Fabrication of HCPB Breeding Blanket components using the Additive Manufacturing Processes of Selective Laser Melting and Cold Spray

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Different manufacturing routes are investigated at the KIT INR for the realization of First Walls (FW) and internal components for the Helium Cooled Pebble Bed (HCPB) nuclear fusion reactor component Breeding Blanket (BB). As result of cost estimation studies in 2017 and 2018, Additive Manufacturing (AM) has been identified to provide promising options beyond conventional technologies. Selective Laser Melting (SLM) and Direct Energy Deposition (DED) applied as Cold Spray (CS) were addressed. SLM was followed with focus on the development of BB internal structures. CS turned out as a very goal oriented and effective fabrication process with regard to the First Wall geometrical requirements. Further, a large potential for cost reduction compared to other technologies was identified. Based on a variation of the DED process CS applied in alternation with machining and an option for temporary filling cavities, an extended process chain was developed in collaboration with industry. This process chain also enables Laser structuring of internal channel surfaces for heat transfer enhancement structures. This paper summarizes the developments in terms of application of AM for the HCPB BB concept where SLM is focused as an option for BB internal structures assembled as hybrid components and CS addressed for fabrication of the First Wall.

Keywords: First Wall (FW), Breeding Blanket (BB), Test Blanket Module (TBM), Additive Manufacturing (AM), Selective Laser Melting (SLM), Cold Spray (CS), Direct Energy Deposition (DED).

1. Introduction

Different manufacturing routes are investigated at the KIT INR for the realization of First Walls (FW) for the nuclear fusion component Breeding Blanket (BB). Conventional but also Additive Manufacturing (AM) routines were tested. As result of cost estimation studies, AM has been investigated as promising option providing significant cost reduction potential in comparison to conventional manufacturing processes. This assumption is based on a rough comparison among procurements of test components manufactured with conventionally technology, but also Additive manufacturing for DEMO but also for TBM relevant demonstrators starting in 2010. The comparison was based on procurement cost / m² surface, extrapolated to a full scale Breder Blanket [1] and [2].

The powder bed process of Selective Laser Melting (SLM) and the open space process of the Direct Energy Deposition (DED) applied as Cold Spray (CS) were addressed. Selective Laser Melting (SLM) turned out as one possible option for fabrication of the First Wall in front of a long-term time horizon, providing ~ 30 % cost reduction potential. Also SLM provides a good option for high complex and thin walled components made from pure SLM segments but also hybrid components assembled by welding.

Cold Spray (CS) was identified as the most effective mid-term solution with regard to the First Wall external dimension requirements and geometry. In terms of cost analysis, a reduction by ~ 60 % seems possible compared to conventional technologies. Based on the CS standard process chain offered by the company Hermle (deposition by CS in alternation with machining and an option

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for temporary filling of cavities with water soluble granulate which is also suitable to carry layers of deposited metal on top), an expanded process chain has been developed in collaboration with Hermle providing additional benefits.

This paper summarizes the progress in fabrication experiments for demonstration of the capabilities of AM (SLM and CS) in terms of application for the HCPB BB manufacturing project.

2. Requirements on the HCPB Breeding Blanket First Wall

Typical requirements on nuclear fusion First Walls as applied for the DEMO Breeding Blanket (but also to Test Blanket Modules for ITER) are summarized in Figure 1 and [1], such as: material, shape, external dimensions, channel structure and licensing issues. Since welds are considered as a potential source of component failiure in Reliability Availability Maintainability and Inspectability RAMI analysis, the number of welds shall be as low as possible. Especially on the First Wall front side welds should be prevented since it faces the maximum radiation level. All wending technology used for the assembly of the Breeding Blanket shall be livenced to codes and standards (e.g. RCC-MRx Code as applied for ITER).

