EUROfusion

Additive manufacturing as tool to manufacture and maintain plasma facing components

D. Dorow-Gerspach, M. Gago, V. Ganesh, J. Tweer, M. Wirtz

JÜLICH Forschungszentrum

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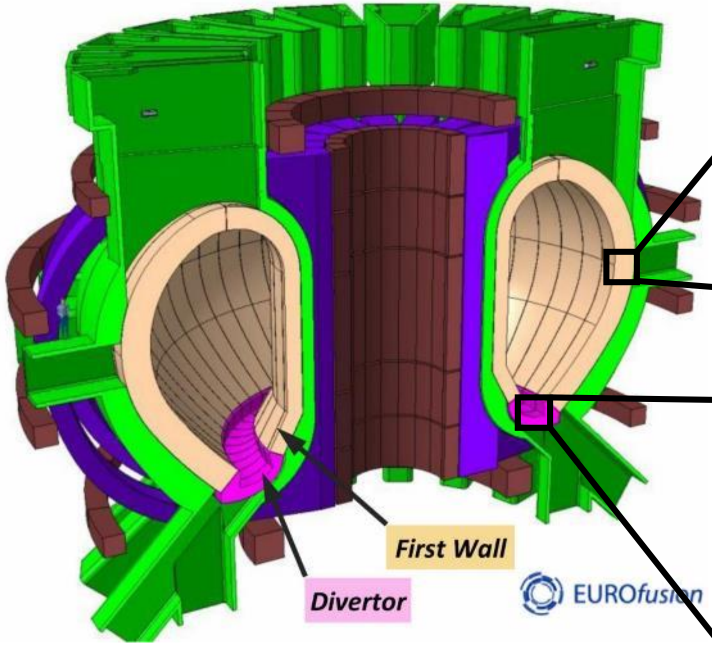
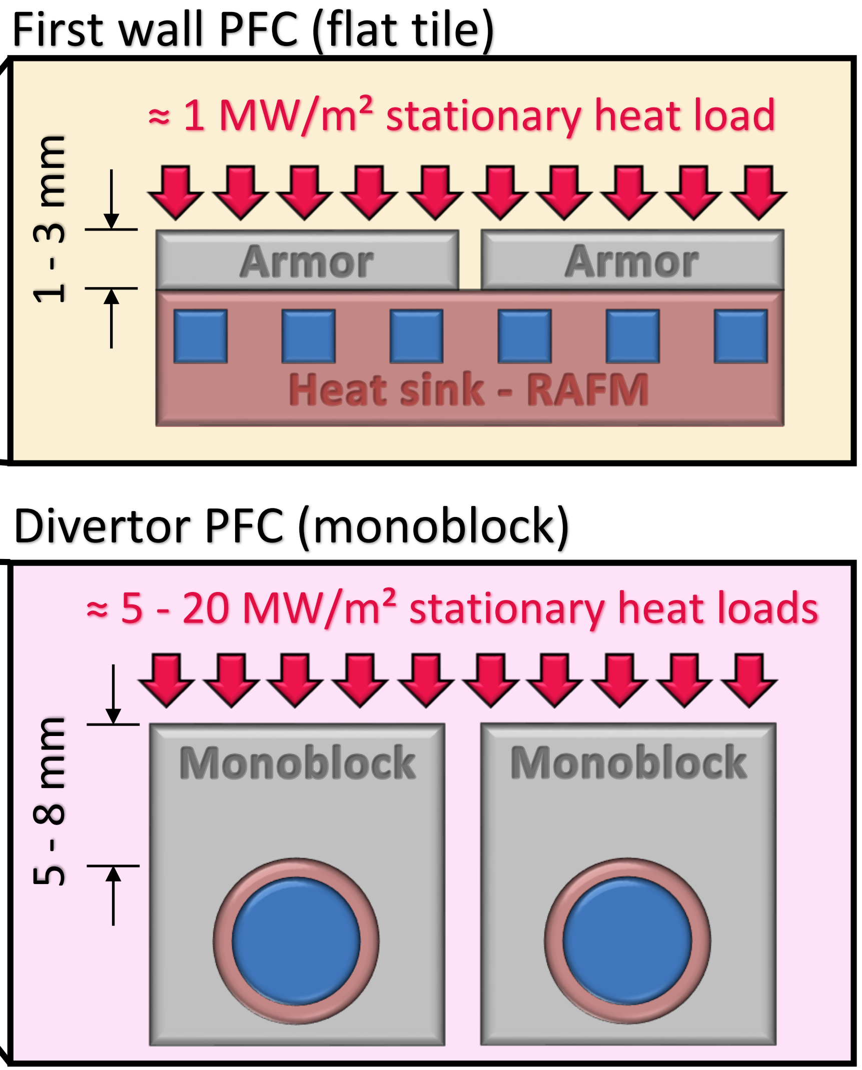
Introduction

DEMO-Fusion reactor



T.R. Barrett et.al., Fusion Engineering and Design 109-111 (2016) 917-92

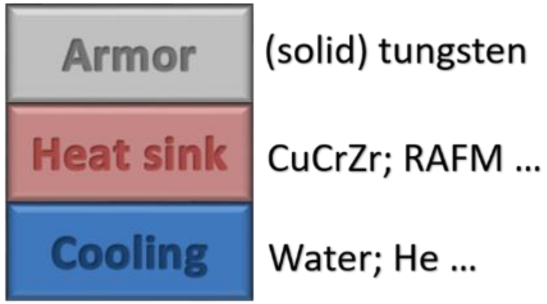


Plasma Facing Component

Armor	(solid) W
Heat sink	CuCrZr ; RAFM …
Coolant	Water ; He …

Introduction

- Principle setup of a **P**lasma **F**acing **C**omponent
- Limiting factors for lifetime: joint and surface
  - Joint: difference in thermal expansion
    ➲ cyclic stress (fatigue + neutron embrittlement)
    ➲ ***failure***
  - Surface: transient heat pulses
    ➲ cracking + crumbling
    ➲ ***plasma breakdown***
  - Erosion: sputtering
    ➲ thickness reduction
    ➲ ***end of lifetime***



➲ ***exchange the whole component***

Introduction

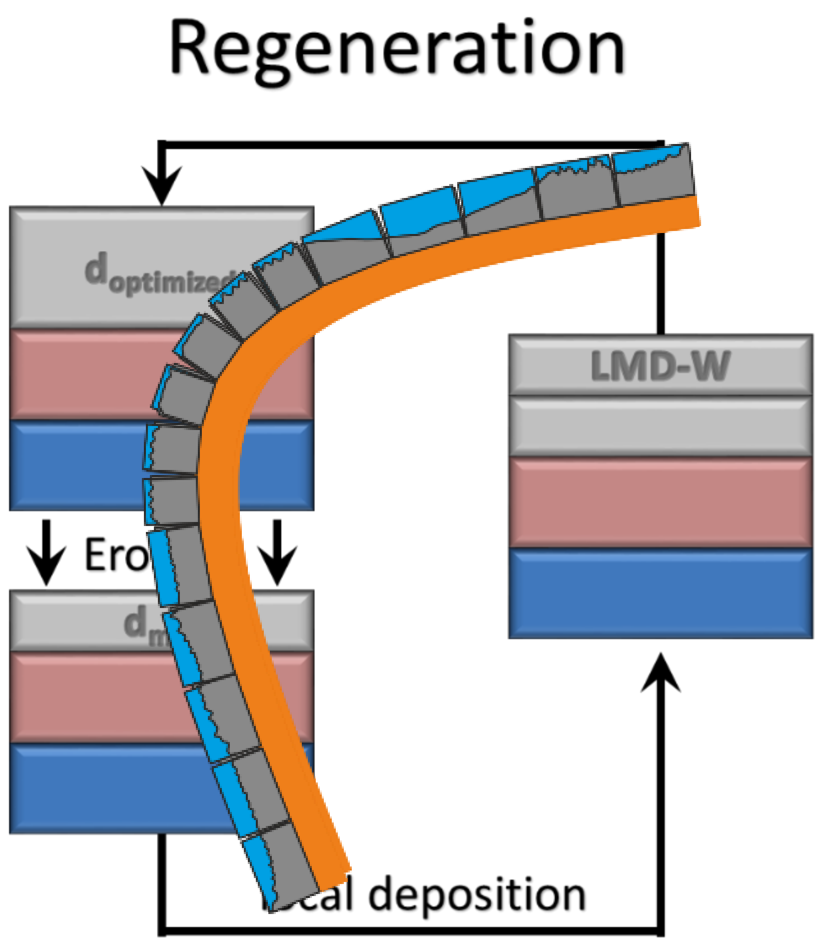
- Combining various AM techniques in order to realize new and tailored designs with the aim:
  - Increase robustness of joint and armor material
  - Less prone to neutron embrittlement

    ➲ ***Larger size of a component ➲ lower cost***

- Regenerate inevitable erosion losses
  - Most erosion locally at strike point

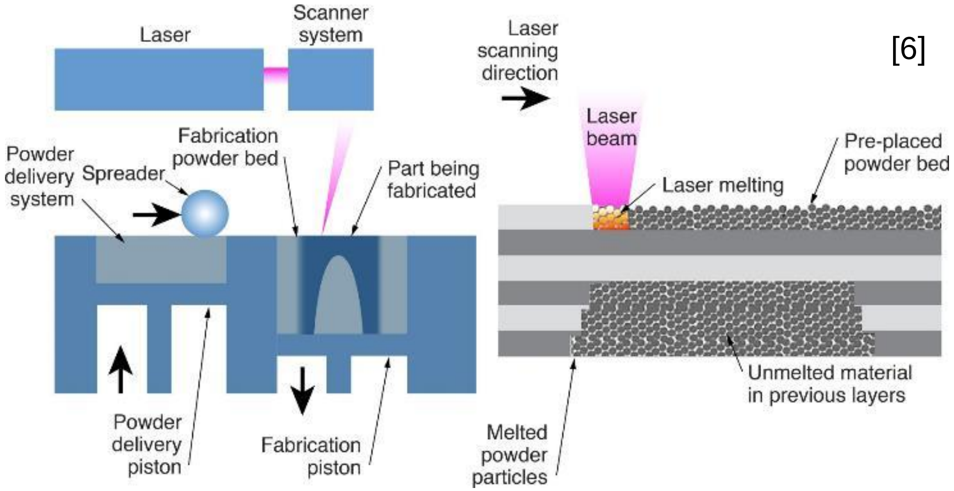
    ➲ ***local deposition w/o need to remove the whole component***
  - Thinner armor possible

    ➲ ***lower surface temperatures and costs***



AM-techniques

- W has very poor, thus costly machinability
  - Limits possible designs and shape variation
- Additive Manufacturing: layer-by-layer process
  - AM-W would allow realization of new ideas
  - Nearly no material is wasted as it is near net shape
  - Unnecessary material can be omitted, reducing weight/cost
- AM-techniques involved:
  - SEBM (**S**elective **E**lectron **B**eam Melting)
  - **LPBF** (**L**aser **P**owder **B**ed **F**usion)



