3D Screen Printing of Solar Absorbers Made of SiSiC, Sintered in an Efficient High-Performance Furnace

L. Birkigt, J. Hennicke, R. Kirchner

New manufacturing methods like 3D screen printing allow for the development of new unique designs with optimized features. In the present paper the core component of the central receiver system in solar thermal power plants like the Solar Tower Jülich – the porous absorber structure – was optimized. The layer-wise printing process allows for the adjustment of form and shape between layers and therefore purposefully varying its geometry along the airflow direction of the volumetric absorbers. By doing so, important properties like the penetration depth of the incident solar irradiation will be improved [1].
This new design with delicate, fine-structured parts calls for innovative sintering methods, on the one hand, to maintain the high quality of the 3D-printed parts, and on the other hand to ensure cost-efficiency of the sintering process. Only in this way the 3D-printed components can successfully be introduced in a wide range of mass applications.

Introduction

New optimized components can only be as good as current manufacturing technologies allow. Therefore, new designs with advanced micro-geometry become technically and economically feasible as manufacturing technologies improve. By combining the optimized volumetric receiver proposed by Capuano [2] with the possibilities of the innovative manufacturing technology of industrial 3D screen printing by Exentis, the German Aerospace Centre, Institute of Solar Research, in cooperation with Exentis, developed the so-called StepRec absorber design. The flexible material selection of the above-mentioned technology allowed for the better-suited absorber material SiSiC. To ensure economic feasibility the sloped pins are replaced by three “step”-like sections (as shown in Fig. 1) since every change in geometry requires a new screen and minimizing the number of screens reduces set-up time and overall screen cost. The present absorber is designed according to the “HiTRec” receiver technology where the receiver is made up of thousands of small modules [3].

3D screen printing of solar absorbers

Exentis Group AG is the inventor of Exentis 3D Mass Customization, an innovative manufacturing technology of industrial 3D screen printing, which can produce fine ceramic structures by layer-wise build-up. By changing the screen with different layouts, complex and at the same time delicate structures are possible, such as the solar absorber with 3-way stepped spikes, which in the finest structure has a web width of 440 µm (as a green body). But even more delicate structures such as walls with a thickness of a minimum of 100 µm can be realized with this technology. A variety of metals, polymers, and ceramics can be processed due to the adaptability of the developed paste recipes for this process.

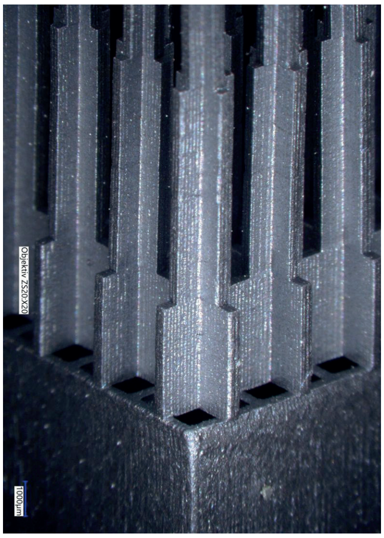

Fig. 1 Step-like pins printed with different screens

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The concept of 3D screen printing is as follows. Like conventional 2D screen printing, it involves creating a stencil on a fine mesh screen and then pushing a specially developed paste through the printing screen, to create an imprint of the design on the surface beneath. In the case of 3D screen print-

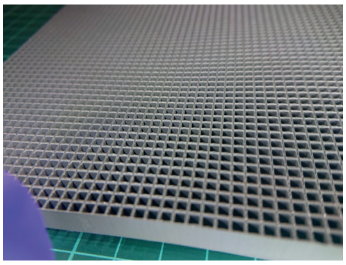
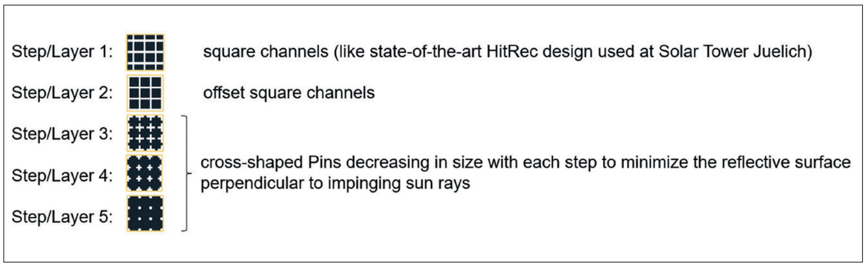


