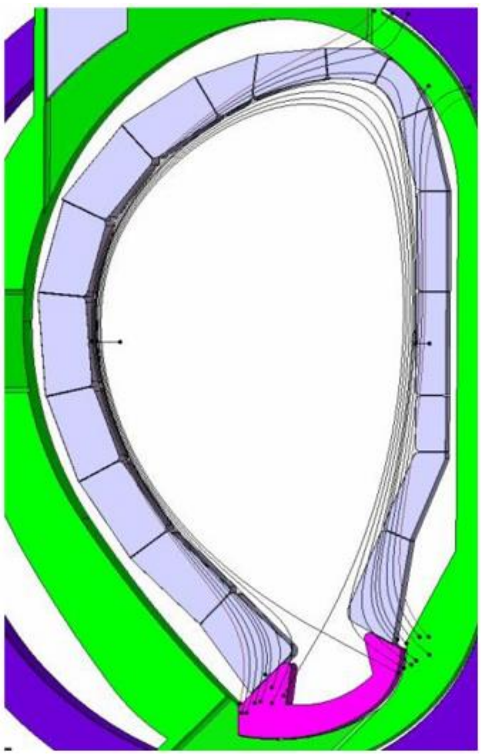
Plasma-facing components in fusion devices

- According to our present understanding exhaust of power and particles in a future magnetic confinement nuclear fusion device will be handled by a **poloidal divertor**

DEMO

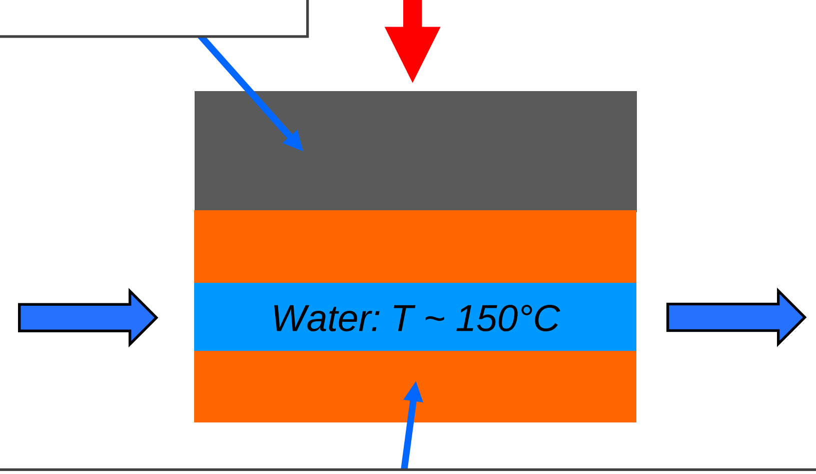


[T.R. Barrett et al., Fusion Engineering and Design, 2016]

Divertor target

PFM: Tungsten (W)
⇛ Low sputtering yield
⇛ Low tritium retention
⇛ Low vapour pressure
⇛ High melting point
...

$$\dot{Q} \sim 10 - 20 \ \frac{MW}{m^2}$$



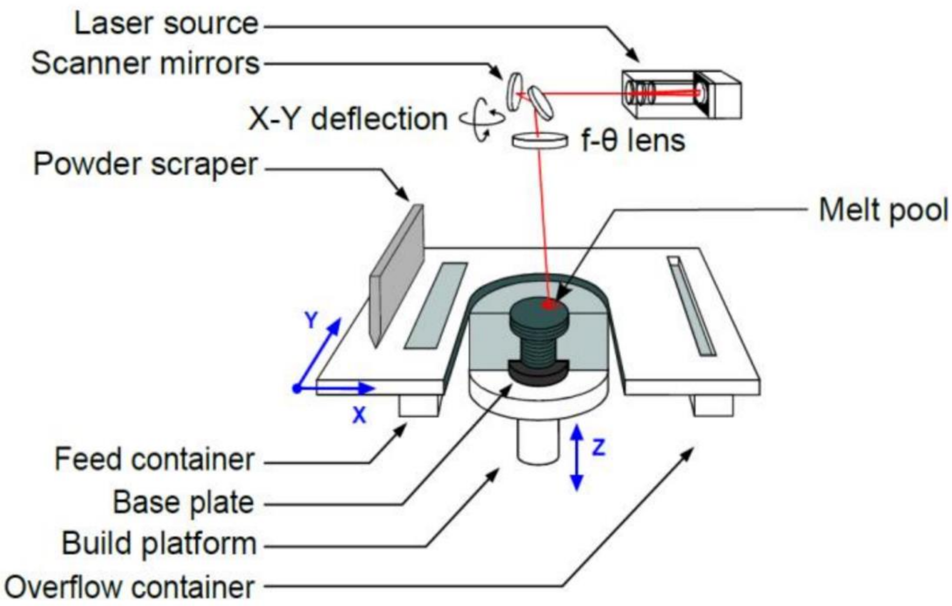
Heat sink: Copper (Cu) alloy or W-Cu composite materials
⇛ High thermal conductivity
⇛ Favourable mechanical properties

What is additive manufacturing?

- **Additive manufacturing (AM)**:
  - ⇛ three-dimensional objects are created by sequential layerwise deposition of material under computer control
  - ⇛ objects with more or less arbitrary shape can be produced

[https://www.ntnu.edu/ivb/additive-manufacturing-laboratory, 06.06.2018]

- **Laser powder bed fusion (LPBF)** of tungsten (W)



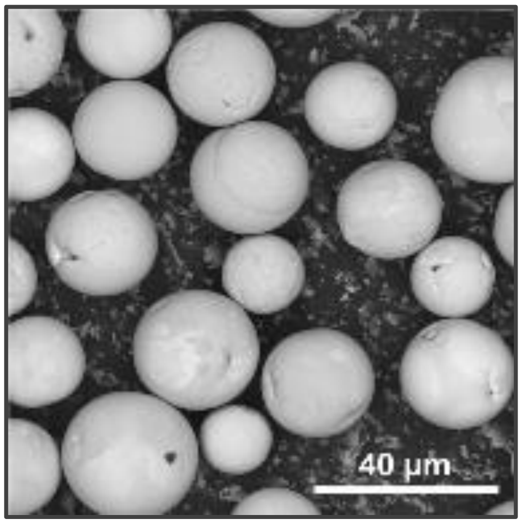
[K. Kempen et al., Solid Freeform Fabrication Symposium, 2011]

Process parameters

Powder

⇛ good flowability required

⇛ spheroidised powder



SEM image of **spheroidised pure W powder** (15-45 µm)