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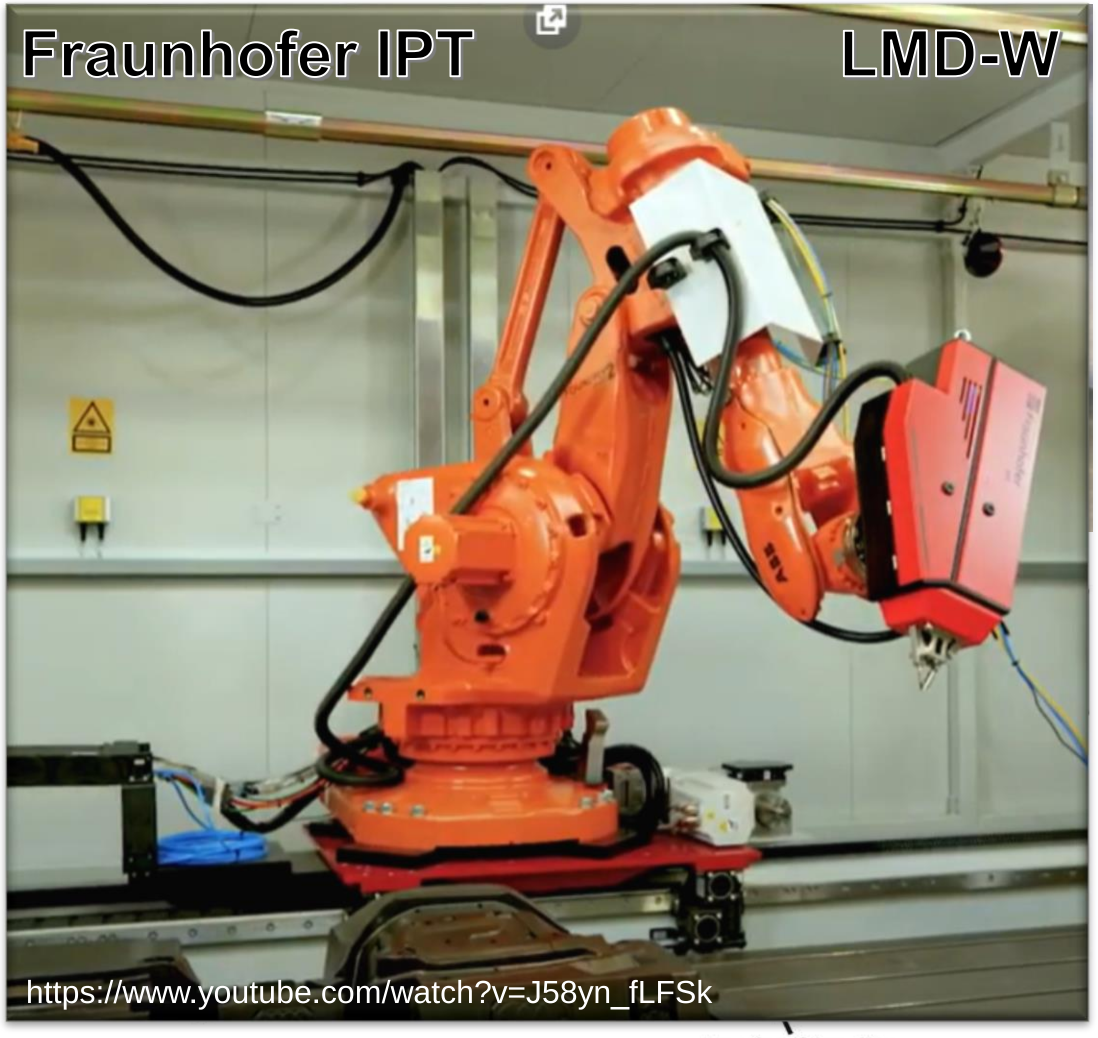
  - LPBF (**L**aser **P**owder **B**ed **F**usion)
  - **LMD-W** (**W**ire based **L**aser **M**etal **D**eposition)
  - LMD-P (**P**owder based **L**aser **M**etal **D**eposition)



Location of deposition

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AM-techniques

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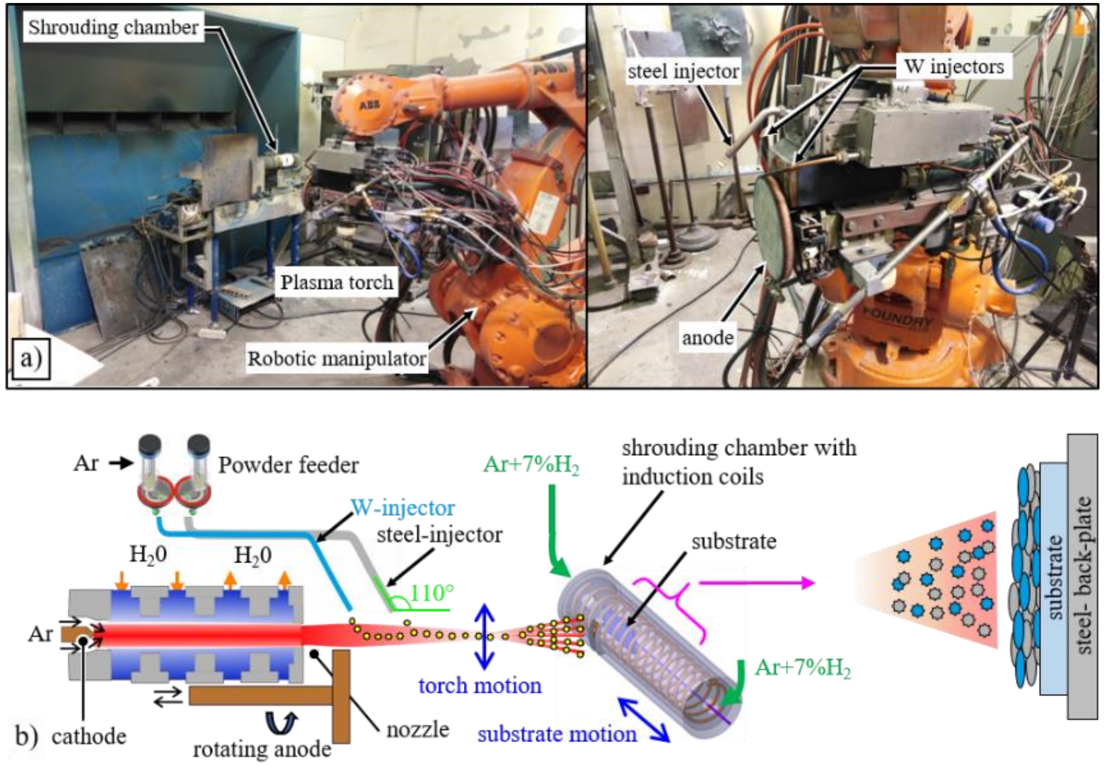
  - LMD-P (**P**owder based **L**aser **M**etal **D**eposition)
  - **APS** (**A**tmospheric **P**lasma **S**praying)
  - …



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Publications during the duration

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- V. Ganesh – ID: 33546
  Processing and properties of sintered W/steel-composites for the first wall of future fusion reactor
  https://doi.org/10.3390/jne4010014
- V. Ganesh – ID: 33870
  High heat flux testing of graded W-steel joining concepts for the first wall
  https://doi.org/10.3390/en16093664
- V. Ganesh – ID: 33870
  Determination of mechanical properties of tungsten/steel composites using image based microstructure modelling
  https://doi.org/10.3390/en16093664
- V. Ganesh – ID: 30420
  Manufacturing of W/steel composites using electro-discharge sintering process
  https://doi.org/10.1016/j.nme.2021.101089
- V. Ganesh – ID: 29595
  Manufacturing of W-steel joint using plasma sprayed graded W/steel-interlayer with current assisted diffusion bonding
  https://doi.org/10.1016/j.fusengdes.2021.112896
- D. Dorow-Gerspach – ID: 33811
  Benchmarking by high heat flux testing of W-steel joining technologies
  https://doi.org/10.1016/j.nme.2023.101508
- J. Tweer– ID: 36194
  First experiments to regenerate the surface of plasma facing components by wire based laser metal deposition
  https://doi.org/10.1016/j.nme.2023.101508
- D. Dorow-Gerspach – ID: 29029
  Additive manufacturing of high density pure tungsten by electron beam melting
  https://doi.org/10.1016/j.nme.2021.101046
- D. Dorow-Gerspach – ID: 31785
  Progress in the realization of advanced armour designs for plasma-facing components
  https://doi.org/10.3390/jne3040020
- J. Tweer– ID: 38122
  Repair of heat load damaged plasma facing material using the wire-based laser metal deposition process
  manuscript: JNME-D-24-00189R2 accepted

Project structure – Outline

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O.1. AM of tungsten
- O.1.1. Exploring new and development of further AM techniques for tungsten
- O.1.2. H-retention and plasma influence on AM-W

O.2. Advanced joints between PFM and heat sink
- O.2.1. Geometrical gradation
- O.2.2. Compositional gradation
- O.2.3. Flexible joint by using W-wire
- O.2.4. Small scale benchmark test

O.3. W-wire as advanced armor to resist thermal shocks
- O.3.1. Sound joining of only the bottom of W-wire
- O.3.2. Impact on thermal performance of W-wire armor
- O.3.3. Influence of plasma on W-wire armor

