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Fabrication of thin-walled fusion blanket components like flow channel inserts by selective laser manufacturing

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The development of new manufacturing methods for the production of key components for nuclear fusion reactors by selective laser melting (SLM) is currently under investigation at Karlsruhe Institute of Technology. SLM offers great potential compared with conventional manufacturing methods. In conjunction with feasibility studies, complex 3D structures such as a thin- and double-walled flow channel inserts (FCIs) for dual-coolant lead lithium blankets have been successfully manufactured and tested on a preliminary level. The paper shows the principal feasibility of SLM technique to fabricate thin-walled FCIs. The complexity of the fabrication process is outlined and application of the SLM technique for production of other fusion blanket sub-components such as thin-walled cooling plates with internal cooling channels is addressed.

Keywords: Blanket, flow channel insert (FCI), dual coolant lead lithium blanket (DCLL), manufacturing, selective laser melting (SLM)

1. Introduction

Several manufacturing strategies and methods for test blanket modules (TBM) have been developed in recent years to show the feasibility of established fabrication methods. These studies focused on blanket components such as the first wall, stiffening and cooling plates for the helium cooled pebble bed (HCPB) or helium cooled lead lithium (HCLL) blankets [1], [2], [3] and on fabrication of thin- and double-walled flow channel inserts (FCIs) foreseen in dual coolant lead lithium (DCLL) blankets [4], [5], [6]. Those fabrication studies show that the referred methods give reasonable results for simple straight geometries, but they may have drawbacks concerning fabrication time and costs and limitations of available methods and machines for 3D components.

A concept considered in the present work is selective laser melting (SLM). It is an additive manufacturing (AM) technique, in which a high-power-density laser melts metallic powders gradually in layers to create solid 3D structures. Preliminary studies of SLM-produced components have been made to check material properties. In addition, hybrid components consisting of SLM parts welded with conventionally fabricated elements such as stiffening plates with cooling channels have been successfully fabricated [3], [7]. Material qualification tests of SLM Eurofer97 have shown almost similar material behavior as for conventionally fabricated components [8]. Feasibility studies to demonstrate the producibility of sub-components for fusion reactors with complex shapes and structures by SLM technique are ongoing. Results of these studies especially for thin- and double-walled components are shown in this paper.

2. Fabrication of flow channel inserts by SLM

2.1 Background of flow channel inserts

Liquid metal flows in magnetic fields induce electric currents, which are responsible for strong Lorentz forces and high magnetohydrodynamic (MHD) pressure drop. The pressure gradient evaluates e.g. for fully developed circular pipe flow in strong magnetic fields [9] as

$$\frac{\partial p}{\partial x} = -\sigma u_0 B^2 \frac{c}{1+c} \quad (1)$$

with the conductance parameter

$$c = \frac{t_w \sigma_w}{L\sigma}. \quad (2)$$

Here, t_w and σ_w stand for thickness and electric conductivity of the wall, L is a characteristic length and σ is the conductivity of the fluid that moves with average velocity u_0 in a magnetic field B. The parameter c gives the ratio of the conductance of the solid material to the one of the fluid. It is obvious from Eq.(1) that MHD pressure drop can be reduced if c is small, i.e. when the solid conductive layer t_w is very thin compared to L.

Several proposals have been made in the past to reduce the MHD pressure drop by interrupting current flow into the well-conducting walls using insulating layers, coatings, or FCIs [10]. One of the preferred concepts is a sandwich-type FCI consisting of a thin ceramic layer protected by two thin steel sheets to avoid contact between the insulating layer and the liquid breeder. FCIs are foreseen in breeder channels of DCLL blankets to reduce MHD effects, but they may apply as well to manifolds and distributing channels in the back supporting structure of water cooled lead lithium (WCLL) or HCLL blankets [5], [11], [12], [13]. For an assured functionality, the inner and outer thin metal sheets must not have any contact with each other to avoid leakage currents.

By inserting FCIs along the walls of liquid metal blankets, the core flow decouples electrically from the well conducting walls and becomes independent of the conductance properties of the wall. As a result, only the conductivity of the inner thin metal sheet of the FCI influences the conductance parameter. The conductance parameter c depends now on the thickness and conductivity of this thin protecting sheet and the pressure loss is therefore reduced. Thus, from a MHD point of view, the thickness of the FCI metal sheets should be as small as possible. Thin FCIs are beneficial for MHD pressure drop reduction and they give more space for the liquid breeder. Nevertheless, the layers should be thick enough to withstand corrosion attack for the entire lifetime of the blanket. A thickness t_w = 0.5-1mm of the protection sheets has been suggested e.g. in [13].

