Advances in Additive Manufacturing of fusion materials

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Recent analysis show significant impact on the design requirements of the Helium Cooled Pebble Bed (HCPB) Breeding Blanket (BB). Especially the main demanding sub-component of the BB in terms of fabrication, the First Wall (FW) is highly affected. As a matter of fact, the relevance of the developments made for the industrial fabrication of the FW used e.g. in the EU HCPB Test Blanket Module (TBM) for ITER is limited: On one hand in terms of the overall dimensions, but also in terms of geometry and cooling channel configuration. Thus, a fabrication strategy for the FW was proposed as an option in 2018 based on Additive Manufacturing (AM) offering a solution to cover the new aspects. The dedicated fabrication routine is based on Cold Spray (CS) in alternation with machining. In terms of manufacturing of non-plasma facing complex shaped thin- or double wall BB structures (e.g. Fuel Pins proposed for the HCPB BB) the use of AM also provides benefits compared to conventional technologies. Therefore, the AM process of Selective Laser Melting (SLM) is further explored in terms of applicability for BBs. This paper gives an overview about the advances in different AM options investigated for nuclear fusion structural low activation steels. Possibilities for spin-offs to other technological fields are discussed and conclusions are drawn reflecting licensing aspects and technological limits.

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

Modifications implemented during the recent years in the design of the HCPB BB turned out in significant influence on their manufacturing routines and fabrication strategies. Thus, the relevancy of conventional industrial fabrication technologies already demonstrated as state of the art and proposed for the TBM for ITER is decreased. Especially the FW is impacted. Also in terms of the BB internal structures significant differences have been proposed compared to the internal arrangement of the HCPB TBM. Thus, concerning the BB internal structures modifications finding its expression in terms of requirements for fabrication technologies. AM has shown promising options for development of fabrication routes towards realization of the new designs developed for the DEMO BB. This paper describes options for fabrication of the FW as well as BB internal structures using two fundamentally different AM concepts: The Direct Energy Deposition process of CS for the FW and the Powder Bed processes of SLM applied for BB internal structures are demonstrated. Both technologies have been customized from standard applications towards the respective design specifications of nuclear fusion devices. The paper describes the present advances of the technologies in application of AM to nuclear fusion.

2. The process of CS customized for the BB FW

The design and the corresponding manufacturing technologies used for the gas cooled FW of a TBM developed for ITER (HCPB concept) are relevant for the DEMO BB only to some extent. In terms of dimensions of the plasma facing surface the DEMO BB FW is significantly larger (~ 1 m² in case of the TBM vs. > 4 m² for the DEMO BB Multi Module Segment or even > 20 m² in case of Single Module Segment [1]). Also, the expected surface heat flux is significantly larger [1], thus heat transfer enhancement structures (e.g. semi-detached ribs)

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on the channels internal surface are required, at least in some locations of the FW. Moreover, the surface configuration has been modified from a plane plasma facing surface to a 3D-shaped surface using a so called “roof-top-design”, [1]. In 2018 a specially customized fabrication process routine has been proposed using CS applied as AM in alternation with machining and diffusion welding, Figure 1 [2]. The process routine provides a possibility to realize all new aspects: non-planar configurations, heat transfer enhancement structures inside of the channels and no strict process driven limits in production of parts in relevant dimensions. In 2020, several aspects of the process chain already demonstrated [2] have been improved and finally the integral process chain has been completed firstly in a small Feasibility Mock Up (FMU) by the end of 2020. Also, the demonstration of the process chain to non-planar surface configurations has been firstly addressed, as well as complex semi detached rib structures inside of the channels.

The material used in the experiments was P92, a 9% Cr-steel with a comparable composition to EUROFER, however available on the commercial market with reasonable cost and delivery time. The powder processed by CS in the fabrication experiments was atomized from solid P92 bars. It was procured and characterized in terms of composition, hardness, grain dimensions and shape in early 2020.

Since the material deposited by CS is used as pressure barrier for a diffusion welding process as illustrated in Figure 2, the key functional aspect is the pressure tightness of the material itself and the bonding between the deposited material and the substrate surface. Therefore, detailed improvements have been carried out in the geometrical arrangement of the contact area between the substrate plate and the deposited material applied during step 3), planarization and machining of the groove filled by CS deposition as shown in Figure 1. The improvement of the adhesion of the CS-deposited layer applied during step 4) is shown in Figure 3. The deposit shows an already high density (no open porosity) already before thermal treatment. The density of the material is further increased by the thermal treatment (Hot Isostatic Pressing, HIP) as well as the quality of the adhesion of the deposit material.

