Additive manufacturing as tool to manufacture and maintain plasma facing components

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

EUROfusion

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Outline

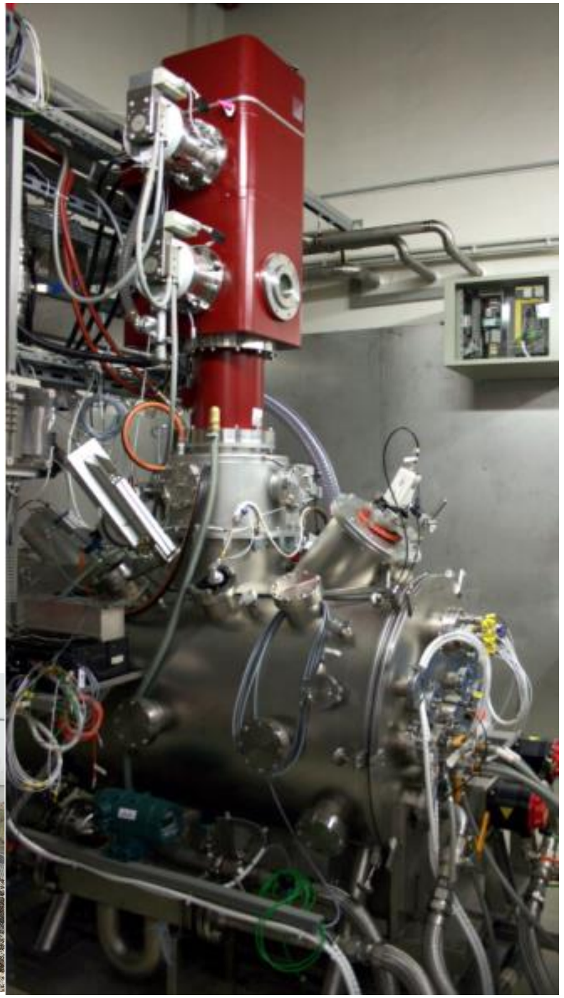
- Fundamentals
- O.1. AM-W: AM of W with density >99% and minimal crack density
- O.2. Joints: Realizing advanced joints (FGM, W/W_w, W/steel, W/copper)
- O.3. W-wire as armour: Realization and testing of W-wire as armour
- O.4. Regeneration: Development of techniques for surface regeneration
- O.5. Advanced heat sink geometries: Development, production and testing
- O.6. Demonstrators of used technologies: Construction of prototype mock-ups

Fundamentals

- Team change
  - Thorsten Loewenhoff had to leave FZJ after 14 years, representing major loss for fusion
  - Mauricio Gago joined the team 01.01.2023
    - PhD about synergistic plasma & thermal load
  - Change of personal at the IPT partner
    - Jannik can work at site
    - Much has to be relearned

Fundamentals

- Team change
  - Thorsten Loewenhoff had to leave FZJ after 14 years, representing major loss for fusion
  - Mauricio Gago joined the team
    - PhD about synergistic plasma & thermal load
- JUDITH 2
  - Upgrading Cooling circuit for high heat flux tests w/o depositing minerals causing failure
  - Begun 2021, delivery of new system end 2022
    - Cleaning of pipe system
  - Massive delay and problems with sensors, pumps, control
    - Subcontractor got sued
    - Work in progress



JUDITH 2 – cooling circuit

temperature:	RT – 120 °C
pressure:	≤ 4 MPa
flow rate:	≤ 200 l/min
power:	150 kW

in-situ high purity control (nominal values)

conductivity:	< 0.3 µS/cm
oxygen content:	< 0.04 mg/l

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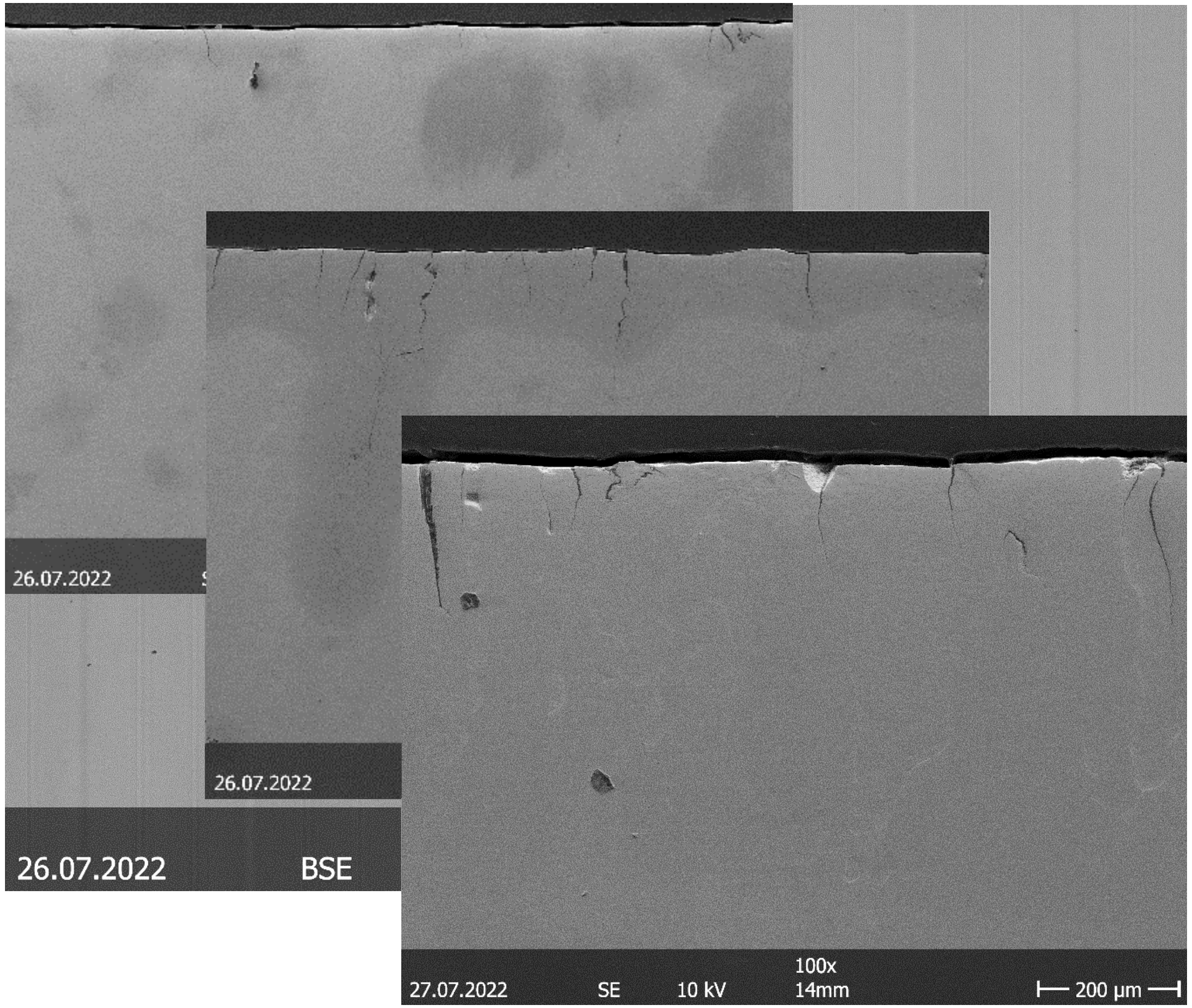
O.1. AM-W

- New cooperation with KIT started
  - Similar SEBM machine as at IFAM
  - Nearly crack free, very few pores after polishing
  - Cross sections very few in depth cracks
- Tested @700°C with 10^5 thermo shocks with F_{HF} = 3, 6 & 12 MW/m²s$^{0.5}$
  - Crack density and depth increases with F_{HF}
  - No macroscopic failure, power handling as standard



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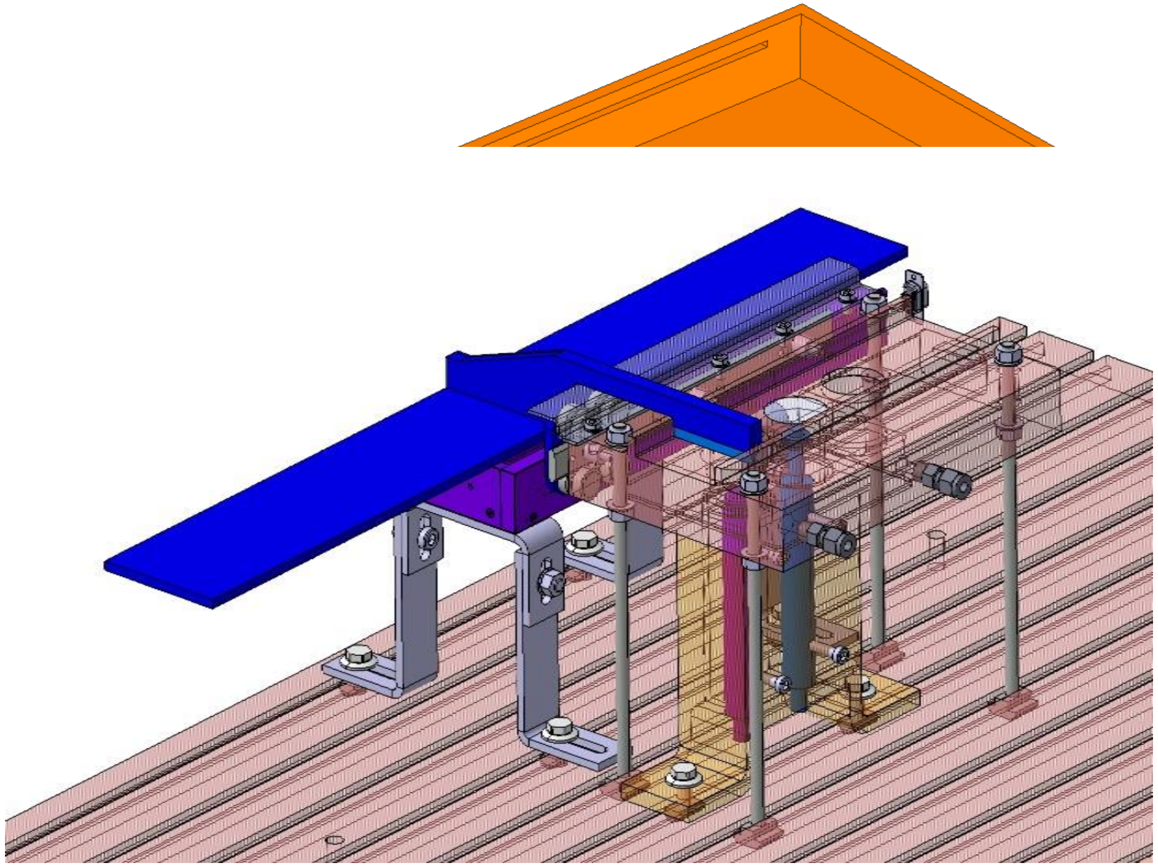
  - Crack density and depth increases with F_{HF}
  - No macroscopic failure, power handling as standard
- An upgrade for JUDITH 2 / 3 was foreseen to screen new material compositions and investigate influence of beam properties
  - Developed iteratively with our central workshop
  - Due to unsolved financing on hold at the moment

