Karlsruhe Institute of Technology

Advances in additive manufacturing of fusion materials

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Institut für Neutronenphysik und Reaktortechnik — Design, Analysis and Fabrication

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Advances in additive manufacturing of fusion materials

1) Introduction

- Institute KIT INR
- Development organization for DEMO Breeder Blanket (BB)
- How to proceed from the ITER TBM towards DEMO BB

2) Additive Manufacturing Technologies

- Brief Overview on technologies for metals, application of:
- Selective Laser Melting → BB internal structures
- Cold Spray based AM → First Wall

3) Strategy towards full scale BB First Wall

- Within the conceptual phase → now - 2024 and beyond

4) Conclusions

1 Introduction

About the Institute for Neutron Physics and Reactor Technology

https://www.inr.kit.edu/index.php

Karlsruhe Institute of Technology

- Active in nuclear safety analysis, system dynamics and experiments
- In Fusion: Neutronics, Near-Plasma component development
- 10 years of experience in fabrication for fusion blankets
- Established a powerful network for key technologies (Industry + research associations)

→~ 20 competences combined
→ Check state of the art / compare to BB specs
→ identify technological limits towards BB realization
→ Address development needs
→ place development contracts to overcome technological limits

Industry

- pro beam – Electron Beam welding
- STAPP – Thermal treatments
- KRÜGER Erodiertechnik – Electrical discharge machining
- bkl lasertechnik – Selective Laser Melting
- Hans Heimerdinger Oberflächentechnik – Chamical surface treatments
- FKM Laser Sintering – Selective Laser Melting
- ROSSWAG engineering – Metal 3D-Printing
- HERMLE – Machining, Cold Spray
- HIP PM Volker – HIP consultant
- TRUMPF – Laser Welding

Materials

- saarschmiede Freiformschmiede
- ArcelorMittal Industeel
- PHA Werkstoff-Technik

Research associations

- KIT – Institut für Angewandte Materialien (IAM)
- Technische Universität Braunschweig – Institut für Füge- und Schweisstechnik – ifs
- Fraunhofer ILT – Institut für Lasertechnik
- FGU Forschungsgesellschaft Umformtechnik mbH – IFU – Institut für Umformtechnik Forschungsgesellschaft Umformtechnik Stuttgart
- ipm Institute of Physics of Materials, Czech Academy of Sciences – Czech Academy of Sciences

1 Introduction

Development organization for DEMO Breeder Blanket (BB) for BB

- Address the fabrication developments on sub-component level

  → Consider welding interfaces between sub-components
  → Addressed welding within "conventional technologies"
  → Focus on structural material for HCPB Breeder Blankets, EUROFER
  → Presently concentrate resources on fabrication First Wall
  → Most demanding sub-component

- Stay flexible in development, not too focused on details → specs evolve and frequently change
- The BB shall be built at reasonable cost + acceptable reliability
- 30 years time horizon → for sure needed → presently many key issues are not solved
- Important: Keep up do date in manufacturing developments

→ Therefore we also address Additive Manufacturing since 2015

1 Introduction

State of the art in fabrication of fusion devices reflected by ITER

- First Wall (**a**) …
- … Internal structures e.g. Cooling/Stiffening Plates (**b**)
- Demonstrated in TBM relevant scale and compatible to conventional technologies

  → CEA: Machining, Laser and HIP (Reference for ITER)
  → KIT: Electrical Discharge Machining + Forming + Machining

- manifold and assembly of the TBM box (**c**) was demonstrated by (CEA)

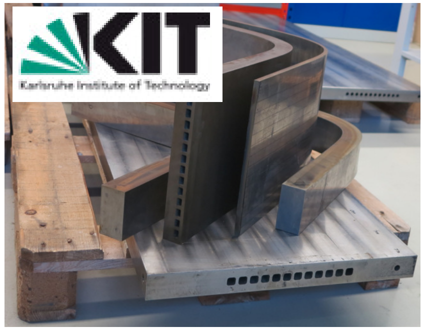
H. Neuberger et al., Evaluation of conservative and innovative manufacturing routes for gas cooled Test Blanket Module and Breeding Blanket First Walls, https://doi.org/10.1016/j.fusengdes.2019.03.124

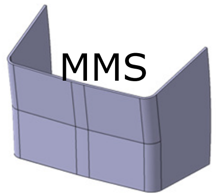
The European ITER Test Blanket Modules: EUROFER97 material and TBM's fabrication technologies development and qualification, M. Zmitko et al, DOI: 10.1016/j.fusengdes.2017.04.051

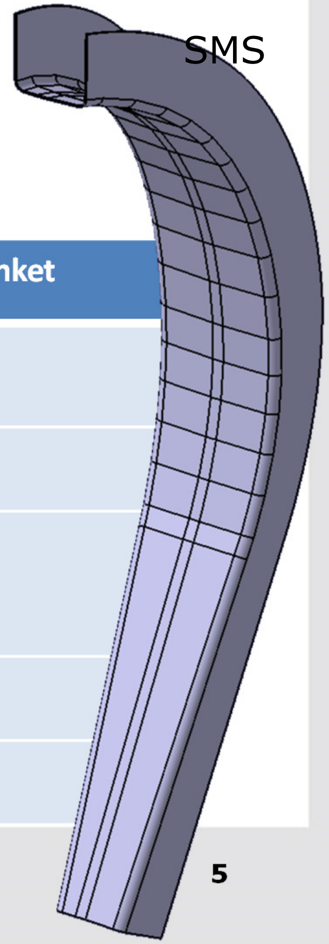
ITER TBM First Wall vs. DEMO Breeding Blanket First Wall

- However: wide gap exists in between TBM and DEMO BB fabrication
- Limits in key technologies are reached for TBM, extrapolation not realistic
- Some new solutions are needed

→ In detail: see comparison of specifications for TBM and BB First Wall







Specifications	First Wall for Test Blanket Module ITER	First Wall for DEMO Breeder Blanket
BB overall dimensions:	~ (**1.6 h x 0.5 w** x 1 d) m³ Channel length: ~ 2.5 m	~ (**12 h x 2 w** x 1 d) m³ (SMS) **~ (2 h x 2 w** x 1 d) m³ (MMS)
Shape:	U-shaped, 2 bends, **plane surface**	3D-surface, „**roof-top-shape**“
Channels Cross Section (CS): Structured channels required (e.g. dimples of semi-detached ribs) ?	~ 12.5 x 12.5 mm² Not mandatory	~ comparable CS as TBM At least locally in some blankets
Manufacturing cost and procurement:	Only few experimental units procured	Mass production compatible
Existing conv. technologies cover specifications ?	**Yes, procurement for ITER is launched**	**No → AM may provide options**

2 Additive Manufacturing Technologies

What characterizes Additive Manufacturing ?

- Huge diversity of processes / variations exists, no details here
- However: All AM processes have one thing in common:

→ A product is built by **adding material**
→ instead of subtracting material (e.g. machining)

- Material added as powder, wire, solid, … Deposition energy is provided by Laser, EB, kinetic, …
- For HCPB BB fabrication: Selected two most developed and promising technologies:

Powder Bed Laser Beam Fusion = Selective Laser Melting (SLM)

→ Good for thin walled and high complex components
→ box internal structures

Direct Energy Deposition Cold Spray + machining:

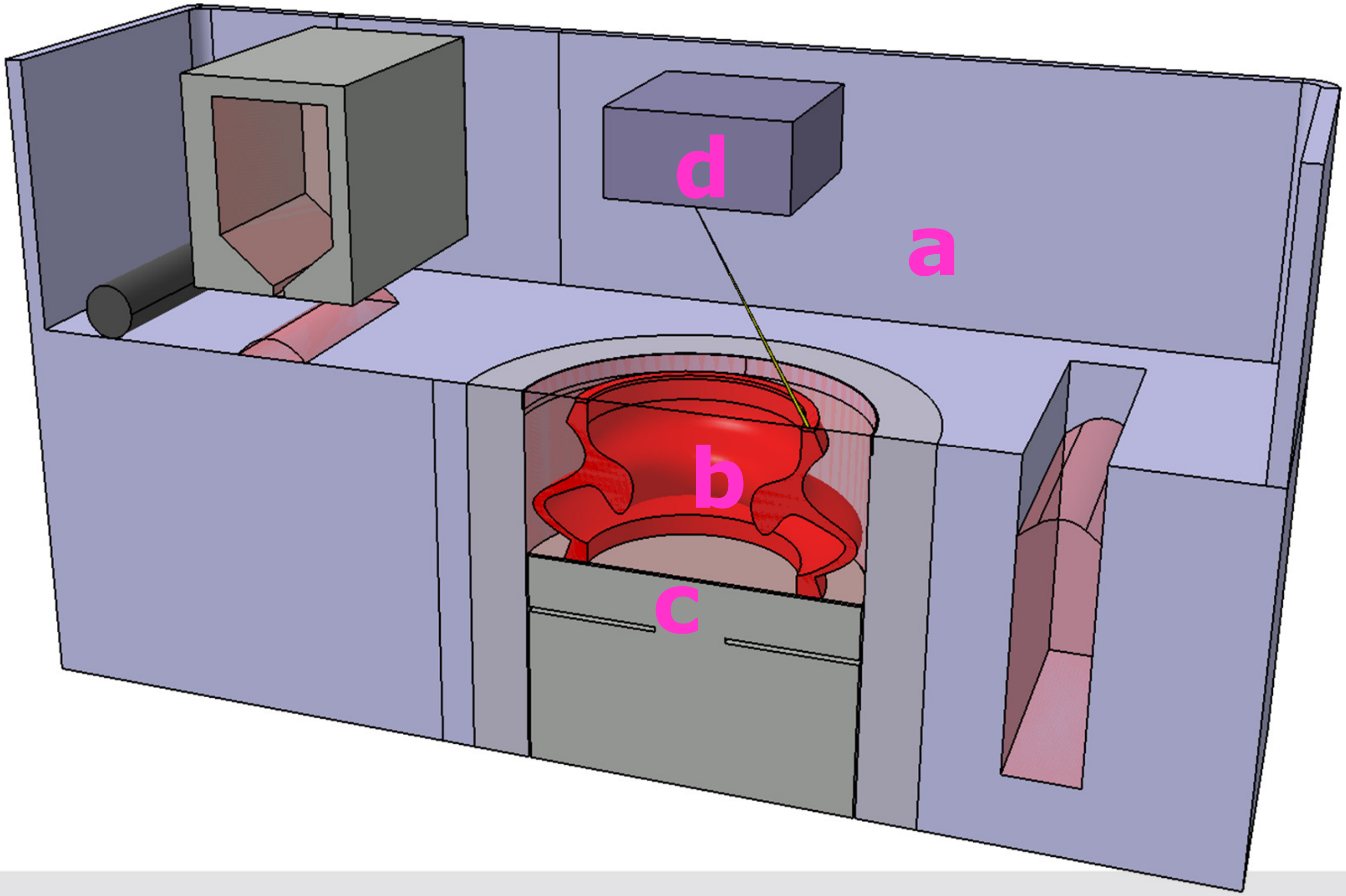
→ Larger dimensions and deposition rate
→ less complex structures
→ selected for First Wall