Double-walled FCIs for straight rectangular ducts or for circular pipes have been successfully manufactured using established methods [4], [5], [6]. However, the mentioned fabrication techniques may have difficulties for complex 3D elements. For such components, alternative fabrication methods like SLM are examined in the present paper.

2.2 Preliminary fabrication tests with SLM

As a generic model for FCIs in bifurcating ducts, a Y-shaped double-walled model has been designed and successfully fabricated from stainless steel 316L, because of existing experience with this material in SLM. The Y-shape prototype has a height of ~140mm and consists of two steel layers with a wall thickness of 1.5mm each and a 1mm insulating gap in-between. This model has been designed to show the principal feasibility of fabricating thin- and double-walled components for complex 3D structures with bifurcations, different dimensions of cross-sections and inclined walls. Figure 1 shows the fabricated Y-shaped mockup. The internal and external walls are perfectly separated from each other, except at openings at the ends of the geometry, where small local spacers are still attached. As visible in the figure, several circular groves are manufactured along the inner surfaces of both walls. They are filled in a subsequent step with small ceramic spheres (ø1mm ZrO_2) to ensure a constant distance between the two walls and to enable the double-walled structure to compensate small displacements caused by thermal expansion when temperature differences between the two layers are present. The remaining gap has been filled and compacted with ceramic powder (ø0.3mm ZrO_2). Finally, the spacers at the ends have been removed and the gaps have been closed by a non-conducting material. This results in a perfectly electrically separated double-walled structure as confirmed by resistance measurements using an ohmmeter.

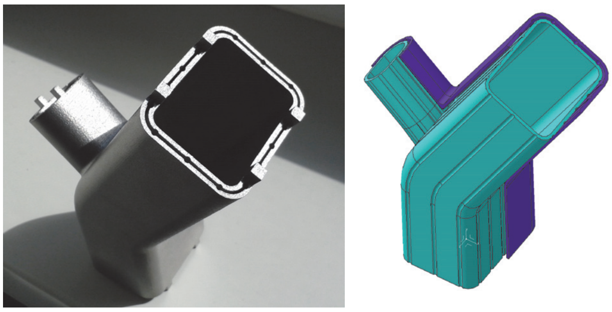

Figure 1: Y-shaped FCI model, total wall thickness 4mm.

The successful production of the Y-shaped model shows that thin and double-walled structures can be produced with SLM methods. Feasibility studies for fabrication of Eurofer97 components by SLM technique will be the subject of the following subsections.

2.3 Fabrication of a FCI mockup from Eurofer97

In a next step, a FCI has been designed as a downscaled model for a liquid metal channel inside the DCLL blanket. Figure 2 shows a view of the present DCLL design and a cut-view of the CAD model of the downscaled SLM FCI mockup. The 3D shape of the mockup is following the liquid metal flow path inside the blanket.

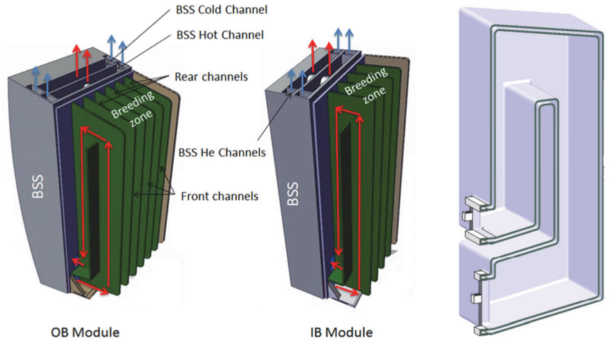

Figure 2: Present design of DCLL blanket (left) [13] and CAD model of the downscaled double-walled SLM FCI mockup, total wall thickness 2.4mm.

