# Towards Ceramic Production via Digitalization and Additive Manufacturing

**By using Additive Manufacturing (AM) techniques for ceramic parts, construction engineers gain access to a multitude of novel designs. Moreover, time to market can be strongly reduced – especially, if AM is combined with the digitalization of the entire development and production process. AM is well established for rapid prototyping. Yet, the increasing use of AM techniques for the production of real parts implies new challenges, among them process stability, consistent part quality and cost efficiency. With ceramic AM, also new printing techniques are developed. They have the potential to overcome inherent quality problems especially relevant for the delicate ceramic manufacturing process.**

## Introduction

Compared to customary manufacturing of ceramic components, AM offers several advantages (Fig. 1):

- Lightweight constructions. Supporting structures can be easily realised using pores on various length scales.
- Individual components. Part production is affordable at a lot size of 1 enabling customised parts, e.g., for prosthetics, decoration or repair.
- On-demand production. Spare parts can be produced on-site and just in-time saving cost for transportation and storage.
- System integration. Complex parts can be manufactured in one piece saving assembly and joining.
- Material efficiency. $CO_2$ footprint during production is significantly improved by decreasing raw material consumption and recycling excess material.

Moreover, time to market and development cost are reduced for new components by the elimination of costly forming tools with long delivery times. This is why AM is generally considered as an essential base for the next industrial revolution the so-called industry 4.0.

However, there are some challenges to be met with AM of ceramic components. Other than most polymers and metals, ceramics are brittle and do not tolerate stresses especially when they are in a weak state during production. This means, that many well-established AM techniques cannot be directly used for production of ceramic parts.

AM techniques are divided into two categories: single-stage and two-stage methods. With two-stage methods the heat treatment, usually debinding and sintering, is performed separately after the printing of green parts, whereas with single stage methods the final material is produced in the printing process itself. E.g., Selective Laser Melting (SLM) is a well-established single-stage method for the production of metallic parts. With most ceramics the large thermal stresses occurring in the vicinity of the laser spot lead to cracks and inferior product quality. With two-stage methods, this issue is avoided. However, the heating process has to be carefully optimized to avoid warpage or cracking of the fragile green parts.

Besides net-shape production, other challenges of ceramic AM are the reliability and reproducibility of the processes. Taking into account that AM parts have to fulfil the same quality requirements as customary parts, some tasks have to be completed. Whereas AM of metals is already described in several standards, up to date no specific standard for ceramic AM exists. A VDI guideline on basic design rules for ceramic AM has been published recently [1], and currently a guideline for specific test geometries is in preparation [2]. An article focusing on quality issues with ceramic AM has already been published by the authors [3]. In the present paper, current AM techniques are compared in terms of key factors like product quality, production time, throughput and cost. Subsequently,

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*additive manufacturing, rapid prototyping, printing methods, additive manufacturing techniques, ceramic parts, Industry 4.0*