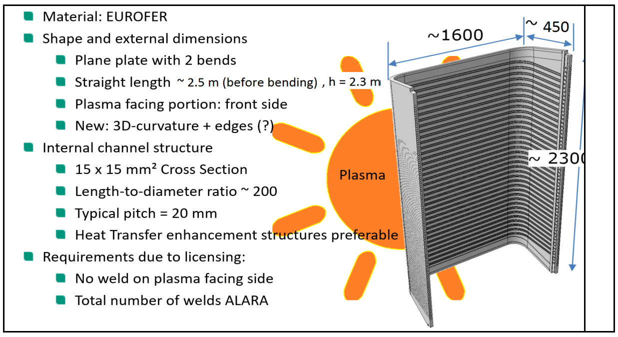

Figure 1. DEMO Breeding Blanket First Wall, typical requirements

3. Selective Laser Melting (SLM)

Selective Laser Melting (SLM) is one option of powder-bed AM processes where parts are solidified from layers of powder material (only metal considered here as relevant) by Laser in slices on top of a substrate plate or building platform. During the processing, the product is fully surrounded by non-solidified powder (hence, the term powder bed process is used). SLM has been investigated as manufacturing option for the FW starting in 2014, however dimensional limits of existing production facilities still remain a key issue. A concept to eliminate dimensional limits in length along the building direction basing on a modified SLM machine was proposed in [1] and [4]. Fabrication parameters for SLM processing of 9% Cr-Steels have been developed by BKL Lasertechnik and Rosswag Engineering on basis of EUROFER (two batches composed from mixed powders plus one batch of sprayed powder from conventionally rolled and melted solids) and P92 (one batch of sprayed powder from melted solids). Concerning powder fabrication for SLM, Rosswag Engineering is the first powder manufacturer who has been audited by TÜV SÜD Industrie Services GmbH, where the audit is part of a new certification program on basis of the AD 2000 rules for pressure vessels in conformity to the European Pressure Equipment Directive (PED). The investigation of the material properties and comparison to EUROFER-97 [5] as well as results from previous experiments using the batches of mixed and sprayed powders with a composition corresponding to EUROFER is ongoing. A customization of the post processing heat treatment parameters taking into account differences of the material structure of SLM products compared to conventional material is developed and tested.

Design studies and dedicated verification experiments were carried out in order to define and test design limits and to minimize or even eliminate support structures to reduce the post processing effort. Also reduction of distortions due to thermal gradients in the powder bed e.g. by optimization of the orientation on the building platform was investigated. Findings of this study have been summarized into a design of a demonstration part completely built without support structures (Figure 2). The design of the component is applicable e.g. for high efficiency heat exchangers or damping and strain compensation elements. In addition, experiments for joining of hybrid components assembled by Electron-Beam (EB) welding from SLM-manufactured segments and conventionally fabricated parts (e.g. Electrical Discharge Machining started in [5] have been continued. Figure 3 shows a Breeding Blanket relevant internal structure: a SLM-manufactured flow distributor made from mixed powder in composition corresponding to EUROFER fully penetrated by cavities and channels, void grade ~ 30 % (left) is joined by EB-welding (Institut für Schweißtechnik, TU Braunschweig) to a EDM fabricated straight segment (right). The preliminary non-destructive examination for parameter verification of the weld across the cooling channel structure by Computer Tomography is shown on the right side of Figure 3.

Concerning SLM for gas cooled nuclear fusion devices, the application of this technology generally seems to be

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a high efficient option if used for high complex and thin-walled structures made from EUROFER and similar 9%-Cr-Steel, e.g. Flow Channel Inserts as developed for the HCLL concept ([5], [6] and [7]). The technology also provides a solution for components with channels or complex cavities with a diameter of 1 – few millimeters and wall thickness values in the same order of magnitude within size limits of existing production facilities. However, size limits may be circumvented as demonstrated by hybridization (e.g. using SLM for building of complex flow distributors segments assembled together with conventionally machined parts, Figure 3).

However, due to the limited deposition rate (typically ~1/10th of one Millimeter per layer) for realization of the FW with an external dimension far beyond 1 m preferably built in vertical orientation to limit deformation, the so called open space AM- processes provide more efficient options. For comparison, if the DED process CS is considered, not the integral component needs to be built additively if a pre-formed (e.g. bended or non-planar substrate plate with already machined cooling channels) is used for deposition. Furthermore, the design of the First Wall is not that complex (several Millimeters of wall thickness, no twisted channels and double- or multi-wall structures) so the high precision in terms of resolution provided by SLM is not mandatory in this application.