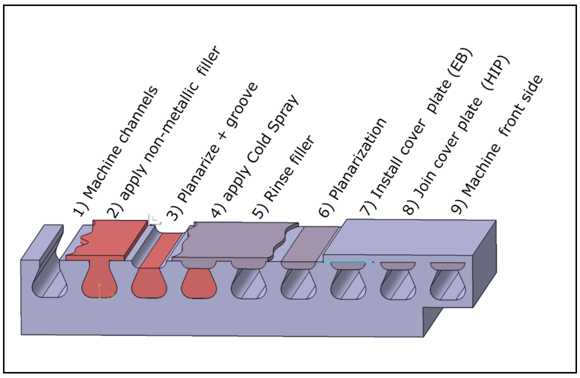

Figure 1. Customized CS based AM process chain for FW

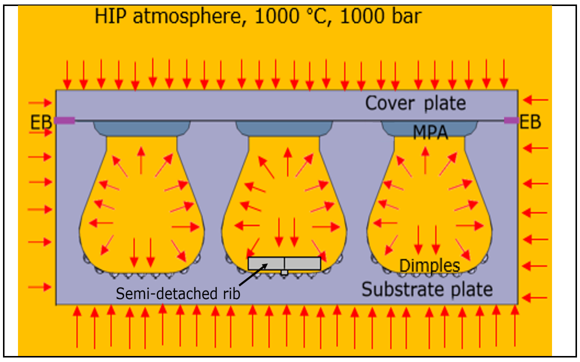

Figure 2. Joining of Cover plate to Substrate plate and CS pressure barrier

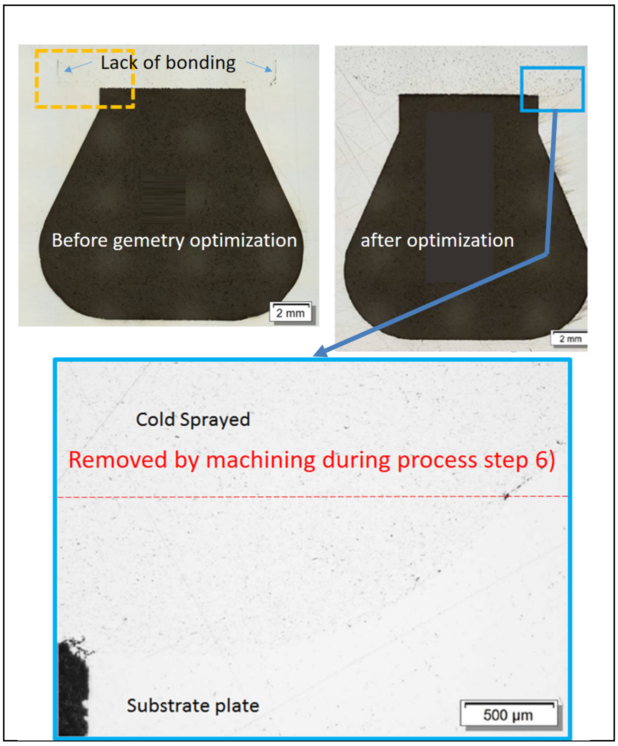

Figure 3. Bonding between surface and CS deposit before and after thermal treatment

The planarization and smoothening of the HIP surface after deposition with CS, step 6) of Figure 1 has been demonstrated for a plate configuration