→ 2 independent development approaches in 2015 + 2017

2.1 Selective Laser Melting

How Selective Laser Melting (SLM) works

- Inside of a process confinement (a) of a SLM machine
- A product (b) is built in slices layer by layer on top of a building platform (c)
- During fabrication the product is fully surrounded in metal powder
- Local solidification is provided by a Laser (d) according to the geometry data of the product
- Details see internet (produces of SLM machines)



Examples of Selective Laser Melting fabricated test parts

- Started benchmarking studies among different suppliers
- Ordered EUROFER-like mixed metal powder batches
- Procured demonstration parts with increasing complexity and dimensions

→ material characterization specimen
→ thin- and double wall structures
→ samples with BB relevant cooling channels
→ Parts to verify numerical distortion prediction tools

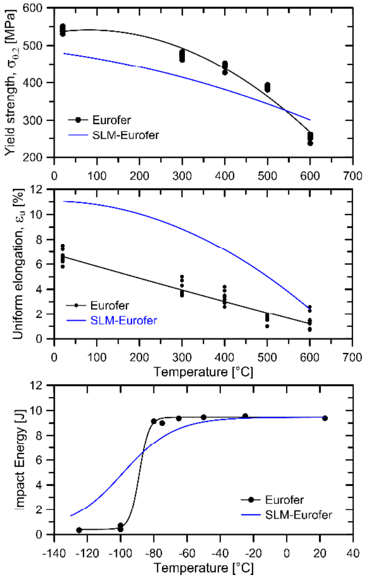
2.1 Selective Laser Melting (SLM)

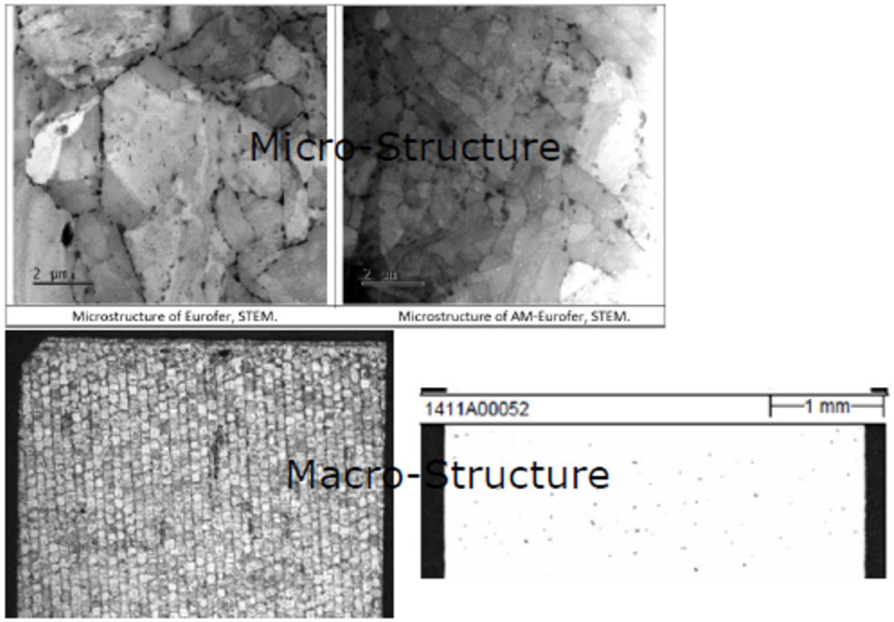
How good are material properties of SLM- compared to conventional EUROFER ?

- Very Important question, strong interactions with material science
- To obtain tempered martensite post heat treatment after SLM is needed
- To reduce porosity after SLM a HIP cycle is recommended
- The specified chemical composition and a high cleanness of the powder is mandatory
- For detailed results: see papers in material journals, published soon:

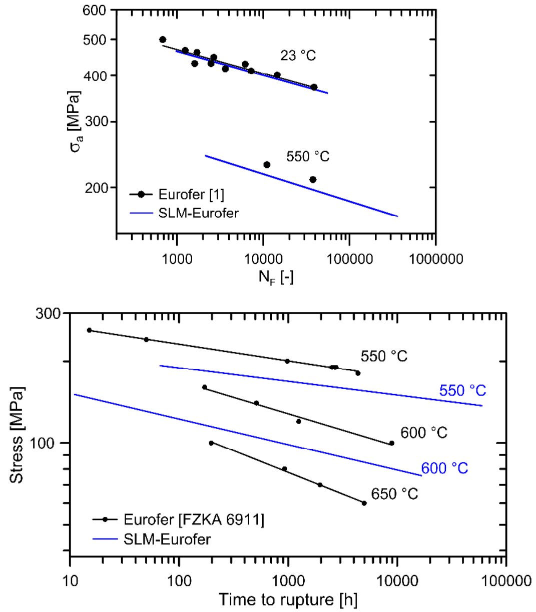
→ M. Rieth: Specific Additive Manufacturing Processes for Nuclear Fusion Applications
→ L. Stratil: Microstructural and mechanical characterization of EUROFER prepared by LBM

Tensile- and Charpy





Creep and fatigue



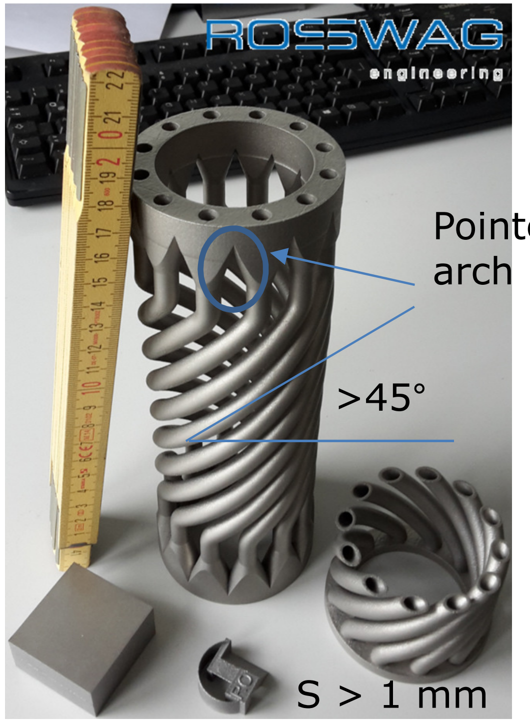
- SLM products demonstrate promising properties close to conventional EUROFER

Technological limits in SLM: geometry restrictions

- Not every geometry can be „just built“, supports may be needed
- Important to understand reasons: Where and why supports ?

  → Follow design guidelines
  → Use assistance by suppliers to improve results
  → Take into account critical issues already during design

- Examples: angles, geometry of arches, wall thickness, orientation during production …

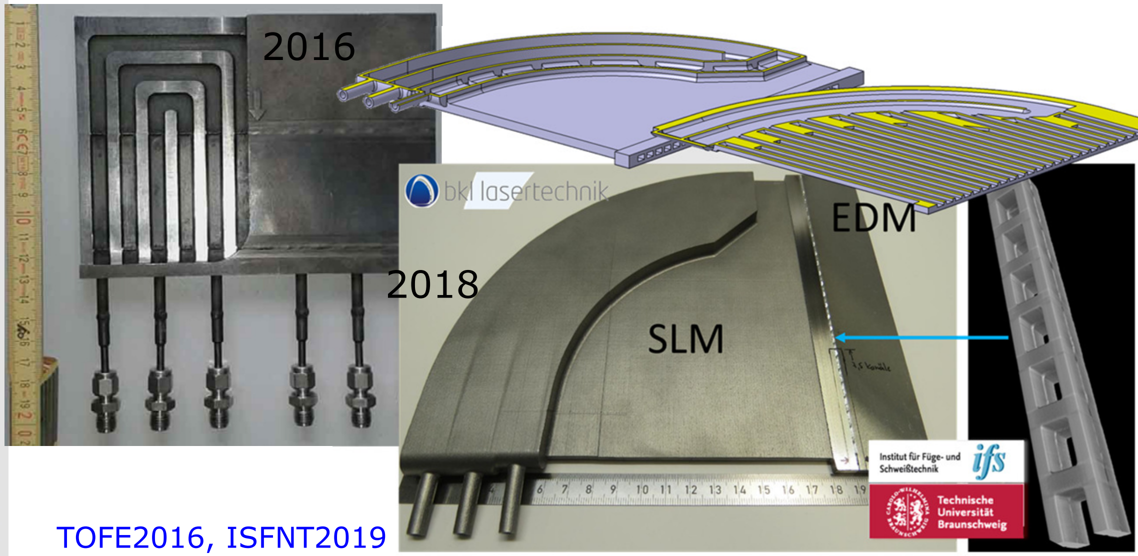


2.1 Selective Laser Melting (SLM)

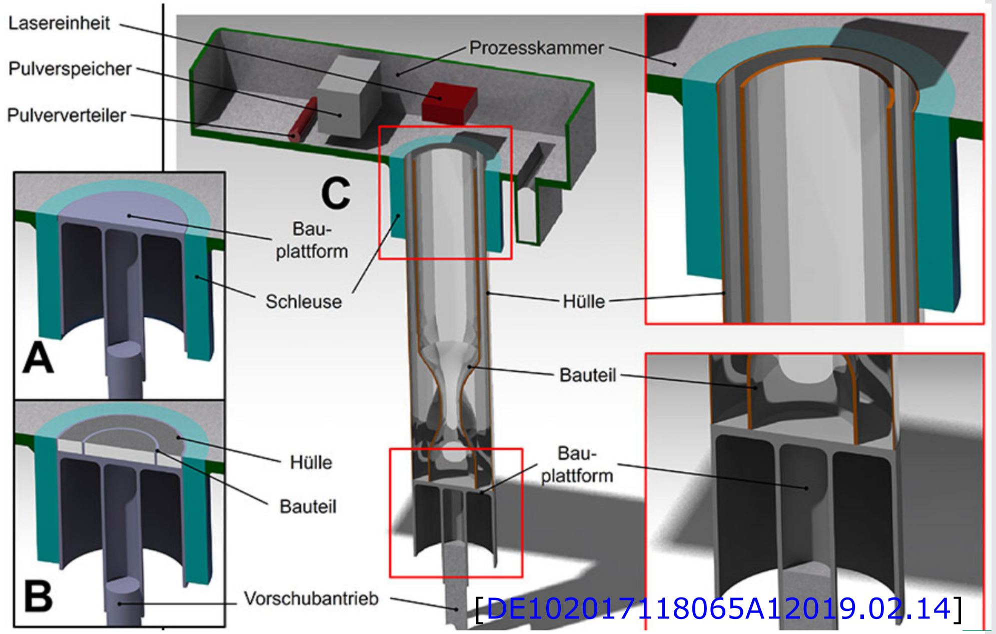
Technological limits in SLM: maximum dimensions