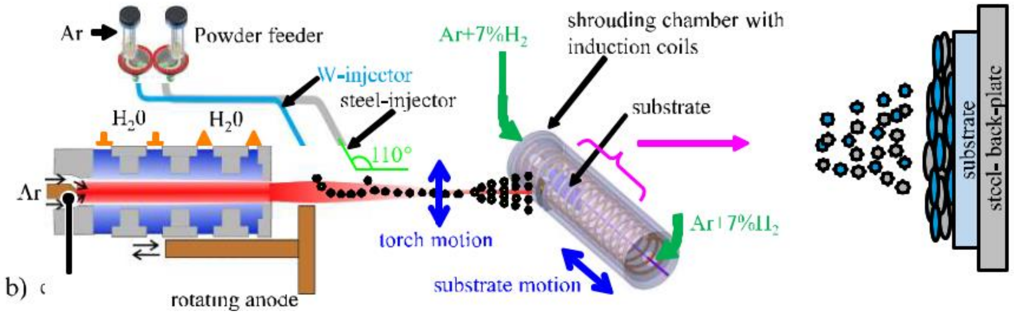


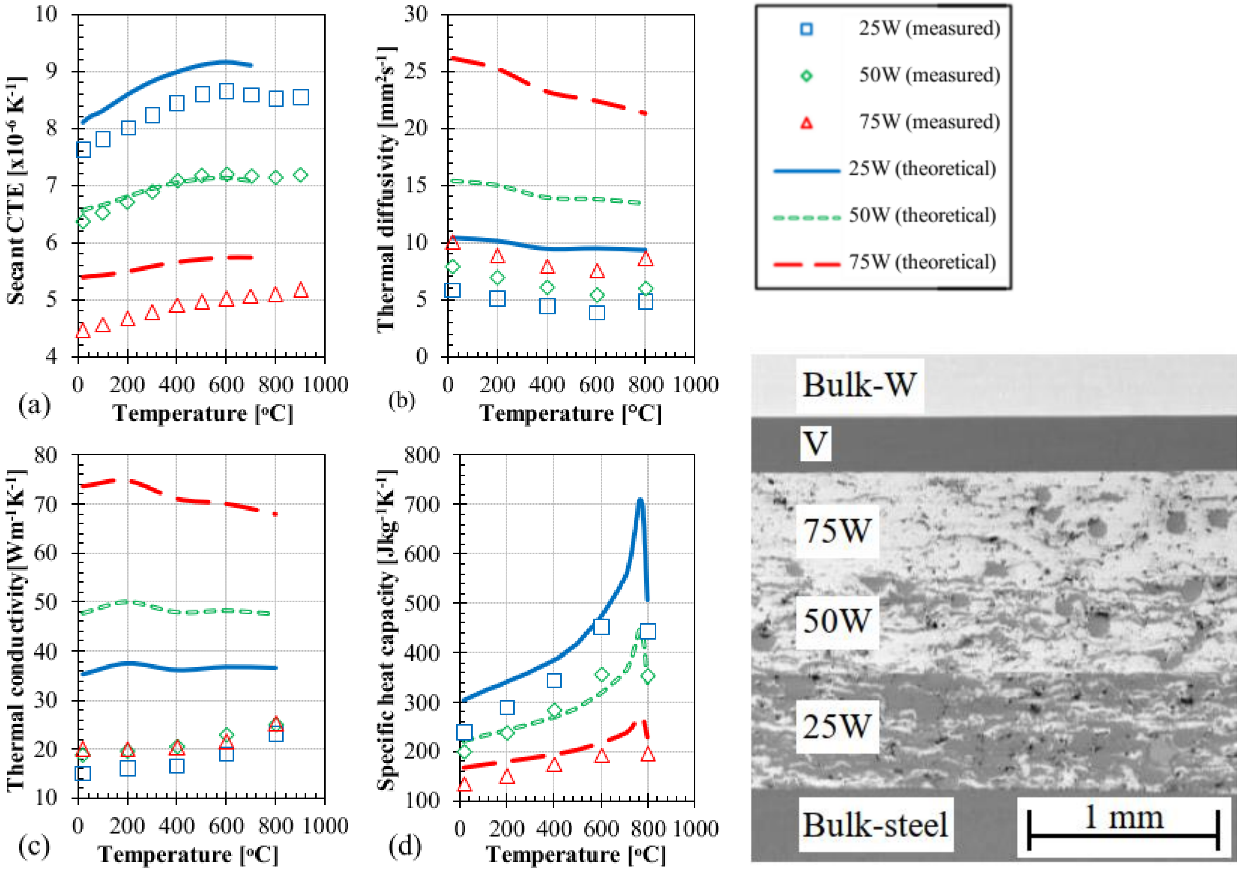
Compositional

O.2. Joints – Compositional FGMs

- Various different methods were used
  - APS, EDS, SPS producing single & full stack
  - Parameter studies to find suitable single- and complete stack manufacturing procedures

Atmospheric Plasma Spraying





https://doi.org/10.1016/j.fusengdes.2021.112896

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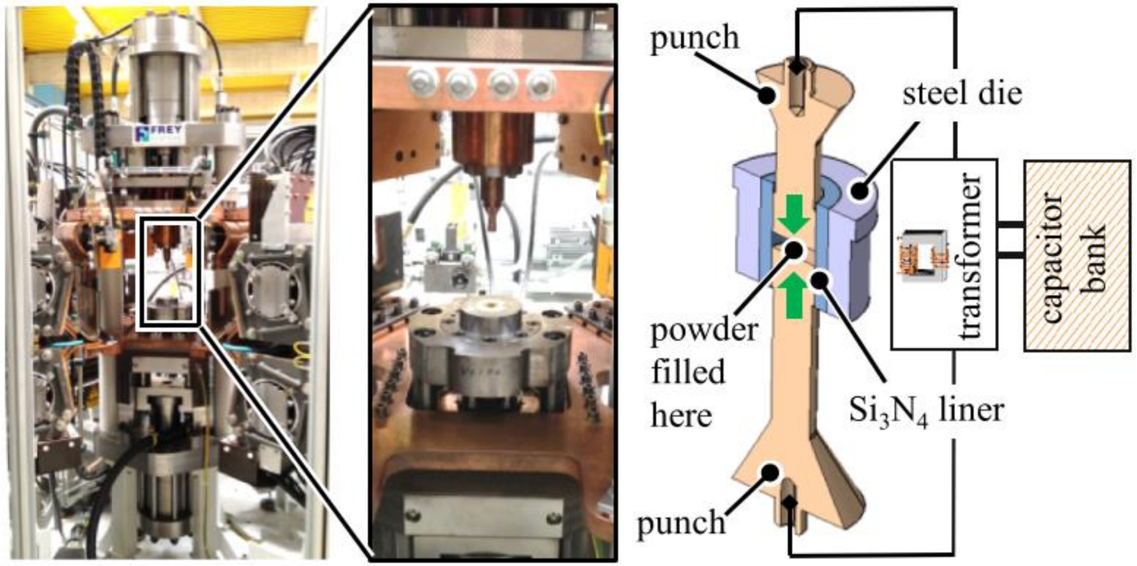
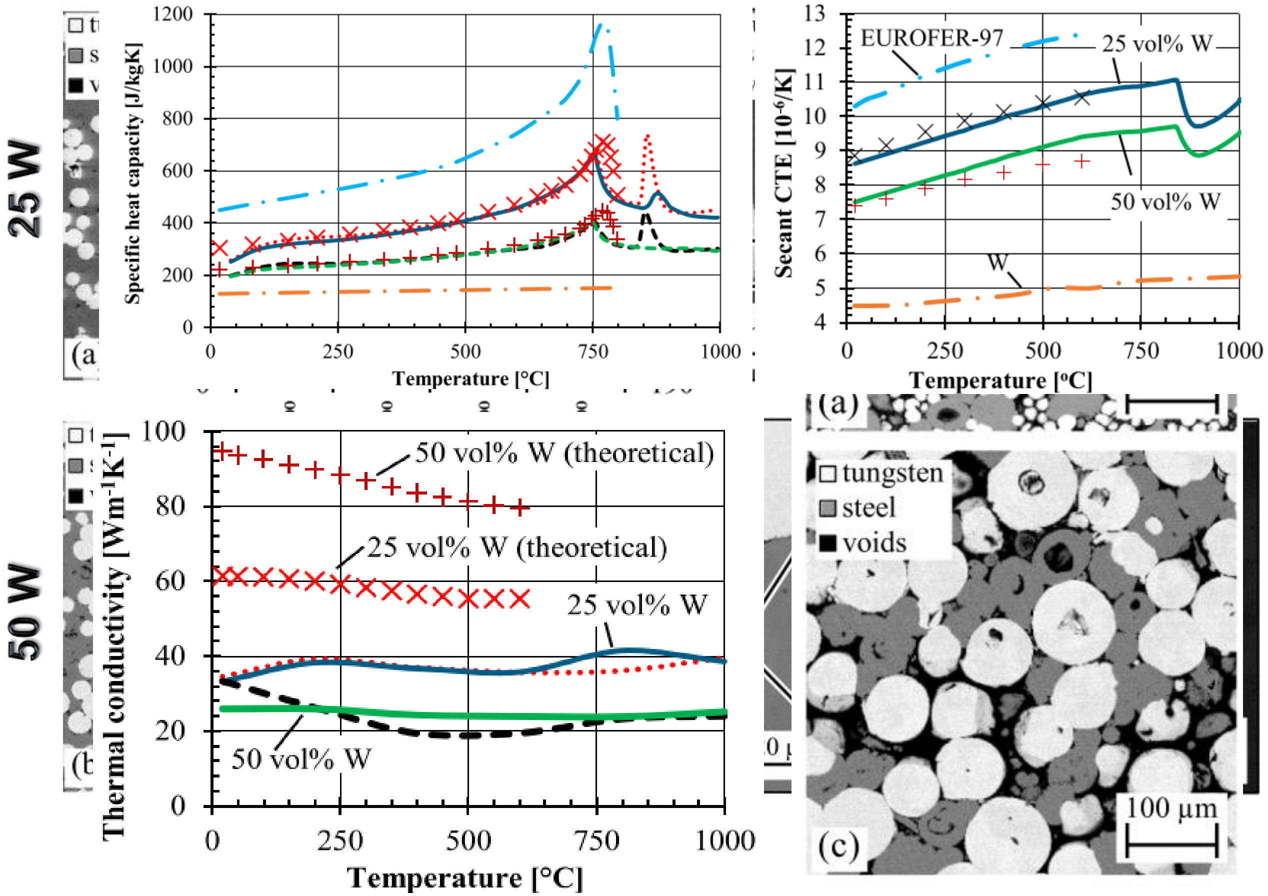