Objective of this mockup is to show the general feasibility of fabrication a complex 3D double-walled structure with very thin walls close to currently lowest machining limits for SLM and to produce them from Eurofer97. Eurofer97 is a reduced activation martensitic Cr-Mo steel developed for application in fusion reactors [14]. The fact that Eurofer97 is not a standard material for SLM and process parameters for this material are unknown, while at the same time the produced walls should be as thin as possible, poses a major challenge for the manufacturer. The first mockup therefore is considered as a test to gain experience about practical limitations of present-day SLM technique. The FCI model has been designed with a height of 110mm. It consists of a double-walled structure with 0.8mm wall thickness each and a gap of 0.8mm. The downscaled shape corresponds to the present concept of a PbLi liquid metal channel in a DCLL blanket [13]. During the SLM process the mockup has been inclined by 45° (see Figure 3).

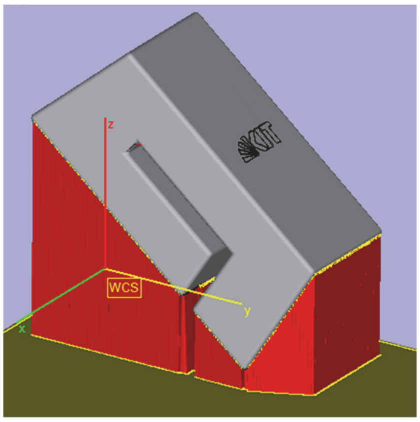

Figure 3: Orientation of FCI mockup during fabrication with supporting structure (red). (*by BKL, Germany*)

As in the previous example of the Y-shaped model, the inner and outer walls are initially connected by spacers at both openings to ensure exact positioning of both walls to each other (see CAD model in Figure 2). After partial filling the gap with ceramic powder (ø0.3mm) the spacers have been removed, the gap has been filled-up completely and closed by a non-conducting cap. Figure 4 shows the FCI filled-up with ceramic powder and closed by caps.

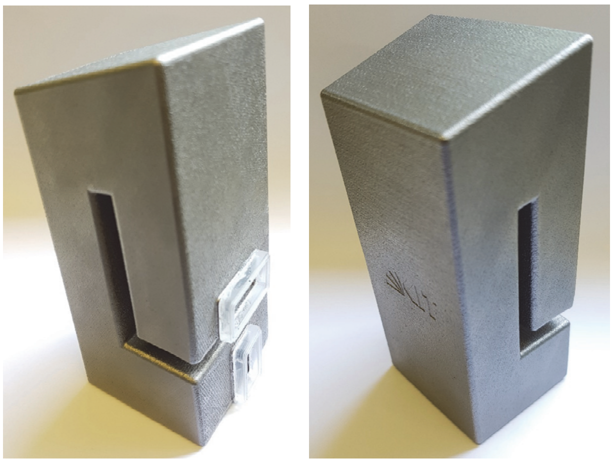

Figure 4: FCI filled-up with ceramic powder and closed by caps.

After the SLM process of this FCI mockup it could be seen, that some of the walls have certain deformations, so that a contact between inner and outer layer could not be excluded. Unfortunately, after filling the gap with ceramic powder, removing the spacers and closing the openings by caps, electrical resistance measurements confirmed this undesired anticipation. Additional examinations by x-ray computed tomography (CT) show positions, where inner and outer walls could be in contact. A CT scan allows nondestructive insight into the component. The images of the performed CT scan of the FCI mockup show areas, where the walls are almost in contact. These areas produce a short circuit, which deteriorates the electrical isolation. Figure 5 shows two pictures of the CT scan, where a longitudinal cut through the FCI mockup (left) as well as a detail of the connecting walls (right) can be seen. The ceramic powder bed can be clearly seen as well as the deformation of the most right wall and a bellying of the left walls.

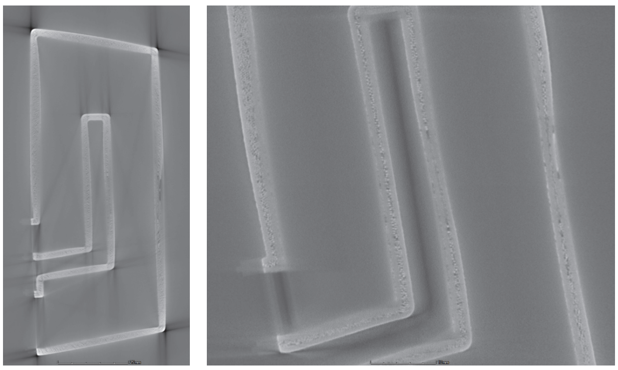

Figure 5: CT scan of the FCI mockup: Longitudinal cut (left), detail of connecting walls (right). (*by Andreas Meier, KIT-IAM*)

Fabrication of this first FCI mockup has shown that SLM of a 3D double- and thin-walled structure is a challenging task. The combination of very thin walls of thickness of 0.8mm, close to currently lowest technical limits for SLM, combined with a complex 3D shape, makes fabrication difficult and requires optimization in future studies, especially since the desired electrical isolation was not yet achieved.