- Size limits in SLM driven (confinement → inert + dust protection)
- Presently max. part dimensions ~ 500 x 300 x 800, details internet
- Scale up to full dimensions and „print" integral BB not applicable
- However options for expand dimensional limits were developed by KIT (already presented):

→ Assemble Hybrid Components by welding from SLM-produced + conv. Segments
→ SLM applied as Continuous production with „printed" confinement chamber extension



TOFE2016, ISFNT2019

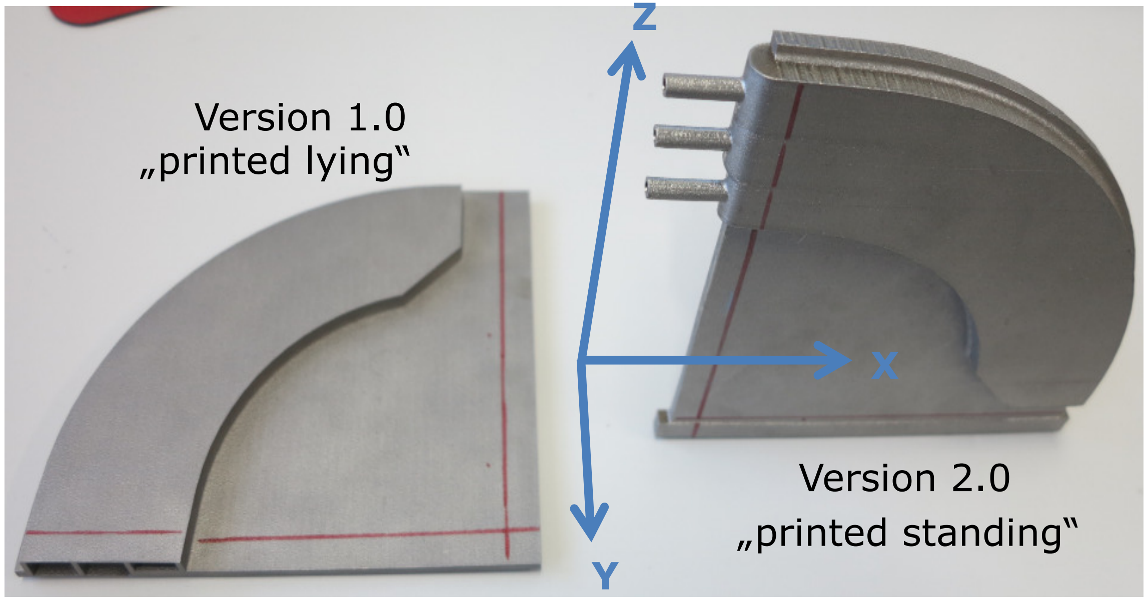


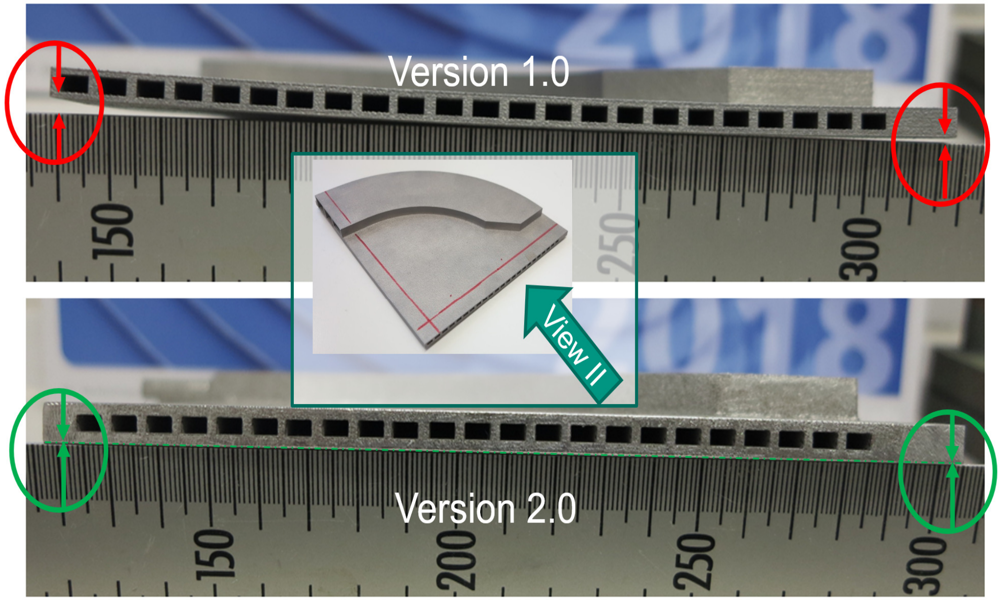
[DE102017118065A12019.02.14]

Technological limits in SLM: deformations due to thermal gradients

- Thermal gradients inside the powder bed lead to deformations:

  → Important to optimize design + orientation for mitigation
  → Example: Version 1 vs. Version 2:
  → Similar part, two orientations, two different results …





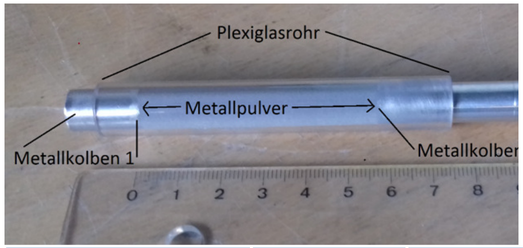
- However production time: version 2 → ~ 10 x number of layers, ~ 3 x production time
- Increasing parts height → increasing again thermal gradients in powder bed

Technological limits in SLM: innovation to mitigate gradients

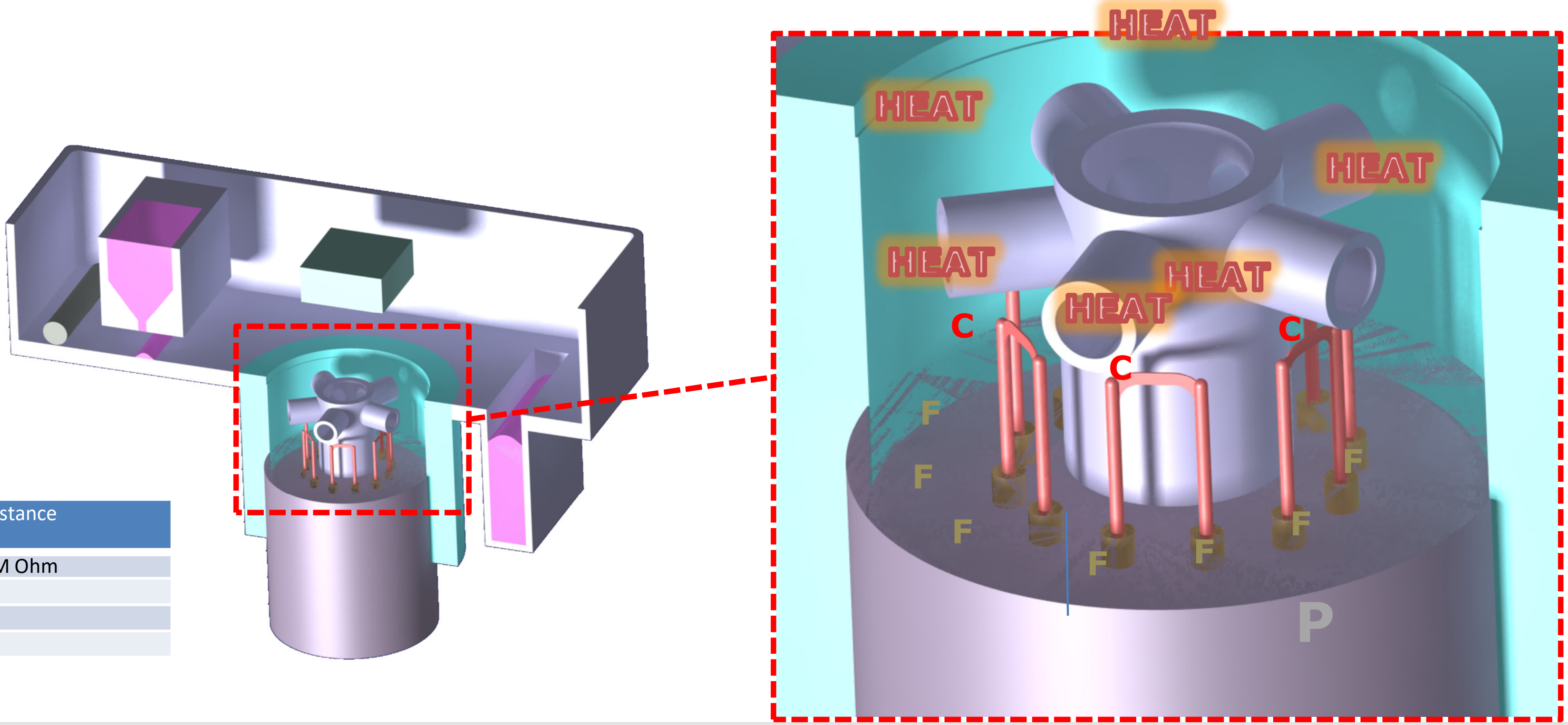
- Innovation to mitigate gradients → „printed resistive heater coils“
- Possible because $R_{powder} >> R_{SLM\ product}$
- Printed coils are operated as in-situ temperature monitoring and regulation device
- Heater coils (**C**) placed on feedthroughs (**F**) on platform (**P**)
- Better than just heating building platform surface