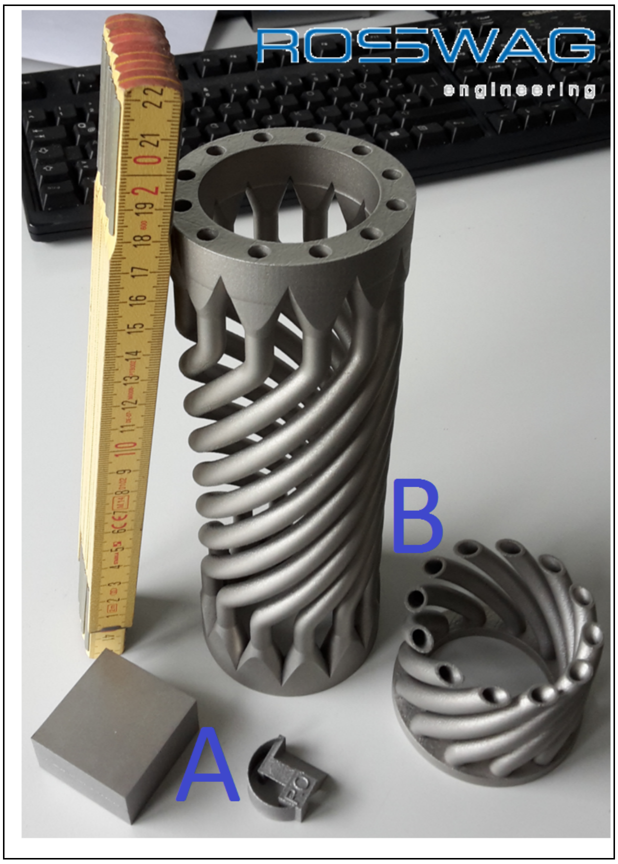

Figure 2. SLM qualification parts P92 (A) and design study (B)

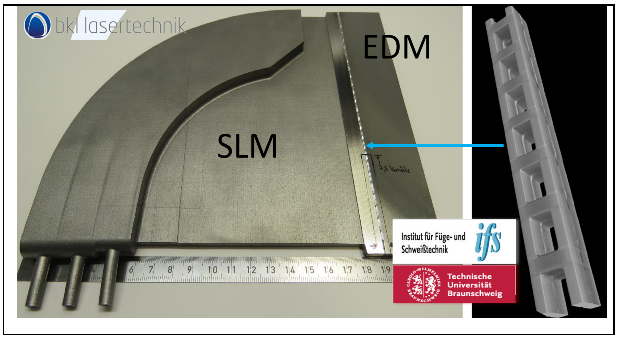

Figure 3. SLM manufactured flow distributed + straight segment

4. Cold Spray (CS)

CS is one variant of a so-called open space (or Direct Energy Deposition, DED) AM processes. In Open Space processes, parts are built into the "open space" on top of a substrate. In contrast to the Powder Bed processes, the product is not embedded into non-solidified material. The deposited material is fed spotty (usually as powder or wire) together with the deposition energy. Thus, the orientation of the product during the built process is less strict compared to SLM. The alternation between deposition of material and removal (e.g. by machining) is possible (e.g. cladding with metal powder by Laser in alternation with milling). An overview on the different and most relevant open space / DED processes

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including examples for machining after deposition as well as the evaluation of products precision and geometrical resolution vs. deposition rates is given in [8], also addressing Powder Bed processes for direct comparison.

In CS, the crucial contrast to arc- or beam based DED processes is, that the deposition does not base on adding material as powder or wire into a melted phase. Thus, the deposition process temperature is significantly lower than the melting point (~ 300 °C). In CS, the metal powder is injected into a high velocity super-sonic gas flow pointing onto the deposition surface of the substrate perpendicularly. The deposition energy is provided by the kinetic energy of the accelerated particles released during the impact on the substrate surface. The process setup and resulting options offered by the company Hermle are shown in detail in [9]. Due to the low process temperature and material deposition without melting phase, CS in alternation with machining allows unique features, which cannot be realized in other DED processes (e.g. cladding using arc and wire), e.g.:

i) Multi-material combinations (e.g. copper-structures embedded into steel): This feature is an option for high heat flux applications to implement a direction for heat flux and presently applied e.g. in manufacturing of injection molding tools.
ii) Temporary filling of channels or cavities by water-solvent granulate is possible in alternation with metal deposition and machining. The granulate is suitable to fully occupy a previously machined cavity and it can be used as support to carry metallic layers applied on top (Figure 4, step 2): These features are mandatory to create geometrically fully defined long (diameter < length) or complex cavities such as the First Wall channels, especially in a non-planar U- or 3D-shaped arrangement. Mechanical post-processing of the cavities surface (e.g. by machining as required to reach a geometrically defined inner surface after deposition of a cover e.g. applied by arc and wire deposition) is not needed in CS due to the presence of the granulate during deposition. After the product is completed, the granulate is rinsed from the channels or cavities by water without residues, subsequently thermal post processing, e.g. HIP can be applied.