Electro Discharge Sintering



https://doi.org/10.1016/j.nme.2021.101089

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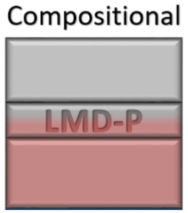
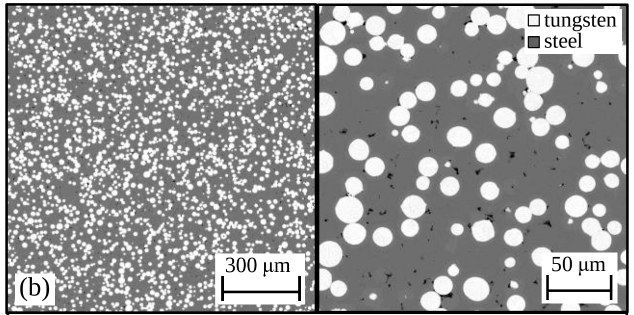
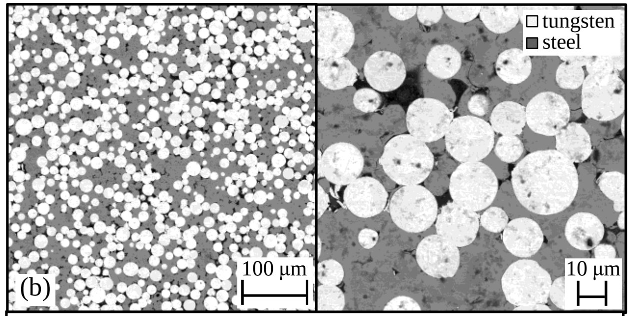


- Various different methods were used
  - APS, EDS, SPS producing single & full stack
  - Parameter studies to find suitable single- and complete stack manufacturing procedures
  - Thermal conductivities are very low for all techniques and below theoretical expectations

Spark Plasma Sintering



$25W_{10-30}+75S_{10-20}$: 1000°C, 5min, 50 MPa, 3 mm



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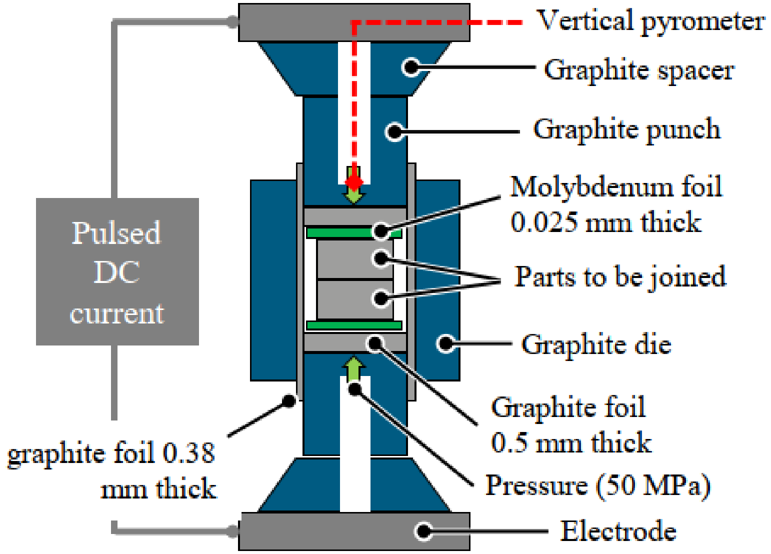
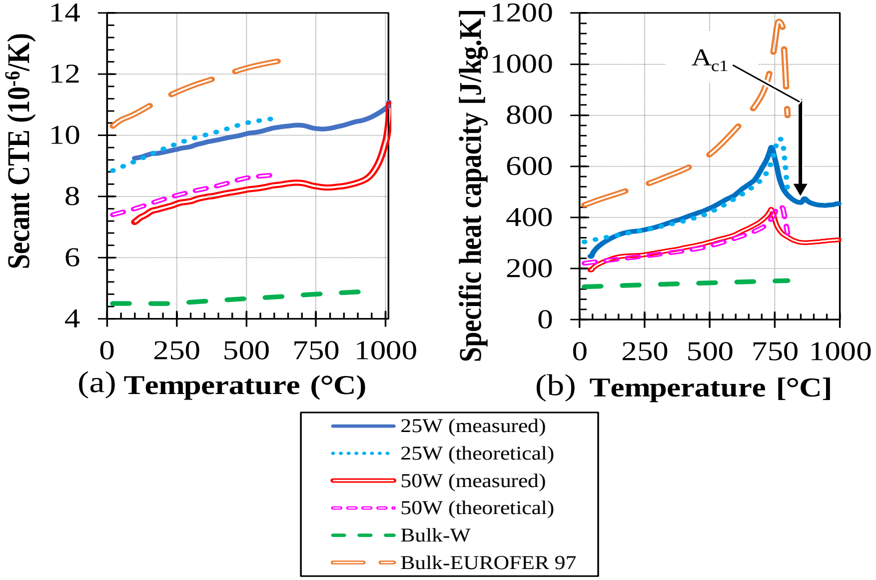
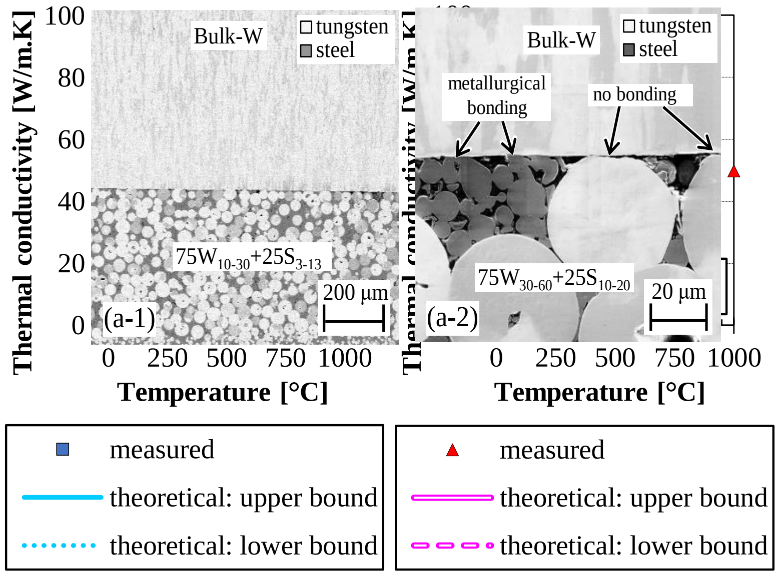
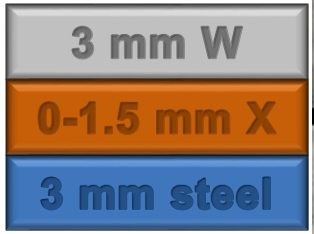