→ Now, measurement and regulation inside powder bed
→ T_{max} is in the centre of powder bed (where it should be)

Simple proof of concept experiments conducted, details: please contact…



Condition:	Filling height [mm]:	Ohmic resistance
uncompressed	56	O.L. = > 6 M Ohm
Compression 1 mm	55	95 k Ohm
Compression 1.5 mm	54,5	45 k Ohm
Compression 2 mm	54	30 K Ohm



How to continue development for SLM

- SLM has been demonstrated as goal oriented option

  → Feasibility of BB relevant internal complex components
  → Innovations have been developed to overcome limits

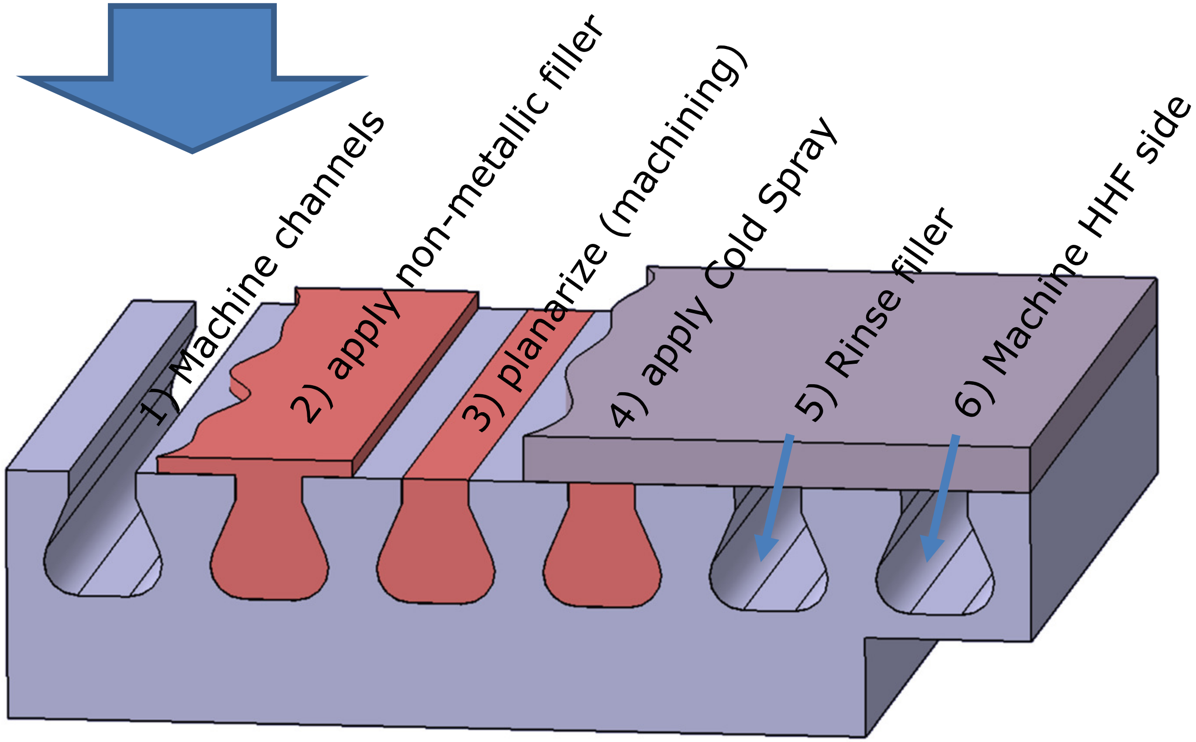
- KIT INR: continue to build demonstration and performance testing parts (hybrid components)
- Passing material qualification activity to material science

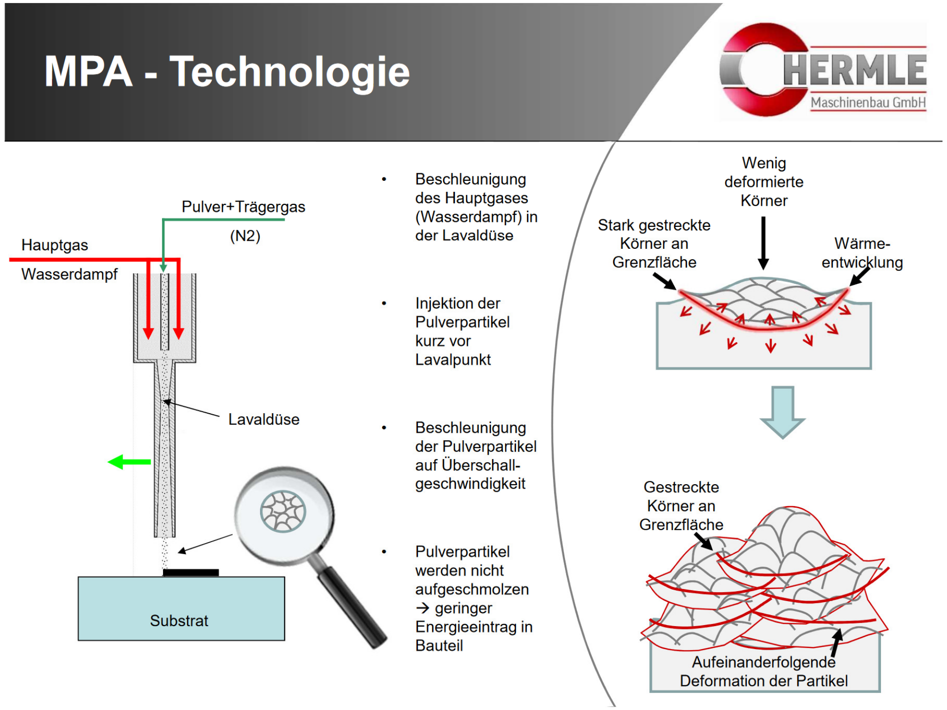
  → Qualification and implementation into Codes and Standards
  → Address irradiation program for SLM processed EUROFER

2.2 Cold Spray + machining + HIP

Cold Spray in combination with machining and HIP

- CS = powder deposition via kinetic energy
- Provides option to temporarily fill cavities with non-metallic and water soluble material (process configuration → Hermle)
- The integral process chain applied for cooling plate fabrication consists of 6 Steps:





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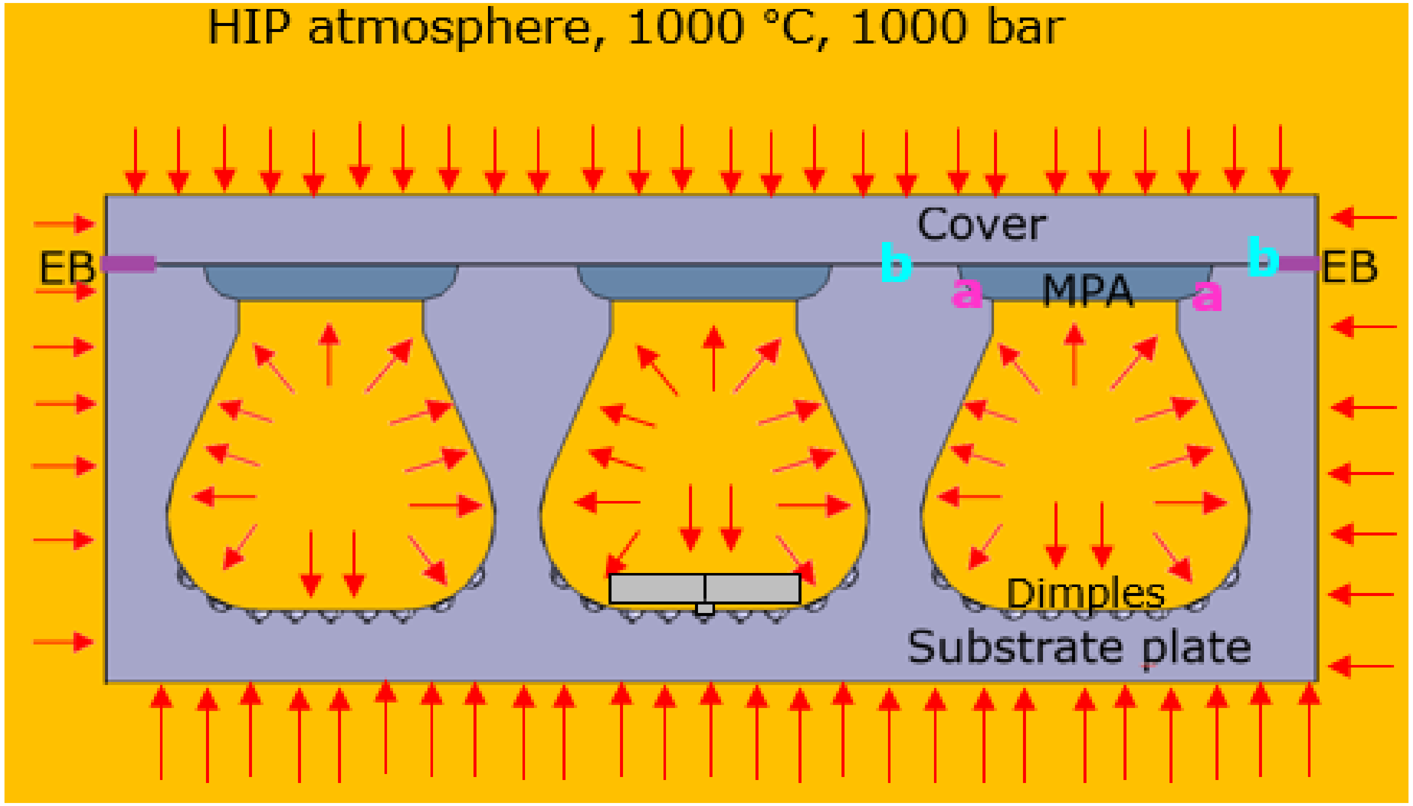
2.2 Cold Spray + machining + HIP