4.1 Development status for Cold Spray (CS) applied for the First Wall

Two possible process chains to realize a Breeding Blanket relevant First Wall structure by CS are shown schematically in Figure 4 (top and bottom):

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On top, the standard process chain of CS offered by the company Hermle is illustrated. It consists of 6 main steps:

(1) machining of channels into a substrate plate
(2) filling the channels temporarily by water solvent granulate
(3) planarization of the top surface by machining
(4) deposition of a continuous metal powder layer
(5) rinsing of the water solvent granulate
(6) machining into final dimensions (on front side)

Using this configuration, the layer of material deposited by metal powder shall provide full structural function in operation since it is the final pressure barrier to carry the channel internal pressure to the environment inside of the vacuum vessel. Therefore, full qualification of the deposited material is mandatory. An expansion of the process configuration by additional steps can be implemented aiming on significant reduction of the share of material deposited using CS in the final product. Furthermore, the deposited material can be even excluded from structural function in operation by design. The dedicated modifications in the process chain are summarized in Figure 4, bottom, where:

- Steps (1) and (2) remain unchanged.
- The first difference is in step (3) where after planarization of the top surfaced a groove is machined on top of each channel filled with granulate, slightly deeper than the plane surface of the standard configuration.
- Step (4) deposition of a continuous layer of metal powder filling the grooves by CS and step (5) for rinsing of granulate by water remain mainly unchanged.
- Subsequently, another planarization of the top surface is done, Figure 4, bottom, step (A). This time, a cutting depth is applied slightly larger than the first planarization operation. So the deposited material is fully removed and the base material is uncovered again on top of the bridges in between the channels. However, the deposited material filling the grooves machined in step (3) remains. After step (A) is completed, the top of the surface of the plate shows an alternation of base material and deposited material covering the channels.
- a cover plate providing the final pressure barrier in operation is positioned and installed by circumferential EB-welding, step (B)
- This cover plate is joined together with the deposited material on top of the channels as well as the substrate plate (bridges in between channels) by diffusion welding (Hot Isostatic Pressing, HIP)

in configuration with opened channels, step (C). During the HIP-process, the deposited covers on top of channels
- Finally the plasma facing surface is machined to final dimensions, step (6)
- In this configuration, the material deposited by CS is only used as pressure barrier during the diffusion welding (HIP) process to establish the structural connection between the substrate plate and a cover plate, step (C). Therefore, the final pressure barrier to be considered in operation is the standard rolled and machined cover plate joined by diffusion welding together with the substrate plate. Both, the substrate- and the cover plate are from conventional origin (melted, rolled).

This feature can provide advantages e.g. in RAMI-analysis or in order to limit qualification routines: The deposited layer may be fully neglected in analysis since it has no structural function in operation. The structural load can be considered to be fully provided by the HIP-weld between the substrate- and the cover plate.

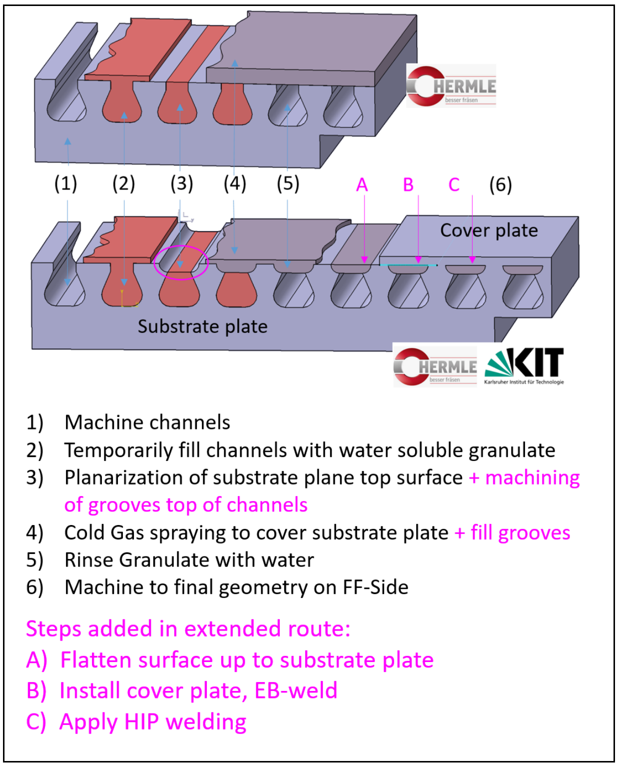

Figure 4. Cold Spray for FW manufacturing: standard (top) and extended (bottom) process chain