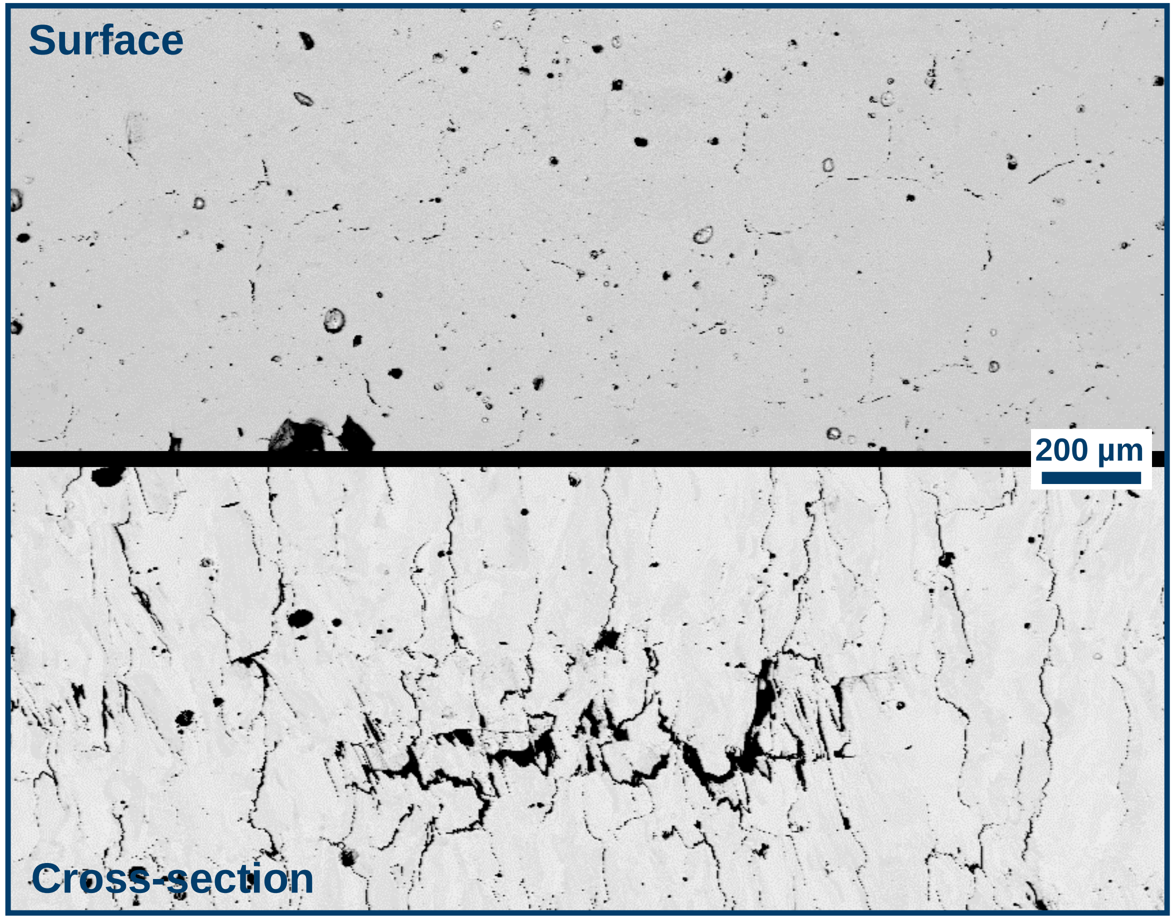
O.4. Surface regeneration to compensate erosion loss
- O.4.1. Regeneration of damaged surface
- O.4.2. LMD-W process optimization to build up W meeting R_a-requirements
- O.4.3. Investigation of post-deposition treatments like HFMI

O.5. Exploring advanced heat sink geometries
- O.5.1. Assessment by FEM simulation of several different monoblock-type designs
- O.5.2. Building several monoblocks based on O.5.1 by AM.
- O.5.3. Production of a monoblock-chain and performance of HHF tests

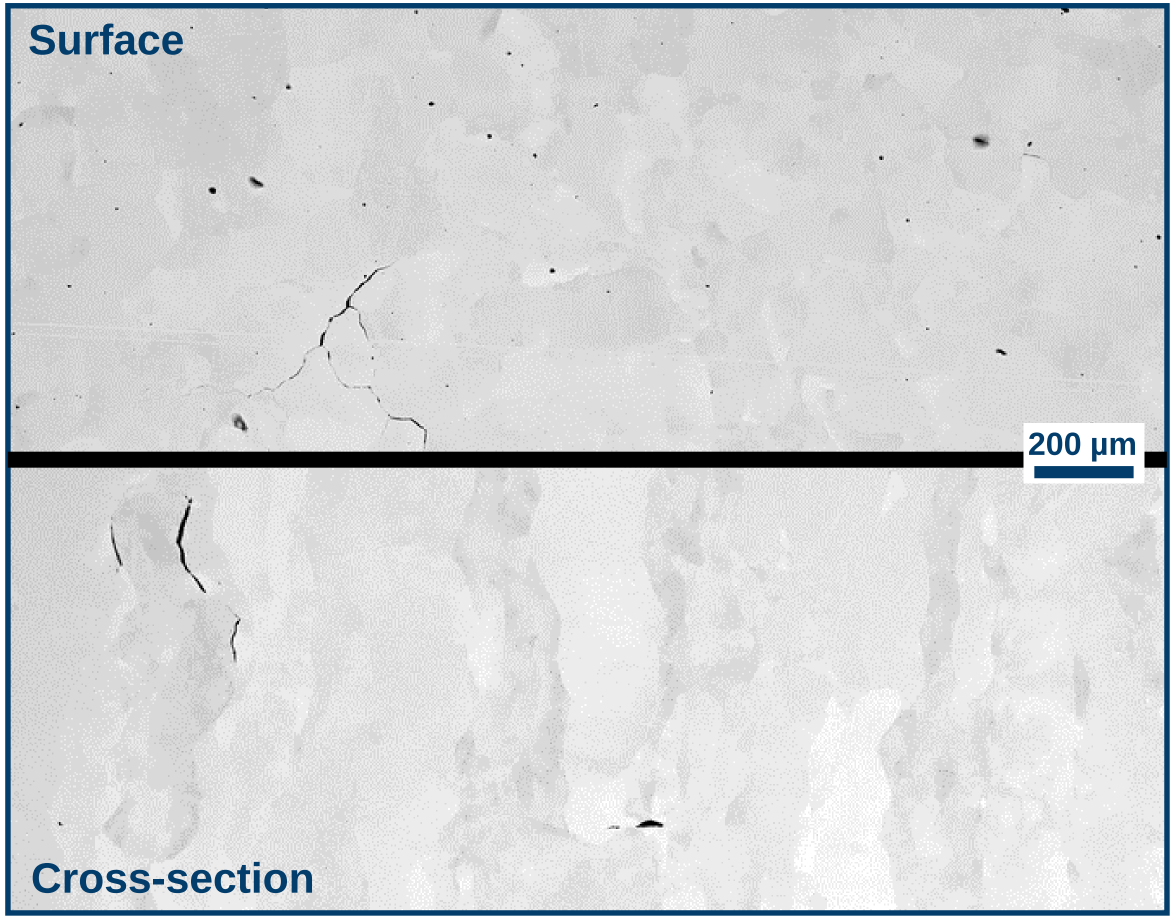
O.6. Demonstrating feasibility and scalability of used technologies
- O.6.1. Construction of cooling structures for test mock ups
- O.6.2. Joining of tungsten to the cooling structures by using the most promising technologies (O.2.4.)
- O.6.3. Build-up of W on part of the mock ups (regeneration)
- O.6.4. Comparative thermal cycling test

O.1. AM-W

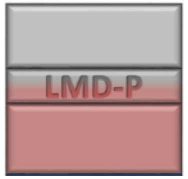
- **L**aser **p**owder **b**ed **f**usion



- **S**elective **e**lectron **b**eam **m**elting



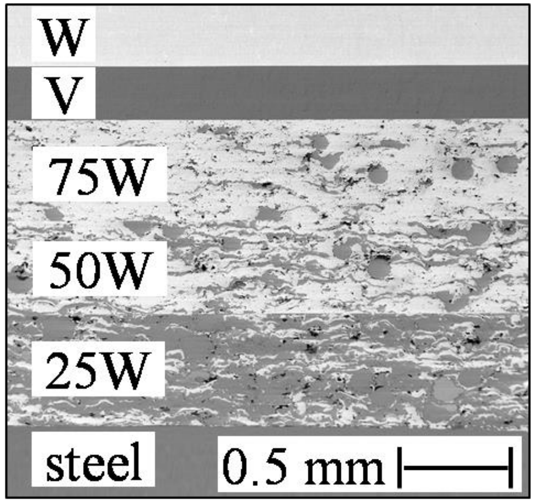
Compositional



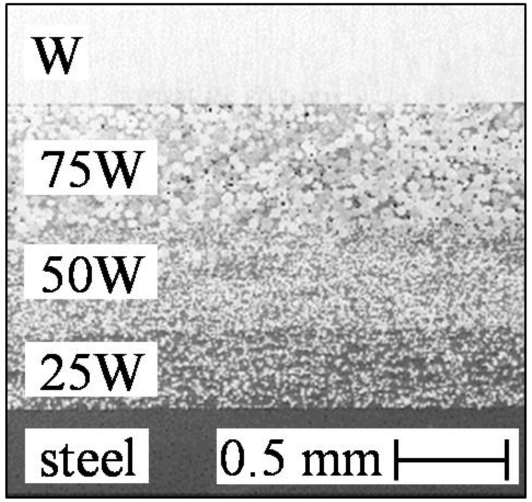
O.2. Joints – Compositional FGM

- Classic approach to mitigate stress occurring by thermal expansion mismatch
  - APS, EDS, SPS successfully producing single layer & full stack 12 x 12 mm² samples
  - Benchmark tests revealed no improved life time

APS

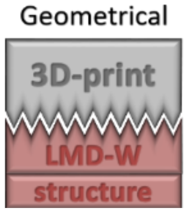


SPS

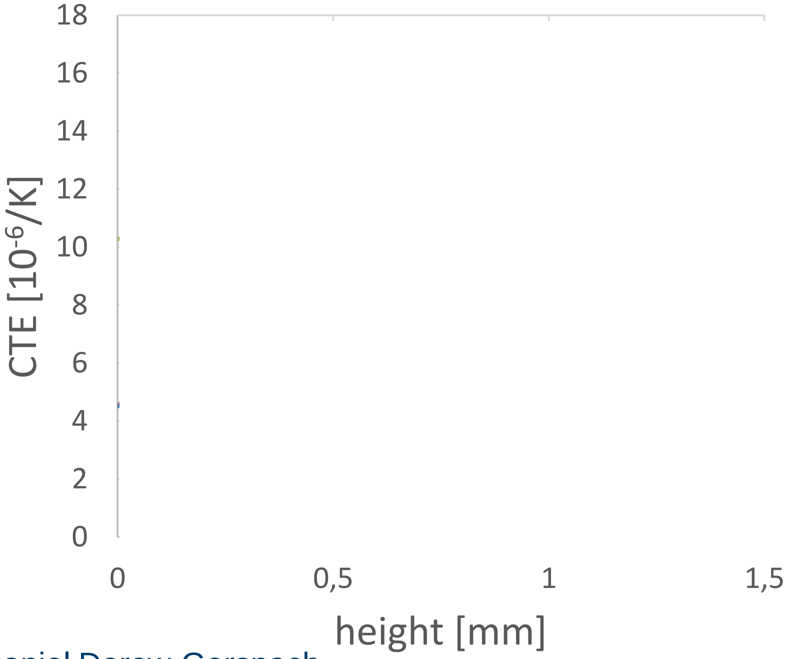


joint type		No. tested	Failure at	
			MW/m²	Locat.
direct		6	**4 - 5**	W - steel
APS	2 layer	3	< 1	W - 50% W
	V+3 layer	3	3.5	in 75% W
SPS	2 layer	9	0 - 2	W - 50% W
	3 layer	6	2 - 3.5	W - 75% W
V	0.3 mm	3	2 - 2.5	W - V
	0.8 mm	2	4	W - V
	1.5 mm	3	3.5	W - V
Ti	0.3 mm	3	4 - 4.5	W - Ti
	0.8 mm	2	2.5 - 5	W - Ti
	1.5 mm	2	3	W - Ti