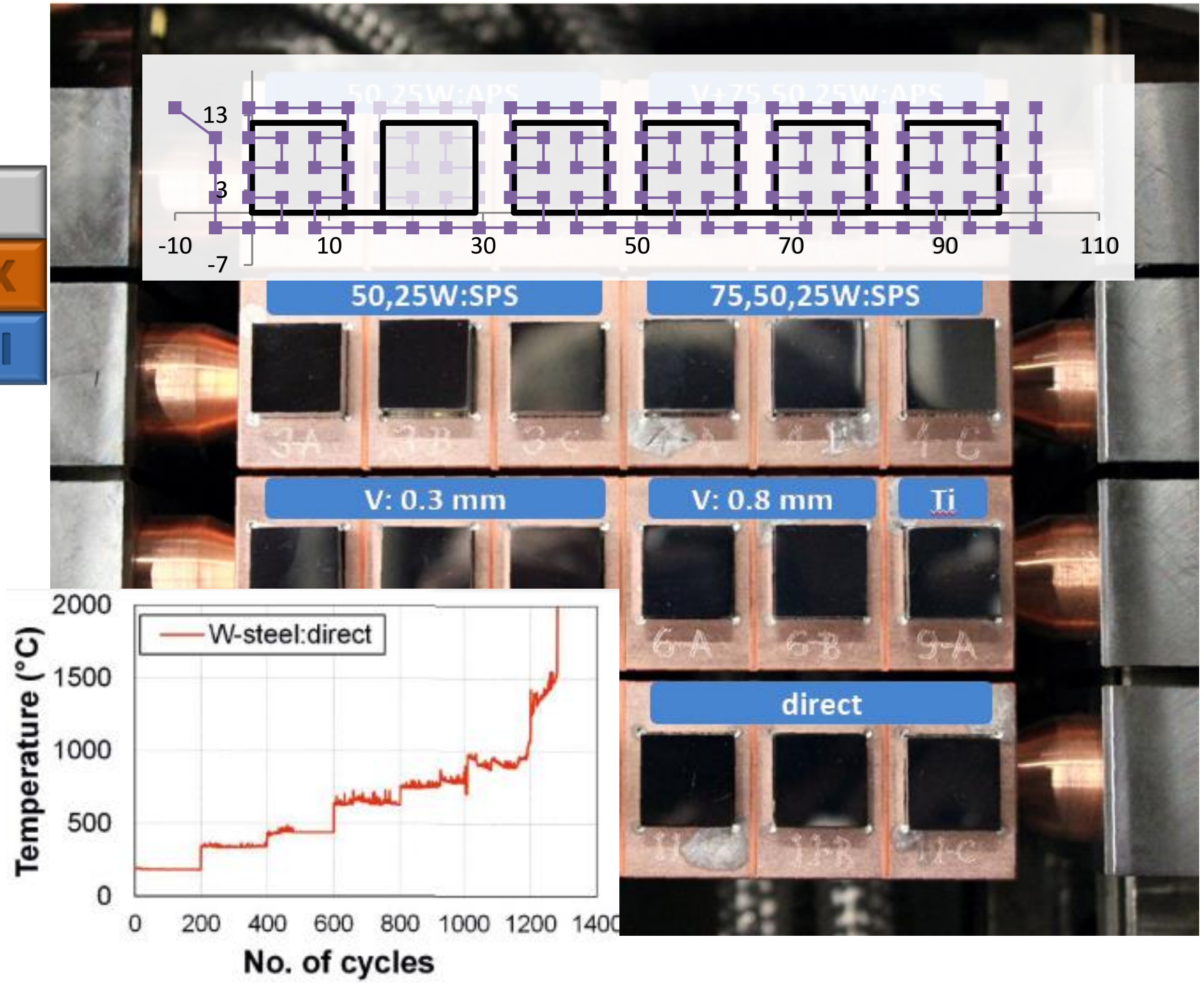




O.2. Joints – Small Scale Benchmarking

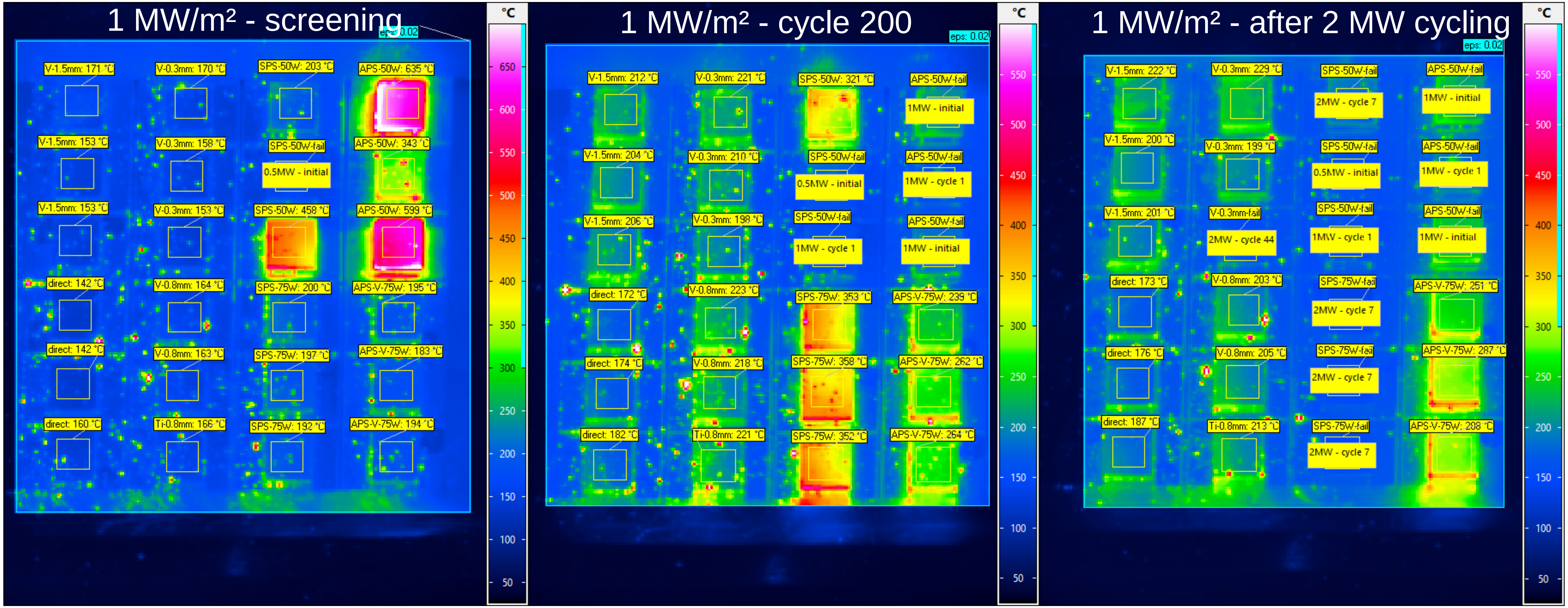
- Clamping device for JUDITH 2
  - Stacks soldered on Cu-holder
- Sample requirement
  - Same size (12x12mm²)
  - Comparable thicknesses
  - Same surface finish for the top-tiles
  - Reasonable reference technology (Direct bonding, brazing…)
- Up to 24 samples at once
  - E.g.: 3 samples per type ➲ ***8 sets***
  - Complex beam patterns allow to load each sample individually
  - Failed samples can be excluded





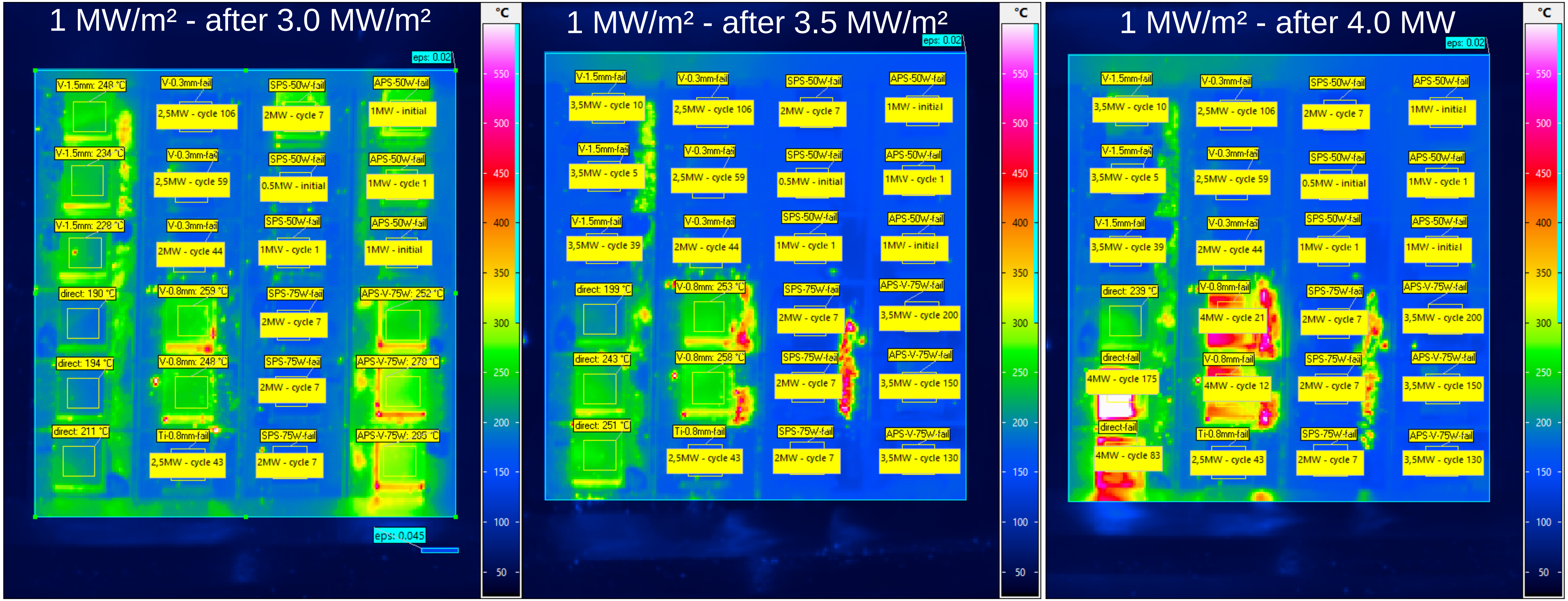
O.2. Joints – Small Scale Benchmarking

- Screening at 1 MW/m² after 200 cycles at each power level to track the evolution



O.2. Joints – Small Scale Benchmarking

- All new types failed after 3.5 MW/m² and during 4.0 MW/m² also the direct joint