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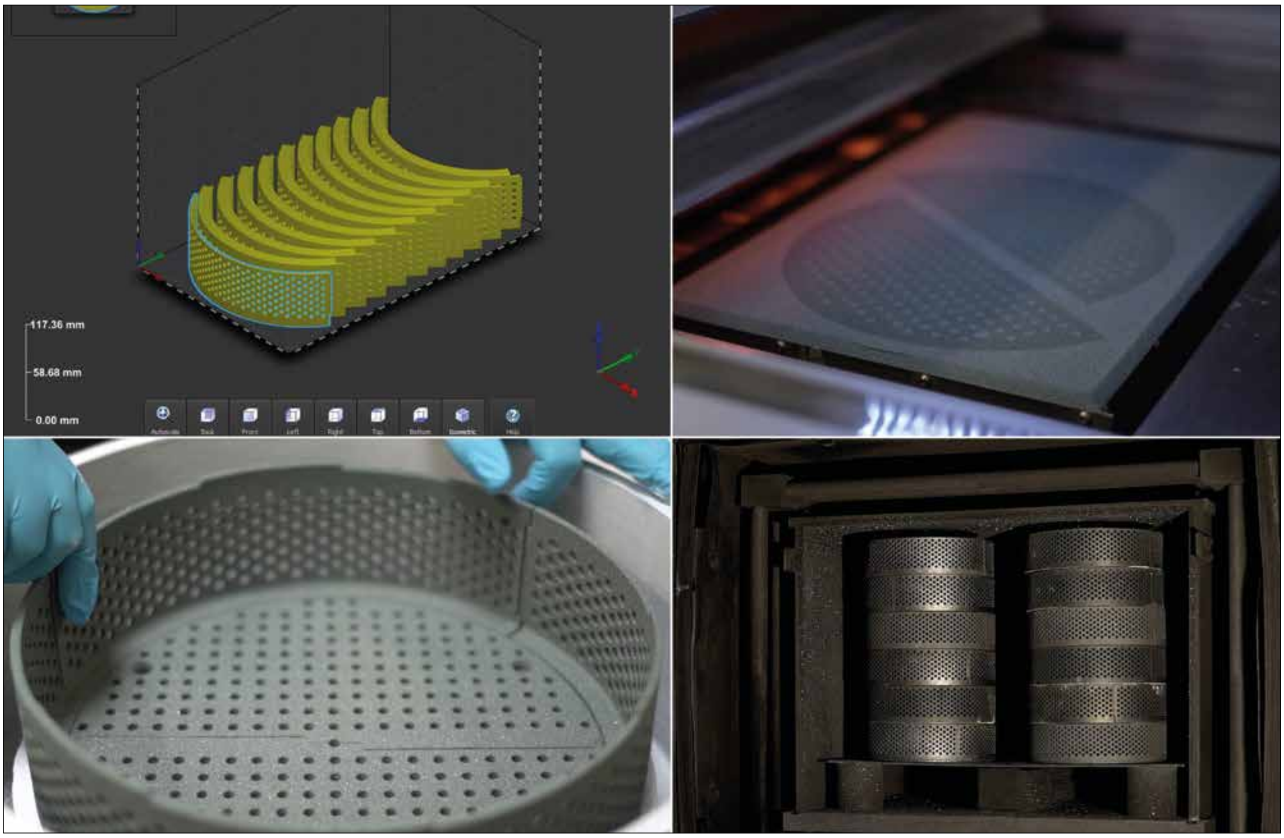


Fig. 1
*Example for cost-efficient production of SiSiC setters via part segmentation and packing (top l.), binder jetting (top r.), assembly and joining to larger components (bottom l.) and use in high temperature heat treatment (bottom r.)*

the potential of digitalization of the entire development and production chain is outlined. Finally, some new AM techniques developed especially for ceramic components are presented.

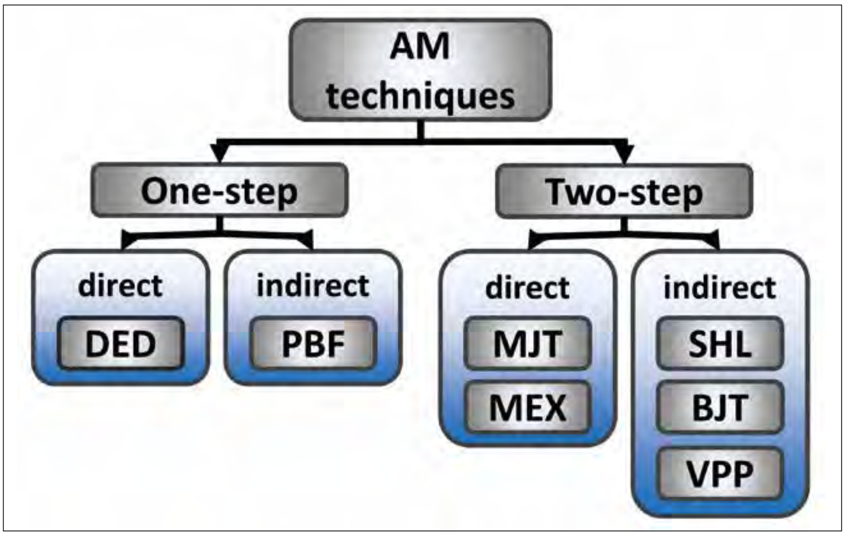


*Fig. 2*
*Classification of the seven AM categories into one-step and two-step respectively direct and indirect processes*

**Overview on AM methods for ceramics**

The existing AM methods have been classified in seven main categories: Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Material Jetting (MJT), Material Extrusion (MEX), Sheet Lamination (SHL), Binder Jetting (BJT) and Vat Photopolymerization (VPP) (DIN EN ISO/ASTM 52900:2018) (Fig. 2). The first two of these categories typically are used as single-stage processes, where forming and densification is done simultaneously. Selective Laser Melting (SLM) is the most widespread technique in PBF. It can only be used for ceramic AM processes strictly observing stress minimisation during laser treatment. For that, either scales have to be very small (thin coatings or very small parts) and/or densification is small and relies on melt formation (e.g., from eutectic compositions) or a viscous sintering mechanism [4]. The latter is typical for glassy materials. Directed energy deposition for ceramic AM basically has the same restrictions as PBF and is still at an early stage of development [5]. Therefore, PBF and DED are not considered in detail in this article.