Laser parameters

⇛ laser power **P ~ 400 W**

⇛ laser focus **~ 100 µm**

$$\sim 10 \frac{GW}{m^2}$$

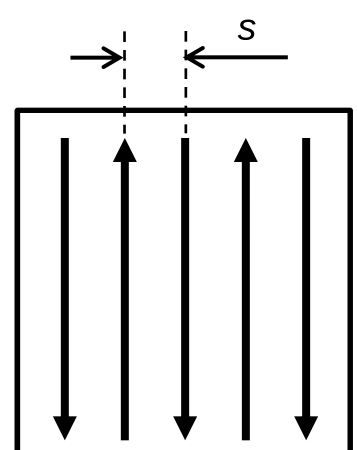
⇛ scanning speed **v ~ 500 mm/s**

⇛ layer thickness: **t ~ 40 µm**

⇛ scan line spacing: **s ~ 80 µm**

energy density: $E = \frac{P}{v\, s\, t} [J/mm^3]$

⇛ scanning strategy

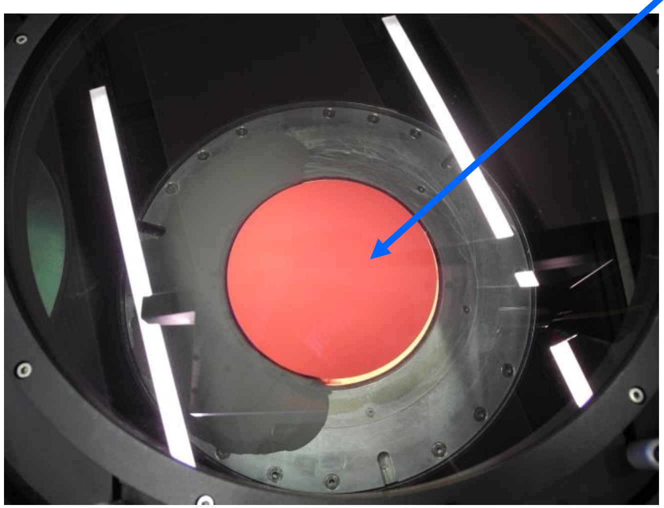


LPBF of W with substrate preheating

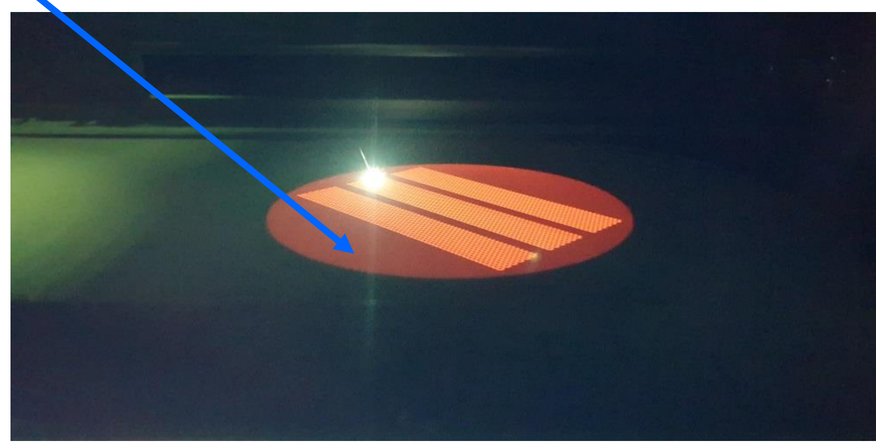
- Typical measure in order to mitigate defects in laser beam melted material
  ⇛ **preheated substrate**

- Experiments performed with preheated W substrate plates
  ⇛ up to **1000°C**

W substrate



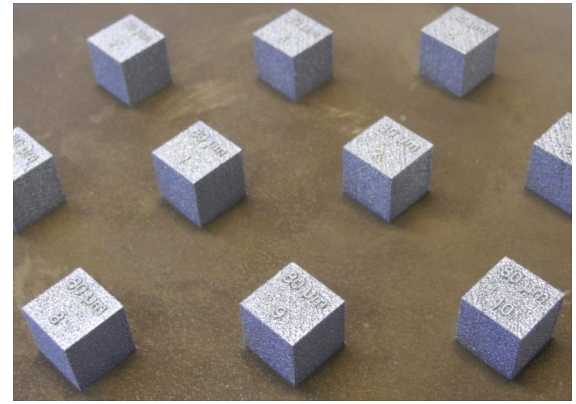
Preheated W substrate plate before material manufacturing



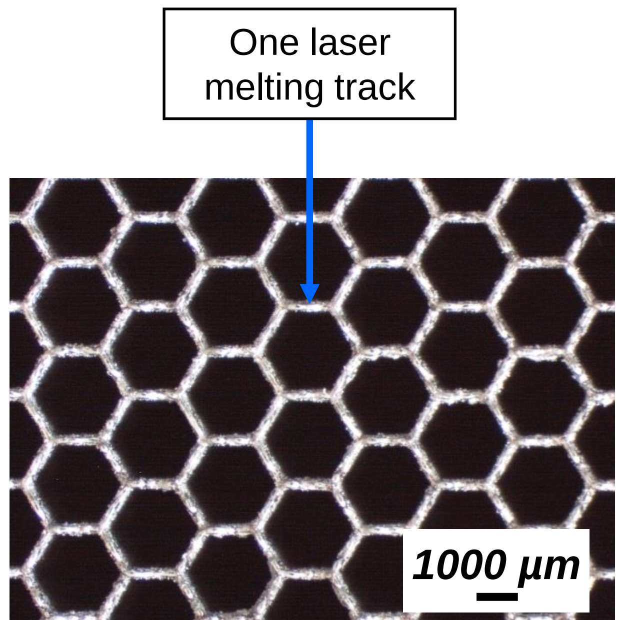
LPBF processing of W with preheated substrate

LPBF of W with substrate preheating

- Fabrication of cube shaped samples for parametric studies (*edge length 10 mm*)