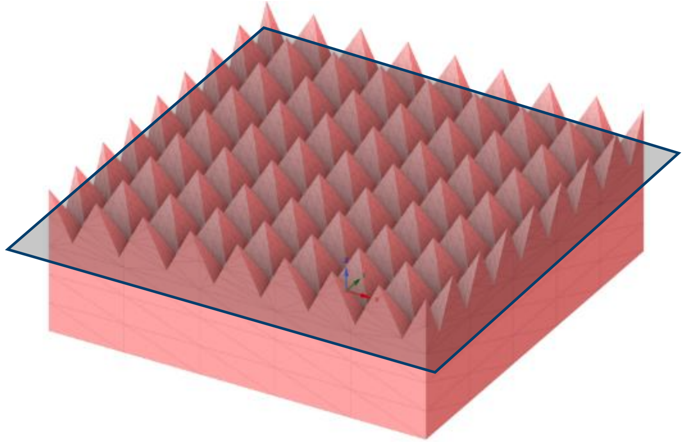
O.2. Joints – Geometrical Gradation



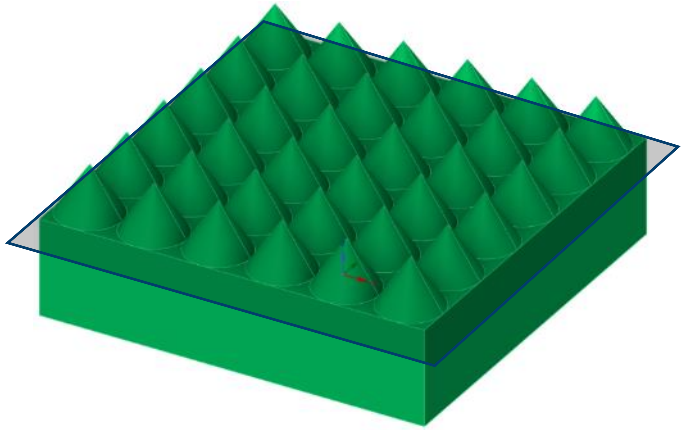
- Assuming CTE determined by volumetric contribution
  - Cu: 16.5×10^{-6} 1/K
  - W: 4.5×10^{-6} 1/K
- Pyramid and LAR will be used



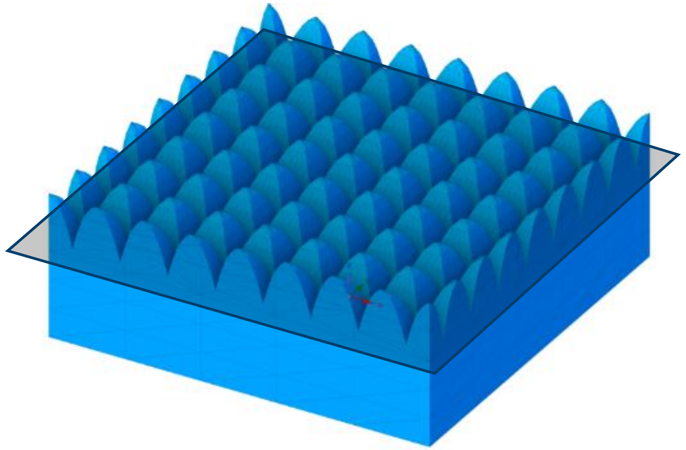
Pyramid



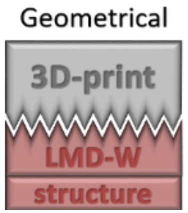
Cone (scp)



Linear Area Ratio



O.2. Joints – Geometrical Gradation



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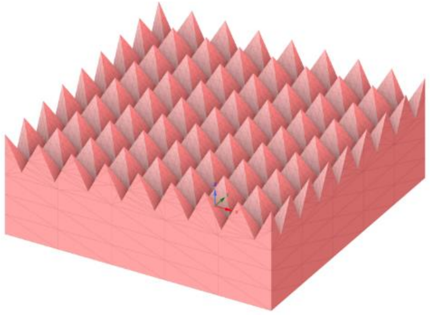
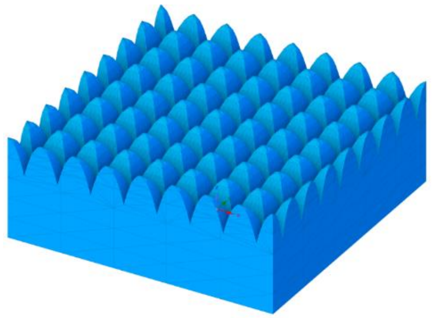
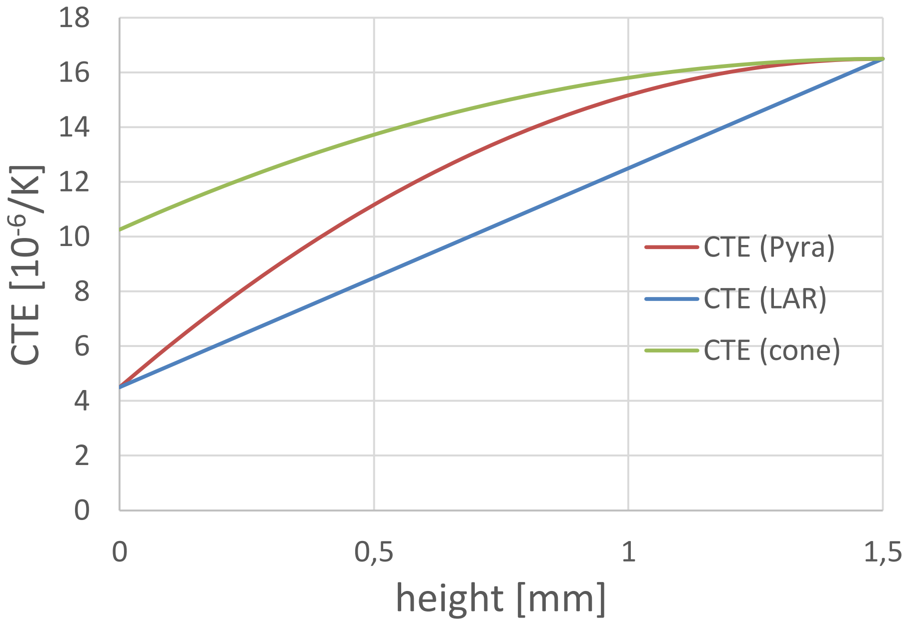
- Assuming CTE determined by volumetric contribution
  - Cu: 16.5×10^{-6} 1/K
  - W: 4.5×10^{-6} 1/K
- Pyramid and LAR will be used
- Advantages against FGM
  - Only one material transition / heat transfer barrier not dozens at every particle/splat
  - Weakest point of the joints is always at bulk W, here this is not also at the hottest/most stressed point
  - Macroscopic stress is not aligned with joint, thus less risk of spontaneous failure i.e. crack deflection
  - Surface area is more than trippled

Pyramid



Linear Area Ratio





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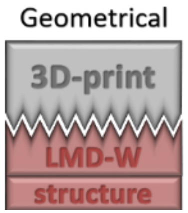
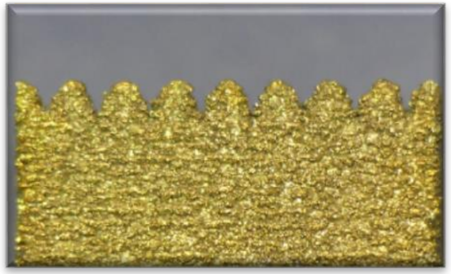


- Two types were chosen
  - Pyramid

steel or Cu
SLM processed

Dimensions:
squares: 12 mm
25 mm
height: 3 mm

  - Linear area ratio



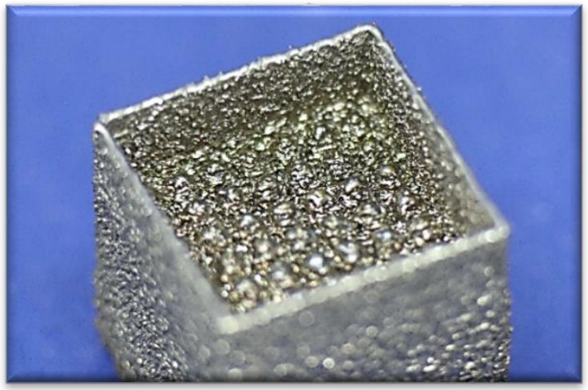
transition structure
length: 1.5 mm
width: 1.5 mm
height: 1.5 mm

W EBM or SLM

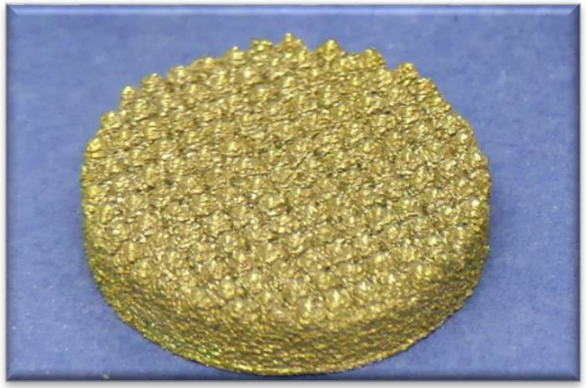
- Cu was printed IFAM
  - First W arrived recently from KIT