Two demonstration parts for the CS process have been built in 2018 from 316L in the initial phase since 9% -Cr-steel powder suitable for CS specifications and parameter sets were not available:

- One demonstrator for the standard CS configuration offered by Hermle as shown in Figure 4, top, relevant for a TBM Stiffening Plate [1]
- Another demonstrator for the new extended process chain as shown in Figure 4, bottom, up to step (5), relevant for a First Wall, Figure 5

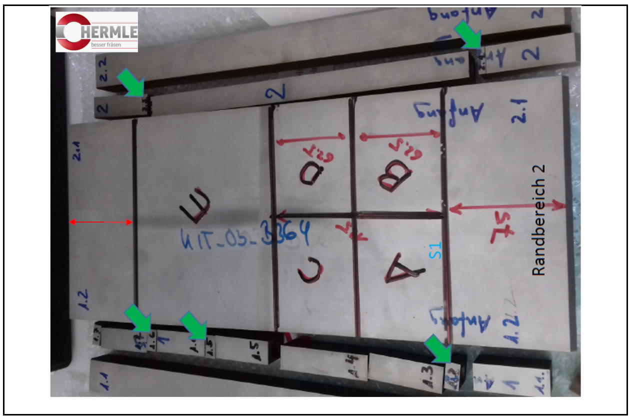

Figure 5. Demonstrator "First Wall_1" during destructive examination (~ 400 x 200 mm²)

Figure 6 shows different samples extracted from the fabrication Mock Up "First Wall" (Figure 5) in different conditions. Metallographic investigations of the macro-structure of the deposited material as well as the investigation of the bonding to the substrate plate are completed.

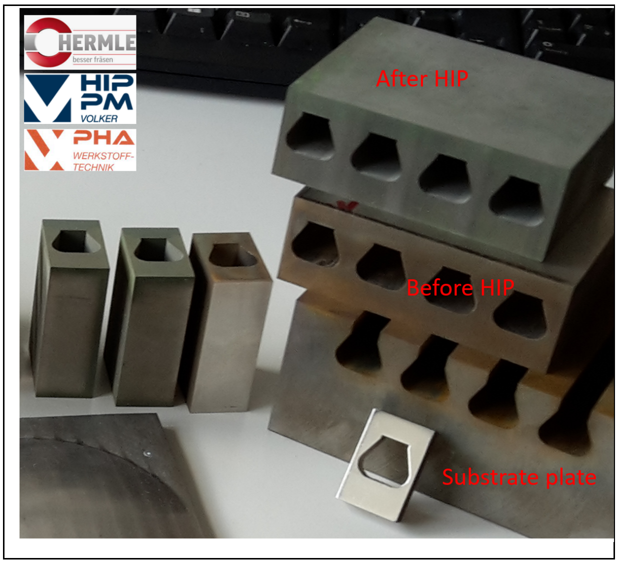

Figure 6. Destructive Examination of Cold Spray samples

To reach the proof the concept of using a deposited layer applied by CS as pressure barrier for a diffusion welding process to join a cover plate on top, two criteria shall be demonstrated.

- There shall appear no open porosity in the deposited material.
- Additionally there shall not be any continuous connection (shortcut) in between the deposited material and the substrate plate connecting the

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channel to the location of the HIP bonding zone (between substrate and cover plate on top of the deposited material).