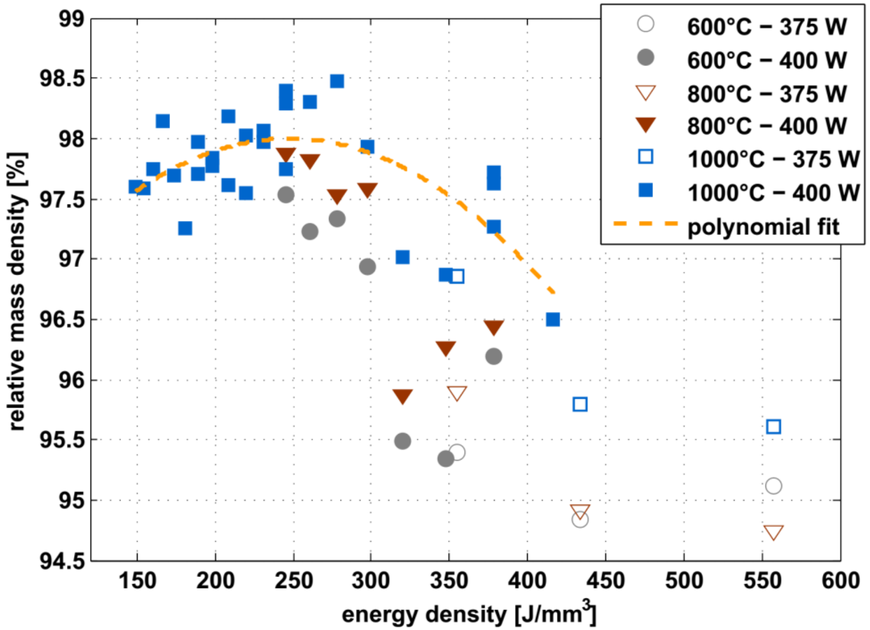


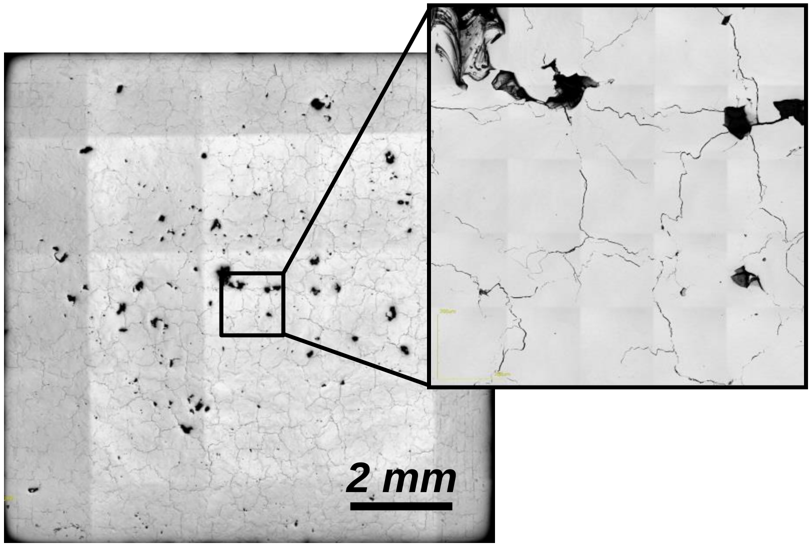
- Example for more complex W parts
⇛ Honeycomb structures



LPBF of W with substrate preheating

- Experiments performed with W preheated substrate plates
  ⇛ **600°C, 800°C** and **1000°C**
- Manufacturing parameter studies (laser power, scanning speed, ...)





Exemplary microsection:
P = 400 W, v = 510 mm/s,
T = 1000°C

Material with relative mass density ~98% produced directly by means of laser powder bed fusion

LPBF of W with substrate preheating

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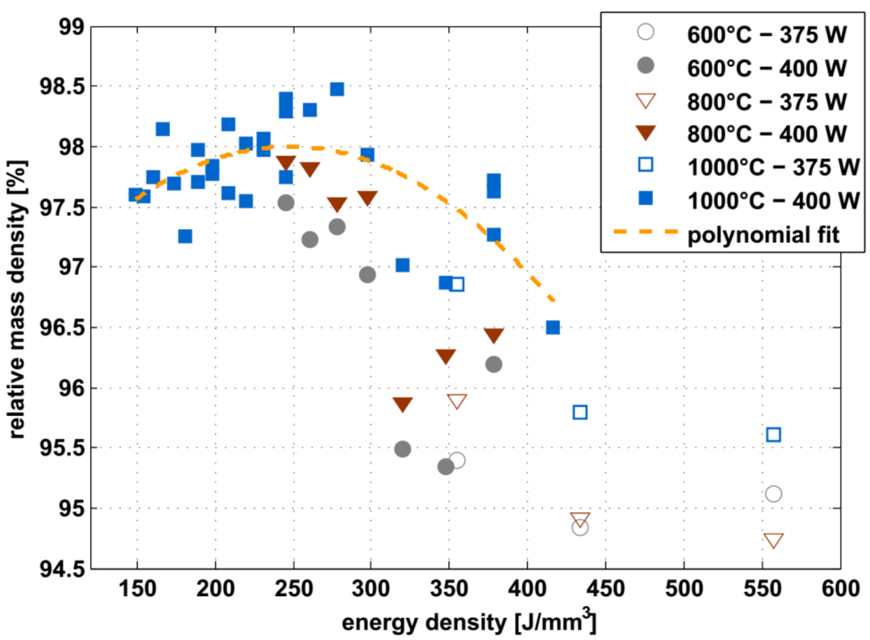
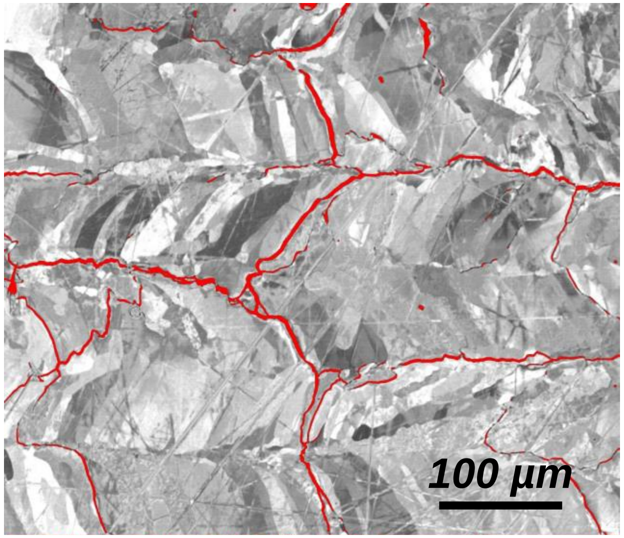


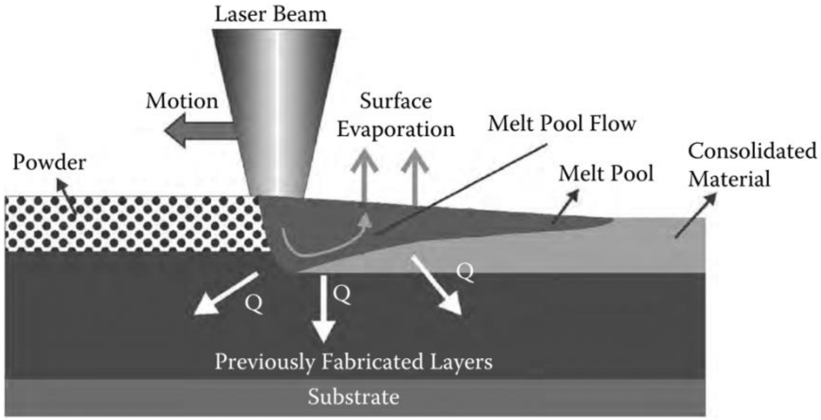


Exemplary microsection:
P = 400 W, v = 510 mm/s,
T = 1000°C

Substrate preheating (above DBTT of tungsten) does not mitigate crack defect formation during selective laser beam melting process