- Diffusion Bonding of bulk

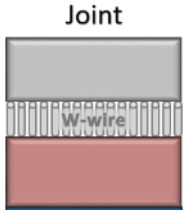
- Melting Cu within a mold



- Spark Plasma Sintering

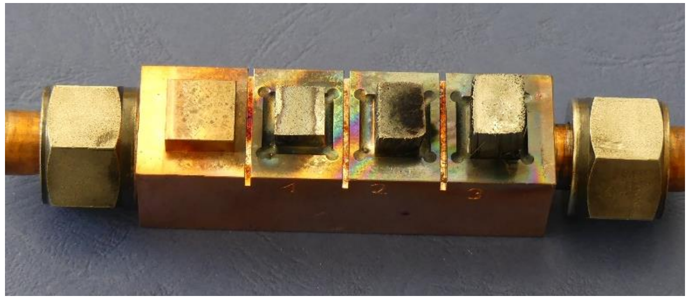


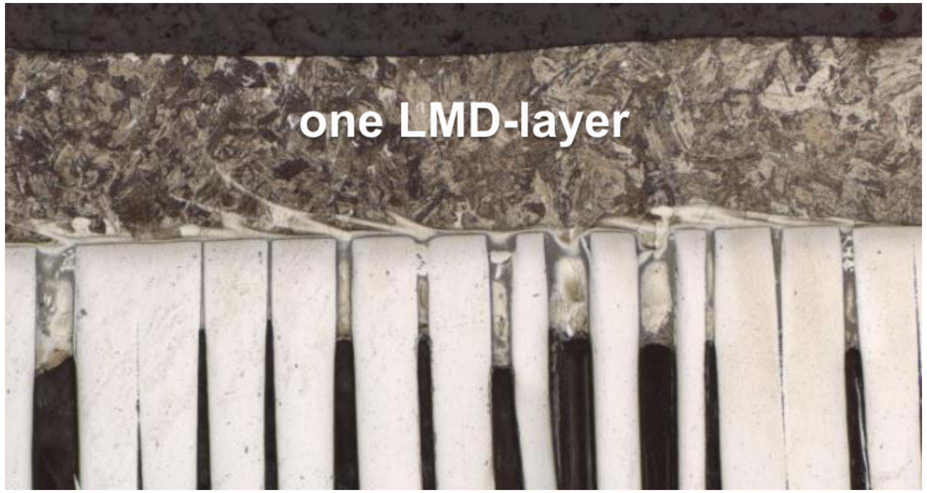
O.2. Joints – Flexible joints with steel

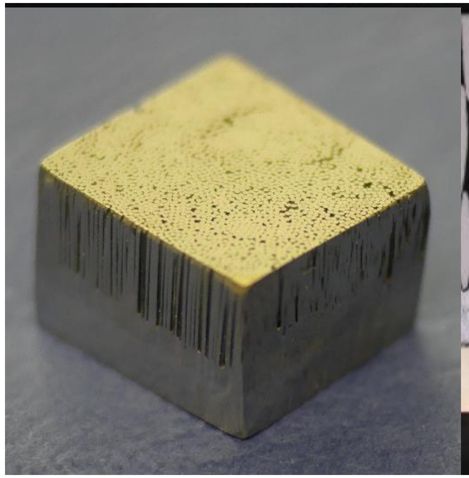


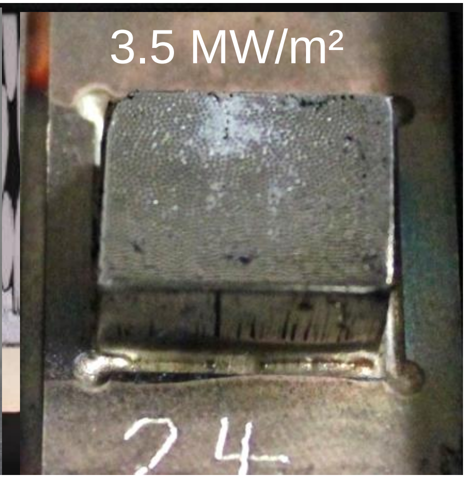
- Use of W_w Ø = 200 µm
  - Directly or as joint
- Laser metal deposition
  - Easily accessible technique
  - At atmosphere using Ar flooding to prevent oxidation
  - Good degree of infiltration
- Cyclic high heat flux test
  - 3 samples with 4; 6; 9 mm W_w
  - 5 MW/m², 2000 cycles, 30s on/off ➲ 600 – 900°C T_{surf}

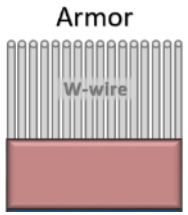
➲ **No loss / break out of W_w**







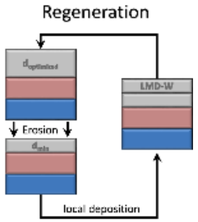




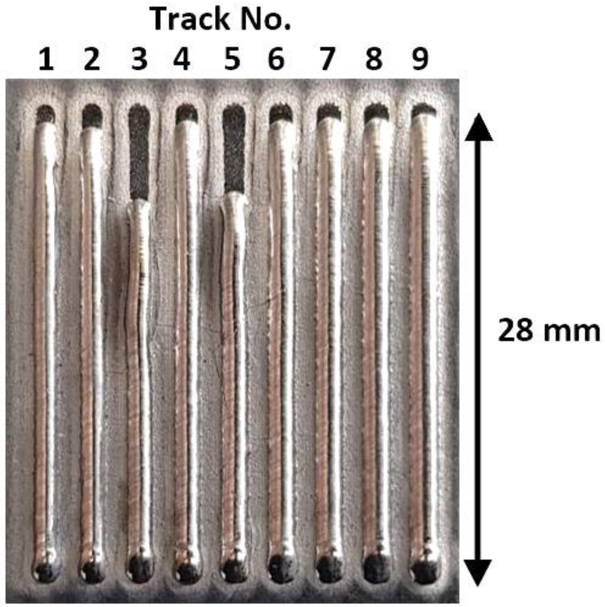
O.3. W-wire as armor: Spool upscaling

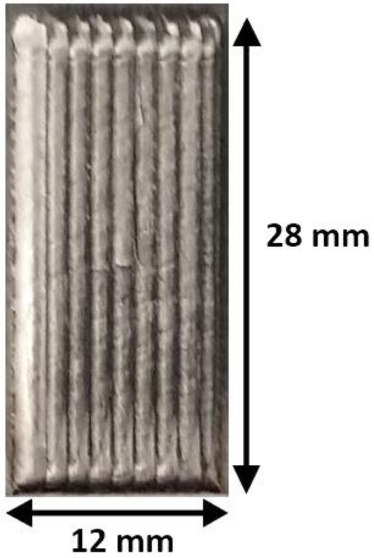
- V1. Small Square (inner edge = 35 mm)
  - 12 × 12 mm W-wire, ~ 45% “waste”
- V2. Cylindrical (inner radius = 100 mm)
  - 16 × 16 mm W-wire area, ~ 10% waste
  - No improve of stacking quality / robostness
  - More effort to form plan parallel slices
  - ➲ **Cylindrical design dismissed**
- V3. Rectangular (inner edge = 150 mm)
  - 25 × 25 mm W-wire, ~ 40% “waste”
  - Less bending stress at the center
  - Easier slicing of any desired thickness
  - “Wall” of 125 µm W-foil for protecting sides
  - Difficult to find a capable winding company

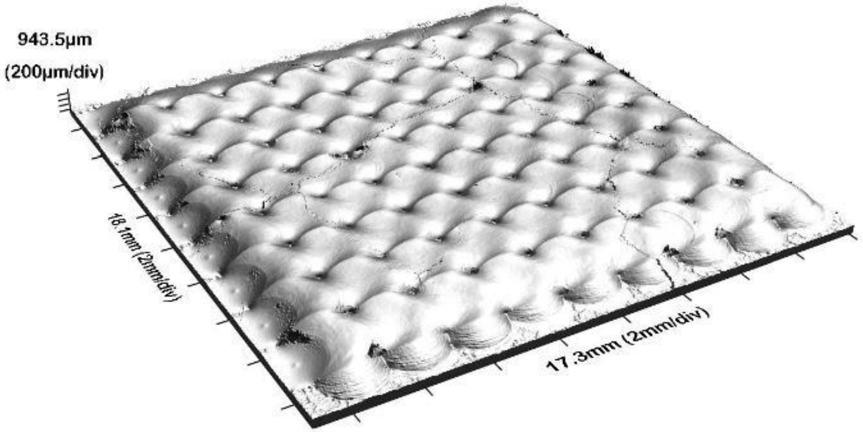
O.4. Surface regeneration - Deposition



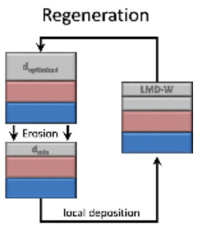
- LMD-W at IPT Aachen
  - Ar flow, 4 kW IR laser, deposit W on W substrate
  - Parametric studies for improving single beads (W-substrate only RT)
  - Full layers (~ 0.7 mm thick) with densities up to 97.5 % were achieved
  - Layers up to ITER monoblock size, multi layer and remelting





