

MATERIALS AND PROCESSES

ADDITIVE MANUFACTURING OF CERAMIC COMPONENTS

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In the field of polymers and metals, additive manufacturing methods are already established and used for manifold applications. For ceramic materials, additive manufacturing, i.e. layer-wise assembling of components from CAD data, is gaining more and more importance, especially as resource-efficient manufacturing method. Nevertheless, additive manufacturing methods for ceramics are right at the beginning of technological development. The present design of ceramic parts is limited by the opportunities of the conventional shaping techniques so far. In contrast, additive manufacturing offers the possibility to produce components of extremely complex geometries, which cannot be obtained by conventional shaping routes. A main advantage of additive manufacturing techniques can be seen in the tool-free shaping methodology. This means that either single components or small series of parts can be produced efficiently without high tooling expenses. Beside the geometrical variety, components with a high position-resolved property profile can also be manufactured by changing the material composition at each freely chosen point of the component. This will provide novel functionalized and individualized ceramic components as single parts or small series for many technical and medical applications in the near future.

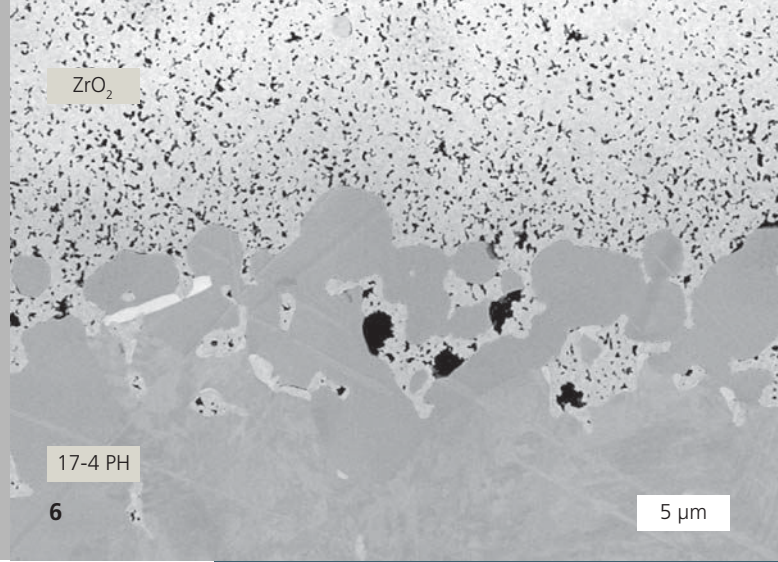
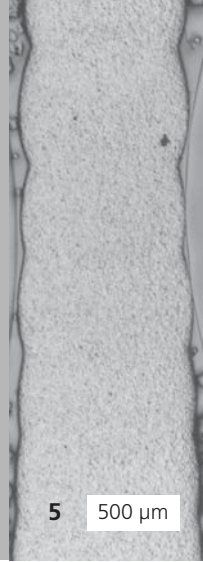
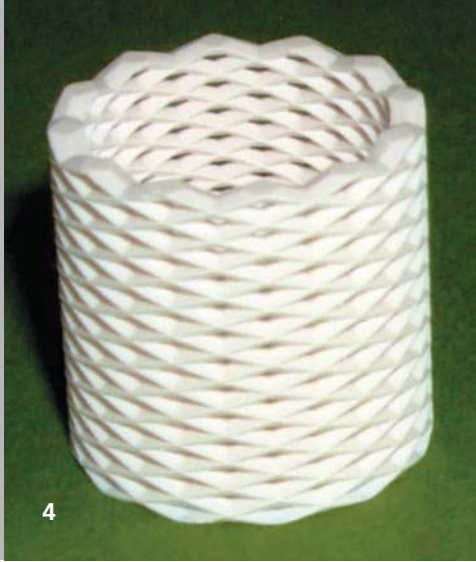
Suspension-based additive methods

For producing dense materials structures with a high level in mechanical properties, additive manufacturing methods have to be used based on suspensions and pastes allowing a very homogeneous distribution of ceramic particles and a possibly high volume content of powder in the suspension media. A very promising method for attaining dense ceramic components with properties which can be compared to conventionally dry-pressed parts is the digital light processing (DLP). Initially, the ceramic powder is homogeneously dispersed in a photo-curable organic binder system. Via selective exposure of this suspension by means of a micromirror, a ceramic green body according to the CAD model is built.