Issues in LPBF

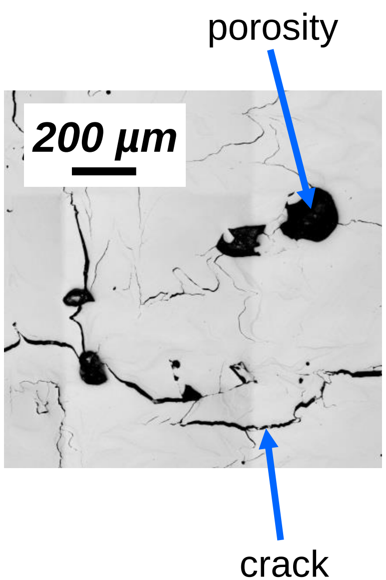
- Laser-material interaction:
  ⇛ **Rapid** heating, melting & solidification



[M. Rombouts, doctoral thesis, KU Leuven, 2006]

- Temperature gradients:
  ⇛ **~ 10^2 – 10^4 K/mm** between center of the melt pool and the solid-melt interface

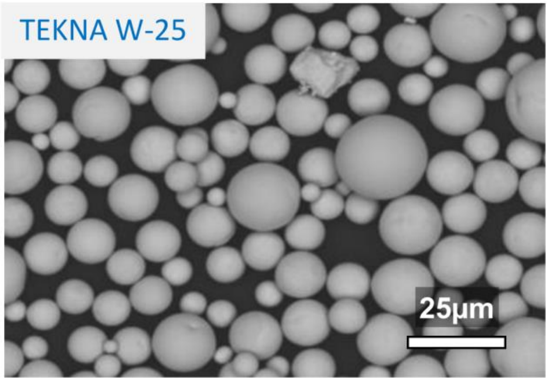
- Cooling rate during solidification: **> 10^4 K/s**

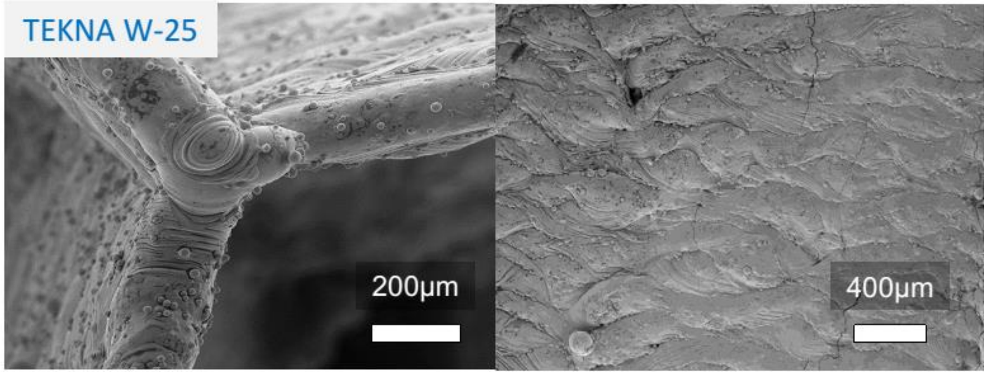


- Potential **defects** in laser beam melted material:
  ⇛ Porosity
  ⇛ Residual stresses
  ⇛ Cracks due to the high temperature gradients between melt pool and surrounding solid
  ⇛ Balling ⇛ material fails to wet the underlying substrate

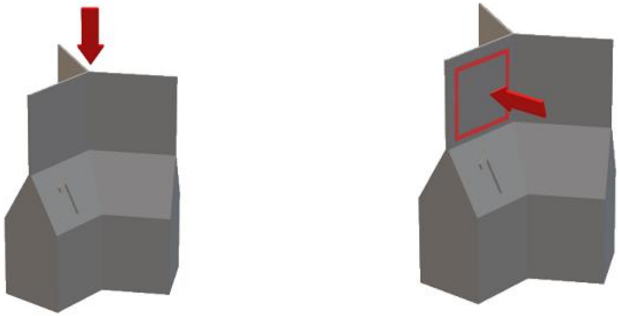
LPBF of W – Influence of powder morphology