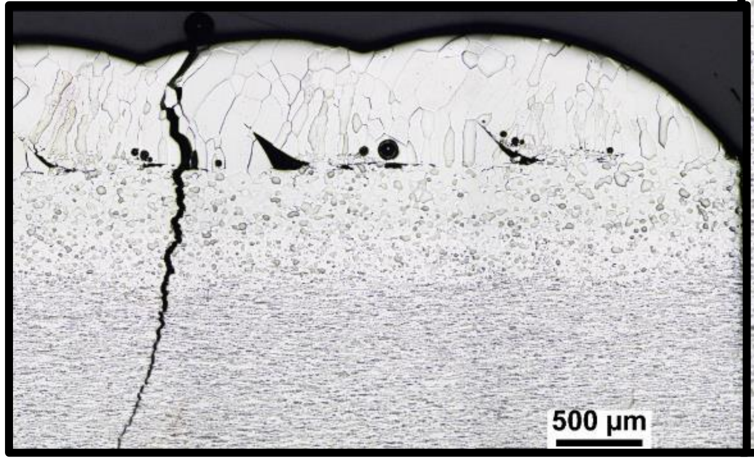


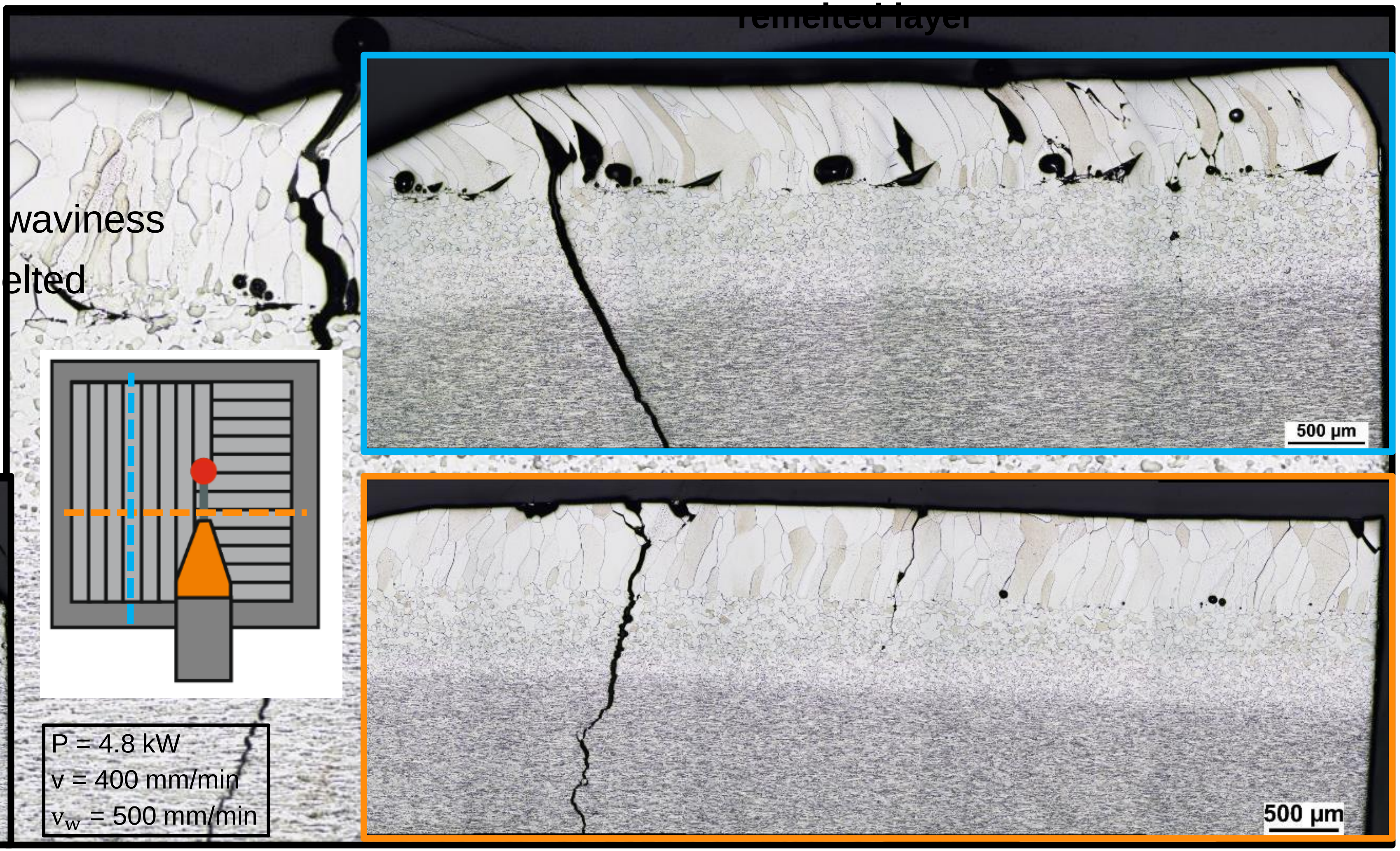
O.4. Surface regeneration – Remelting



- Single layer
  - Large cracks due to lack of substrate heating!
  - Remelting with 90° to reduce waviness
  - Not the complete layer is remelted
  - Strong defect anisotropy

Single as deposited layer





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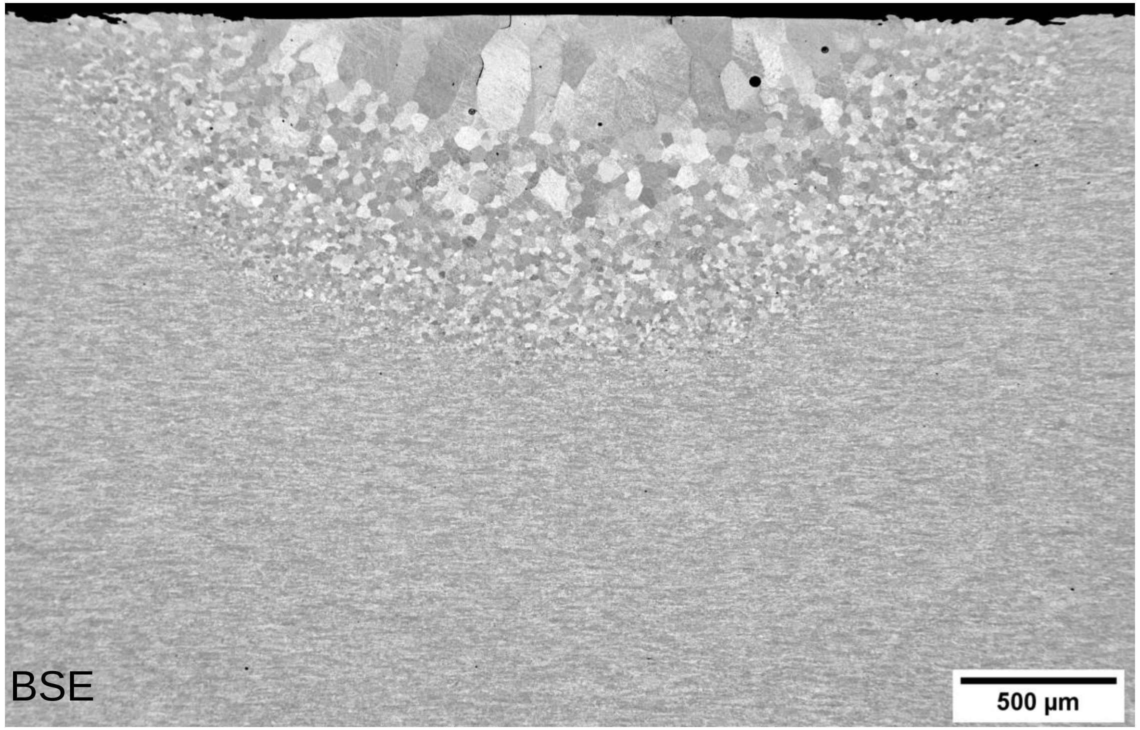
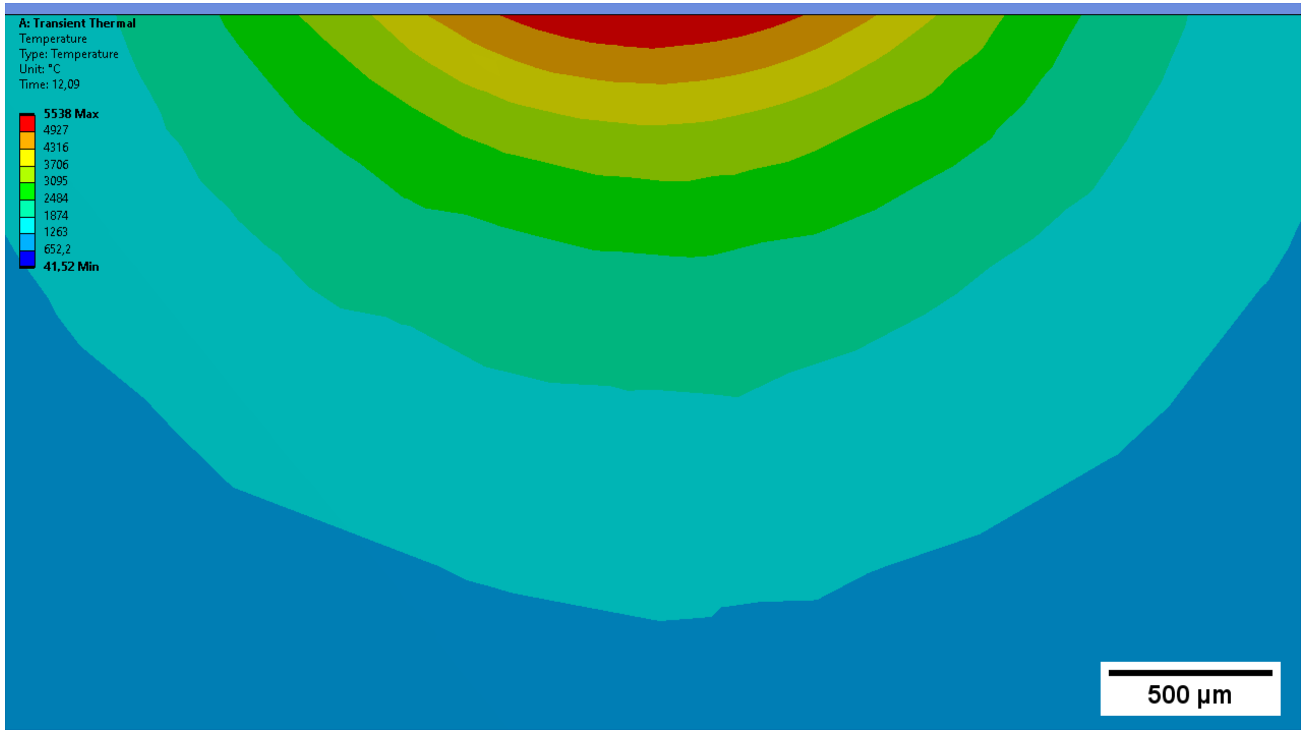
O.4. Surface regeneration - Remelting

Crosssection single melt bead



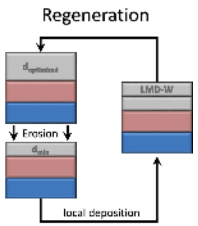
real melt pool depth (the large grains) ~ 370 µm

Temperature distribution according to simulation

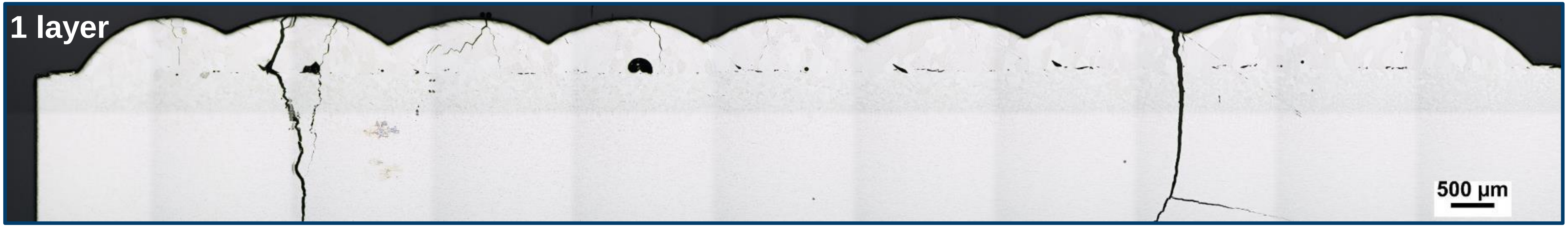


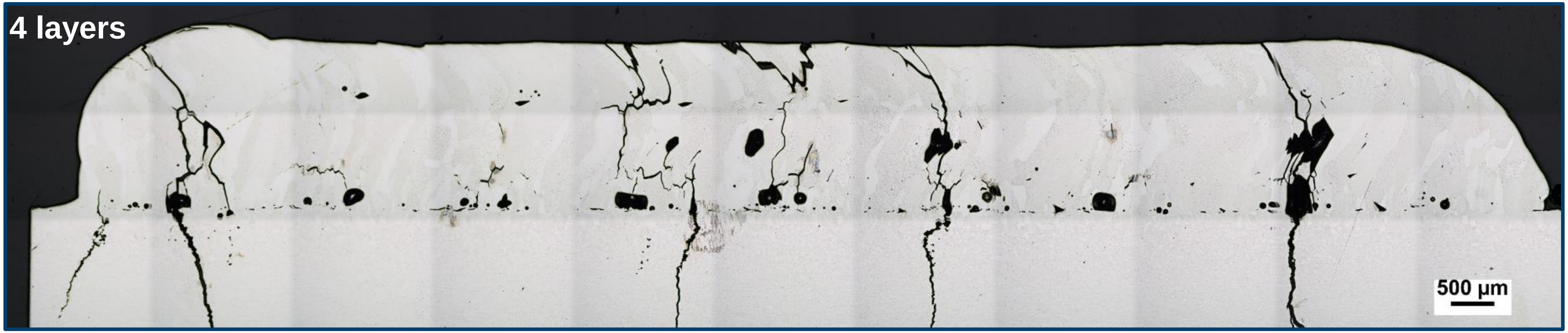
Calculated melt pool depth ~ 370 µm

O.4. Surface regeneration – Multilayers

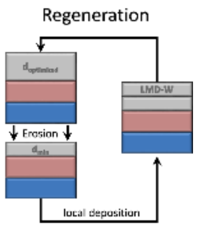


- Perfect interlayer bond: no visible oxide films etc, grain structure continues through layers
  - Waviness doesn't increase with each layer but is determined by last one