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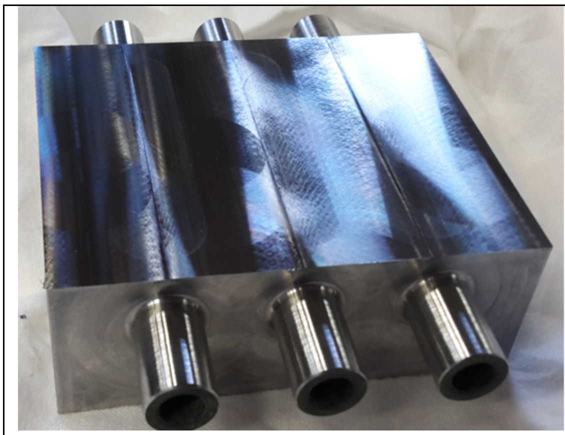
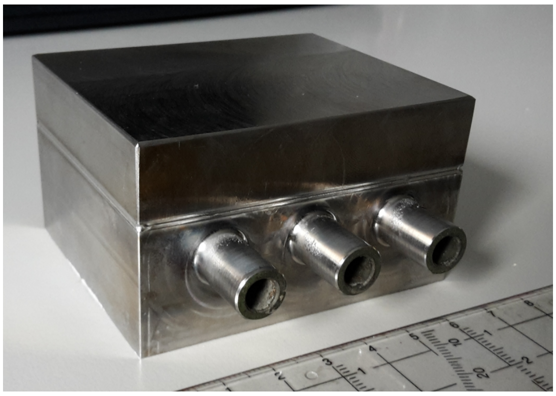
with three parallel channels, see Figure 4, top. A dry machining process was used. Additionally the opposite surface of the cover plate was prepared accordingly. Subsequently the cover plate was installed on top of the substrate plate by EB welding according to step 7) as shown in Figure 4, bottom. The HIP welding has been completed afterwards. Thus, all the key steps of the integral fabrication process chain has been demonstrated firstly. The qualification of the demonstration component will be done by destructive examination and investigation of the HIP welding quality in early 2021.



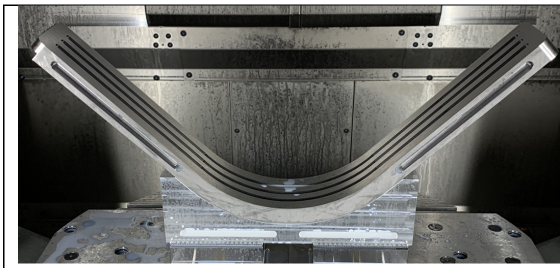
Smoothed HIP welding surface



EB-welded substrate + cover plate top

Figure 4. Substrate-top surface smoothed and prepared for HIP Process

The process chain described above has also been launched firstly to demonstrate a non-planar bent plate configuration. A dedicated series of two test parts with a similar three channel configuration and channel length of > 500 mm was procured from Hermle. The machining of the channels into the bended plate (Figure 1, step 1) up to the deposition by CS and rinsing of the filler (Figure 1, step 5) has been completed in late 2020 as shown in Figure 5. The integral process chain is planned to be demonstrated in 2021 by completing the fabrication sequences and procurement as well as joining of a corresponding cover plate according to steps 6) – 9) illustrated in Figure 1.



Machining of channels, step 1) completed

After CS deposition and rinsing of filler, step 5), including pressure connectors machined

Figure 5. Bended plate configuration demonstration part

In late 2020 another non-planar configuration demonstrator has been developed and designed in collaboration with Hermle representing a spherical surface segment with a meandering channel flow path, see Figure 6. The CS deposition will be done in early 2021, as well as the procurement and joining of the cover plate to demonstrate the integral manufacturing process chain.

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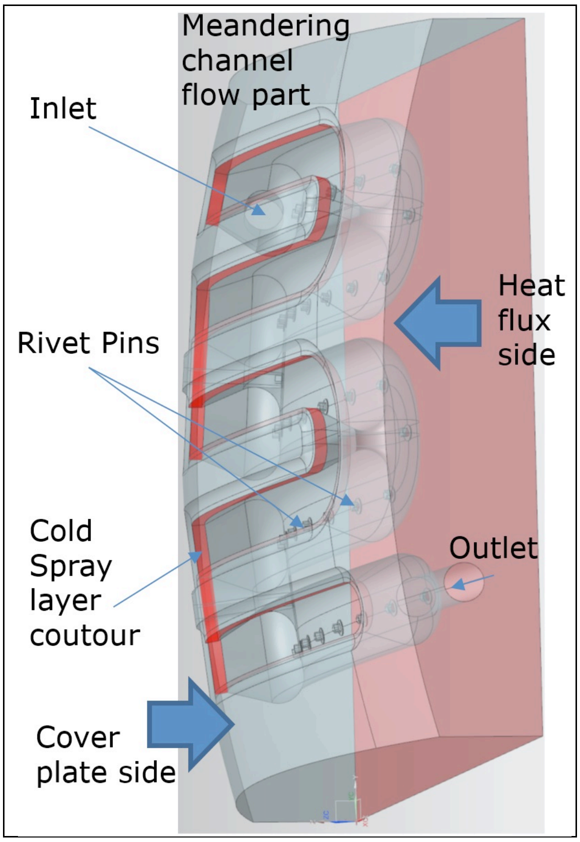