The metallographic tests to demonstrate that these two criteria have been met are shown in the following two pictures:

- Figure 7, which illustrates two samples extracted from the demonstration part "Stiffening Plate_1" before HIP
- Figure 8, which illustrates two samples extracted from one channel of the demonstration part "First Wall_1" after step (5) is completed:
    - before HIP was applied, indicated in green
    - after HIP was applied, indicated in red

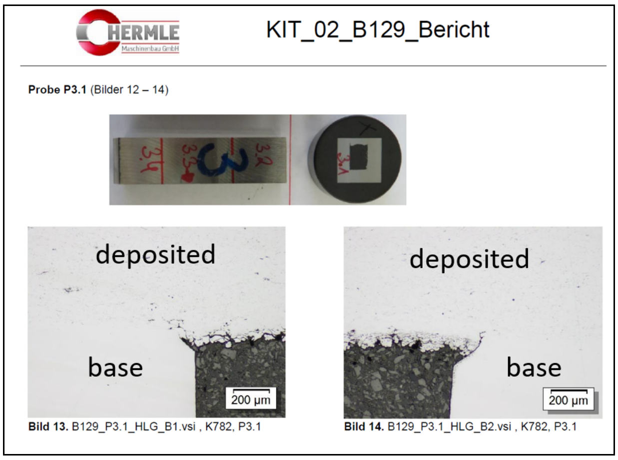

Figure 7. Metallographic macro structure analysis of bonding in between deposited material and substrate plate

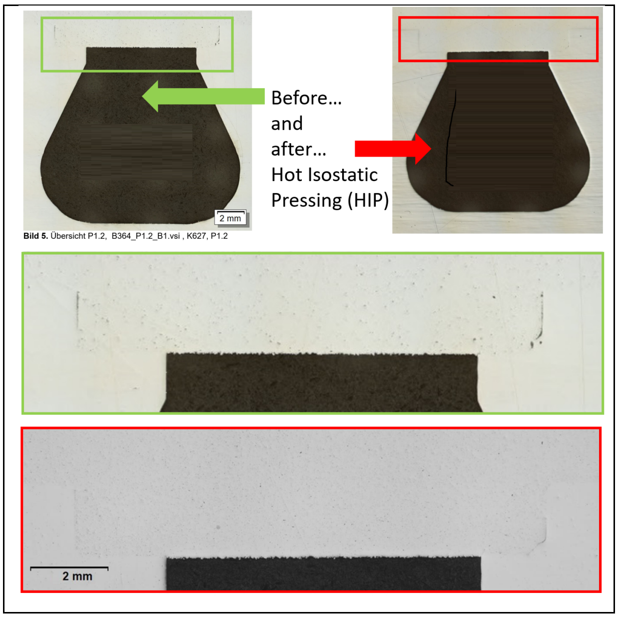

Figure 8. Metallographic macro structure analysis of bonding in between deposited material and substrate plate, before and after HIP

Exclusion of an opened porosity: The metallographic analysis demonstrate that no opened porosity occurs inside the deposited material. This conclusion is supported if the deposited material is compared before- and after HIP. The number and size of pores quantitatively appear lower after HIP is applied, see detailed view in Figure 9. This would not be the case if an opened porosity exists.

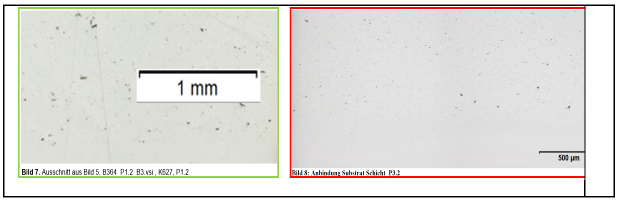

Figure 9. Sample of "First Wall_1", porosity before (left) and after HIP (right)

No shortcut has been observed in the metallographic analysis. A lack of adhesion in between substrate and deposited material in vertical direction (parallel to spraying direction) is visible on both sides of the channel (Figure 8). This kind of defect was expected since it is well known that the adhesion of particles decreases with decreasing angle in between spray direction and deposition surfaced. However, as demonstrated correspondingly for the standard configuration of the CS process shown before (Figure 7), the horizontal transition line in between substrate and deposited material (perpendicular to spray direction) is continuously free of defects. Thus a suitable pressure barrier is demonstrated for the HIP process to join a cover plate on top after planarization.

During this HIP process the lack of bonding in vertical direction is improved by plastic deformation (Figure 8, bottom. Indicated in red): on the left side of the channel full adhesion has been demonstrated, however on the right side still some lack on bonding remains in the corner. Therefore, the minimization in lack of bonding defects in vertical direction and corners will be addressed in the next series of experiments by design measures, e.g. implementation of a radius or angle to prevent full parallel orientation between spray direction and deposition surface. Process parameter improvements (e.g. tilting of the spray nozzle) may be also an option.