2.4 Parameter study for SLM with Eurofer97

The fabrication of the mockup described above was based on the manufacturers experience with stainless steel. In order to improve SLM production of Eurofer97 samples, a systematic study has been performed, where three main process parameter laser power, movement speed of the laser and layer thickness has been varied (see Table 1). The geometry of the test parts has been chosen as thin plates with internal channels changing stepwise from circular to rectangular. Figure 6 shows samples of this parameter study.

Table 1: SLM parameter study with Eurofer97, set of parameters

Laser power	Movement speed	Layer thickness
W	mm/min	mm
135	500	0.04
165	750	0.06
195	1000	0.08

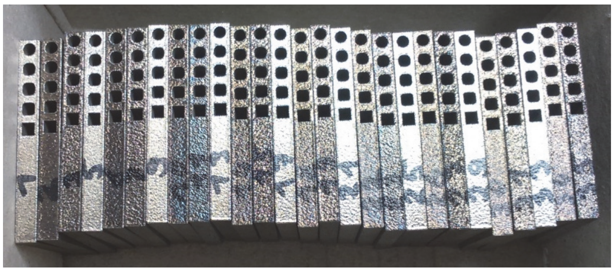

Figure 6: Parameter study, SLM manufactured samples with different parameters for laser power, movement speed and layer thickness.

Visual and microscopic examinations determined the most appropriate set of SLM parameters for future mockup fabrication with Eurofer97. The results of this parameter study show that variation of parameters for SLM Eurofer97 in the range shown above has only minor influence on the results. To ensure further results that are more reliable the next mockup had been fabricated in addition with slightly thicker walls.

2.5 Fabrication of a FCI mockup from Eurofer97 with optimized parameters and slightly increased wall thickness

The next FCI mockup has fabricated with the new set of parameters. It consists of same 3D shape than the previous model, but the wall thicknesses has been slightly increased up to 1mm for each wall and the insulating gap has a width of 1.4mm (total wall thickness 3.4mm). As result, it could be observed and confirmed by CT scans, that there are much less deformations of the walls. Figure 7 shows pictures of this scan. All walls of this model are much straighter than in the previous one and do not show any regions of contact between inner and outer sheets. After filling the gap with ceramic powder and closing of the openings, electric resistance measurements confirmed perfect electrical isolation and therewith ensured full functionality of the mockup for electrically decoupling of the liquid metal flow from the well conducting blanket structure.

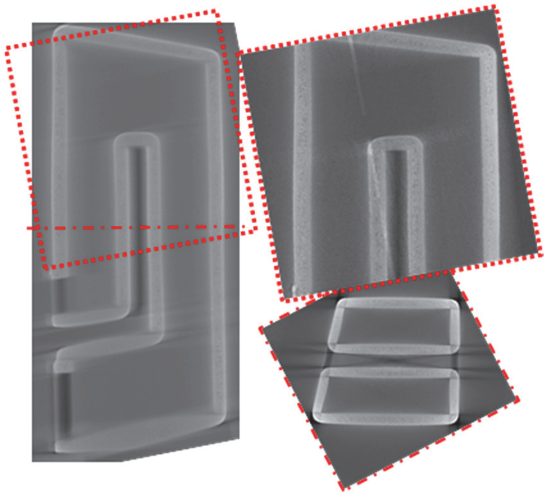

Figure 7: CT scan of the improved FCI mockup: Longitudinal cut (left), detail of longitudinal cut (right, top), cross section (right, bottom). (*by Andreas Meier, KIT-IAM*)

In summary, it could be shown, that complex 3D thin- and double-walled FCI structures from Eurofer97 can be fabricated by SLM. With optimized parameters and a wall thickness of 1mm the produced FCI mockup shows full functionality along with no local interruptions of the electrical insulation layer. The present work should be considered as proof of suitability based on available technology for SLM production of 3D sandwich-type insulating elements for liquid metal blankets. For fabrication of full-scale components, commercially available SLM machines would require upscaling in their dimensions. To overcome space limitations of today's SLM machines new approaches for bigger respectively longer parts are currently under development [7].