Figure 6. Non-planar spherical surface segment configuration

Another novelty in relation to the CS based process chain demonstrated firstly in 2020 is the realization of semi-detached rib structures ([3] and [4]) inside of cooling channel surfaces. The semi-detached ribs are positioned onto riveting pins machined on the bottom side (heat flux facing surface during operation) of the cooling channel and fixed by plastic deformation of the rivet pin. The precise distance in between the wings of the ribs and the channel internal surface (~1/10 millimeter) is provided by a spacer ring. The ring is machined into the channel surface located below the riveting pin. The semi-detached ribs fabricated by SLM, the bottom side of the channel with spacer rings and riveting pins as well as the installed semi detached ribs inside of the channel are shown in Figure 7. The installation of the ribs can be added into the process chain shown in Figure 1 directly after step 1) and has been already demonstrated to be compatible to the following process steps by production of another test part as shown in Figure 4 however equipped with semi-detached ribs inside. A huge variety of channel surface conditioning can be offered by installation of semi detached structures which can be also combined with the option of Laser surface structuring already demonstrated in 2019 [2].

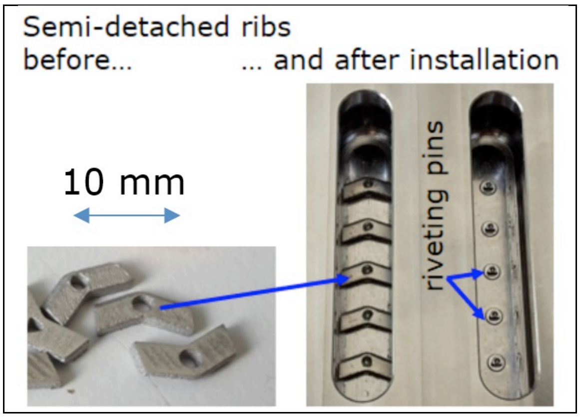

Figure 7. Semi-detached ribs installed inside of cooling channel

In 2020 significant progress has been made in terms of development of the customized CS based fabrication developed in collaboration between Hermle and KIT. The integral process chain could be completed firstly, also non-planar configurations as well as semi-detached rib structures for heat transfer enhancement in gas cooled applications could be demonstrated. In 2021 the qualification of the first demonstration parts will be launched, as well as the qualification of the material properties of the deposited material. Further, the non-planar demonstration parts production will be continued and the qualification started, as well as the procurement of medium scaled demonstration parts in non-planar configurations including semi-detached ribs inside of channels.

3. The Powder Bed Process of SLM applied for BB internal structures

The AM Powder-Bed-Process of SLM was continued to be investigated with focus on complex and thin walled internal structures of the HCPB BB ([6], [7] and [8]). Preliminary mechanical properties of SLM fabricated products from several batches of EUROFER powder (and comparable 9%Cr-steels) with different post processing parameter sets were investigated with promising results [9]. Also options to extent existing limits in terms of parts dimensions have been developed, e.g. by assembly of hybrid components by EB-welding [2], [6] and an innovative SLM process configuration [5]. The further material qualification and properties verification is addressed by material researchers in KIT IAM and IPM (Cz).

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Within the manufacturing activities of the KIT INR for the HCPB BB, the development focus in terms of SLM in 2017 – 2020 was mainly on the feasibility demonstration of complex geometries and the improvement of the geometrical precision by minimization of thermal distortions of thin walled components.

To minimize thermal distortions in SLM products the first approach shall be to re-consider the design of the product in terms of an optimized orientation during production. The effect of the orientation on the distortions is significant as demonstrated in Figure 8. Two almost identical components were "printed" in lying (version 1.0) and standing (version 2.0) orientation in order to demonstrate the effect of the orientation. Version 1.0 shows significant deformation in the order of several millimeters where the precision of the version 2.0 is acceptable (deformation significantly less than 1 mm). Suppliers provide guidelines and support in fabrication-oriented design of SLM-fabricated components. Additionally numerical tools are offered to be used to predict the distortion of a product which helps to optimize the result either by design modification, flipping of the orientation or introduction of separation planes to fabricate the part in optimized segments which are assembled later, e.g. by EB welding. However, the best orientation in terms of distortions may be in contradiction to the minimization of the fabrication cost. In the example shown in Figure 8 the version 2.0 "standing" requires ~ 10 times more production layers than the version 1.0 "lying" resulting in significantly higher production cost and time. Also the powder material turnover may be increased if only one unit is manufactured within one build job.