Fig. 2 Grid-like green body with a still wet freshly printed layer on top



Step/Layer 1: square channels (like state-of-the-art HitRec design used at Solar Tower Juelich)
Step/Layer 2: offset square channels
Step/Layer 3:
Step/Layer 4:
Step/Layer 5:
cross-shaped Pins decreasing in size with each step to minimize the reflective surface perpendicular to impinging sun rays

Fig. 3 Schematic view of the 5 different layer designs

ing, this process is repeated while the printing screen is very precisely moved upwards along with the layer-wise "growing" part. In Fig. 2, a grid-like green body is shown with a still wet freshly printed layer on top. The flexibility in material selection is possible due to applying pastes, which usually combine the desired material in powder form with binder and other additives.

While the concept is straightforward, the actual printing of 3D parts requires a precisely tuned process, including highly developed machines, paste, screens, and printing parameters. For example, in the case of the solar absorbers, a specialized paste containing SiC and additionally carbon powder for better infiltration needed to be developed and optimized for fine structures as well as the best possible green body stability. So, the thin pins would withstand layer-by-layer printing and further processing. To accomplish the varying geometry, five different screens are used.

The base channel width of 2,29 mm and the wall thickness of 0,44 mm stay constant, but as shown in Fig. 3 layers 1 and 2 are grid-like forming offset square channels. Layers 3–5 are cross-shaped pins decreasing in size, to minimize the reflective surface area perpendicular to impinging sun rays. The final product is shown in Fig. 4, and a closeup of the top part can be seen in Fig. 5. After optimizing the printing parameters on a small laboratory machine, the industrial 3D screen printing developed by Exentis allows for easy scale-up of production volume by transferring the process to an Inline production unit.

Thermal processing of 3D screen printed absorbers

The solar absorber, which can be made of SSiC or SiSiC, is sintered at FCT Systeme GmbH. FCT Systeme is a producer of innovative high-temperature furnaces for sintering predominantly non-oxide materials. Together with Exentis, FCT developed efficient sintering methods, specially designed for filigree, fine-structured parts. Besides the optimized process, FCT also integrated a fast-cooling system in order to guarantee an economic production of the parts.

As mentioned above, SiSiC (Silicon Infiltrated Silicon Carbide) is a very well-suited absorber material. It is manufactured by infiltrating a molded part made of silicon carbide and carbon with liquid silicon, with virtually no shrinkage of the part, in contrast to classical sintering. The infiltrated silicon melt is partially reacting with the free carbon to secondary SiC. The other part fills the remaining pore structure almost completely. The resulting, nearly pore-free material consists of two interpenetrating phases (80–95 % primary and secondary SiC + silicon). This special microstructure leads to high thermal conductivity and strength, making it insensitive to thermal shock. Additionally, corrosion and wear resistance is high. All these are key properties for high-performance solar absorbers.

After the 3D screen printing process, the green absorbers (Figs. 4–5) consist of silicon carbide, carbon and a relatively high amount of organic binders, which give the filigree printed parts sufficient strength for handling without damage. To allow the subsequent silicon infiltration, this binder must be removed at first. But in the debound state, the filigree parts are very sensitive and difficult to handle without damage.

That is why the thermal processing of the absorbers is carried out in a so-called combi-process, in which the debinding and infiltration are carried out in the same process and furnace, without having the parts to be moved between debinding and infiltration.