- Spheroidised W powder

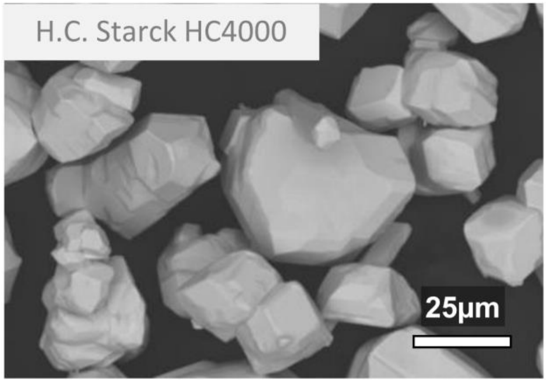


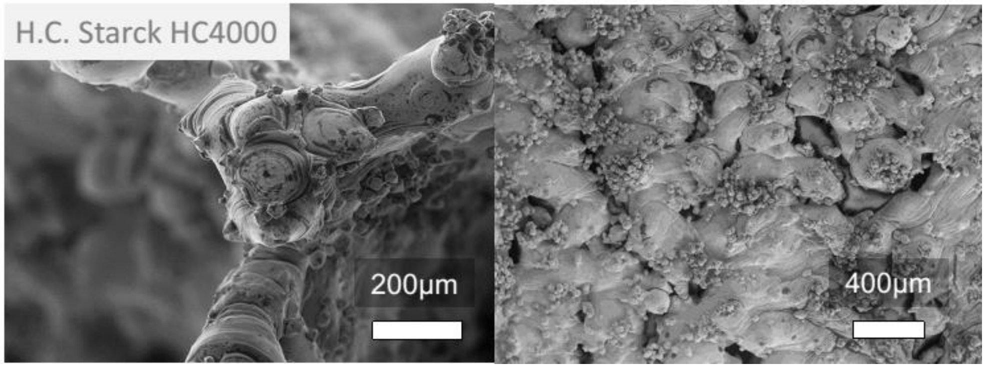


Junction of
3 thin W walls



- Polygonal W powder



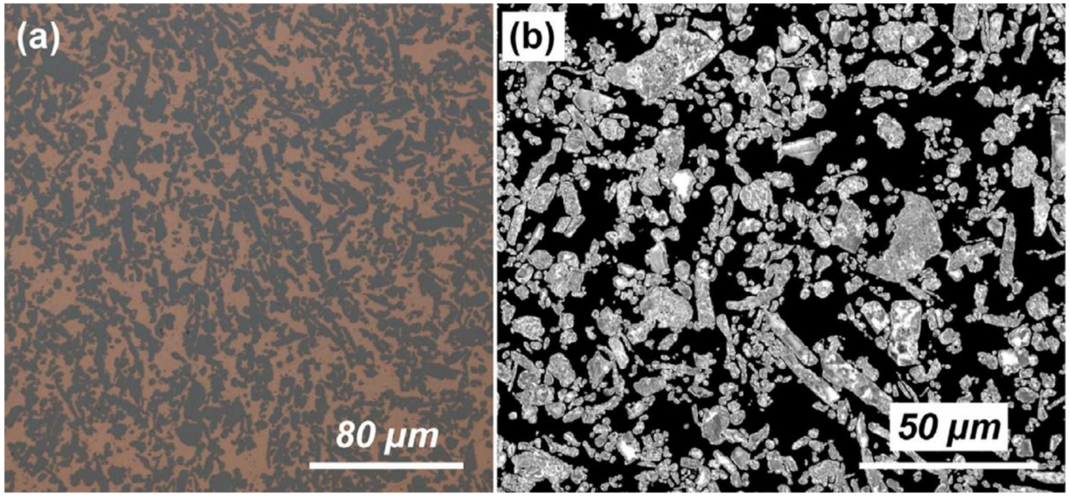


Tungsten-copper composite materials

- **W-Cu composite materials** currently of interest with regard to plasma-facing component heat sink applications

⇛ High thermal conductivity
⇛ High strength at elevated temperatures
⇛ Tailoring of macroscopic material properties possible

⇛ No mutual solubility
⇛ Wettability W – liquid Cu
⇛ Constituents readily available

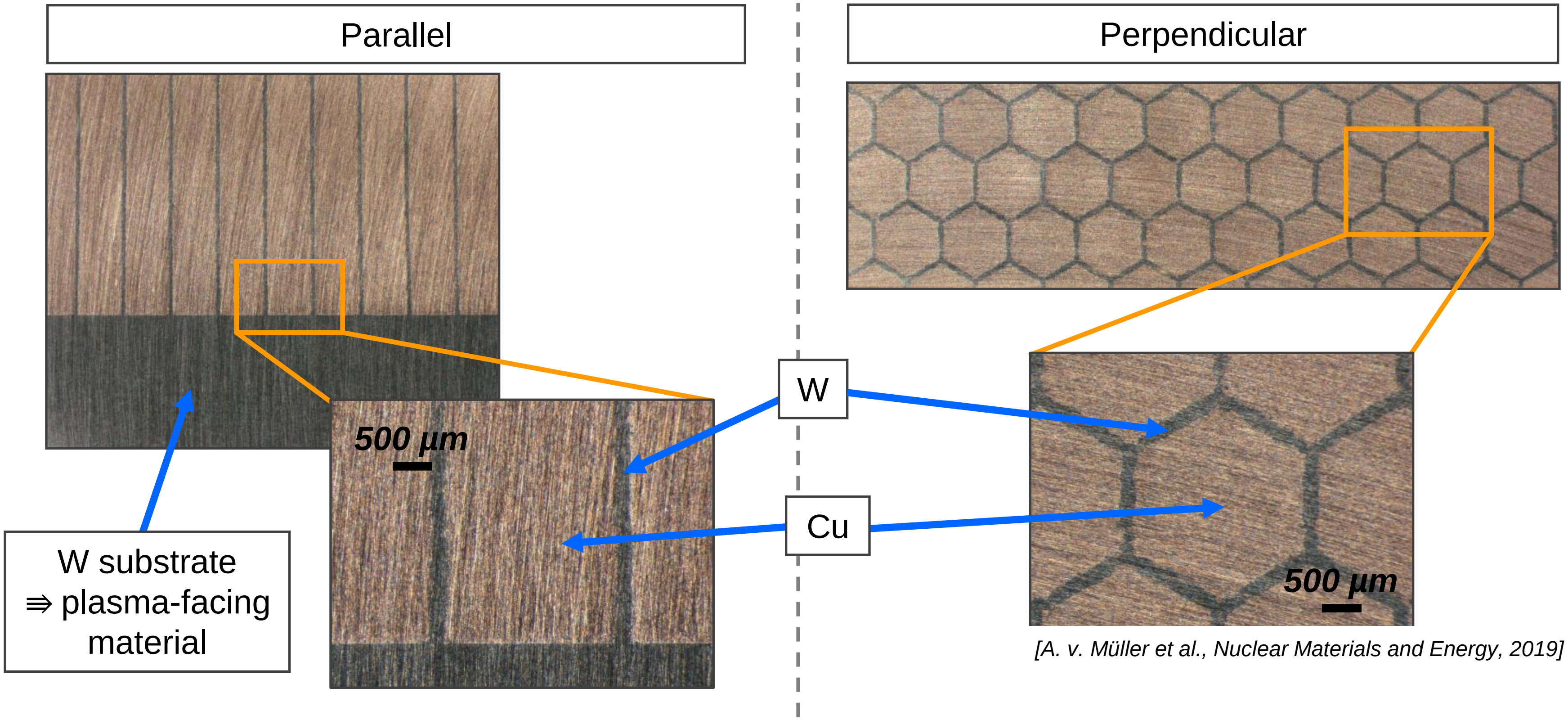


[A. v. Müller et al., Fusion Engineering and Design, 2017]

W-Cu (60/40 wt.%) composite metal manufactured by means of Cu melt infiltration

⇒ **Additive manufacturing of W** beneficial for W-Cu composite material design

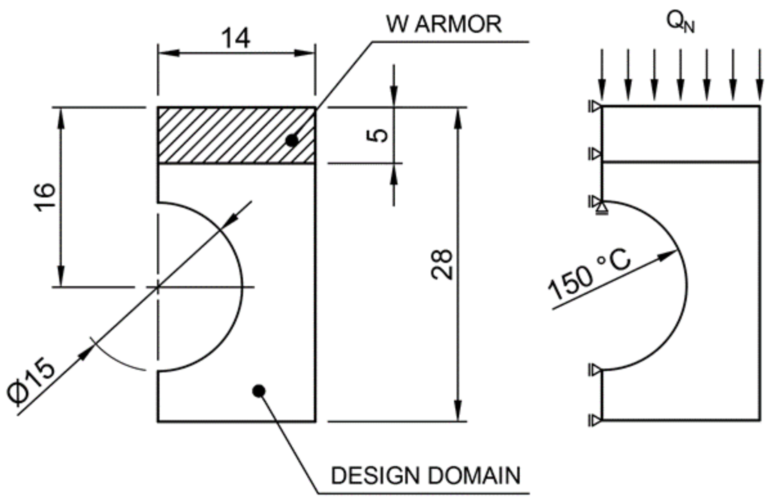
Tailored W-Cu composite structures



- W-Cu composite structure realised through Cu liquid melt infiltration of additively manufactured W part
- Possibility to realise tailored/optimised W-Cu composite structures for plasma-facing component application