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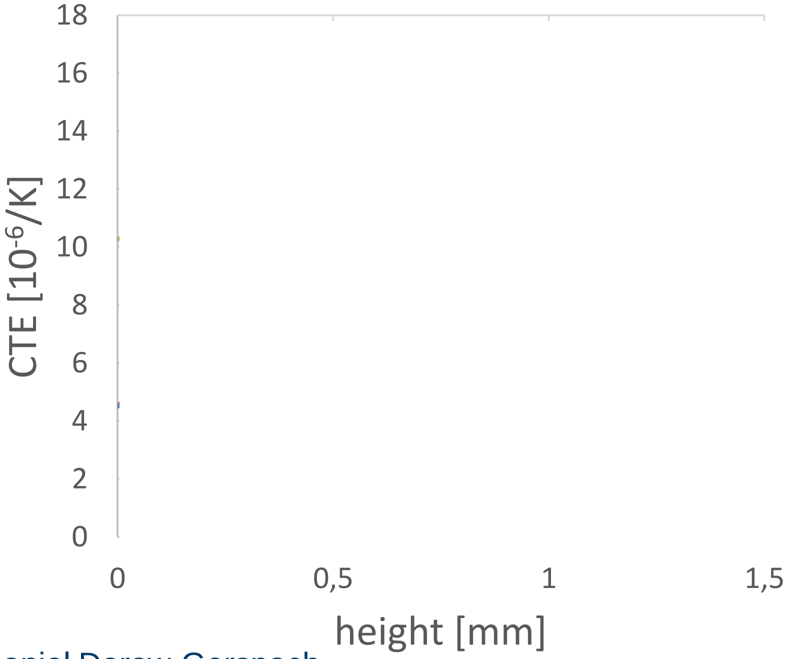
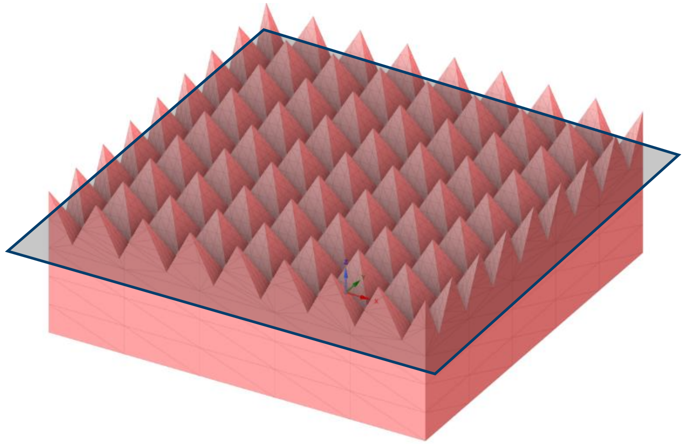
O.2. Joints – Geometrical Gradation

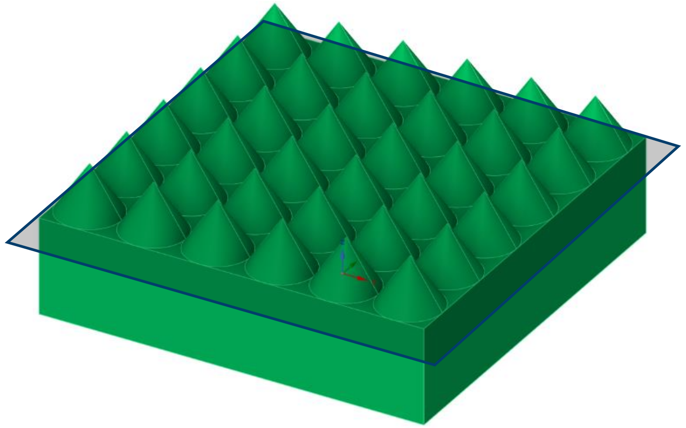
- Assuming CTE determined by volumetric contribution
  - Cu: 16.5×10^{-6} 1/K
  - W: 4.5×10^{-6} 1/K
- Pyramid and LAR will be used



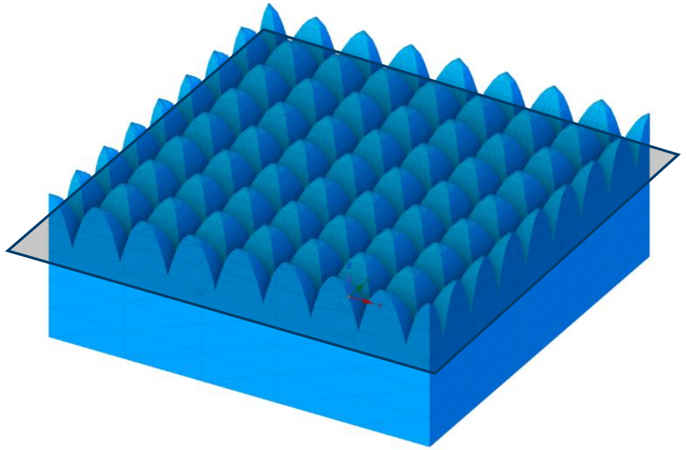
Pyramid



Cone (scp)



Linear Area Ratio



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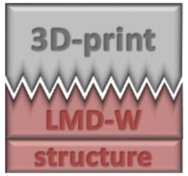

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- Two types were developed
  - Pyramid

  - Linear area ratio

- Cu has been printed
  - W is foreseen next months

steel or Cu
SLM processed

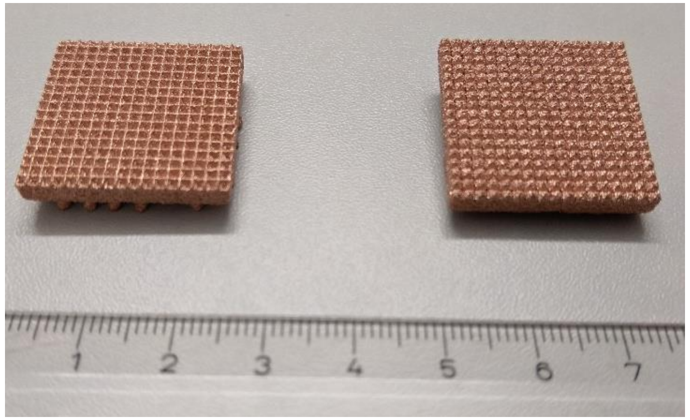
Dimensions:

basic body
length: 12 mm
width: 12 mm
height: 3 mm

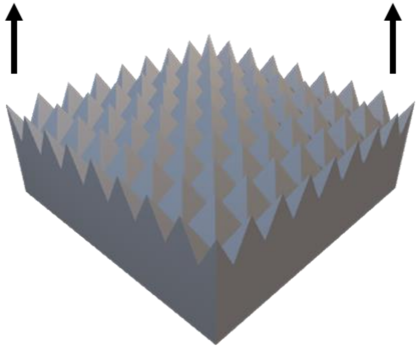
transition structure
length: 1.5 mm
width: 1.5 mm
height: 1.5 mm

W EBM or SLM

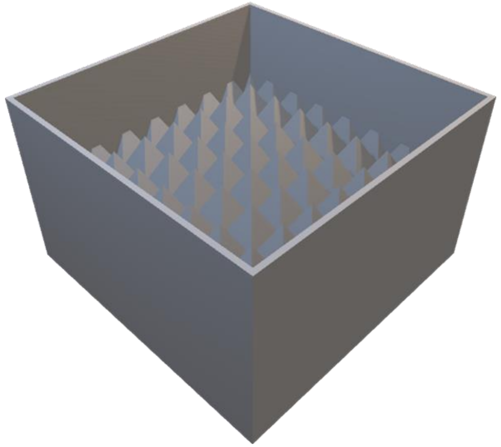
- Diffusion Bonding of bulk



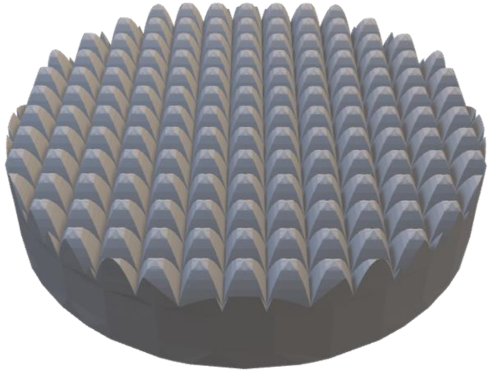
Diffusion bond them together



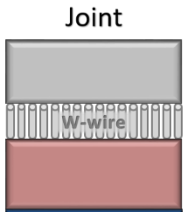
- Melting Cu within a mold



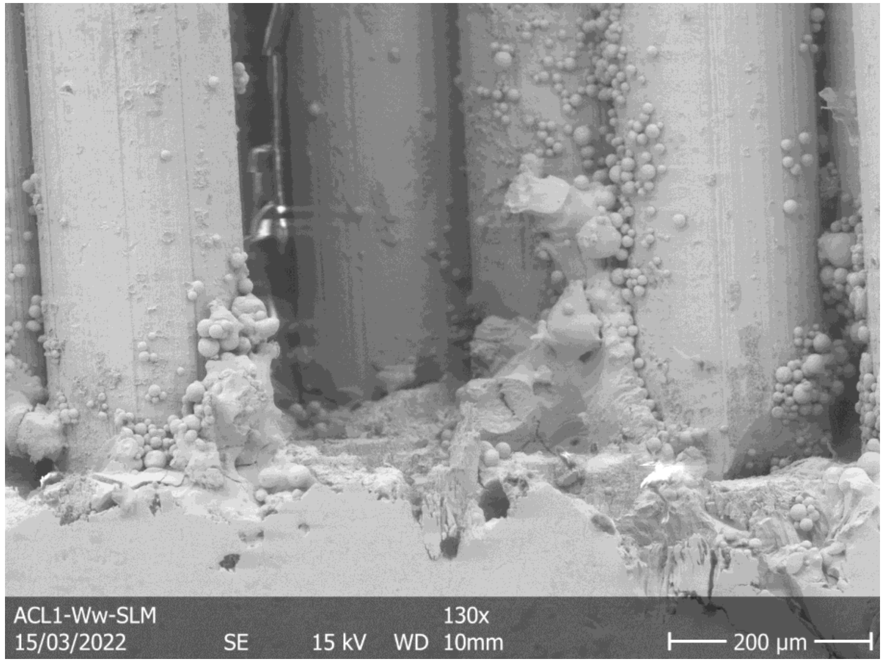
- Spark Plasma Sintering



O.2. Joints – Flexible joints with W



- Laser metal deposition
  - Melting and mixing with W_w
  - Very wavy surface
  - “Bubbles” / high porosity
  - ➲ **Not suitable**
- Selective laser melting
  - Fraunhofer IGCV and A. v. Müller from IPP
  - Powder preheating up to 1000°C
  - High density and versatile
  - First tests on W_w slice
  - Survived grinding and polishing
  - Evtl. release of small particle