Process configuration customized for BB First Wall application

- Goal: Simplify licensing by:

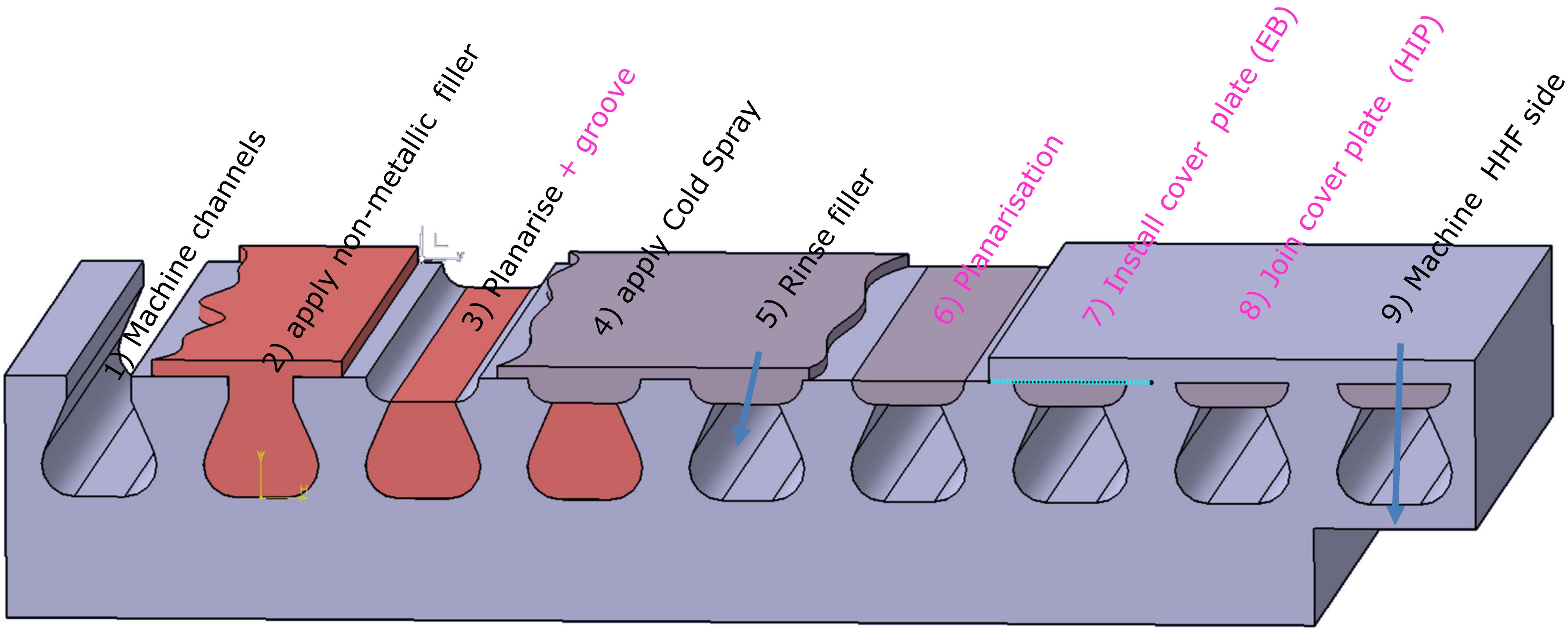
→ Excluding CS deposited material from structural function of the product …
→ … and use CS only as pressure seal during a HIP weld (a)
→ HIP weld joins substrate plate to cover plate → provides pressure (b) barrier



Process configuration customized for BB First Wall application

- Detailed modifications are

→ machine additional groove in step 3
→ introduce one additional planarization by machining → step 6
→ install and join a cover plate by EB (Steps 7) and HIP (Step 8)

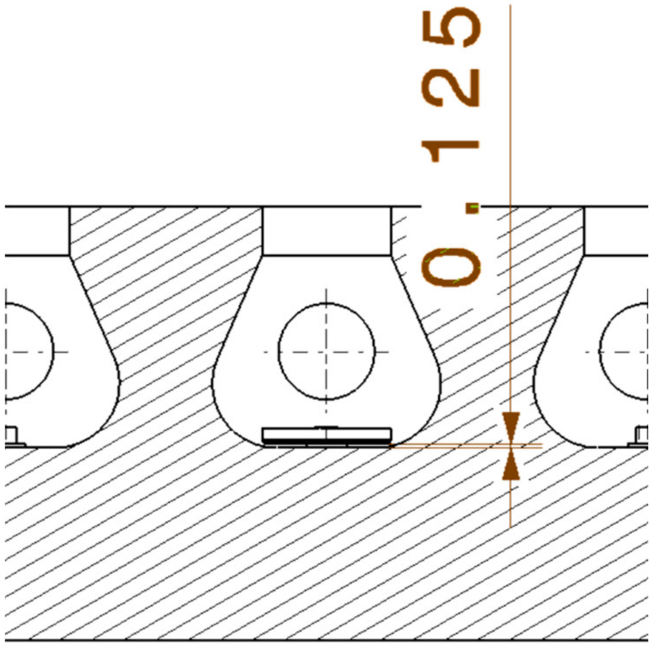


2.2 Cold Spray + machining + HIP

Fabrication experiments results in 2020

- Semi-detached V-shaped ribs were firstly demonstrated of inside of a channel

  → Riveting pins machined on HHF side of the channel
  → Ribs build by SLM were installed and attached onto pins
  → Installation time ~ 1 min / rib “by hand”
  → Can be automated
  → Soon tested is hydraulic experiments

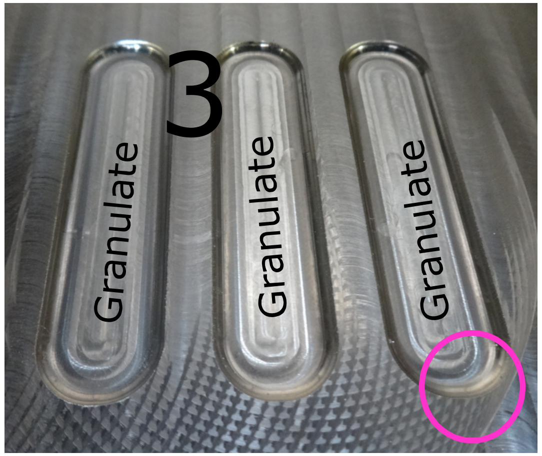


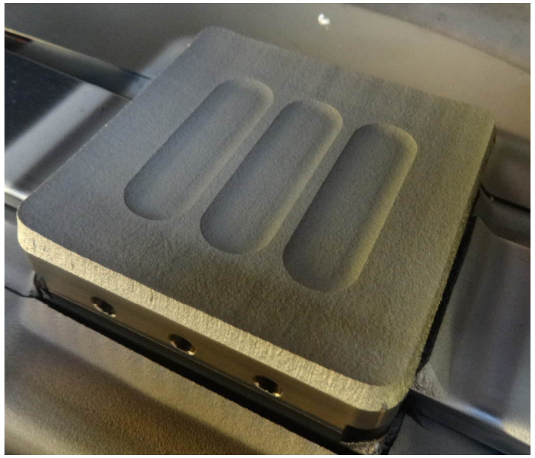
2.2 Cold Spray + machining + HIP

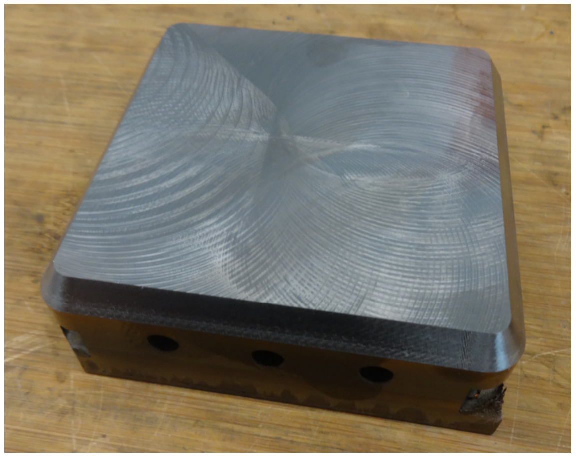
Fabrication experiments results in 2020

- General improvement of process parameters is ongoing, e.g.:

→ Optimization of geometry of grooves on top of the filled channels
→ Round edges to improve adhesion between CS and substrate by
→ Improvement is verifies by Destructive Examination presently