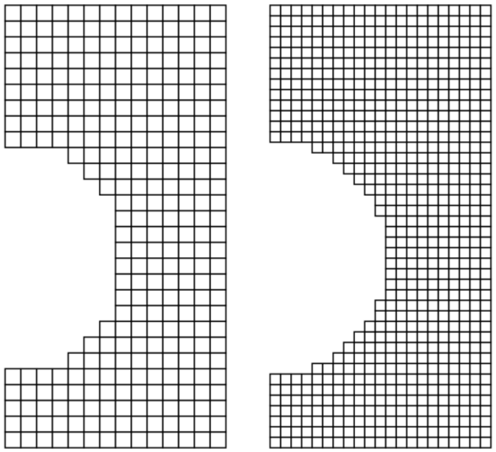
Tailored W-Cu composite structures

- How should a W-Cu material distribution be in a plama-facing component?



- Development of a FE code for optimisation of W-Cu composite material distribution developed

- FE implementation: Each element in the design domain is assigned a design variable that may vary continuously between 0.0 – 1.0 and specifies the volume fraction of tungsten



- Objective: Minimisation of the peak *von Mises equivalent stress*

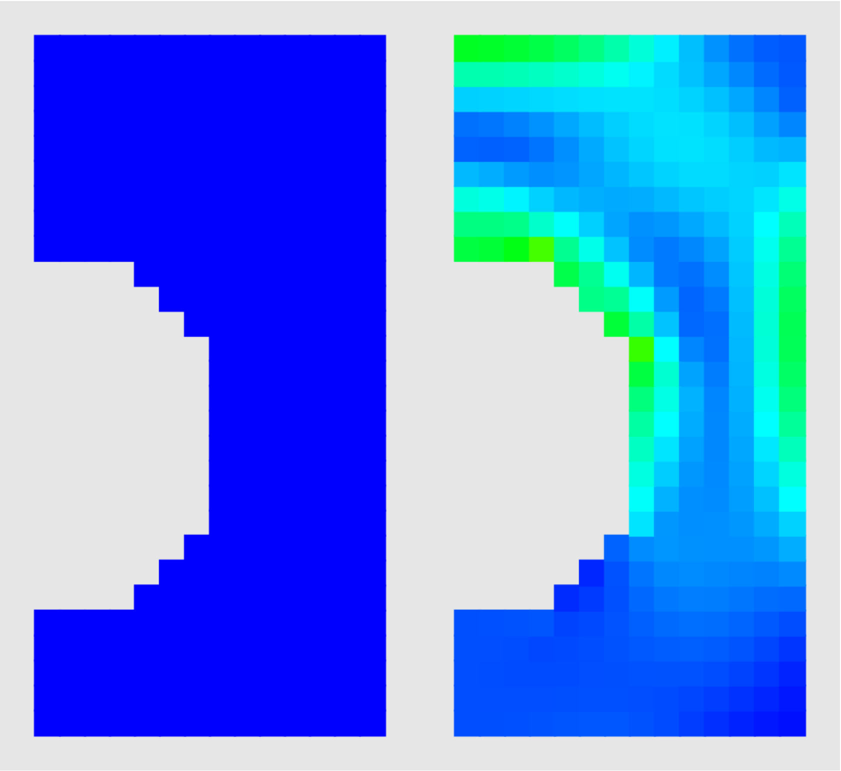
[B. Curzadd, Nuclear Fusion, 2019]

Tailored W-Cu composite structures

W

Cu

Q_N = 10 MW/m^2
T_0 = 650 °C



Reference: full-W domain

Tailored W-Cu composite structures

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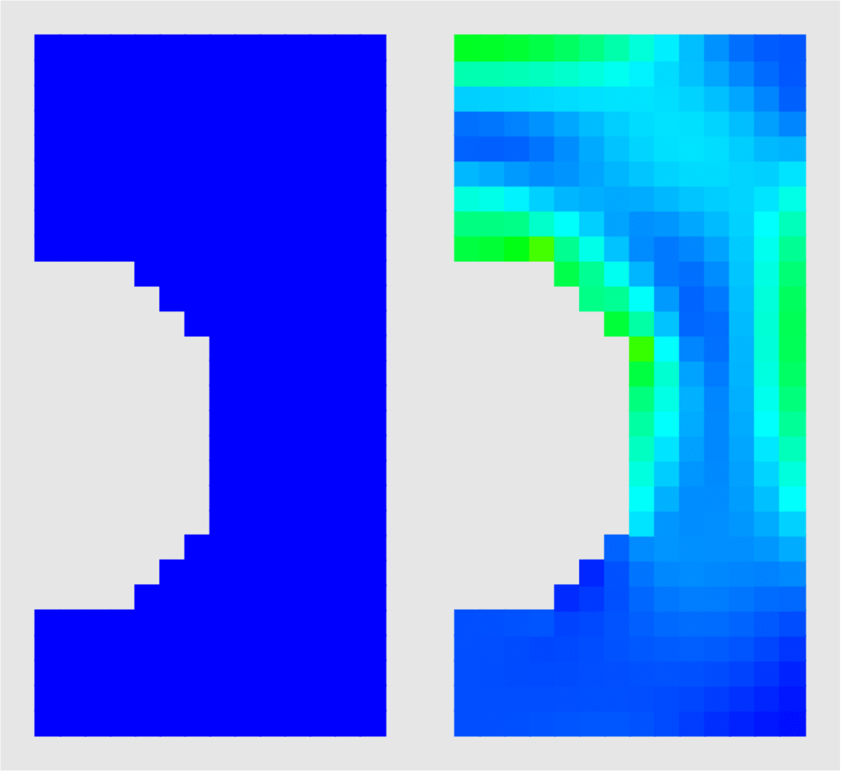
Material Distribution **Stress Field**



Peak Stress

576.1 MPa

-85.7%

82.2 MPa

Reference: full-W domain

Final Avg. Composition	**ΔT_{max}**
60.5% W 39.5% Cu	-112°C

Tailored W-Cu structures indicate high potential for plasma-facing component performance enhancement