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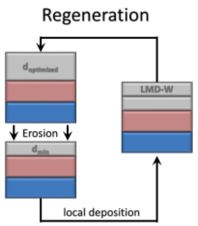
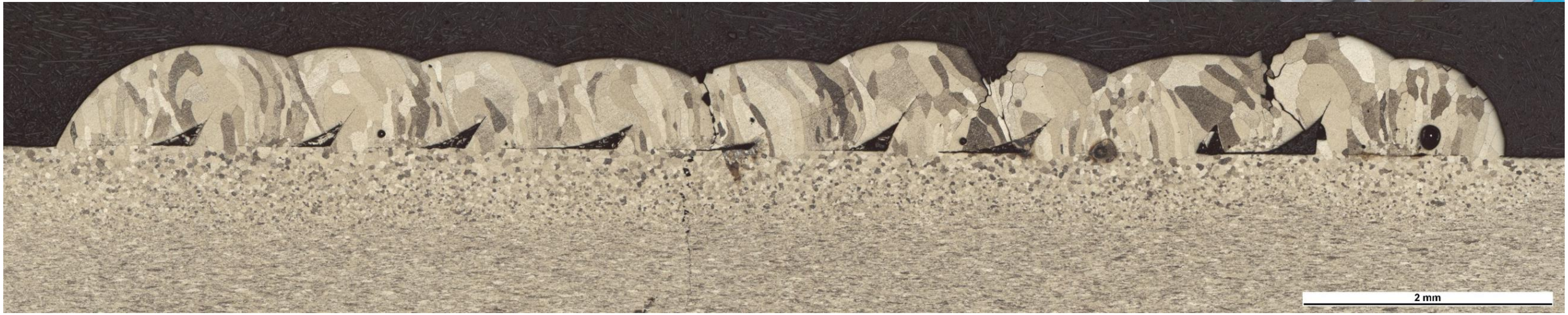
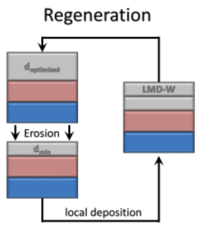
O.4. Regeneration



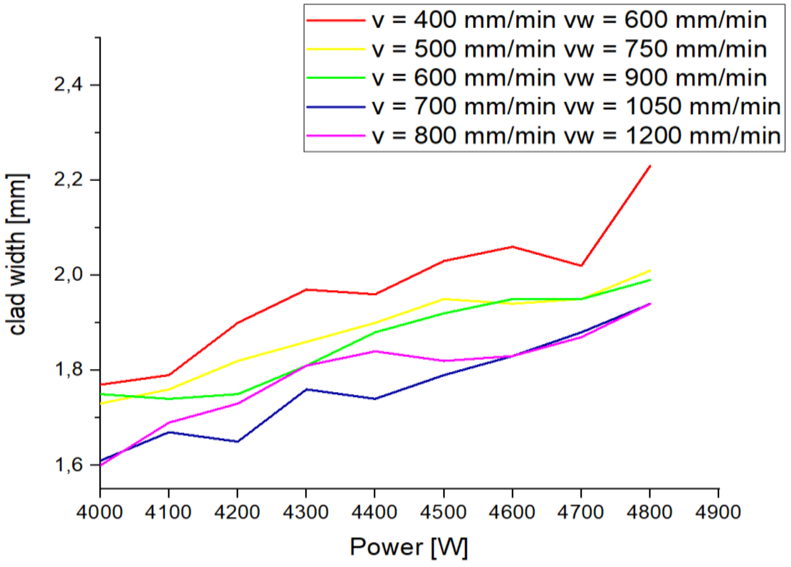
- LMD-W at IPT Aachen
  - Ar flow, 4 kW IR laser, W on steel, W, W_w
  - Porosity, Cracks have to be reduced

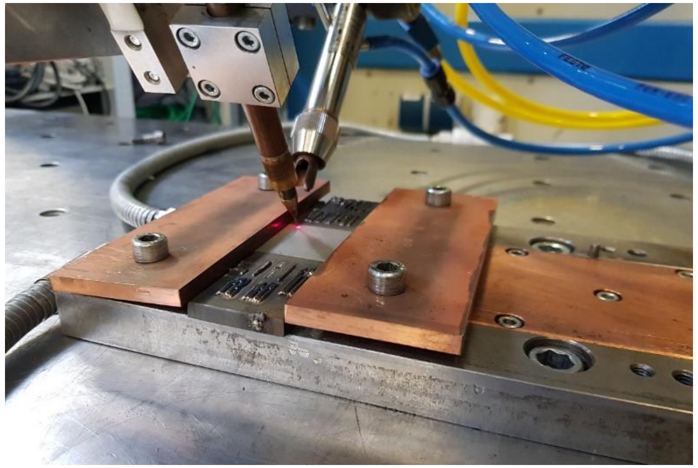


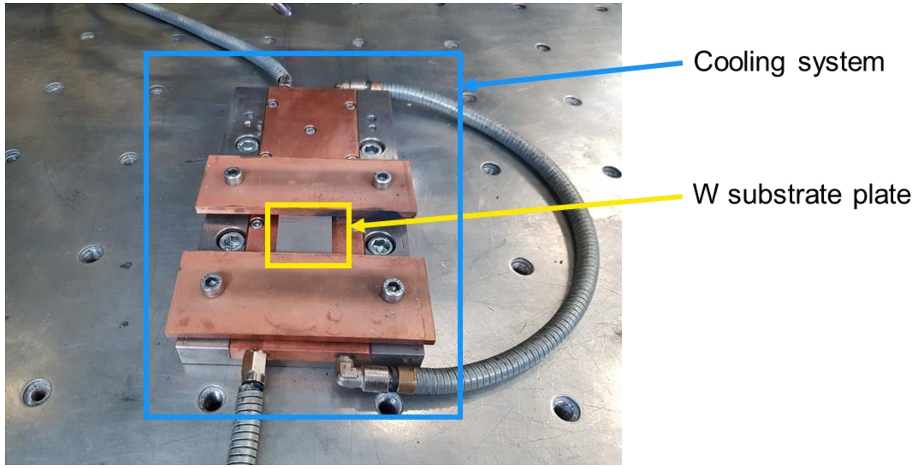


O.4. Regeneration

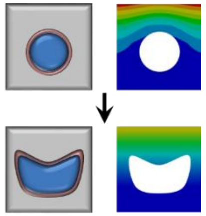
- LMD-W at IPT Aachen
  - Ar flow, 4 kW IR laser, W on steel, W, W_w
  - Porosity, Cracks have to be reduced
- Cooling holder to improve substrate temperature control during the deposition
  - Parametric studies are performed -> work ongoing
  - Width nicely tailorable by power and velocity





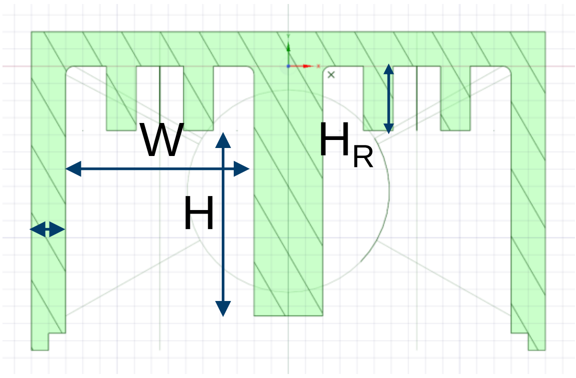


O.5. Advanced heat sink geometries

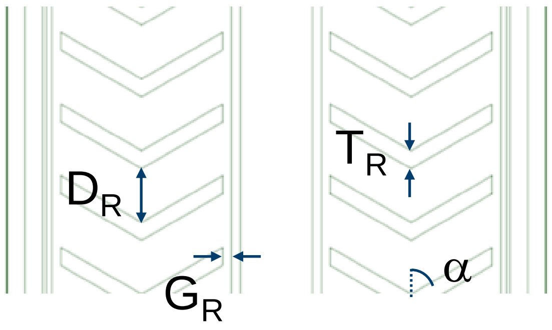


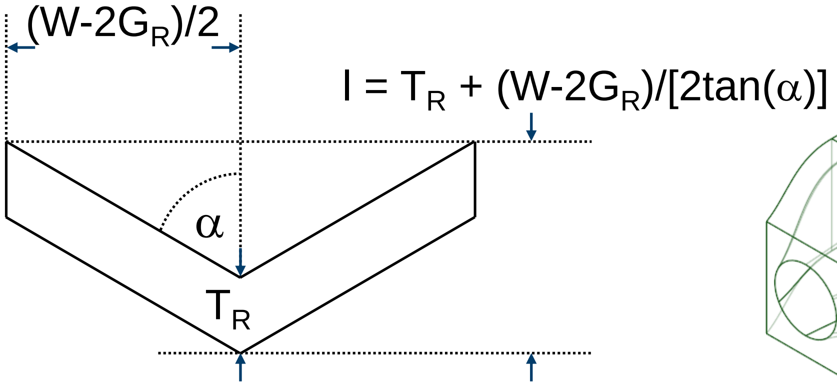
- Improving the heat transfer of the cooling channel
- Double Channel
  - W: 11 mm
  - H: 10.82 mm
  - L: 150 mm
  - T_W: 2 mm
  - R_C: 0.5 mm
  - L_C: 20 mm
- Ribs:
  - G_R: 1 mm
  - α: 60°
  - T_R: 1 mm
  - D_R: 3 mm
  - H_R: 3.75 mm
  - $l \approx 3.6$ mm