The other five AM categories always require two stages, which means the green

*Tab. 1*
*Qualitative comparison of the seven different AM categories concerning ceramic AM: "++"= very good; "+"= good; "0"= average; "–"= poor*

| **Technology** | **Forming Principle** | **Building Speed** | **Build Volume** | **Resolution** | **Green Part Density** | **Surface Roughness** | **Manufacturing Cost** | **Feedstock Cost** |
|---|---|---|---|---|---|---|---|---|
| PBF | Powder fusion (laser) | – | 0 | – | – | – | – | + |
| DED | Powder fusion (laser) | – | – | – | – | – | – | + |
| MJT | Ink jetting | – | 0 | ++ | 0 | + | 0 | 0 |
| MEX | Feedstock extrusion | + | ++ | – | 0 | – | ++ | + |
| SHL | Preform lamination | + | + | – | + | – | 0 | + |
| BJT | Powder bonding | ++ | + | 0 | – | 0 | + | + |
| VPP | (Slurry) polymerization | – | 0 | ++ | ++ | ++ | 0 | – |

part forming process via 3D-printing and the final consolidation and densification are separated. They are subdivided into two additional categories: direct and indirect printing techniques. MJT and MEX are direct AM techniques, where the structure is deposited directly using either small droplets of a ceramic ink or extruded profiles of a ceramic feedstock. With MJT, an ink containing ceramic particles is jetted by one or multiple printheads. The inks can be water-, solvent- or polymer-based, and need to immediately consolidate after jetting in order to yield dimensionally stable green parts. A lateral resolution of down to 25 µm can been achieved.

This technology is particularly suitable for multi-material 3D-printing (multi-material jetting, MMJ). For example, cavities and support structures can be printed using a second ink, which can be completely removed after the forming process, e.g., by dissolution in a solvent or thermal decomposition during the heating process. However, the solid content of the processed inks is limited due to requirements concerning viscosity for jetting, and building rates are comparatively slow [6]. One interesting MMJ technology is the so-called Nanoparticle Jetting (NPJ), which is commercialised by Xjet. It uses a heated print bed which causes the carrier liquid of a nanoparticle-loaded ink to immediately evaporate after jetting, resulting in green parts with a packing density around 60 % and low organic content.

As the building speed is rather low (about 1,5 mm/h), it is particularly suitable for the simultaneous production of many small parts [7]. Another promising MJT technology on its way to commercialisation is thermoplastic 3D printing (T3DP), which uses heated print heads and thermoplastic suspensions as inks, which solidify upon cooling after deposition. Due to larger droplets, it has a smaller lateral resolution (about 200 µm) but allows for a significantly faster production with up to 4,5 $cm^3$/h per dispensing system [8].

MEX includes well known AM processes like Fused Filament Fabrication (FFF)/ Fused Deposition Modeling (FDM) and robocasting or Direct Ink Writing (DIW). In these processes, a highly filled cold plastic or thermoplastic feedstock in the form of filaments or pastes is extruded by a nozzle and selectively deposited. This allows for a much faster printing of large parts, preferably with closed part contours in order to avoid defects from extrusion breakup. However, the surface quality of the printed parts is limited due to the diameter of the extruded feedstock and its plastic deformation during the process. Therefore, these processes are particularly suited, e.g., for the 3D-forming of large lightweight support structures or elements for tissue engineering, whereas stress intensification in the contact area between the profiles is detrimental in the printing of compact bodies. All direct AM techniques need control of component dimensions during printing to exploit their full potential regarding net shape performance. However, so far this is not realised in most commercially available printers.