Simulation results need to be translated into manufacturable designs

Tailored W-Cu composite structures

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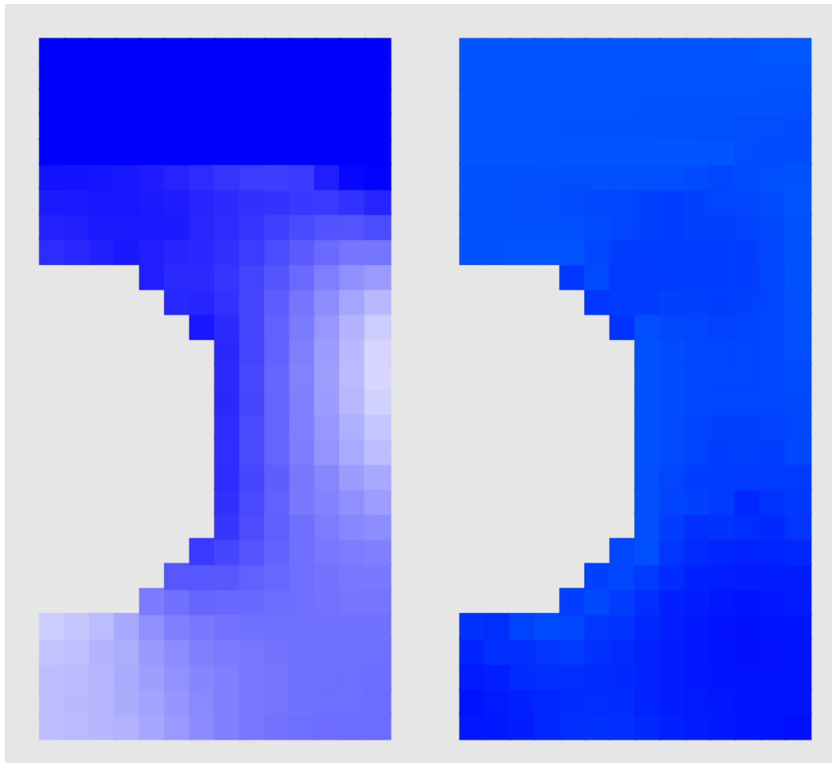

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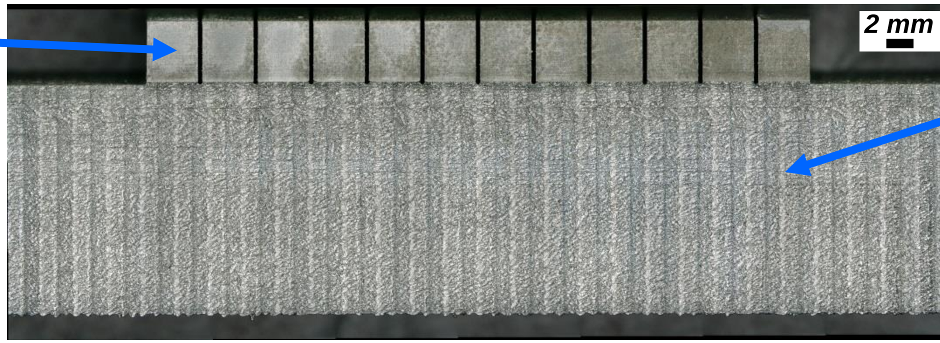
LPBF of W – PFC mock-up manufacturing

- Additively manufactured LPBF W on W tiles

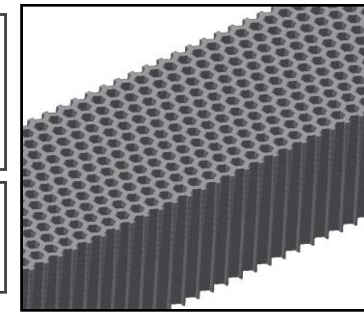
W tiles



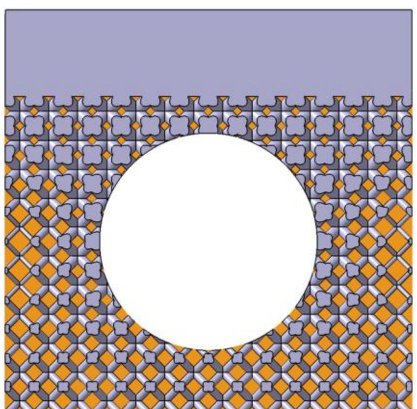
additively manufactured LPBF W

W honeycomb structure

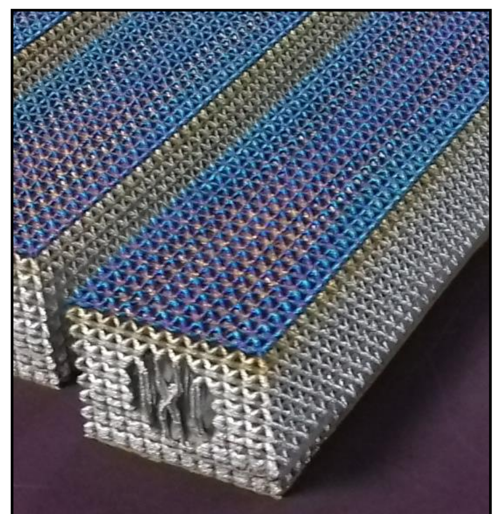
CAD model



- Tailored W-Cu material distribution optimised design



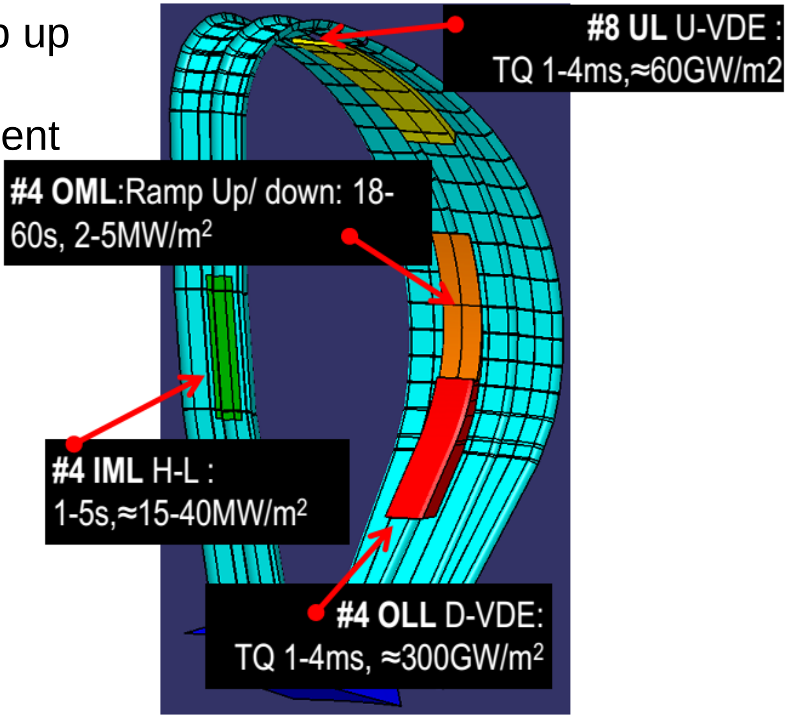
CAD model of lattice structure deduced from W-Cu material distribution optimisation