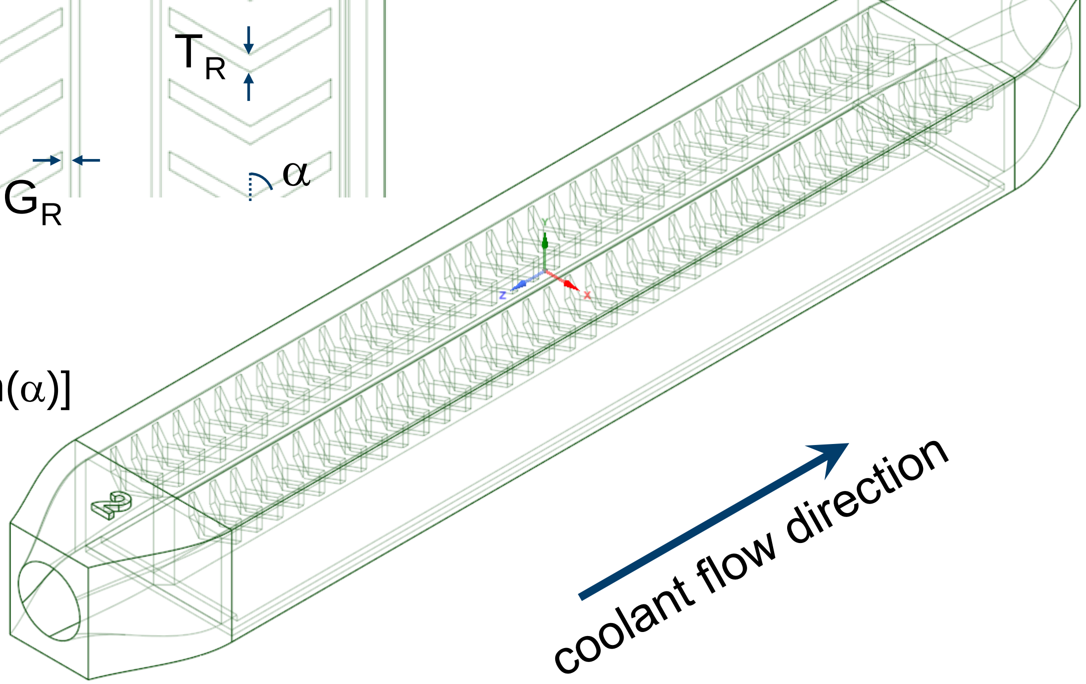
cross section



top view

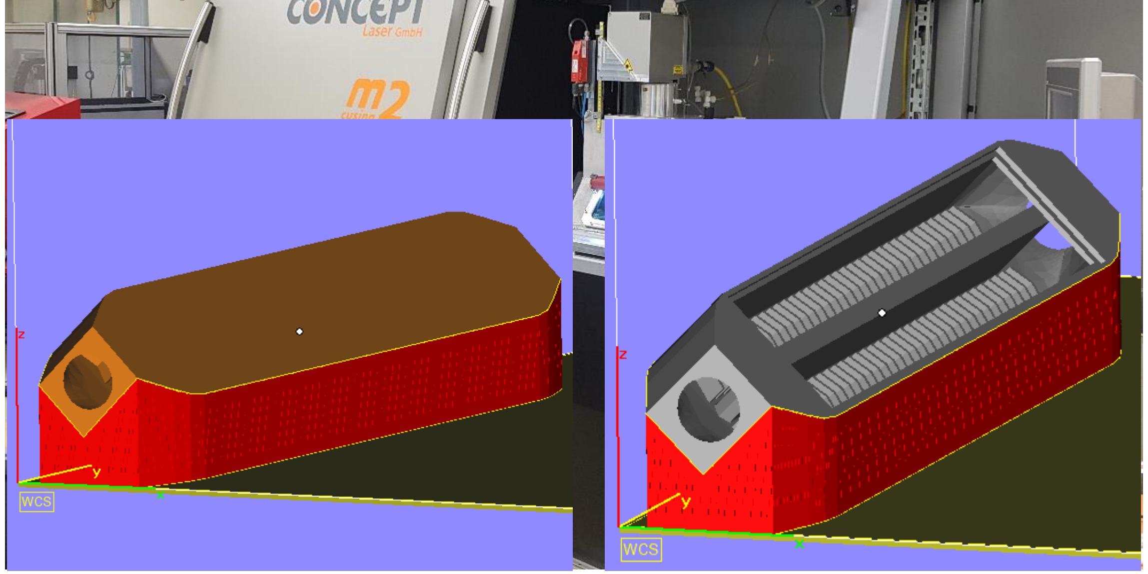


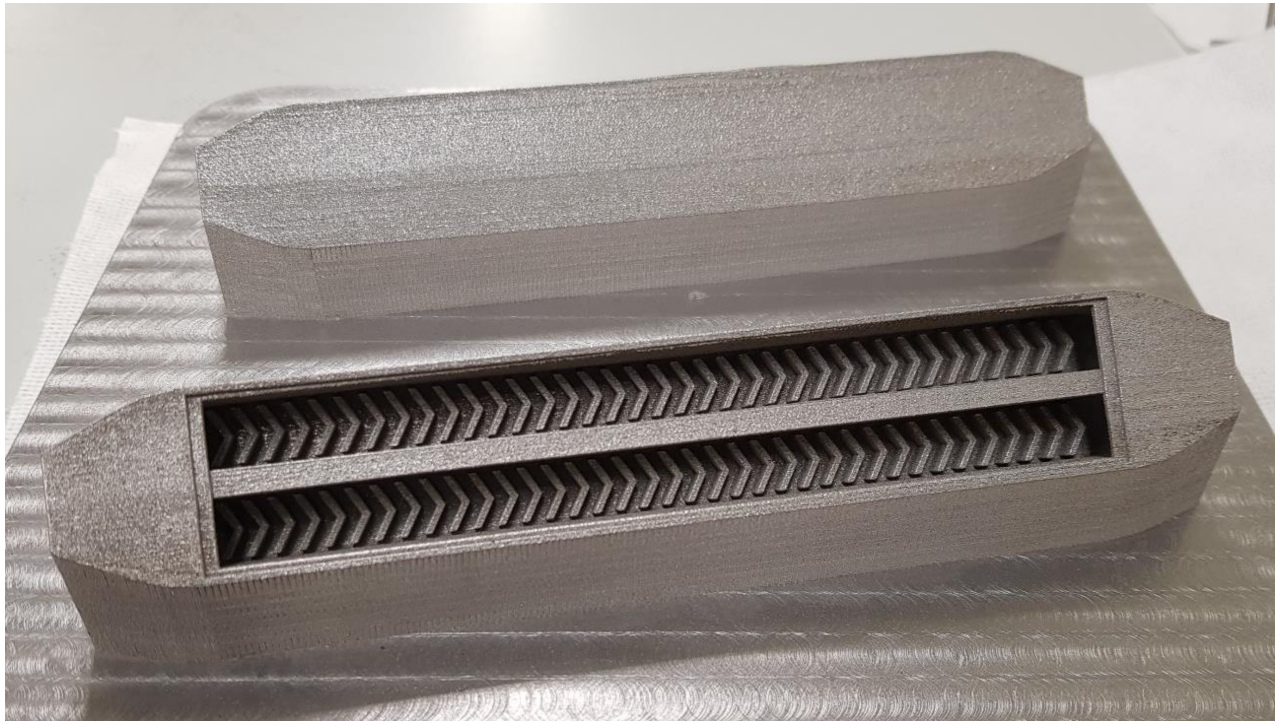




O.5. Advanced heat sink geometries

- Printing of steel at FZJ (SLM)
  - He tightness measured on test cylinders
  - Open and closed channel successful printed
- Hydraulic tests performed
  - Water leaking at high pressure
  - Support structure, design has to be improved





