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**

**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

- **Water: T \sim 150^\circ C**

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

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

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

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

Powder

⇒ good flowability required
⇒ spheroidised powder

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

Laser parameters

⇒ laser power \( P \sim 400 \text{ W} \)
⇒ laser focus \( \sim 100 \text{ µm} \)
⇒ scanning speed \( v \sim 500 \text{ mm/s} \)
⇒ layer thickness: \( t \sim 40 \text{ µm} \)
⇒ scan line spacing: \( s \sim 80 \text{ µm} \)

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

⇒ 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
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
  \[ \Rightarrow 600^\circ\text{C}, 800^\circ\text{C} \text{ and } 1000^\circ\text{C} \]

- Manufacturing parameter studies (laser power, scanning speed, ...)

Exemplary microsection:
- \( P = 400 \text{ W}, v = 510 \text{ mm/s}, T = 1000^\circ\text{C} \)

Material with relative mass density \( \sim98\%\) produced directly by means of laser powder bed fusion
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, ...)

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

- Temperature gradients:
  ⇒ $\sim 10^2 - 10^4$ 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

- Polygonal W powder

Junction of 3 thin W walls
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

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

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

[Image: Diagram of W-Cu composite structure with design variables and optimization parameters.]

[B. Curzadd, Nuclear Fusion, 2019]
Tailored W-Cu composite structures

Material Distribution

Stress Field

$Q_N = 10 \text{ MW/m}^2$

$T_0 = 650 \, ^\circ\text{C}$

Reference: full-W domain
Tailored W-Cu composite structures indicate high potential for plasma-facing component performance enhancement.

Simulation results need to be translated into manufacturable designs.

Material Distribution

Stress Field

Peak Stress

576.1 MPa
-85.7%
82.2 MPa

Final Avg. Composition

60.5% W
39.5% Cu

ΔT_{max} 

-112°C

Reference: full-W domain

Q_N = 10 MW/m²
T_0 = 650 °C
Tailored W-Cu composite structures indicate high potential for plasma-facing component performance enhancement.

Simulation results need to be translated into manufacturable designs.
LPBF of W – PFC mock-up manufacturing

- Additively manufactured LPBF W on W tiles

- Tailored W-Cu material distribution optimised design

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

  additively manufactured LPBF W

  W honeycomb structure

  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

- Porous W as possible limiter material:
  \[ \Rightarrow \text{structures with defined combination of mass density, specific heat and thermal conductivity} \]

\[ \alpha = \frac{\lambda}{\rho \ c_p} [m^2/s] \quad \text{thermal diffusivity} \]

- Possible solution:
  \[ \Rightarrow \text{additively manufactured W lattice structures} \]
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!