Substrate plate with rounded edges with temporarily filled cavities before…

…during and …

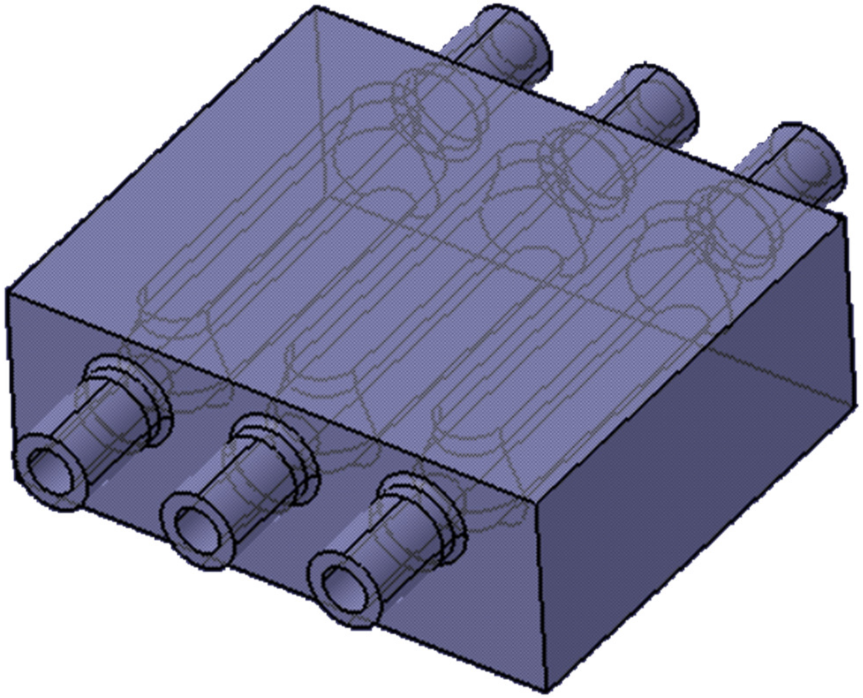
…after Cold Spray deposition

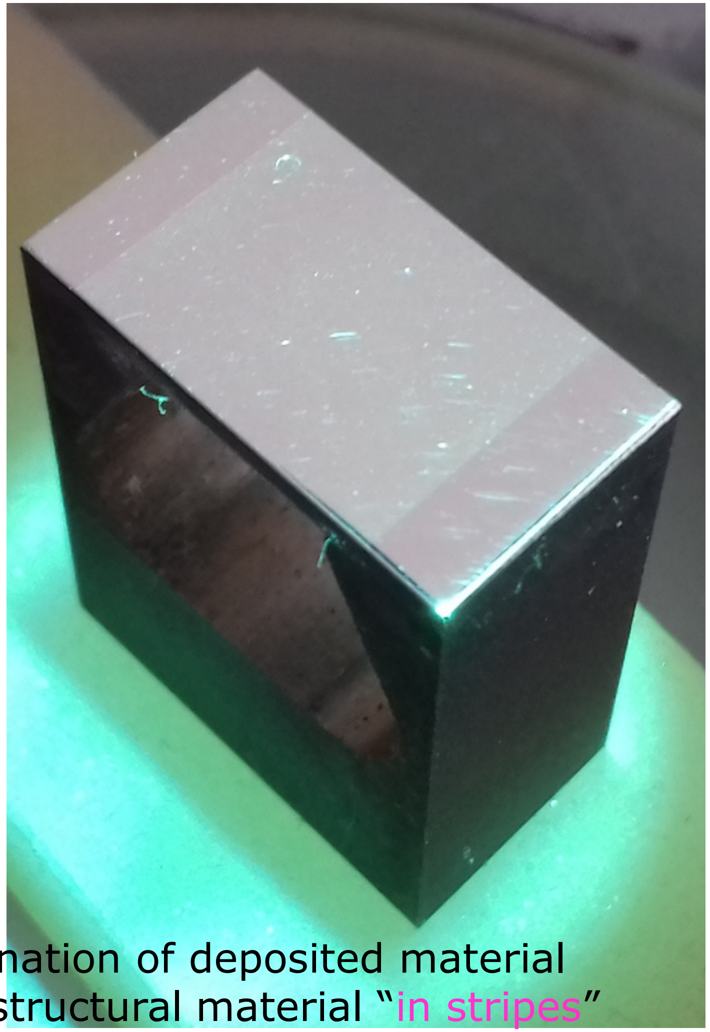
2.2 Cold Spray + machining + HIP

Fabrication experiments results in 2020

- Experiments to optimize planarization and
- preparation of HIP-welding …

This is where we are now…
Lost some weeks due to CORONA
Step will be completed (hopefully)
by end of 2020 →





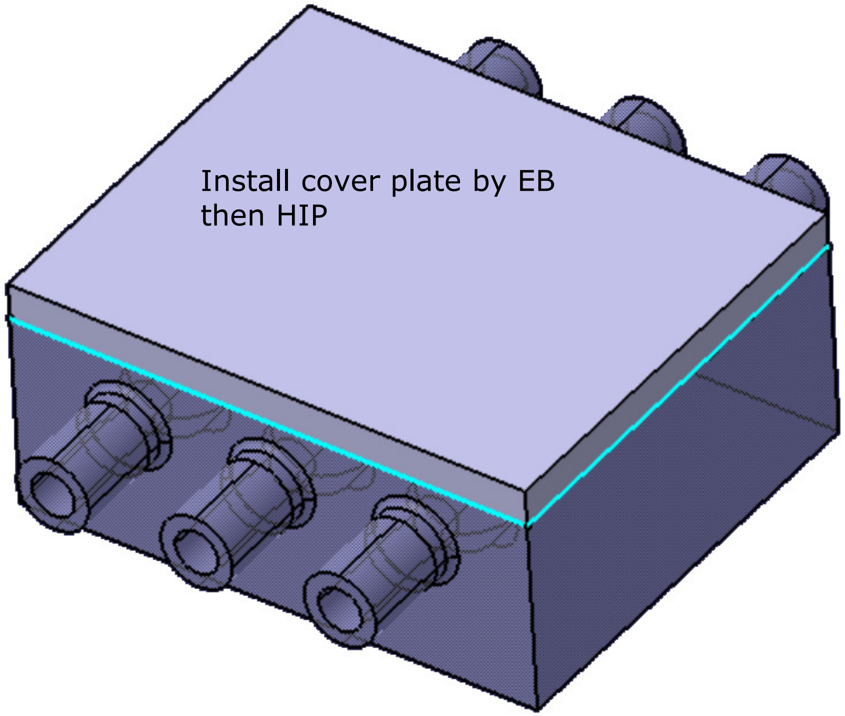
Alternation of deposited material and structural material "in stripes" visible in plate surface

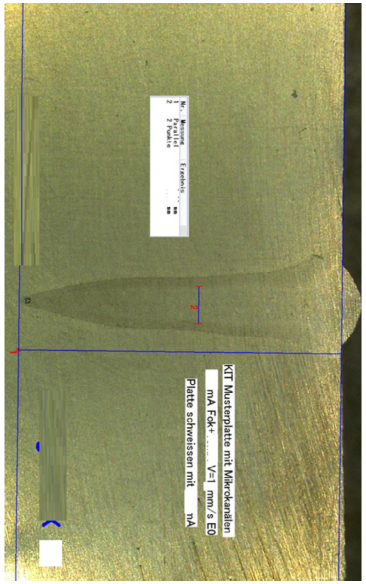
2.2 Cold Spray + machining + HIP

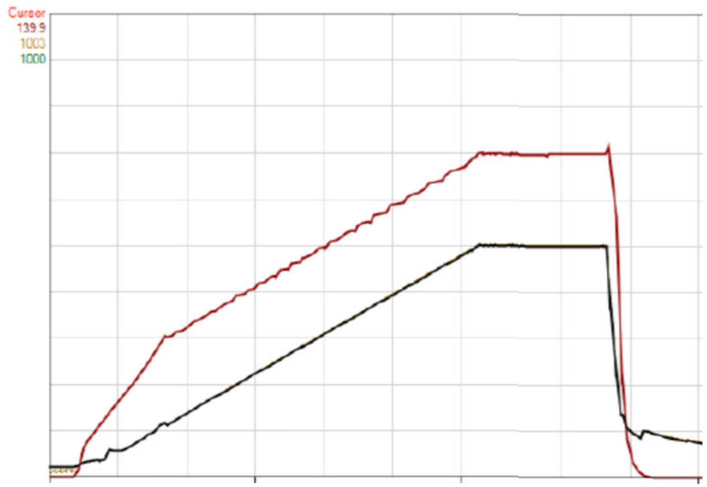
Fabrication experiments results in 2020

- Installation of cover plate on top of channels by EB-weld
- and Diffusion welding (HIP) will be demonstrated by end 0f 2020

→ Technology is available and parameters tested
→ surface conditioning, EB and HIP process







EB welding parameters to seal contact surfaces and T/t- curves for HIP

2.2 Cold Spray + machining + HIP

Fabrication experiments results in 2020

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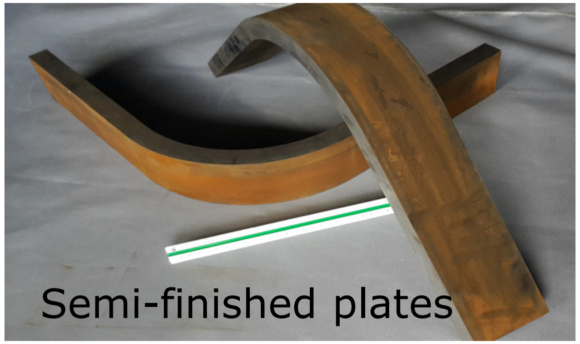
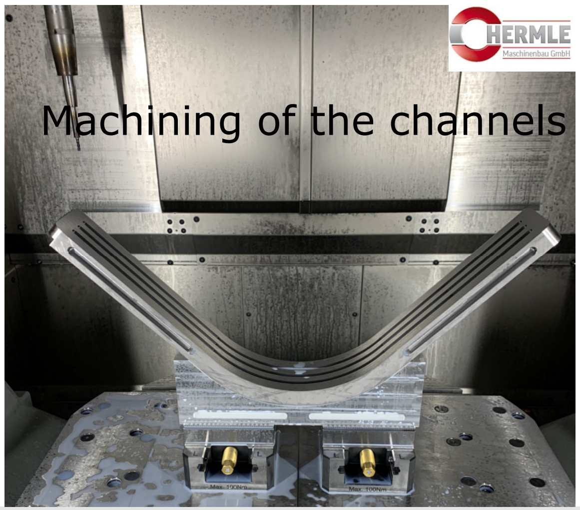
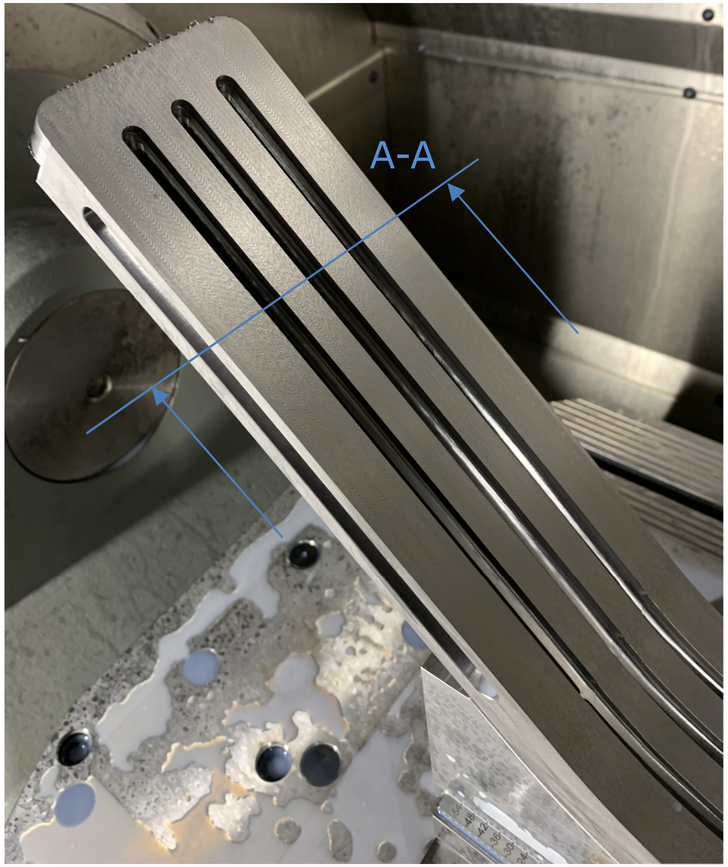
- Non-planar demonstration parts in medium scale are also addressed
- Two cold formed and heat treated shells are processed