Alternatively, long straight FCIs can still be produced with established fabrication methods [4], [6], while complex 3D components could be fabricated using SLM. FCIs could to be produced in parts and assembled in the blankets, accepting the drawback of local interruption of the insulation [11], [12].

3. Fabrication studies of cooling plates by SLM

Fundamental technologies have been studied in the past to fabricate HCPB and HCLL TBM breeder blanket sub-components like first wall or breeder unit cooling plates. Focus was on creating long parts with embedded cooling channels using electrical discharge machining (EDM) and cold forming [1], [2], [15]. Recently, also AM methods have been investigated to produce blanket sub-components like stiffening and cooling plates. Preliminary studies of SLM produced parts have been performed to check material properties of AM fabricated components. In addition, hybrid components consisting of SLM parts welded with conventionally fabricated parts like the stiffening plate of a HCBP or a HCLL blanket with cooling channels have been successfully fabricated [3]. A detailed overview of manufacturing routes for TBMs and breeder blanket first walls can be found in [7]. A detailed study of Eurofer97 SLM material qualification can be found at [8].

Studies of SLM produced parts such as cooling plates with internal cooling channels are progressing. Recent SLM tests of these cooling plates have shown, that AM of flat parts with internal complex structures is also challenging. The cooling plate has been designed as a flat plate with different sizes of internal cooling channels, internal curved channels and steps within the plate. Main objective of fabricating these cooling plates has been set to achieve planarity in two directions. This aim could not be reached with the first fabricated part. As a result, design modification have been applied by installing radii inside the channels and by smoothing sharp corners (see Figure 8). In addition, the first cooling plate has be fabricated in a lying (horizontal) position, because SLM of flat parts are much more time and cost saving than higher ones due to the fact that machine times for SLM processes are most depending on the height of the components and therewith the amount of processed layers. It is known, that the orientation of a component during the manufacturing process has significant influence on the result. Therefore, additional to the design changes, also a rotation of the cooling plate during AM process by 90° has been applied for the second cooling plate. Instead of a horizontal position, the plate has been produced in upright position (see Figure 9).

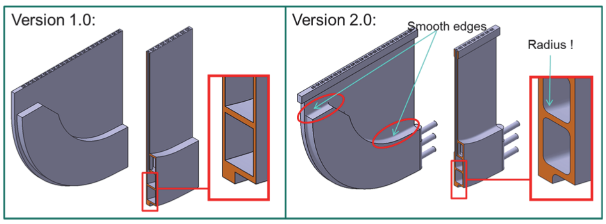

Figure 8: Applied design changes on AM cooling plate.

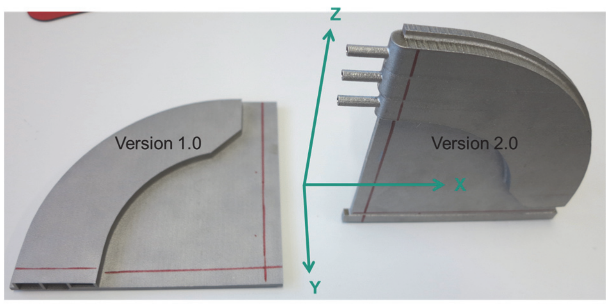

Figure 9: Applied rotation of AM cooling plate.

In Figure 10 the results of both fabricated cooling plates are compared in two views. The strong deformation of Version 1.0 (red marks) could be eliminated with the improved design and with the upright orientation during the fabrication process in Version 2.0 (green marks). Main objective of planarity could be achieved. In summary, for SLM produced flat parts with internal complex structures like the cooling plate as shown above, an upright spatial orientation during the SLM process is required and design optimizations like eliminating sharp corners and applying smooth transitions are recommended.