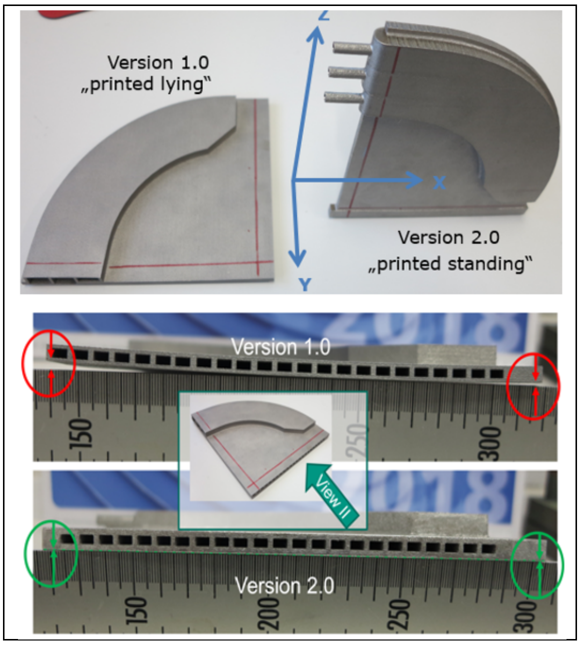

Figure 8. Effect of orientation to two almost identic BB internal segments

The deformation is mainly induced by thermal gradients inside of the powder bed where on top of the powder bed in the layer where the Laser (or Electron Beam in case of EBM) solidifies the powder the highest temperatures occur. One common measure to decrease thermal gradients inside of the powder bed is to operate heaters inside of the building platform of a SLM machine. However, with increasing height of the product the thermal gradient increases again since the heat is conducted into the periphery of the powder bed and the metal powder has a low thermal conductivity. Other existing concepts base on heating of the powder bed by induction coils surrounding the powder bed and the product solidified inside. However, none of the existing solution provides the option of an in-situ temperature monitoring and control of the powder bed temperature to minimize thermal gradients and the dedicated distortions.

KIT has developed a concept offering the option of an in-situ temperature control of the powder bed temperature for minimization of distortions but also for an increase of the production temperature (e.g. desired in processing of Ti-alloys outside of nuclear fusion applications). The concept bases on the high electrical resistivity of the metal powder compared to the solidified metal. This allows the operation of electrical heater coils inside of the powder bed without electrical shortcut. The heater coils are built onto electrical feedthroughs on the top surface of the building platform together with the product

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(Figure 9, A). The coils are connected to a current supply as soon as the coil is completed and closed (Figure 9, B). Several coils can be established in several positions during the course of the production process and corresponding with the products geometry (Figure 9, C and D). The temperature control can be provided by observing the electrical resistivity of the heater coils and using the values as control signal to adjust a homogeneous temperature distribution inside of the powder bed.

Simplified proof of concept experiments have been performed at KIT demonstrating the main functional aspects, such as the high electrical resistivity and the thermal conductivity of the metal powder and the dependence of the properties to compression of the powder. Also, the operation of a printed coil as a heater inside of metal powder inside of an Argon atmosphere without electrical shortcut and the corresponding heating up to 250 °C was shown immediately without considerable experimental effort. The effect of the heater coils on the temperature distribution inside of the powder bed has been estimated and verified in preliminary numerical analysis: already a low number of heater coils (as shown in Figure 9) operated together with a heating device inside of the build platform turn out in a significantly homogenized temperature.