LPBF W preforms fabricated successfully

W lattice structures for DEMO limiters

- Limiters in DEMO for transient events: plasma ramp up and down/U-VDE/D-VDE/H-L transitions/all events characterised by a sudden loss of plasma confinement



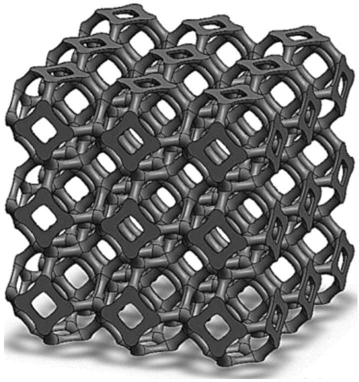
[F. Maviglia et al., ISFNT-14, 2019]

- Porous W as possible limiter material:
  ⇛ structures with defined combination of mass density, specific heat and thermal conductivity

$$\alpha = \frac{\lambda}{\rho\, c_p}\,[m^2/s]$$

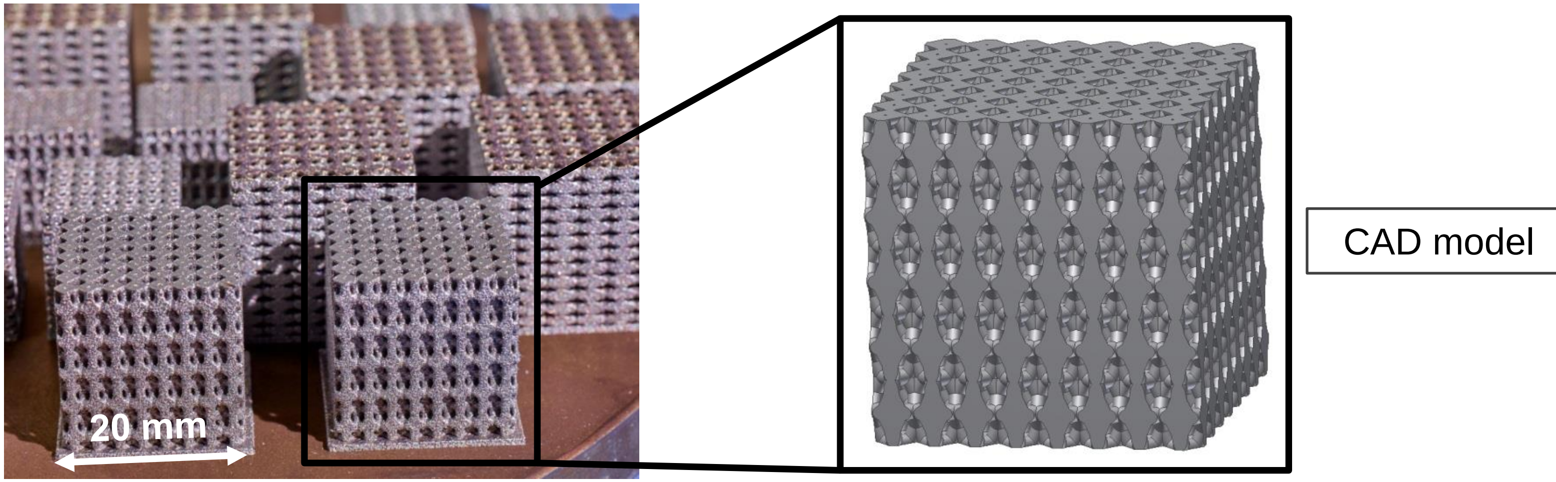
thermal diffusivity

- Possible solution:
  ⇛ additively manufactured W lattice structures

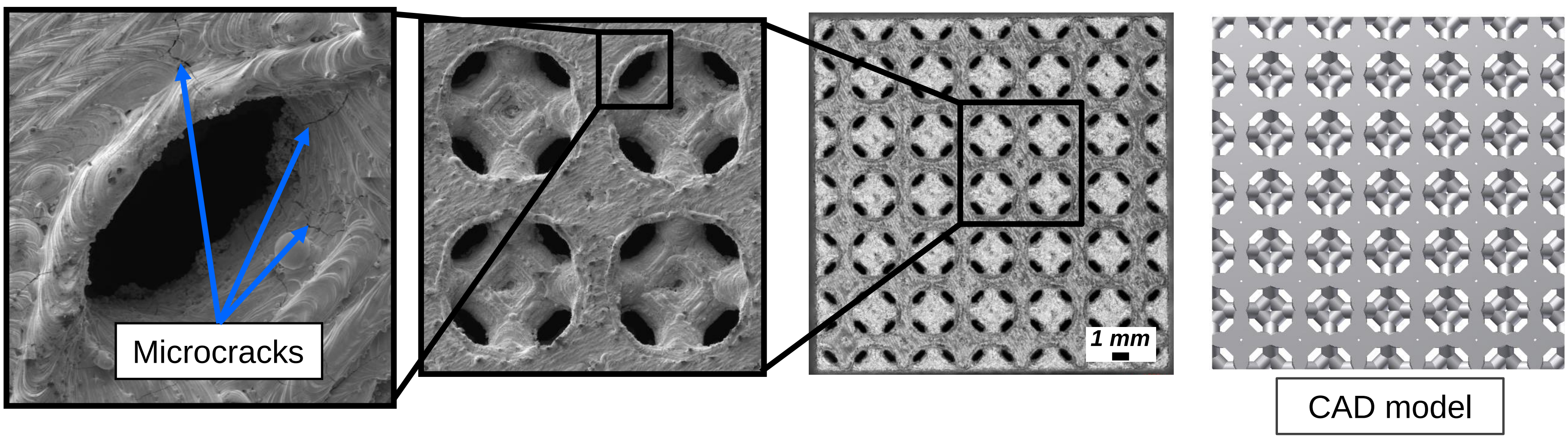


W lattice structures for DEMO limiters

- W lattice structure samples manufactured by means of LPBF



- Microscopic top view on W lattice structure



Conclusions

- By means of **laser powder bed fusion (LPBF) pure W** with **relative mass density ~98%** can be consolidated

- **High temperature processing**
  ⇛ LPBF process with elevated substrate temperatures (up to 1000°C)

- Especially material consolidated with high relative mass densities shows **formation of microcrack defects**

- **Strong influence** of the raw **powder** material on the quality of the additively manufactured material/part

- **Additive manufacturing of “complex“ W structures is feasible**
  ⇛ Tailored W-Cu composite structures for plasma-facing component heat sink application → Mock-up manufacturing for high heat flux testing
  ⇛ Porous W lattice structures for limiter applications

Many thanks for your attention!