Presently the procurement of a new batch of 9%-Cr steel (P92, 100 kg) is launched and the development of a parameter set for CS is planned in collaboration with Hermle and HIP PM. First test parts from this batch of material are expected to be manufactured in early 2020

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also using the substrate plate shown in Figure 12. Detailed non-destructive and destructive tests as well as preliminary functional tests (pressure- and leak tightness tests) are envisaged. Also the demonstration of the process sequence to a non-planar demonstrator (e.g. a 3D- free form geometry is intended.

Mechanical tests (Tensile- and Charpy tests) before- and after HIP and comparison to the base material of the substrate plate are addressed.

4.2 Additional features as options in the extended Cold Spray process chain

The AM-process of CS (Figure 4) allows the introduction of additional features providing additional benefits in manufacturing and operation, the dedicated developments are:

- Cold mass forming applied for manufacturing of U- or even 3D-shaped substrate- and-cover plates, and
- Laser structuring for implementation of turbulence promotion structures into channel surfaces

4.2.1 Cold mass forming: To economize the procurement for U-or even 3D-shaped substrate- and cover-plates used in the standard or the extended CS process (described in Figure 4), cold mass forming is an option, especially if serial production is considered. Thus, minimization of the machining effort and raw material cost by using plates as wrought material instead of solid blocks can be reached. A variety of equipment up to full scale FW mass forming tools is already available and tested by KIT in collaboration with Forschungsgesellschaft Umformtechnik, FGU (Institut für Umformtechnik IFU, Stuttgart). One example for application of cold mass forming for manufacturing of FW size relevant U-shaped components is given in [1], another example shows a U-shaped configuration after machining of a First Wall relevant channel structure into the surface (nationally funded project BMBF-03FUS0011, 2010-2015, Figure 10). The components are intended for verification a First Wall processing chain using HIP-welding [10] but they are generally also suitable for Laser structuring of channel bottom surfaces and closing with the described CS deposition process chain.

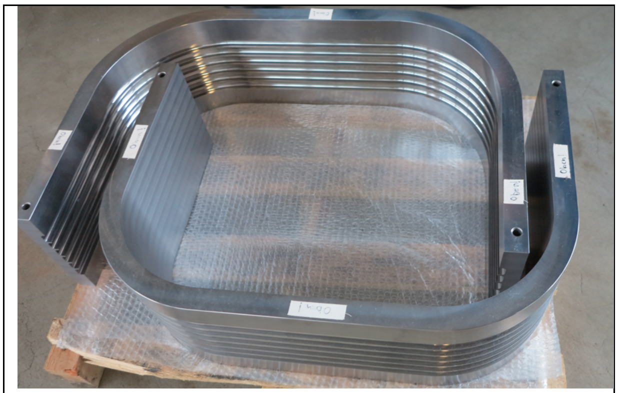

Figure 10. Cold mass forming applied for U-shaped configuration, machining of channels completed

Figure 11 illustrates an experimental configuration for a scaled down feasibility demonstration of a 3D-shaped mass forming experiment e.g. for production of a substrate- or cover plate as described in the extended CS process chain (scaling factor ~ 1/6, plate thickness 5 mm). The design of the experimental geometry includes a spherical calotte with a transition into a rooftop shaped extension surrounded by edges. The precision of the geometry of the plate after forming has been verified by laser scanning to be within +/- 0.3 mm. The geometry of the tool with its edges has been depicted clearly and sharp. Comparable bended U-shaped and 3D-configurations in full scale can be used as substrate plate for machine the channels inside before applying of Laser Structuring of the channels bottom surface followed by the CS extended process chain to cover the channels and installation of a similar formed cover plate.

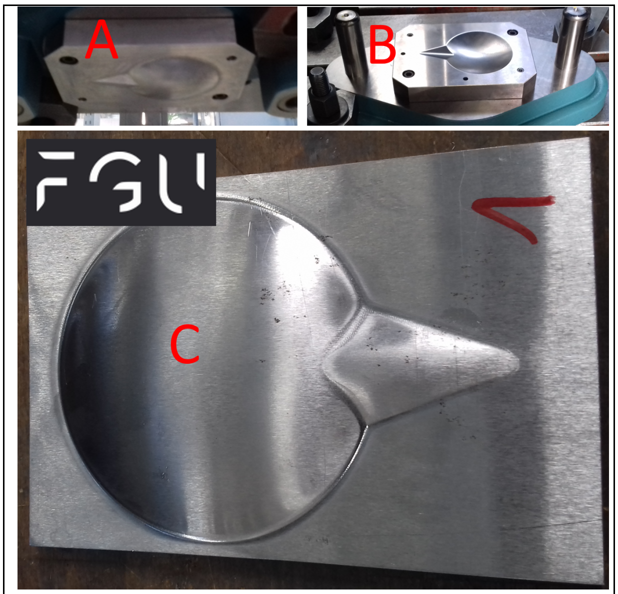

Figure 11. Cold Forming applied for substrate- and cover plate (tool top and bottom side A and B, as well as the resulting formed plate C)