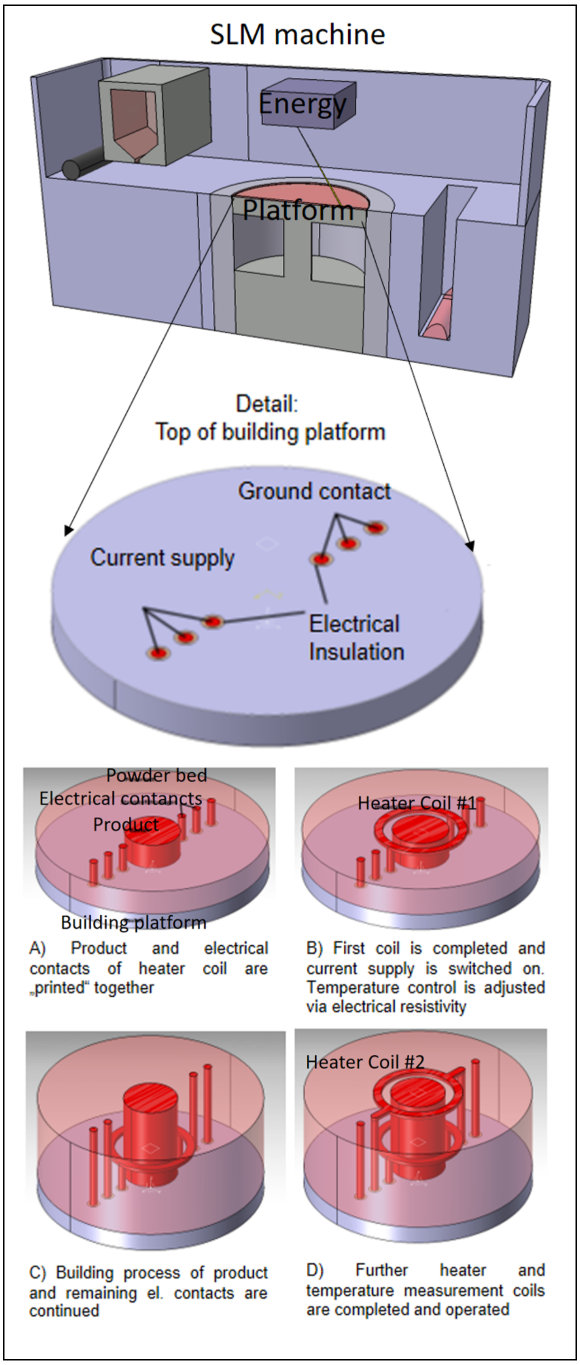

Figure 9. Concept of printed electrical heater coils

The technology proposed by KIT could be developed e.g. by producers of SLM machines and in case coupled to numerical tools simulating the SLM process in order to optimize the positioning of the heater coils and to align the coils in correspondence to support structures also in the printing job. As a result, a further optimized production process may be provided finally resulting in a maximum possible part quality in terms of distortions for nuclear fusion BB internal components as well as properties in applications of high temperature materials such as e.g. Ti-alloys (outside nuclear fusion).

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4. Licensing aspects and technological limits of the AM for nuclear fusion

In terms of the CS based process routine for fabrication of the FW described in 2, the strategy is to exclude the deposited material from licensing considerations since it is only used as a thin pressure boundary layer (< 1 mm thickness) used during a conventional diffusion welding process (see Figure 2). During operation of the product, the pressure boundary is provided by a diffusion weld in between two conventionally rolled structural plates (substrate and cover plate, see Figure 2). The existing rules for development and qualification of fabrication specifications in codes and standards will be applied in the next stage for the upcoming series of demonstration parts. In terms of technological limits the maximum dimensions of the products presently is limited to ~ 0.6 x 0.6 m². However, the limit is mainly driven by the equipment presently used for the experiments and not by physical reasons like e.g. process confinement restrictions. However if full scale BB FW fabrication is considered, the procurement of semi-finished pre-formed substrate plates shall be addressed since complex 3D-roof top shaped plates with several m² surface exceeds limits of existing cold forming processes and equipment. Also machining from the full does not provide a practicable economic solution. Alternative options have to be found, e.g. hot forming/forging may provide a way out. Also cladding (e.g. using high deposition rate TIG welding) in alternation with machining may be addressed.

In terms of SLM described in 3, the products shall be treated in terms of licensing as a new material. Thus, a full material qualification program needs to be launched. In terms of limits, innovations have been proposed and developed to circumvent restrictions in maximum dimensions and distortions of the products. However, the production time for large components and the linked production cost remains an issue due to the thin production layer dimensions in the order of 1/10 of a millimeter resulting in a deposition rate in the order of 10 % of the deposition rate provided by CS.

5. Conclusions

This paper summarizes the developments in AM applied for the HCPB BB FW (Direct Energy Deposition using CS) as well as for BB internal structures (Powder Bed Process of SLM). Significant progress and innovations have been demonstrated by the end of the pre-conceptual project phase within the HCPB BB manufacturing project. Within the coming years the new technological approaches reported in this paper will be continued and the technology readiness level will be increased steadily to demonstrate AM options for realization of nuclear fusion for energy production. Technology spin-offs should be taken into account and be exploited, especially for concentrating solar power energy production with heat loads and geometry specifications comparable to the nuclear fusion FW concepts.

6. Acknowledgment

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