The remaining three categories SHL, BJT and VPP are indirect printing techniques, using the structuring of layers which are subsequently supplied to the building chamber. The direction perpendicular to the layers is usually denoted as z-axis. With SHL, ceramic green tapes are used as layers. They are structured by mechanical or laser cutting. The resolution in z-direction is limited by the thickness of the tapes and the cutting process to about 0,4 mm. Nevertheless, this technique has potential especially for the production of large, flat parts with limited degree of complexity. BJT is one of the fastest printing processes, enabling a printing speed up to more than 20 mm/h. It customarily uses a dry powder, which is spread in a thin layer on the powder bed by a doctor blade or a spinning roll. Structuring within the layers is done by selectively printing a binder system on the areas defining the component contour. The lateral resolution is about 60 µm, while the minimum layer height is essentially defined by the about twofold particle size. For the required flowability, the ceramic powders commonly need to have a particle size of at least 15 µm. Due to the low sinterability in this particle size range and the low initial packing density of about 50 %, dense ceramics are hard to obtain. Therefore, BJT is

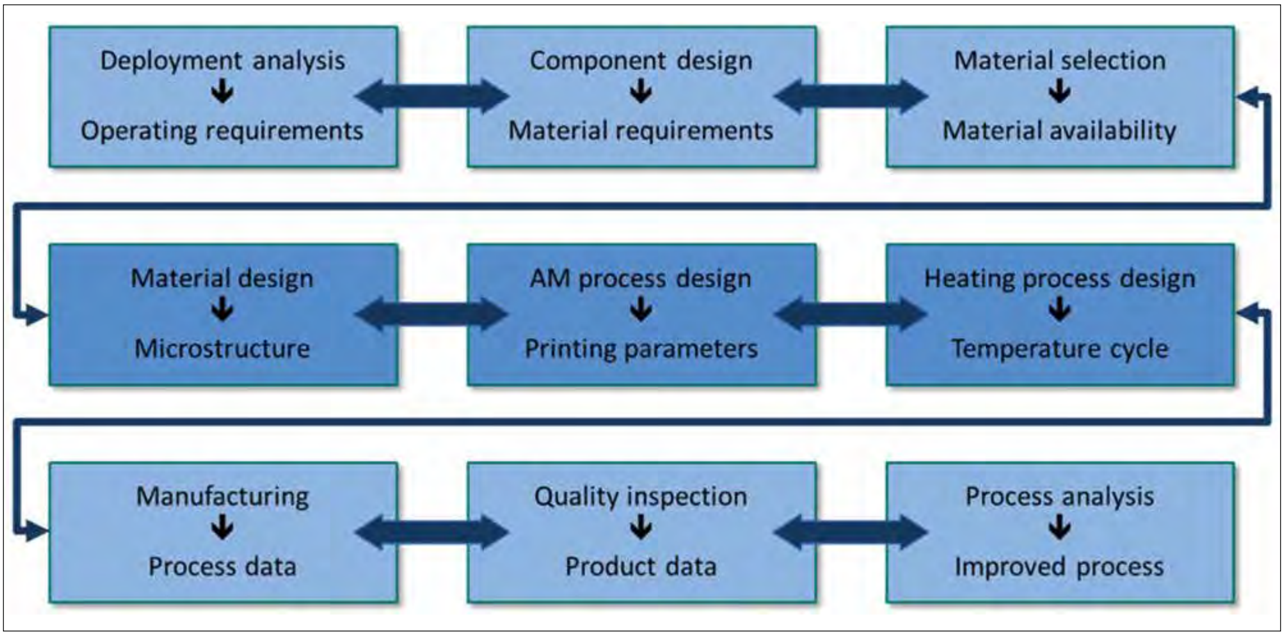


*Fig. 3*
*Process chain for digital development and production of AM parts*

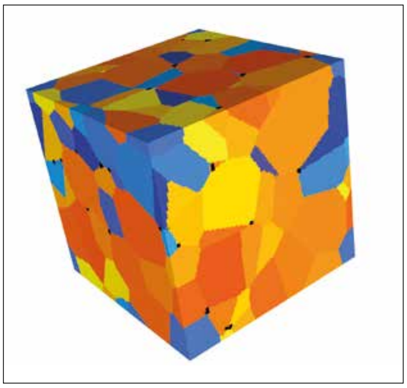


*Fig. 4*
*RVE of a two-phase ceramic material: yellow and orange grains represent one phase, blue grains the other phase*

particularly suited for the fast production of large, porous parts for applications with limited mechanical load. Nevertheless, one important route to yield dense parts via BJT is the infiltration of a melt into the porous compacts. E.g., recuperative burners/heat exchangers or lightweight kiln furniture are already produced via infiltration of a Silicon melt into porous SiC components made by BJT [9, 10].