O.5. Advanced heat sink geometries

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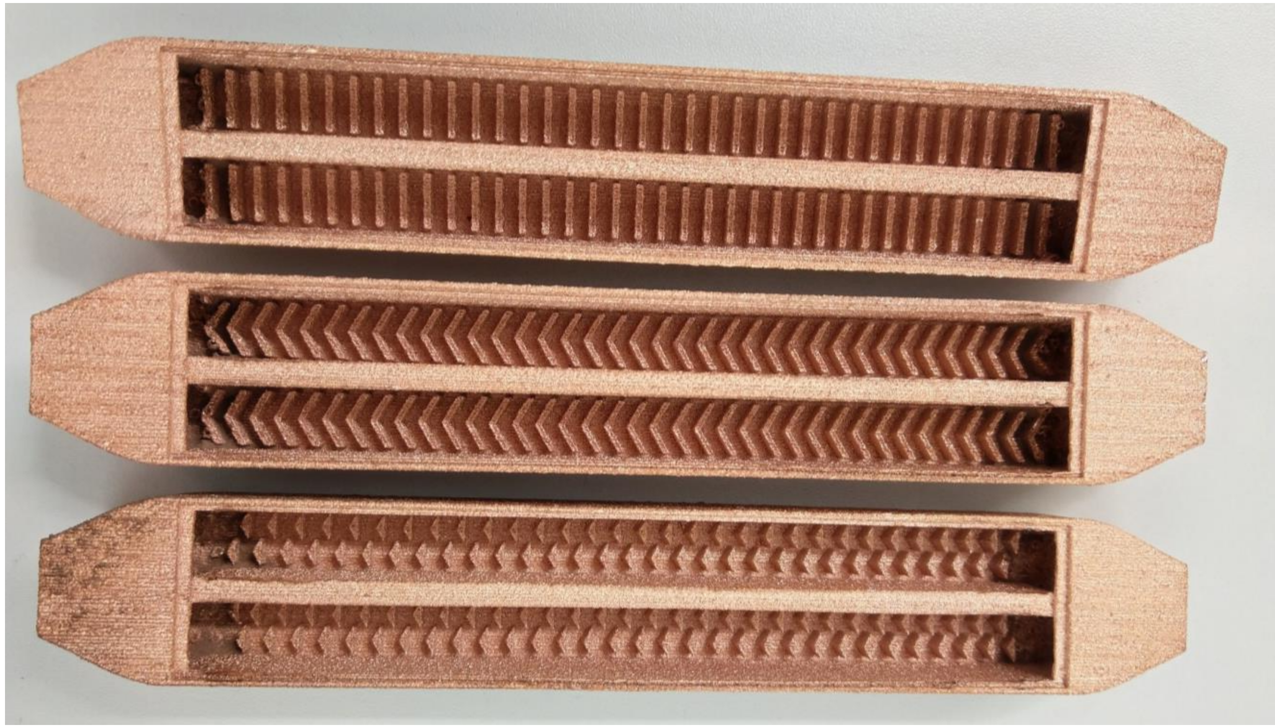
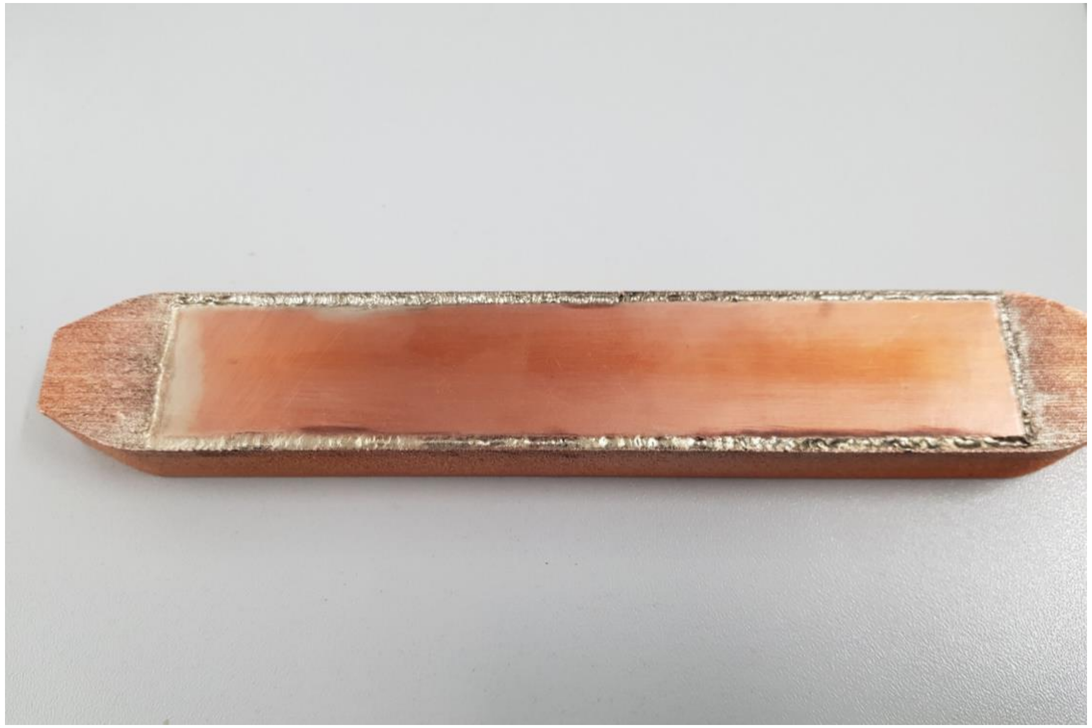
- Further geometries with Cu was printed at IFAM
  - Hydrodynamic and high heat flux tests to assess potential and impact of designs are planned
  - Simple thermal comparative FEM simulations to assess HTC and disentangle area from flow dynamics
  - Backplate soldering is ongoing





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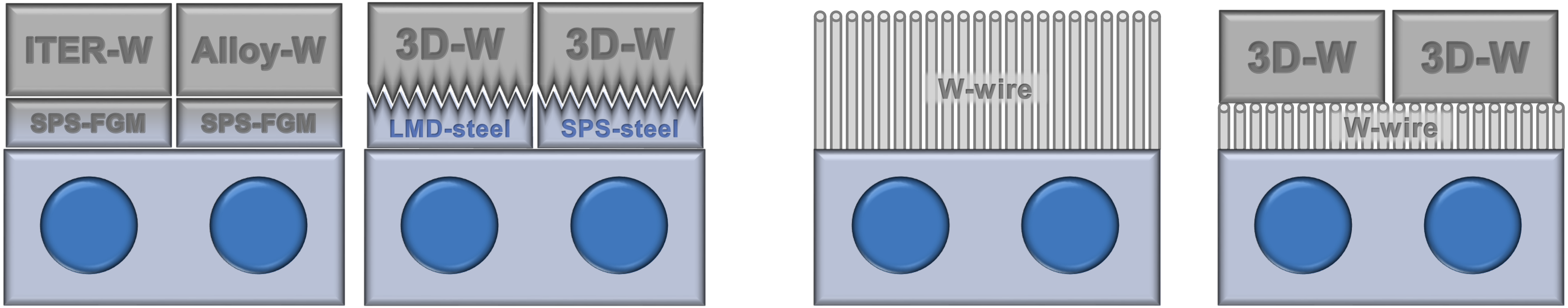
O.6. Prototype mock-up: W on steel

- "Best" FGM as Interlayer
  - Based on benchmark test: SPS (2, 3 layer)
  - Tile size: 12×12 mm² or 20×20 mm²
  - Combination with other fields possible, e.g.
    - WfW, Oxidation resistant W-alloy, Barrier

- Using W-wire as armor and as joint
  - LMD of steel on one side
  - Diffusion bonding thin steel layer on mock-up
  - Using LMD or SLM to print W on W-wires
  - Several can be combined for full coverage



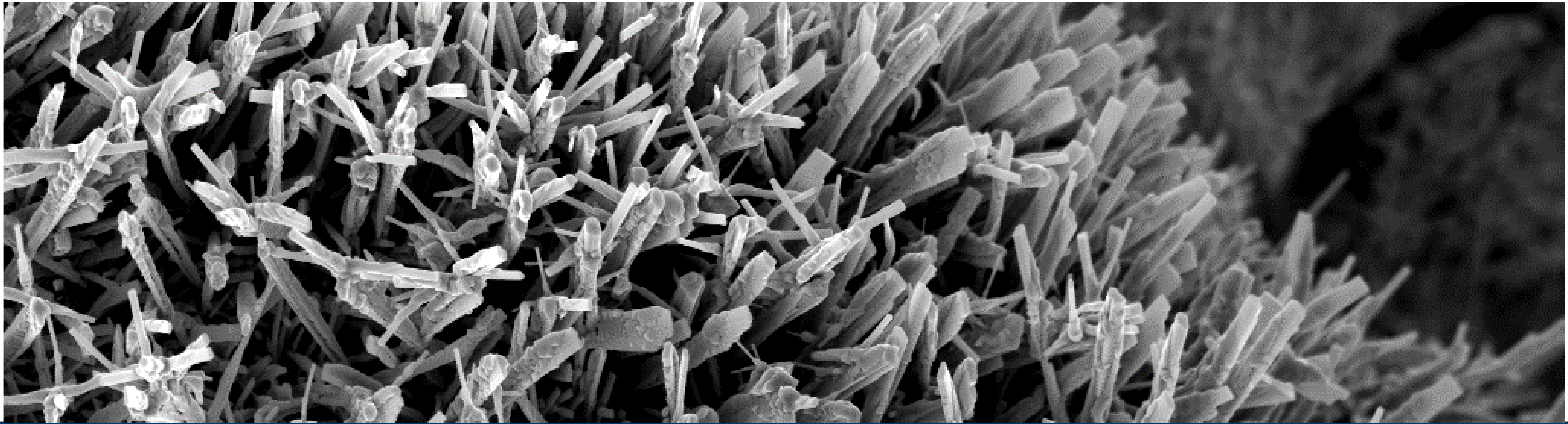
Publications / Contributions

Publications

- 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: 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 (SOFT 32)
  https://doi.org/10.3390/jne3040020

Conference

- PFMC 18: **Poster**: V. Ganesh – ID: 28839
  First results on the manufacturing of W/steel composites using plasma spraying under inert atmosphere
- ICFRM 20: **Poster talk**: D. Dorow-Gerspach – ID: 29028
  Additively manufactured W, produced by laser and electron beam, under stationary and transient heat load
- CIMTEC 20: **Invited**: D. Dorow-Gerspach – ID: 30667
  Additive manufacturing of tailored plasma-facing fusion wall components
- CIMTEC 20: **Poster**: V. Ganesh – ID: 32745
  W/steel composites as a potential interlayer for the joining of W and steel for the first wall of a fusion reactor
- SOFT 32: **Oral**: D. Dorow-Gerspach – ID: 31785
  Progress in the realization of advanced armour designs for plasma-facing components
- SOFT 32: **Poster**: V. Ganesh – ID: 32746
  High heat flux testing results of various W-FGM-steel joints



Thank you for your attention

Outtakes