Lithography-based ceramic manufacturing (LCM)

The DLP principle described above is adapted by a device (CeraFab 7500, Lithoz GmbH, Vienna), which is used at Fraunhofer IKTS. This method, which has especially been developed for additive manufacturing of ceramic components, is called lithography-based ceramic manufacturing (LCM). In the device, the layer thickness of the suspension can be varied between 25 µm and 100 µm, the lateral resolution is 40 µm. As known from stereolithography, a radical polymerization of the binder system is initiated by selective exposure with blue light by means of the DLP modulus. All regions of a layer necessary for constructing the desired component are cured simultaneously by this method. In this way, the productivity of this technique can be increased in comparison to the dot-wise exposure by means of a UV laser beam in stereolithography.

The suspensions used for LCM show relatively high solid contents allowing green densities of the components up to 55 %. Since the components are made upside down in hanging position in the LCM method, the suspension volume necessary for the production process is relatively low, which is important for resource-efficient processing. After curing the bottommost layer close to the bottom of the glass vessel containing the suspension, the component is raised by a distance corresponding to the thickness of the next layer. A novel suspension layer is now applied by a doctor blade, which is exposed in the next processing step. At present, three different ceramic materials can be processed using the LCM machine: alumina, zirconia and tricalciumphosphate. Densities achieved after sintering of the debindered green bodies are 99.4 % theoretical density in the case of alumina and 99.0 % theoretical density for zirconia. For efficient curing of the binder polymer by exposure to blue light, the ceramic particles dispersed in the binder must not absorb the radiation. For that reason, dark ceramic powders are strongly limited for use in the LCM process.



Thermoplastic 3D printing (T3DP)

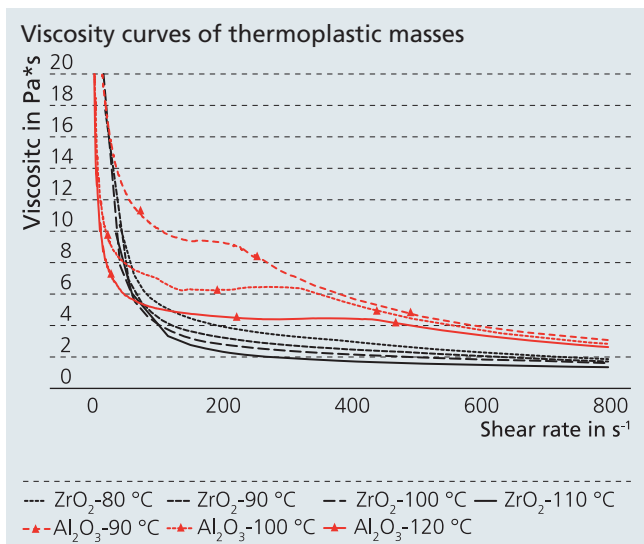
Thermoplastic 3D printing is a new approach Fraunhofer IKTS follows, which excludes the limitations of the above-mentioned method. This approach bases on highly particle-filled thermoplastic suspensions with relatively low melting temperatures (80 – 100 °C). The viscosity of these suspensions should be relatively low compared to thermoplastic feedstocks used for conventional fused deposition modeling (FDM) as shown for a zirconia feedstock (Figure 4). In T3DP, the material is only applied to these positions where it is needed for construction. A heatable dispensing unit assessable in three axis is moving over a fixed platform carrying a metallic or glassy plate as carrier for the ceramic part. The thermoplastic suspension is molten in the dispensing unit for attaining a sufficient flowability and solidifies immediately when cooling down. For that reason, the solidification of the feedstock takes place almost independently from the physical properties of the ceramic powders. Binding between the single layers applied in this way is excellent (Figure 5). Thermoplastic feedstocks developed for this purpose show a solid content of 67 vol.-% in the case of alumina powder ($d_{50} = 1.5 \mu\text{m}$) and 45 vol.-% in the case of zirconia powder ($d_{50} = 0.3 \mu\text{m}$), respectively. For both materials, samples have been made by T3DP, debinded and sintered showing densities of 97.3 % theoretical density (alumina) and 98 % theoretical density (zirconia). By using two or more containers for the suspension and two or more dispensing units, different materi-

als can be applied by this method for attaining multi-material components. Furthermore, also functionally graded materials can be manufactured in this way. Differences in the shrinking behavior of the materials can be adjusted by the solid content of the different feedstocks or by adjusting the particle size distribution and the particle shape, if necessary. First positive results could be attained for components consisting of a material combination of zirconia and stainless steel 17-4PH (Figure 6) showing the potential of T3DP for manufacturing multi-component parts with multifunctional properties.