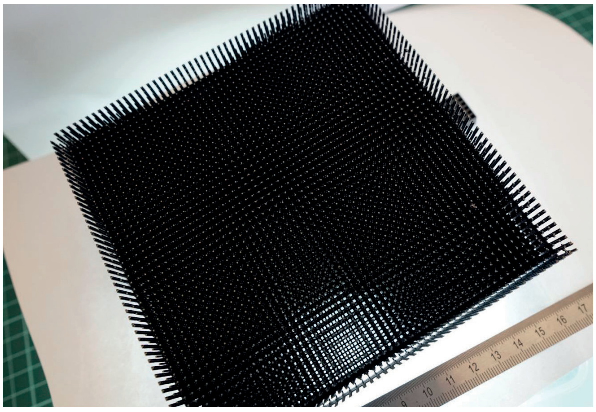


Fig. 4 Final solar absorber in transmitted light to show the continuous channels

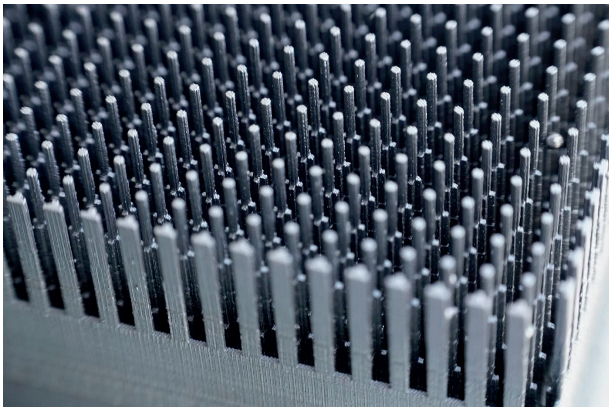


Fig. 5 Closeup of the top part with pins

This greatly reduces the number of broken parts, and at the same time, it results in much better overall efficiency, by reducing the heat treatment to one thermal processing step instead of two separate ones (debinding, infiltration).

Of course, the furnace must be specially designed to be able to support the different requirements of the combi-process steps. For example, special gas vacuum management as well as precise temperature control are of crucial importance for a complete infiltration, and thus optimal material quality. The exhaust gases generated during the combi process must be managed inside the furnace appropriately, not to impair the service life of the furnace. This is especially important for high-volume mass production. For the same reason, the furnace must be equipped externally with an appropriate exhaust gas treatment (thermal post-combustion and dust separator).

Fig. 6 shows a typical example of such a batch furnace equipped with the above-mentioned features, in this case with a size of 400 l of useful volume. The material quality and the overall efficiency of the process do not only depend on a suitable furnace/peripheral design, but are also decisively influenced by the configuration of the components to be infiltrated in connection with the supply of liquid silicon during the infiltration. With different methods (crucibles, wicks, etc.), the supply of liquid silicon during the infiltration must be optimally matched to the component shape and size. This is the only way to ensure, that the free carbon reacts as completely as possible to SiC and that the remaining pore space is filled as completely as possible. On the other hand, the component should not be soiled with excess silicon sticking at its surface, since this would entail a high cleaning effort (Fig. 7). The described relationships between process requirements and its demands on the furnace design are listed in Tab. 1.

Fig. 6 Batch furnace, specially equipped for thermal processing of SiSiC 3D screen printed parts

Increasing the efficiency of thermal processing for mass production of 3D screen printed parts

In ceramic technology, thermal processing not only significantly influences the key properties of the final part but has also a huge impact on energy consumption and required equipment. Hence thermal processing massively influences the overall process cost. This indicates the huge relevance of the efficient design of the thermal processing step, also in the case of 3D screen printed parts, e.g. solar absorbers. The main influencing factors are:

- Batch size (useful capacity of the furnace);
- Cycle time;
- Feed time;
- Availability rate;
- Shift operation;
- Scrap rate.

Regarding the "effort", it is not sufficient to consider the energy consumption alone (energy efficiency), although this is one of the most important aspects. Instead, a holistic view of effort is becoming increasingly accepted (TCO = Total Cost of Ownership or LCC = Life Cycle Costing), which generally covers the following factors:

- Investment costs (equipment, kiln furniture, auxiliary units, infrastructure);
- Expected useful life;
- Disposal of equipment;
- Required space;

Tab. 1 Relationships between process and furnace requirements for SiSiC

Process requirements	→	Furnace requirements
➢ Debinding (organics of printing process)	→	Exhaust gas guidance within the furnace
➢ Liquid silicon infiltration	→	Vacuum controlled atmosphere
➢ Control of silicon supply	→	Optimized set-up (e.g. coatings, wicks, …)
➢ Formation of secondary silicon carbide	→	Precise temperature control
➢ Evaporation of inorganic substances	→	Exhaust gas guidance within the furnace
➢ Formation of exhaust gases	→	External exhaust gas treatment (thermal post-combustion, dust separator)

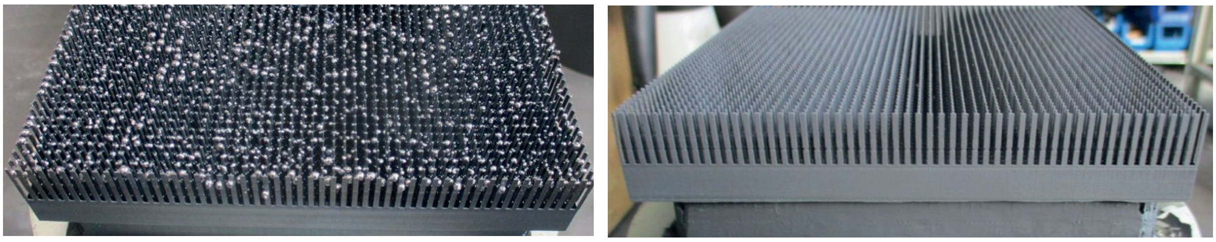


Fig. 7 SiSiC absorber with excess silicon (l.), and after optimization of infiltration configuration (r.)