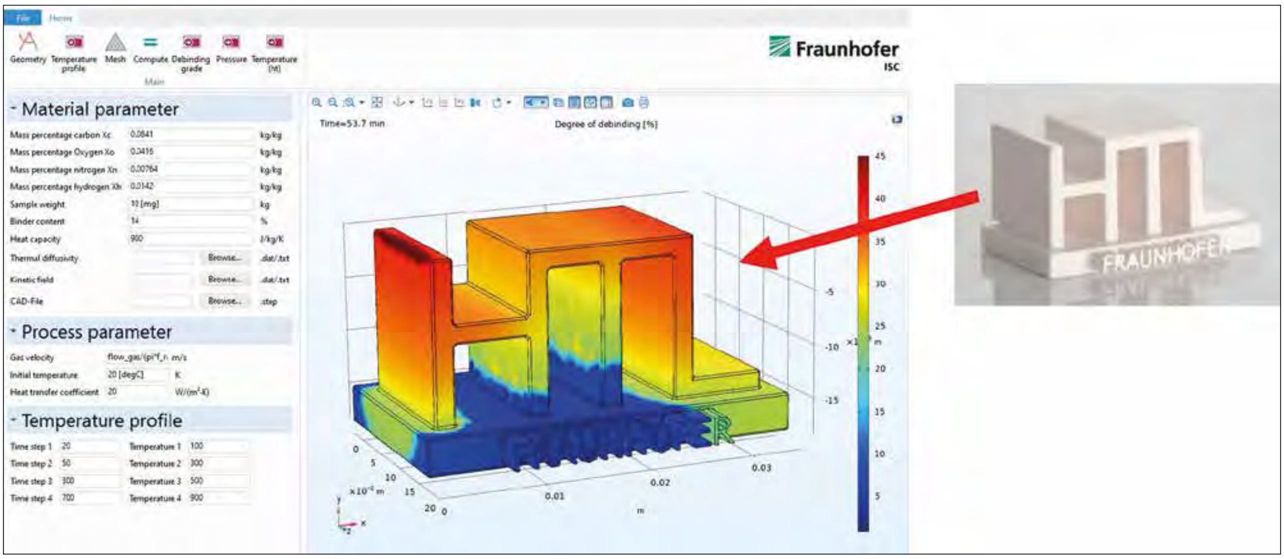
VPP, among them also Digital Light Processing (DLP), Layerwise Ceramic Manufacturing (LCM) and Stereolithography (SLA), is one of the ceramic AM techniques with the highest degree of maturity, as it has been in use for ceramic AM part production for more than one decade. All VPP techniques (except 2PP, see below) are based on thin layers of ceramic slurries which are formed by doctor blade technique. Structuring within the layers is done using curing of a photopolymer within the slurry by UV or visible light. The lateral resolution of VPP mainly depends on the optics used and light scattering, reaching down to <25 µm. Also, very good green densities >60 % are achieved. A specific disadvantage of the latter technique is the comparatively low building speed and high content of organic additives required in the ceramic slurries. The latter usually leads to slow debinding processes and limits wall thickness of structures to a maximum of about 10 mm. Nevertheless, the ceramic AM printer with the up to date largest building platform, which is commercially available, uses SLA [11].

Another technology belonging to VPP is Two- or Multiphoton-Polymerization (2PP or TPP), which uses the simultaneous absorption of two or more photons for initiating the cross-linking of a photocurable precursor material. Laser light is concentrated in a spatially localised spot in a bath of preferably liquid precursor material in order to initiate cross-linking. In moving the focal spot it is possible to write freeform structures into the precursor bath material with an extremely high resolution down to <200 nm [12]. Due to this (and its rather low building speed) it is rather suited for the fabrication of ceramic microstructures [13]. A common disadvantage of the three indirect two-step AM techniques is the poor adhesion respectively strength between the layers. The density in the interface region between the layers is lower than the density within the layers and structuring of the layers unintendedly affects neighbouring layers. For a deeper insight into the various AM techniques for ceramic AM the reader is referred to recent review articles [6, 14]. Some important criteria for their selection are summarised in Tab. 1.