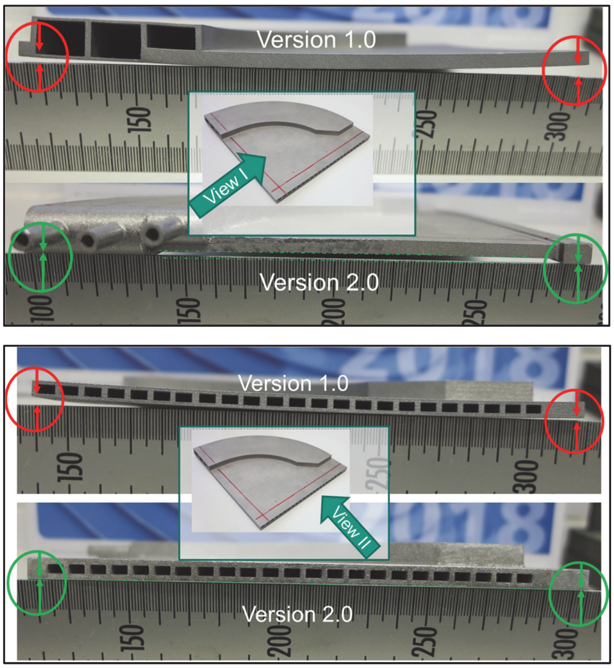

Figure 10: Shape distortion of SLM produced cooling plates, Version 1.0 (horizontal position) and Version 2.0 (upright position) shown in two perspectives.

4. Further fabrication studies of fusion blanket components by SLM

Further test parts have been designed and additive manufactured to investigate limits and possibilities of manufacturing of even more complex components for fusion blankets. Purpose and design of these parts are described in captions of Figure 11-Figure 13. Research using SLM methods to create fusion blanket components is still ongoing. Additionally, concepts to exceed size and technical limits of additive manufacturing machines have been developed and are under patent examination right now. [7]

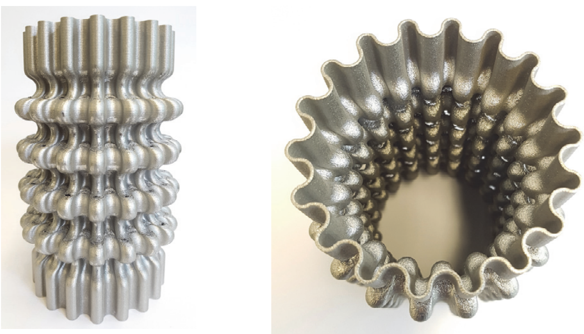

Figure 11: Test of a thin-walled compensator like component (height ~150mm, 1mm wall thickness) fabricated in upright position. Design has been hyperbolized by purpose to check fabrication limits. This component exceeds limits of today's SLM machines and results are not satisfactory. Especially at bend areas, the test sample has many holes and material is missing.

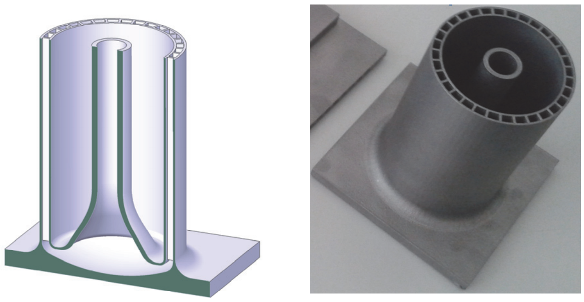

Figure 12: HCPB fuel pin with aim to create a thin-, double-walled structure with internal redirecting channels (height 100mm, smallest wall thickness 1mm). The test part has been successful fabricated and fulfills all requirements.

Figure 13: Circular thin-and double-walled FCI mockup with 200mm length and a total wall thickness of 1.5mm. Walls and gap have a thickness of 0.5mm each. The aim was to create straight parts similar to those produced with conventional methods by SLM. Result was a straight part with constant distance and good resolution of the circular shape. The circular shape could be further smoothed by with improved parameters.

5. Conclusions

The development of manufacturing methods for key components of fusion reactor breeding blankets is currently under investigation. Beside conventional fabrication methods, also selective laser melting has been selected for preliminary studies. Several blanket components like thin- and double-walled 3D flow channel inserts for DCLL, HCLL or WCLL blankets as well as breeder blanket cooling plates with a complicate inner channel structures could be successfully fabricated by SLM. Concerning the results, SLM offers a great potential compared to conventional manufacturing methods, especially fabrication of thin- and double-walled structures like sandwich-type flow channel inserts (FCIs) or components with complex internal geometries like cooling plates or fuel pins. Feasibility studies to demonstrate the producibility of sub-components for fusion reactors with complex shapes and structures by SLM are ongoing. SLM is still an innovative process. But, the results as shown in this paper are very promising, so that design limitations of today and with conventional fabrication methods could be overcome by SLM.

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