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4.2.2 Laser structuring: The realization of turbulence promotion structures into channel surfaces by Laser structuring has been introduced in the development program for the HCPB BB recently. A dedicated collaboration was launched in early 2019 with Fraunhofer ILT in Aachen.

Since the internal surfaces of the channels are accessible during the manufacturing process chain (directly after machining of the substrate plate, see Figure 4), the implementation of heat transfer enhancement structures by Laser is included as option. Typical structures (e.g. arrowheads, grooves, dimples, etc. [11] and [12]) onto the plasma-facing bottom side of the cooling channel can provide a significant contribution to increase the efficiency by turbulence promotion in gas (Helium) cooled high heat flux applications. Conventional options to apply the structures macroscopically, e.g. by machining or die sink erosion were tested [13]. However, Laser structuring is considered as promising and effective to be used to realize macro- but also microstructures for turbulence promotion in combination with an acceptable pressure drop. Figure 12 shows the first experimental demonstration using Laser structuring for manufacturing of First Wall relevant heat transfer enhancement structures. Further existing examples of applications e.g. from automotive industry (Fraunhofer ILT) is shown to demonstrate the capabilities of the technology, especially in terms of precision [14].

The development activity also includes the application of Laser structuring for internal surfaces of pipes using an in-bore-tool, aiming on the fabrication of HCPB Breeding Blanket fuel pins [1] but also on fabrication of semi-finished pipes used for assembly of tube heat exchangers in gas cooled applications to realize high efficiency components. The application of the technology may also be considered in plate heat exchangers (Laser-structuring of semi-finished plates during fabrication).

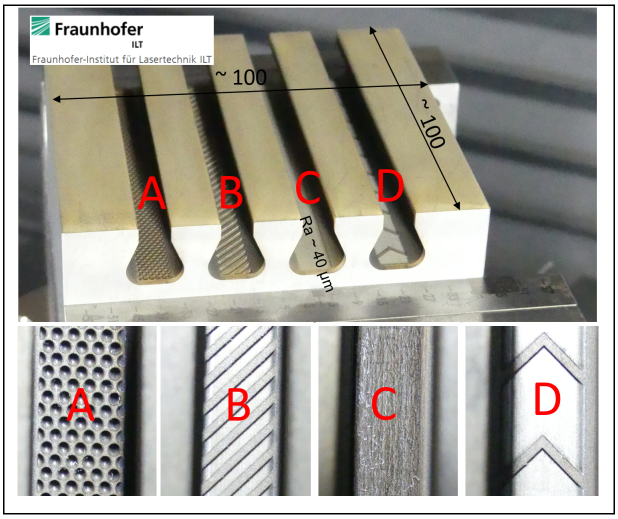

Figure 12. Heat Transfer enhancement structures implemented by Laser structuring (Fraunhofer, ILT)

5. Conclusions

This paper summarizes the developments in Additive Manufacturing applied for the HCPB Breeding Blanket First Wall. Selective Laser Meting and Cold Spray have been investigated. Selective Laser Melting presently is intended to be followed for manufacturing of Breeding Blanket internal structure segments with high complexity and low void grade, assembled to hybrid components in case with conventionally manufactured parts. Concerning First Wall manufacturing, the focus is presently on the Direct Energy Deposition process of Cold Spray since it is available in larger scale (compared to SLM); the cost reduction potential is higher due the high deposition rate and application of cold forming for substrate and cover plates instead of machining from the full block. In addition, the accessibility of the channels during manufacturing for operations as Laser structuring is a significant benefit in view of efficiency of a gas cooled Breeding Blanket for commercial electricity production, also considerable for applications outside of nuclear fusion (e.g. gas cooled receivers in concentrating solar power energy production).

6. Acknowledgment

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