→ CS deposition is planned by end 2020
→ Fabrication of the cover plate +
→ EB and HIP for installation of the cover plate is planned in 2021

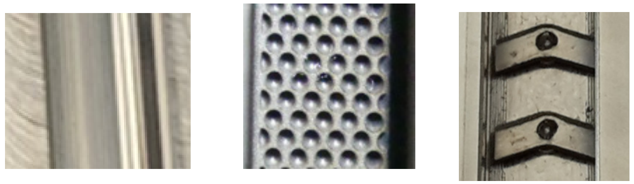


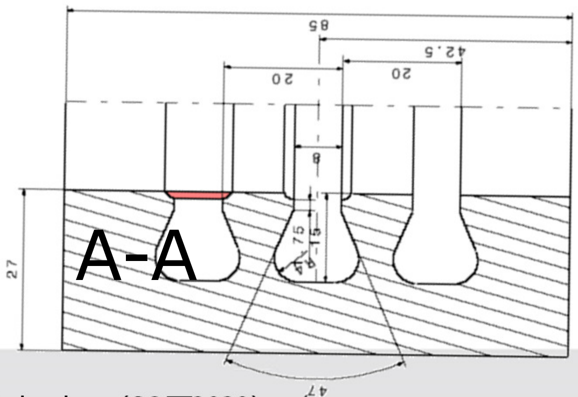




HTE-structures are included:
- 1 smooth,
- 1 laser structured
- 1 with semi detached ribs

Parts used in experiments



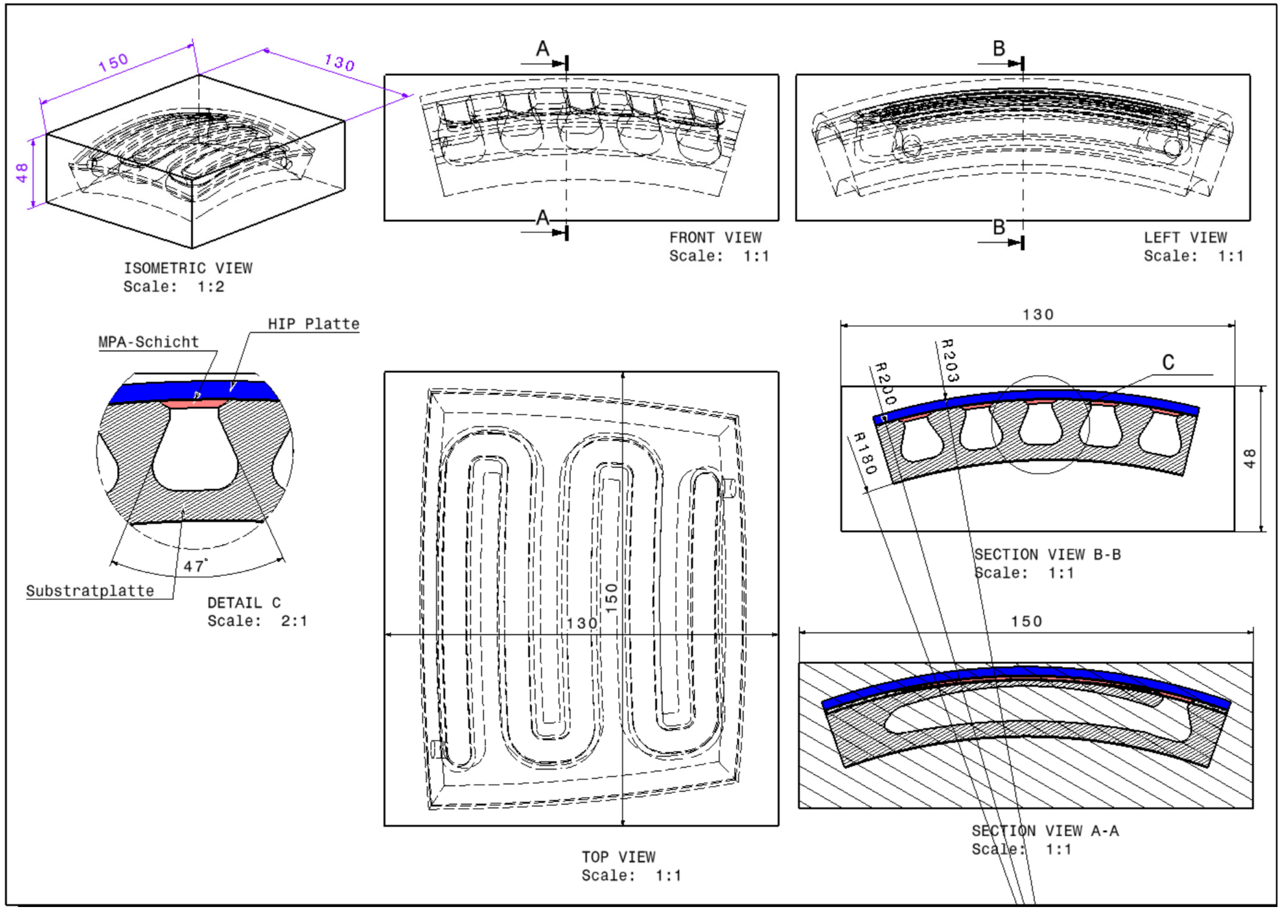


2.2 Cold Spray + machining + HIP

Fabrication experiments results in 2020

- Spherical shell segment: Origin: machined from full

  → Machining and deposition are planned by end 2020
  → Machining of cover plate + EB + HIP in 2021

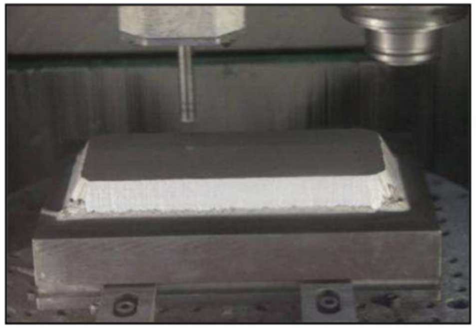


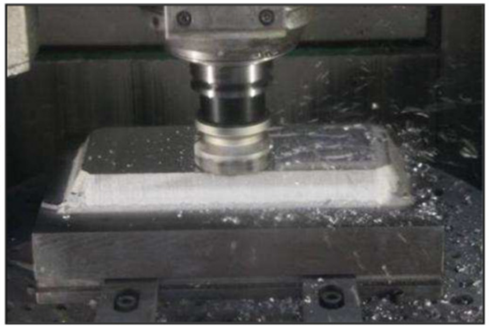
Specifications:
- 130 x 150 mm²
- One meandering channel
- Smooth channel internal surface

2.2 Cold Spray + machining + HIP

Mid-term demonstrators by end of conceptual phase → 2024:

- Use max. dimensions of available equipment, has to fit into CS machine (**a**)
- Both Shells (substrate + cover) machined from the full
- Channel Cross section will be FW relevant (**b**)
- Shape will be relevant but scaled down (**c**)
- Three identic parts are built for NDE, DE and testing
- Qualification procedures will be addressed
- Notified bodies will be involved to agree licencing aspects

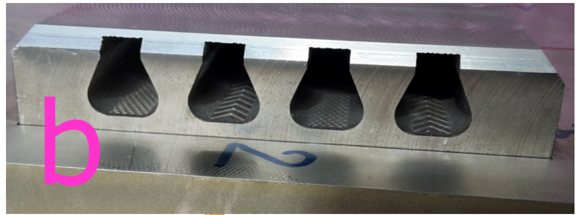


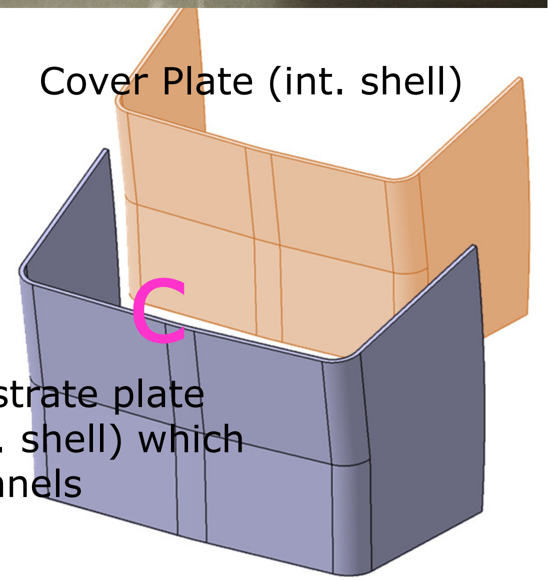


MPA 40

http://werkstoffwoche.de/fileadmin/user_upload/Hermle_Praesentation__Additive_Fertigung_mit_der_MPA_Technologie_.pdf