## Digital production chain

AM is perfectly suited for a completely digital product development and production chain, which is a decisive competitive advantage over customary manufacturing technologies. It is a special CAD/CAM solution providing a perfect link between component design and component forming. Time to market is further significantly reduced using Integrated Computational Materials Engineering (ICME). ICME combines several computational and systematic experimental techniques to achieve a well-aimed development process [15].

The steps from first planning to small or medium batch production are outlined in Fig. 3. Whereas deployment analysis is usually done using communication techniques like QFD, TRIZ or design thinking [16], the next steps are essentially based on computational tools. Component shape



- Material parameter

Mass percentage carbon Xc 0.0841 kg/kg
Mass percentage Oxygen Xo 0.0416 kg/kg
Mass percentage nitrogen Xn 0.00764 kg/kg
Mass percentage hydrogen Xh 0.0142 kg/kg
Sample weight 10 [mg] kg
Binder content 14 %
Heat capacity 900 J/kg/K
Thermal diffusivity .dat/.txt
Kinetic field .dat/.txt
CAD-File .step

- Process parameter

Gas velocity flow_gas/(pi*f_n m/s
Initial temperature 20 [degC] K
Heat transfer coefficient 20 W/(m²·K)

- Temperature profile

Time step 1 20 Temperature 1 100
Time step 2 50 Temperature 2 300
Time step 3 300 Temperature 3 500
Time step 4 700 Temperature 4 900

*Fig. 5*
*Debinding app, exemplarily showing the degree of debinding of a LCM-printed logo of the Fraunhofer HTL upon fast heating*

is designed by Finite Element (FE) methods, where AM in particular offers completely new design possibilities, e.g., freeform surfaces, grid structures, undercuts and cavities. Topology optimization using automated tools like phase field or level set methods, genetic algorithms, density based as well as surface gradient methods is especially efficient for the construction of AM parts [17]. Note that there are some design restrictions, e.g., overhanging parts requiring support structures during printing and sintering which lead to a special Design for Additive Manufacture (DFAM) and the development of specific software [18].

The next step is performed selecting appropriate materials from material databases. E.g., a set of self-consistent material data together with highly developed tools for material selection is provided by the ANSYS Granta Selector database [19]. Thermodynamic compatibility can be checked using commercial software like FACTSAGE [20] or, more general, by CALPHAD methods, which are also available as Open-Source solutions [21]. Ab initio simulations get increasing importance since they produce material data in a very short time leading to databases with millions of phases [22]. Conflicting material attributes are systematically evaluated calculating material indices [23]. After selecting appropriate materials, their microstructure has to be designed. Microstructure design is particularly important in multiphase ceramics with high material contrast. Pores or grain boundary interphases can considerably affect thermal, mechanical and electrical behaviour of technical ceramics. Commercial tools for microstructure – property simulations are available. However, they often fail in the representation of special ceramic microstructures, since they are developed for use in metal and polymer science [24]. Computational methods for microstructure design following a bottom-up approach have already been validated for many ceramic systems [25, 26]. Fig. 4 shows an example for the basic element of this design technique, a Representative Volume Element (RVE) of the ceramic microstructure. A top-down approach, where materials composition, structure and processing parameters are derived from the product requirements is currently being developed [27]. For the control of the AM process, component geometry can be transferred directly from CAD models. Arrangement of components in building space can be optimized using 3D packing software [28].

During the AM building process, inline process monitoring will be an essential aspect to maximise the quality of the green parts produced [29]. For direct AM techniques and techniques without use of a powder bed, e.g. CCD cameras, stripe light projection, Optical Coherence Tomography (OCT) or Laser-Speckle Photometry (LSP) can be used for the observation of part contours, while the latter two also allow for the monitoring of defects [30]. Concerning the monitoring of PBF and DED processes,