Fig. 8 Twin furnace, specially equipped for thermal processing of C/SiC and SiSiC parts

Fig. 9 Several equally sized batch furnaces, forming a "quasi-continuous" sintering technology network

- Costs for consumables (energy, auxiliary media, e.g., protection gas, cooling water, etc.);
- Disposal of potential waste or exhaust gas;
- Personnel costs;
- Service, repair, and spare part costs (e.g., kiln furniture);
- Cost of regular and unscheduled downtime.

The above-mentioned influencing factors show that the efficiency of a sintering facility depends critically on how carefully the sintering technology is selected and how precisely its design is matched to the respective application. This selection and matching are forming the basis of the company strategy at FCT Systeme GmbH [5].

Here for nearly 30 years sintering facilities for engineering ceramics and powder metallurgy are not only built. Rather very early during project planning, technological development is performed in close collaboration with the customers and with the use of the company's well-equipped pilot plant lab [6].

This customer service ranges from simple feasibility tests to pilot production under real industrial conditions if required. The result is a complete package of optimally matched sintering technology and equipment design, ensuring the user obtains a tailored, highly efficient sintering technology.

A core consideration in the design of sintering facilities is the realization of the required productivity. Here it is often not advisable to try to reach the required productivity with the use of one single, big sintering furnace. It is often much better to split production between more than one, identical small-size furnaces operated parallel (downsizing). Small furnaces have lower electrical connection power as well as shorter cycle times, which increase productivity compared with a single big furnace and benefit product quality in many cases. Furthermore, the potential downtime of just one of several smaller furnaces is much less significant.

The twin-concept is one step in this direction. It is based on the pair-wise aggregation of furnaces using a common process control system, power supply, gas and vacuum supply, thermal post-combustion (if required), etc. Now every single furnace is no longer independent, but significant costs can be saved because the single steps of thermal processing (heating, debinding, dwell time, cooling) don't need every peripheral for full-cycle time. With a respective time offset of the sintering cycles, a twin system shows practically the same productivity as two single furnaces, but at a lower price. This concept has proven itself in many industrial applications.

Fig. 8 shows by way of example an industrial twin furnace used for pyrolyzing and siliconizing C/SiC brake discs. The process and furnace requirements of this process are very similar to the case of 3D-printed SiSiC parts, described above (Tab. 1). Each of these furnaces provides 4000 dm^3 useful volume, using a common process control system, power supply, gas and vacuum supply, and thermal post-combustion.

Depending e.g., on the ratio of heating, dwell, and cooling duration, in some cases even three furnaces can be combined to one assembly. Of course, even several such assemblies can be combined to form a "quasi-continuous" sintering technology network (Fig. 9). In this case, the potential downtime of just one of several assemblies is much less significant, and the advantages of both concepts can be harnessed.

In industrial thermal processing, real continuous sintering technology, e.g., roller or push cup kilns, are state-of-the-art for many years. But in SiSiC or other engineering ceramics, special features are required as described above (Tab. 1). In continuously working furnaces these requirements can only be realized with high technical effort, making the equipment expensive, complex, difficult to operate and service as well as susceptible to failure and malfunction. Because even small continuous furnaces have high productivity, any downtime results in a significant loss of productivity, like the failure of a large batch furnace, as described in the last section.

All these facts are, in the authors` view, arguments against real continuous furnace technology in engineering ceramics. In contrast – as explained in the last section – a larger number of small furnaces working in parallel with a smart time offset can facilitate "quasi-continuous" sintering technology, which works in effect more robustly, reliably, and uniformly.

Conclusion

New innovative manufacturing technologies like the industrial 3D screen printing developed by Exentis Group AG together with optimized thermal processing and specially developed furnaces by FCT Systeme GmbH allow the production of yet unthinkable geometries in a variety of materials.

Both technologies are now available at the highest Technology Readiness Level (TRL), allowing a successful introduction of 3D screen printed components made of high-quality ceramic material in a wide range of mass applications. Therefore, with these capabilities in mind, future projects can shift the boundaries of what is possible even further.

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