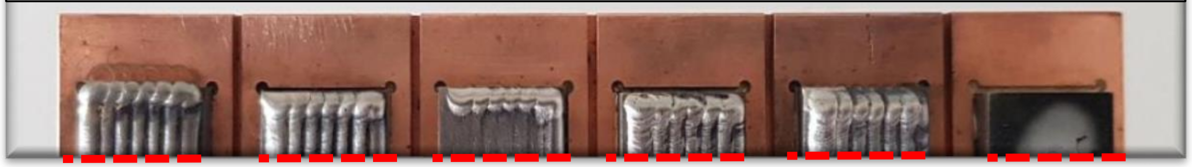


O.4. Regeneration – Repair of damaged W

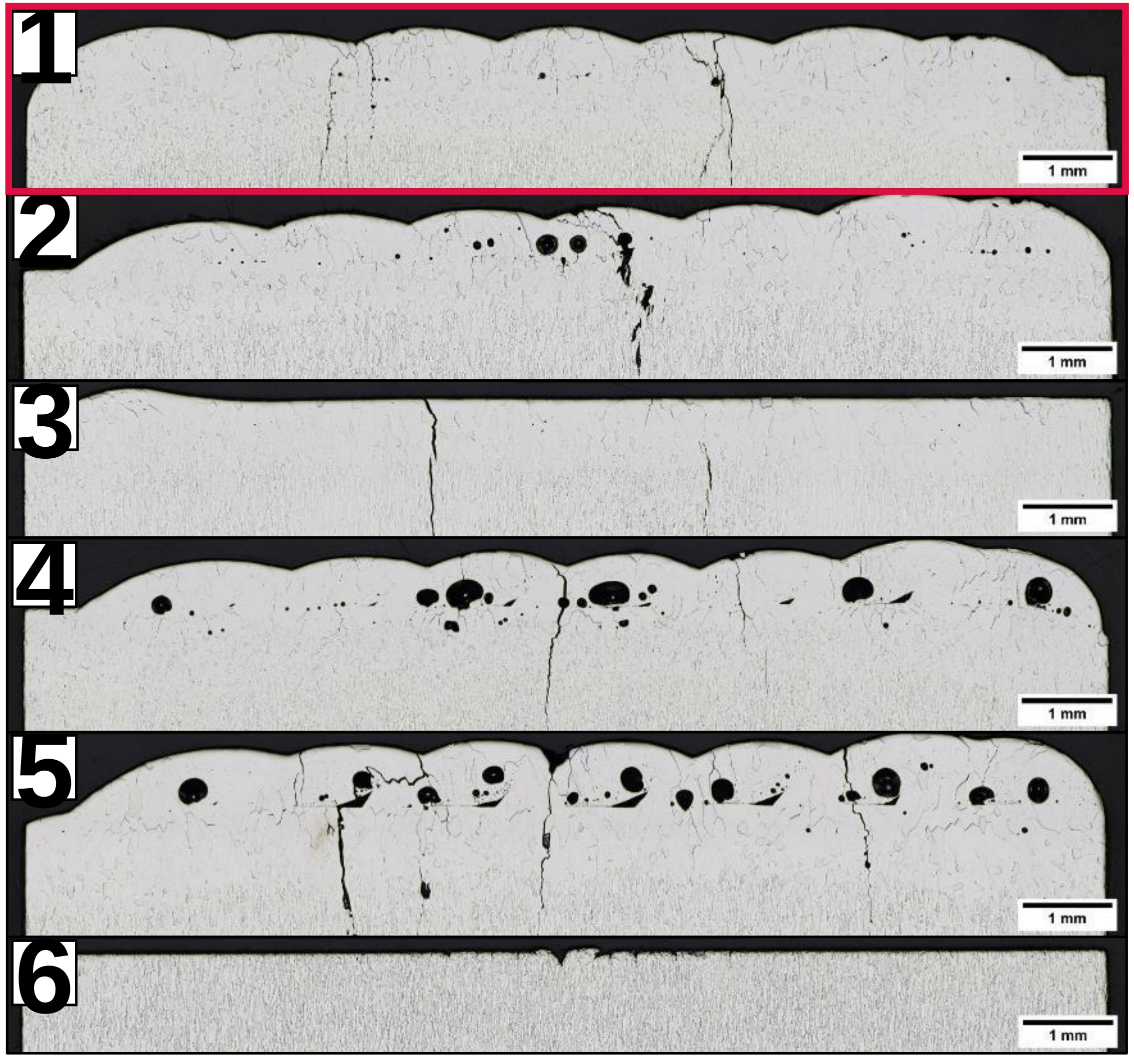


- Predamage on 12 × 12 mm² W-blocks
- Transients: 10^5 pulses of 0.5 ms at 700°C with F_{HF} = 12 MW $m^{-2}s^{0,5}$
- Successful deposition on damaged surface
  - No remelting / cleaning step necessary
  - Prior remelting increases number of key holes/defects

J. Tweer– ID: 38122 - *manuscript: JNME-D-24-00189R2 accepted*

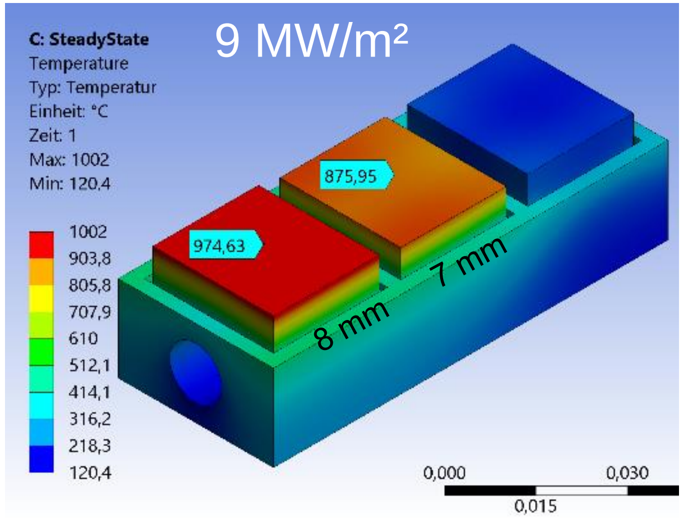


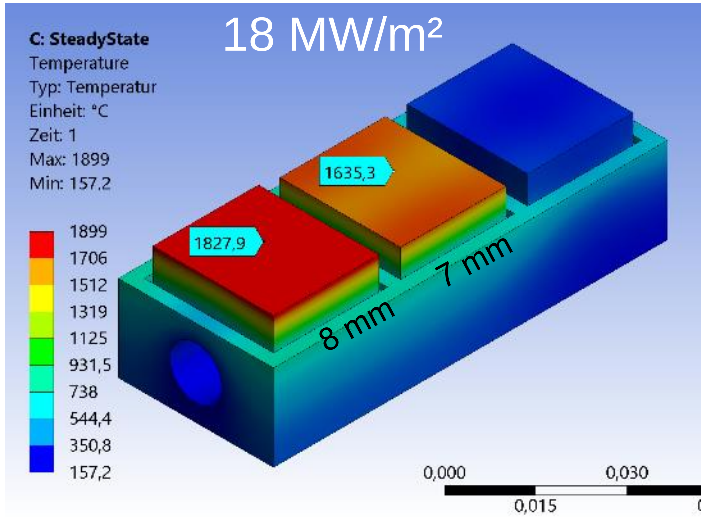
Sample	Procedure
1	Single layer (standard deposition parameters)
2	Single layer (half the velocity to double energy density)
3	Remelting
4	Remelting + single layer (standard parameters)
5	Remelting + single layer (half the velocity
6	Reference



O.6. Testing conditions for a LMD-w PFC

- Test conditions to mimic monoblock chain
  - Aiming for the same surface temperatures as for 10, 15, 20 MW/m²
  - 70°C cooling water temperature, 7 m/s, temp. dependent HTC
  - 8 and 7 mm thick W-tiles and 2.5 mm Cu similar to center of MB
  - ➲ **“Simulate” the center of a MB with flat tile design**
  - Only slightly lower cooling capability thus: 9, 14 and 18 MW/m²





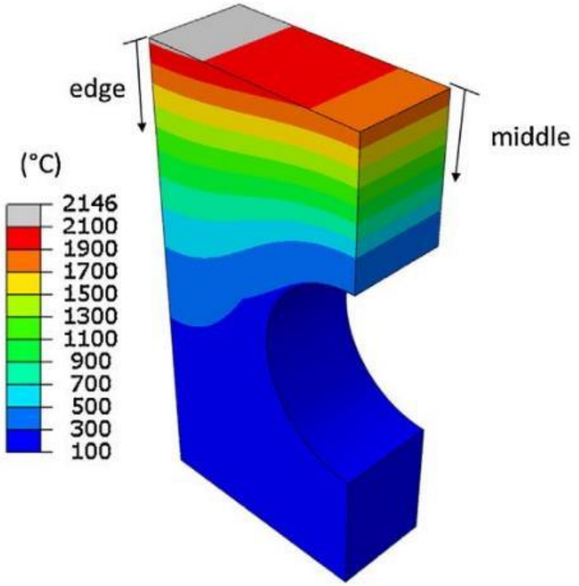


Fig. 4. Temperature field in the divertor target under stationary HHF load of 20 MW/m².

Table 3
Calculated temperature range on the armor surface during steady state HHF loading.