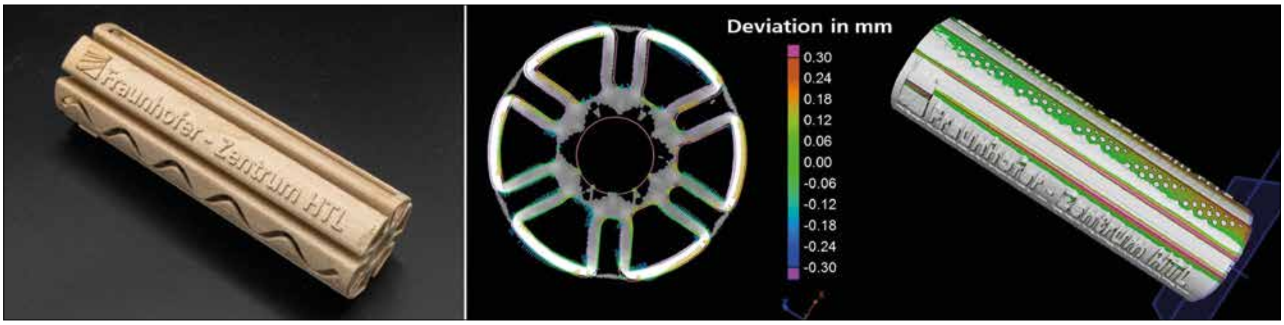


*Fig. 6*
*Demonstrator part fabricated via binder jetting (l.) and CT scan (r.), showing the deviation from the target dimensions in colour code*

developments for the AM of metals using techniques like pyrometry and optical interferometry can be transferred directly. In BJT, layer-wise powder bed imaging is essential for process monitoring [31]. The linkage of all acquired data to methods of artificial intelligence, especially machine learning, and its immediate feedback to the process will enable a sophisticated process control, which is crucial when part geometries vary continuously like in AM [32].

The next step, the design of the heating process for the printed green components is critical in achieving high quality ceramic parts. Debinding has to be carried out as fast as possible to minimise throughput time. But cracking and warping due to thermal stresses and overpressure typically correlated to high heating rates have to be avoided. Computational tools which are based on experimental data have been developed to enable careful optimization of debinding cycles [33].

After debinding, the ceramic parts are sintered to obtain a dense and strong microstructure. Shrinkage and deformations of the parts during sintering are simulated using an experiment-based continuum mechanic model. It combines a robust kinetic approach, a thermal FE simulation and the simulation of stresses and strains to predict final shape after sintering [34]. Application programs (apps) are developed by the Fraunhofer HTL for debinding and sintering enabling users to obtain optimized process parameters for different component shapes (Fig. 5).

Following thermal treatment of the parts, methods of quality assurance are applied. Especially when dealing with complex freeform structures, 3D-scanning tools are most efficient way to determine deviations from actual to target geometry. Various commercial 3D-scanners exist which can be easily used, and which can efficiently scan the outer part surface. However, especially if internal cavities are relevant, Computational Tomography (CT, Fig. 6) is the most powerful choice. The extracted data can be directly correlated with the part CAD models, and deviations can be highlighted graphically. This can be used to adjust CAD models for subsequent cycles, or to prepare subsequent steps for machining or polishing.

## New developments

One common goal in the R&D for ceramic AM is the fast and cost-efficient production