Fit inside



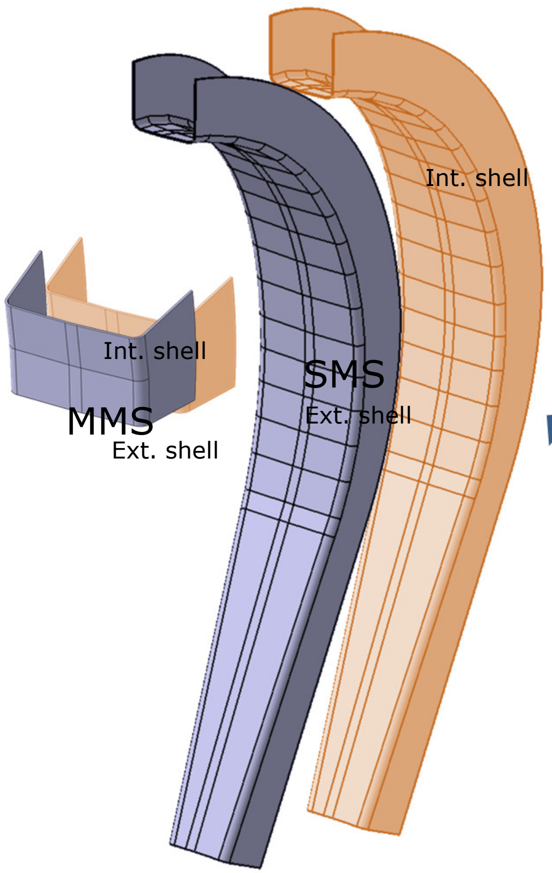


3 Strategy towards full scale First Wall

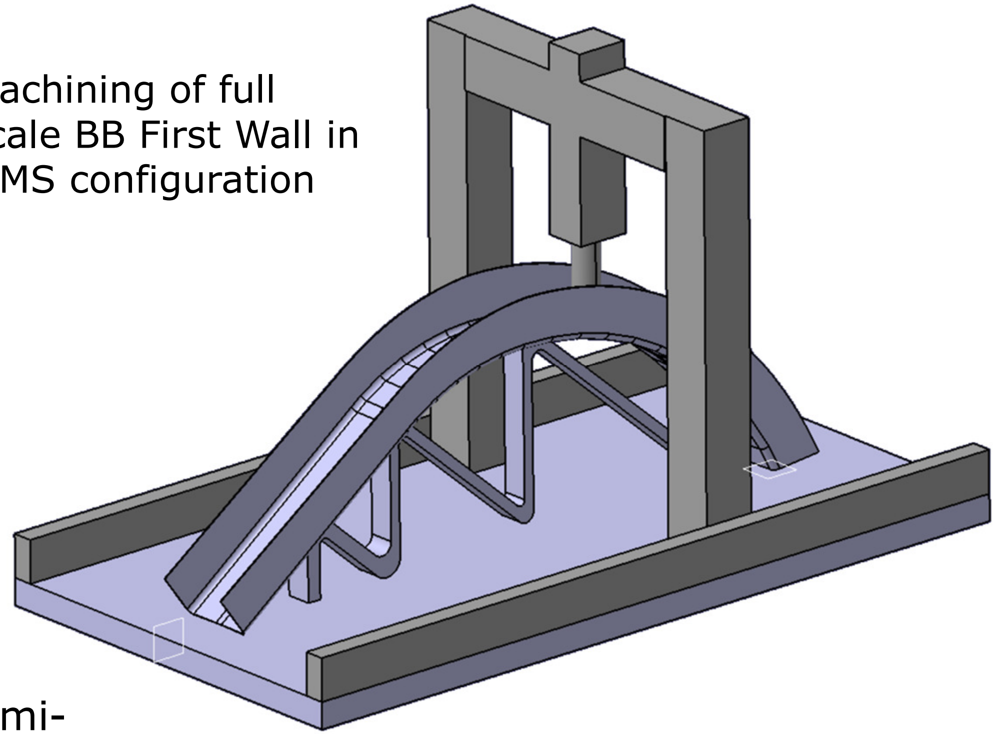
Defined beyond 2027 (if CS + HIP demonstrated successfully)

- Adapt integral process setup towards full scale serial production
- In terms of Cold Spray + machining:

→ Use portal machines, comparable equipment exists e.g. in shipbuilding



- Machining of full scale BB First Wall in MMS configuration

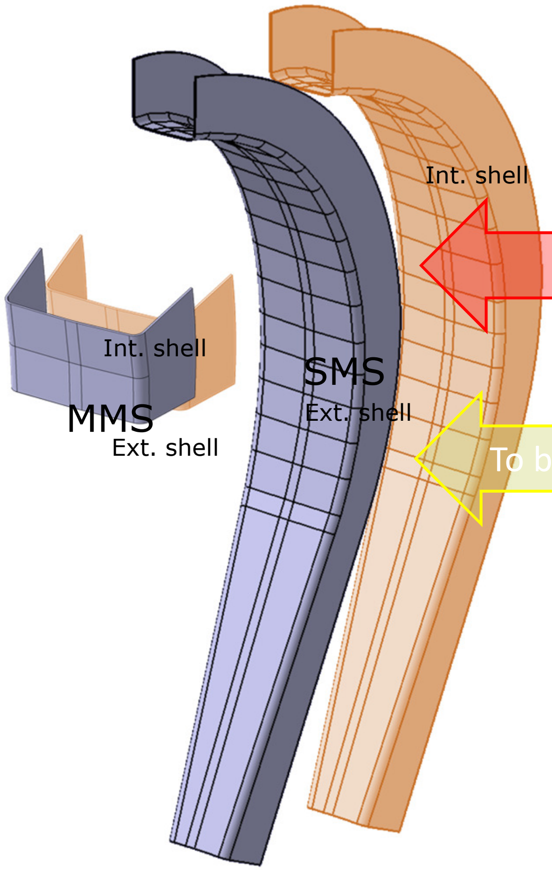


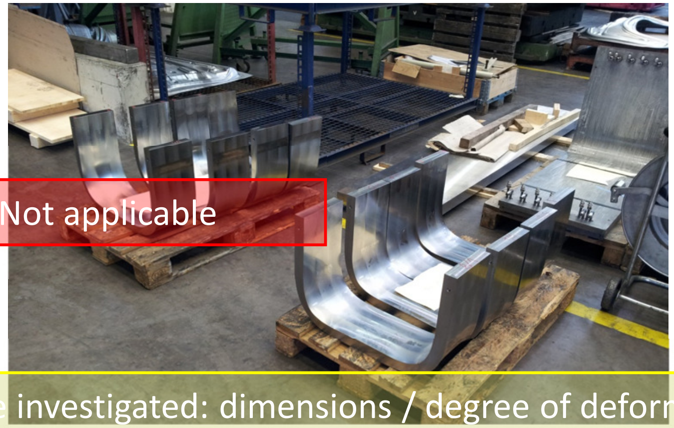
- But where do the semi-finished substrate + cover plate come from ?

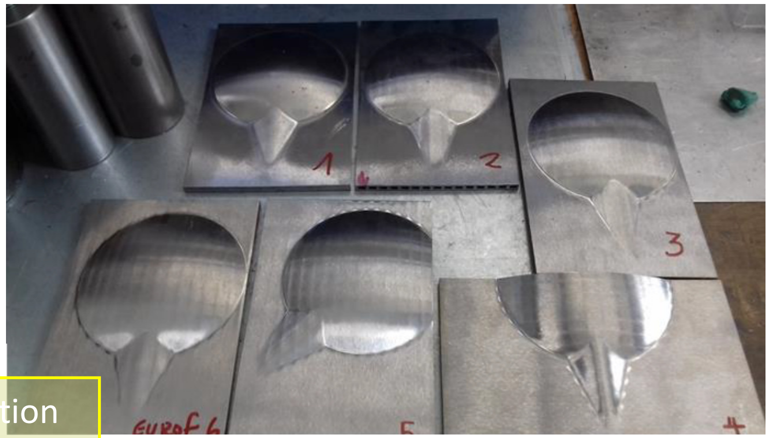
Problems in procurement of full scale semi finished FW shells

- Machine SMS shells from full → block with 12 x 2 x 5 m³ = ~ 1000 t
- Apply forming from sheets will significantly exceeded limits for MMS (even for SMS)

→ Apply experiences in forming for TBM,
→ Extrapolate the numbers for TBM and BB development
→ Neither free bending nor deep drawing provide solutions





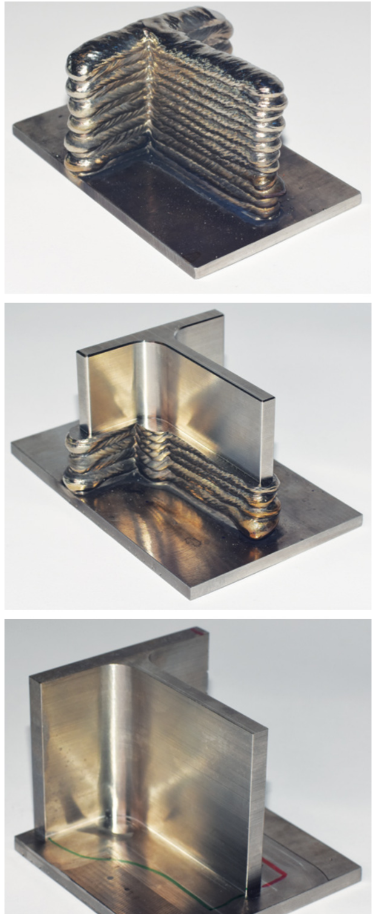


- Forging may provide alternatives → reduce forces → investigate
- However similar size and handling limits remain

- Maybe more „Additive Manufacturing" can provide an alternative ?

High deposition rate cladding (also an AM-process) may be an option

- To be considered to building of semi finished Breeder Blanket First Wall shells
- In SMS full scale dimensions and complex geometry
- How does it work?



https://www.mfgnewsweb.com/archives/4/57088/Advanced-Mfg-Solutions-aug20/Wire-Arc-Additive-Manufacturing.aspx

→ Build up a part by ADDING layer by layer using conventional welding technology (e.g. TIG)

→ Deposition is applied in alternation with machining to build precise external contours

→ technology may be an option for production of semi-finished solid FW shells

→ Shells can be processed used CS + HIP routine described before

→ However: Welding on the plasma facing side !

4 Conclusions

- Many key issues are still not solved, not only in fabrication
- There is not “the one” process covering all requirements for a fusion BB

  → Neither AM nor conventional technologies

- But: Additive Manufacturing provides new opportunities and aspects

  → Cold Spray as customized AM process → promising for the First Wall
  → Selective Laser Melting applied for BB internal structures

  → Important to combine all existing technologies wisely to overcome limits and create new opportunities

- Licensing and material properties verification remain the key issue

  → To be addresses by material science

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