Heat flux loads	Temperature ranges
10 MW/m²	950–1058 °C
15 MW/m²	1411–1612 °C
20 MW/m²	1864–2146 °C

M. Li and J.-H. You; Nuclear Materials and Energy Nuclear Materials and Energy, vol. 14, pp. 1-7, 2018, doi: 10.1016/j.nme.2017.12.001

O.6. Prototype mock-up: LMD-w on W

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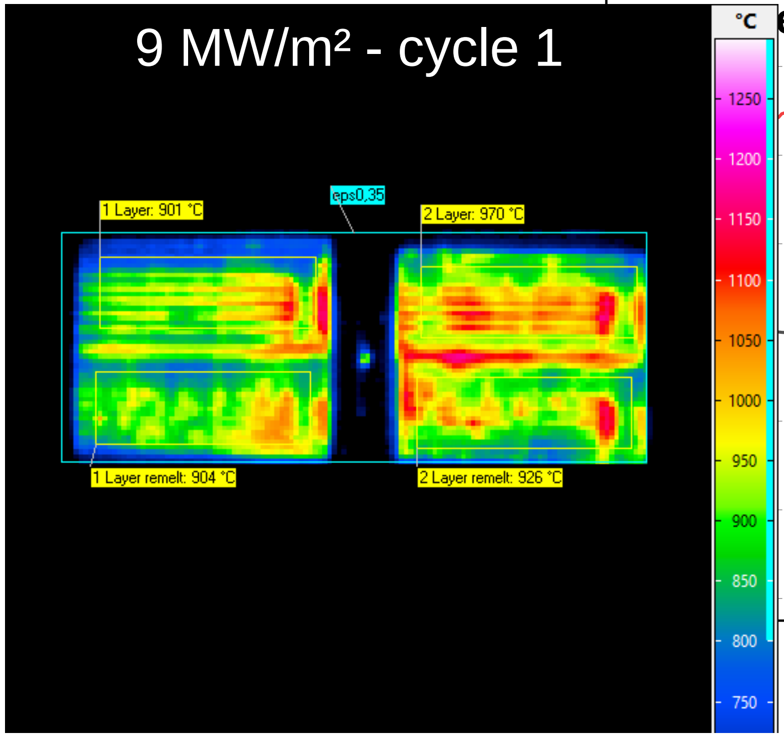
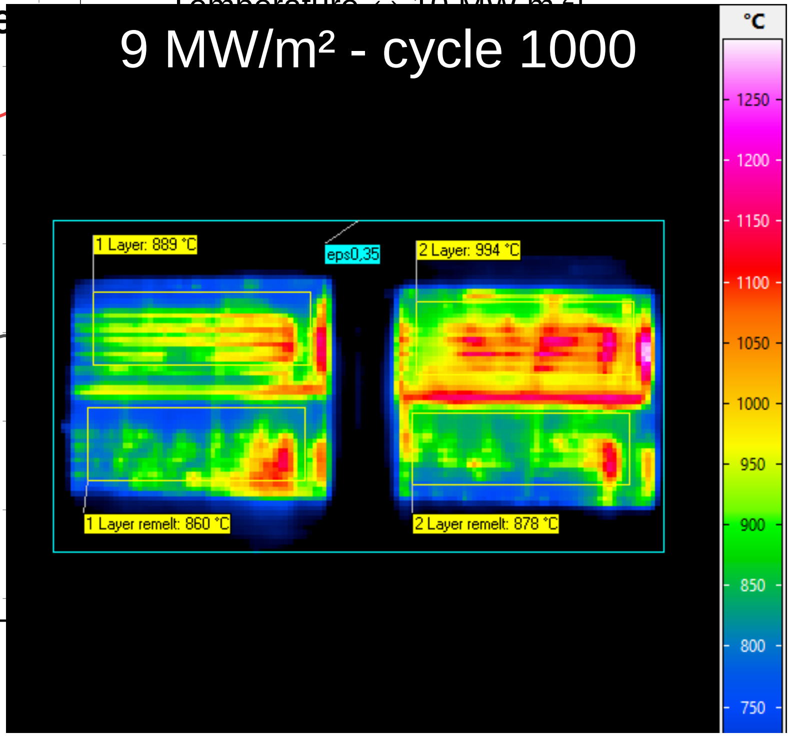
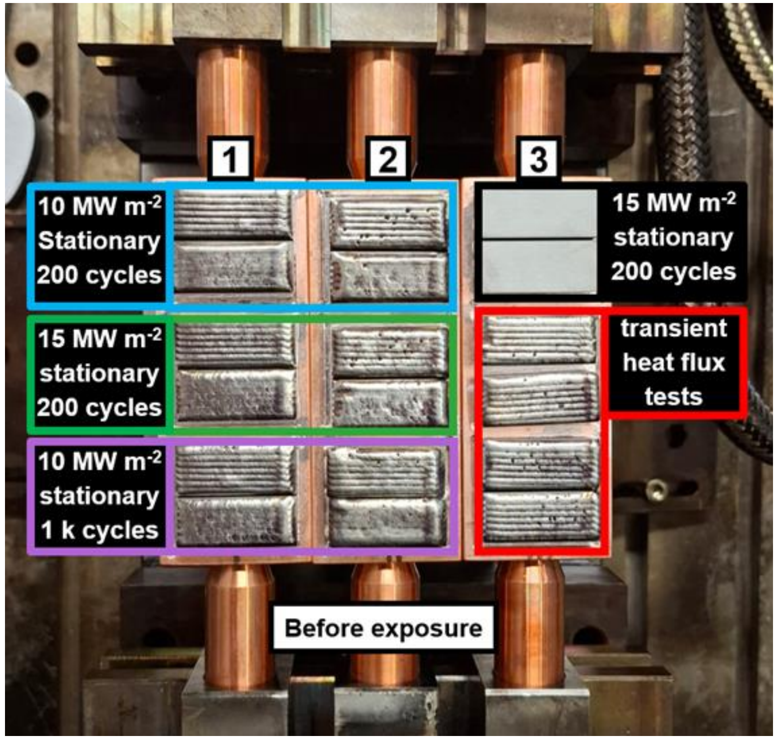
- Monoblock like testing samples
  - MB size: 28 mm × 12 mm, 7-8 mm thickness
  - Double blocks to realize the intended 0.5 mm gap for checking whether LMD-w bridges it or not
- Four different configurations were prepared
  - One and two layers with 0.6 mm height each
  - With and w/o applied laser remelting to reduce roughness and waviness
  - Precision of deposition technique accurate enough to cover full MB and without bridging the gap in between
  - Brazed at 850°C on Cu cooling structure

O.6. Prototype mock-up: HHF test

- Test at “10 MW/m²” and “15 MW/m²“ on 1 and 2 layers
  - Transient loadings on LMD-w material at < 200°C and 700°C both up to 10^5 HFF12
  - Surface temperatures during stationary HHF like simulated
  - No changes during cycling at “10 MW/m²”

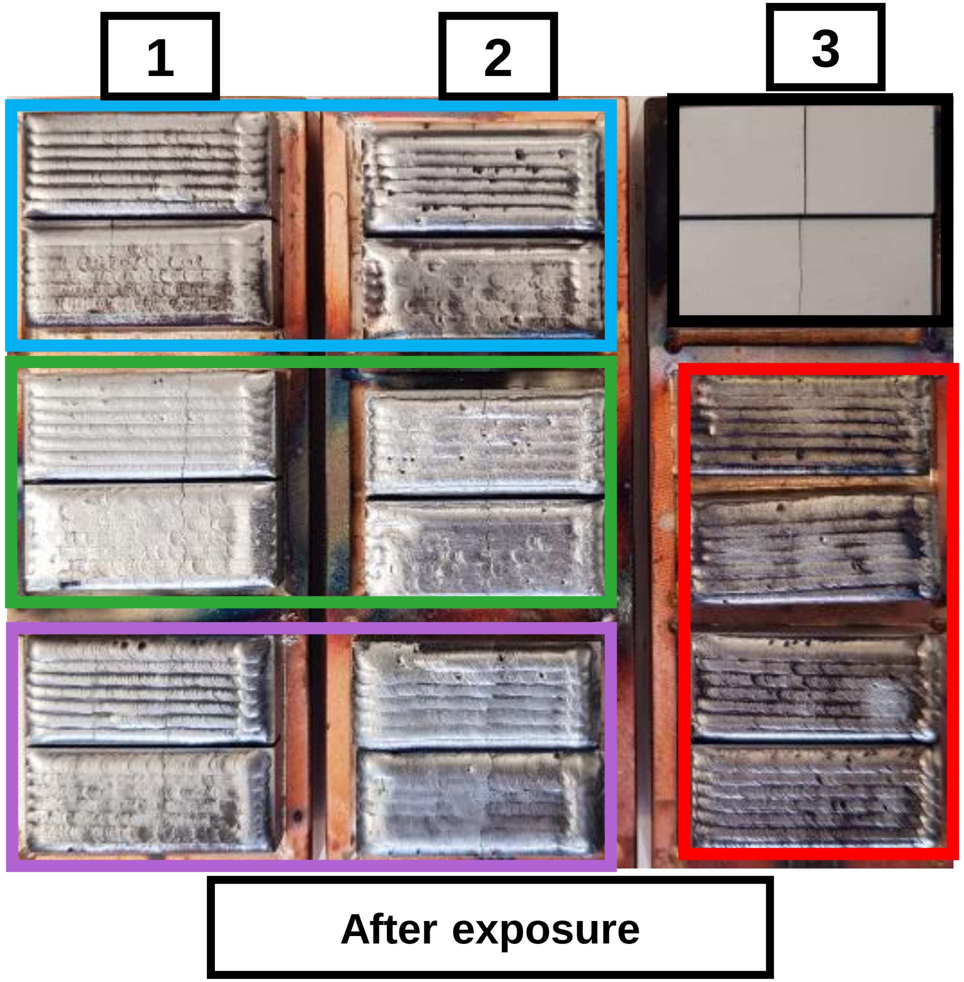






O.6. Prototype mock-up: HHF test

- Analysis of the tests is ongoing…
  - Classic macro cracks in the center of the MB parallel to the cooling pipe appeared during the 15 MW/m² phase latest
  - All samples including the reference cracked but deposited once have already small ones in the beginning
  - For this first experiment IGP-W was not used as substrate but older single forged W from Plansee which might be the reason for the reference crack
  - ➲ **No delamination of full layers or breaking loose of parts**



Recommendations for further development

- SEBM for full/dense W structures
  - Iterations by designer/plasma physicist which shapes would be really helpful with which needed accuracy and experimentalist try to realize them including testing
  - Geometrical gradation as joining approach
- W-wires as µ-brush (with Cu, steel or W joint)
  - Armour in strike line or other areas with strong transient loads
  - Possible candidate as limiter, as molten W gets sucked in/stays
- Repair and Regeneration
  - LMD-w as in-vessel tool for local compensation of erosion losses
  - No layer/part broke of despite surface condition
  - Surface temperature eventually up to 1000°C during deposition necessary to avoid new cracks (similar to SEBM / LPBF of W)