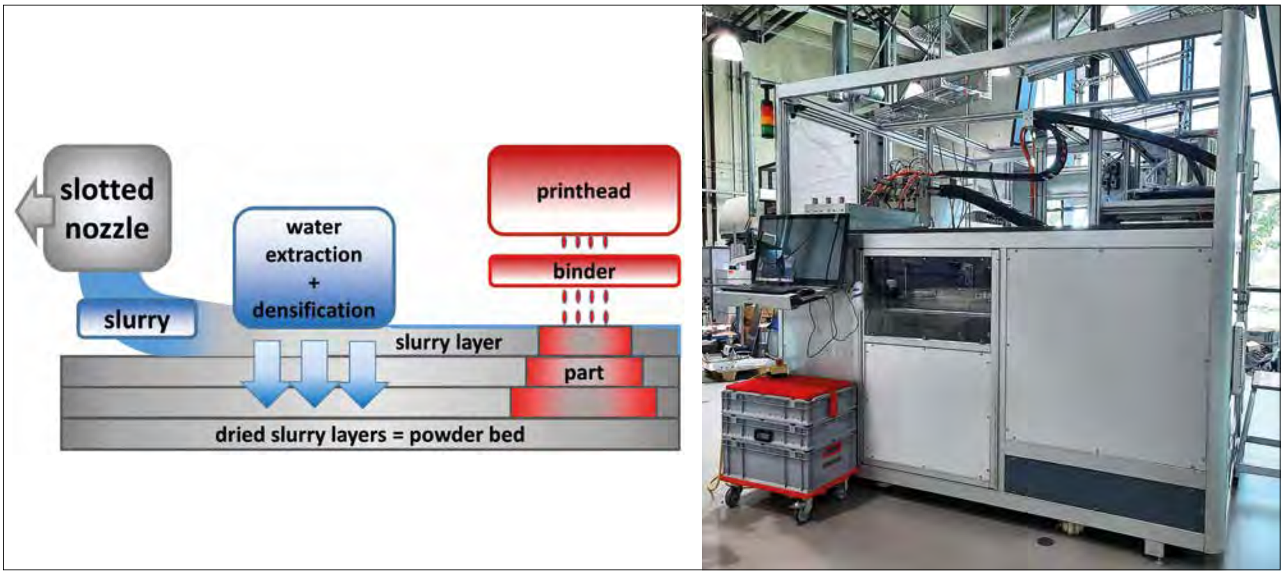


*Fig. 7*
*Schematic of the fabrication procedure in the FFS method (l.), and AM-machine based on FFS with a building platform of 35 cm × 50 cm constructed at the Fraunhofer HTL (r.)*

of ceramic parts with a high final density. Continuously, technologies get adapted, improved, and new technologies emerge along the ceramic AM process chain.

One promising technique in MEX is 3D-screen printing. Although being patented back in 1993, the commercial use for ceramics still has not been fully exploited. In using multiple screens, part layers down to 10 µm in height and down to 100 µm in wall thicknesses, are subsequently deposited. This perspectively allows for a fast and cost-efficient production of well-defined green parts with limited change in part cross section with packing densities close to 70 % at building rates even up to 1000 cm³/h. Also, multi-material printing is easily applicable. As specifically fabricated screens are used, 3D-screen printing is particularly suitable for the production of large batches [35].

As mentioned above, BJT also has an enormous potential for the large-scale industrial production of ceramic AM parts. Slurry-based BJT offers the possibility to overcome the drawbacks originating from the use of coarse, flowable powders in powder-based BJT, while being able to basically maintain the benefits from binder jetting like large building platform and high production speed. In using highly loaded ceramic slurries as a starting material, it is however able to achieve full part density. For that, different technologies have been developed. At the German BAM/TU Clausthal, the layer-wise slurry deposition (LSD) process has been developed. It uses the layerwise deposition of a slurry with a doctor blade onto a baseplate. The slurry layers are consecutively dried to yield a densified dry powder bed consisting of fine ceramic particles. After some initial powder layers, capillary pressure from dried precedent layers leads to increased dewatering of the applied slurry layers from below and to an increased densification of the particles via a slip-casting effect. This leads to increased packing densities beyond 65 %. As in binder jetting, a binder is applied via a printhead on top of each deposited dried layer. After printing, the parts are released from the powder bed before debinding and sintering [36].

Another development in this field is the so-called Laser-Induced Slip Casting (LIS) technique. In this technique, the part contour is defined by selectively evaporating solvent from a slurry reservoir with a laser, which causes particles to agglomerate in a controlled way. In doing so, e.g., silicon nitride parts with almost full density could be produced [37]. Despite being limited in its resolution, this process, which is easily scalable and particularly suitable for large ceramic parts, is currently being commercialised.

The Fraunhofer-Center HTL develops a similar process called Free Flow Structuring (FFS), which is based on an idea of Sachs et al. [38]. Instead of doctor blading, this process uses the application of slurry layers via extruder nozzles or slotted nozzle in a continuous slurry jet or slurry curtain. This prevents the formation of stresses or scratches in the green powder bed and prevents agglomerate buildup. After their application, the slurry layers are dried and a binder is jetted onto the dry powder layers in order to define the part contour. Fig. 7 shows a scheme of the FFS method and an FFS machine with a building platform of 35 cm × 50 cm constructed at the Fraunhofer HTL.

As outlined in the chapter above, the integration of AM into a fully digitalized process chain will be the key for a flexible, efficient and application-oriented production of ceramic parts in the future. The implementation of digital twins in the production allows for the anticipation of errors and conflicts along the process chain and prevents time and resource consuming development cycles. A direct digital coupling of part design and digital manufacturing twins enables the preselection of suitable printing parameters, estimation of time and resource demand, and provides a basis for lean production planning.

As most of the AM technologies for ceramics are two-step processes, these developments also need to include digital twins for thermal treatment, which is crucial for final part quality. Based on thermal data of the furnace and sintering aids and the existing models for debinding, sintering and melt infiltration, this allows for a precise simulation of the thermal treatment of multiple, also different parts in the furnace. This will be especially of concern for the simultaneous thermal treatment of individual AM-based parts.

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