Powder-based additive manufacturing

3D printing

In this manufacturing method, a thin powder layer is applied by a doctor blade. Afterwards, the powder particles are glued by a binder solution added to the powder bed by a printing head. Densification of the powder particles during this 3D printing process is relatively low, i.e. completely densified ceramic components cannot be obtained by this method. 3D printing is, for instance, used for manufacturing porous bioactive ceramic structures made of hydroxyapatite. Furthermore, the production of components for filtration applications, as catalyst support and for complex shaped ceramic cores or molds for investment casting is possible. Fraunhofer IKTS uses a commercially available 3D powder bed printer with a construction area of 350 x 250 x 200 mm³ and a minimum layer thickness of 87 µm.



- 1 LCM method: Demonstration part processing.
- 2 LCM method: Al₂O₃ honey comb structure.
- 3 CT reconstruction (detailed) of the mixing structure from figure 2.
- 4 LCM method: Open-cell structure Al₂O₃.
- 5 Thermoplastic 3D printing: Al₂O₃ layers.
- 6 Thermoplastic 3D printing: Interface ZrO₂ steel.



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Selective laser sintering (SLS)

For selective laser sintering, a powder bed is applied by a doctor blade, too. The selective solidification by means of a laser beam results in a dense material structure for ceramic powders, which contain a liquid phase forming additive, e.g. mixtures of $\text{Al}_2\text{O}_3/\text{SiO}_2$. Moreover, the laser sintering process can be used for simply attaining ceramic green bodies. For example, complex shaped SiC components were made by means of a CO_2 laser. The porous structure was infiltrated with liquid silicon forming SiSiC. The properties of these components are comparable to SiSiC parts made by conventional shaping techniques like dry pressing, green machining and finishing.

Laminated object manufacturing (LOM)

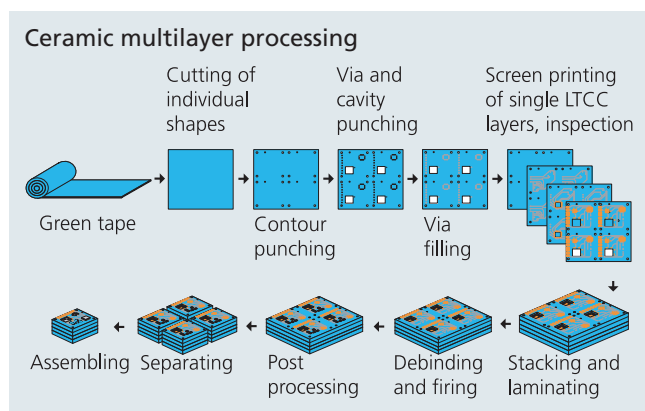
LOM or multilayer technology has been applied at Fraunhofer IKTS for more than 15 years. Beside the opportunity to obtain 3D-structured components, this method offers a layer-wise integration of further materials and an opportunity for embedding different functionalities, like conducting paths, passive components (R, L, C), heaters and sensors. For LOM, ceramic single or multilayer tapes are produced initially, structured layer by layer subsequently and provided with the necessary functional structures by sieve and mask printing. By stacking and laminating the single layers, the desired 3D component is generated. Fields of application of LOM are, for instance, ceramic and glass-ceramic multilayer wiring supports for high-frequency and power applications, multilayer capacitors and chokes, piezo electrical stack actors, microfluidic components for medicine and biotechnology, such as various physical and chemical

sensors. The spectra of materials for LOM technology is very wide both for the ceramic tapes (LTCC – low-temperature cofired ceramics, HTCC – high-temperature cofired ceramics) and functional pastes.

Fraunhofer IKTS covers the complete process chain starting with the initial material over simulation-based component design and manufacturing technology to functional testing and system integration. Present focal points in LOM technology are further miniaturization of components, e.g. for MEMS packages on wafer level (see Figure 10), which demands an increase in the structural resolution of the used manufacturing technologies, a forced integration, such as 3D printing of passive components, and integration of non-electrical functions in multilayered assemblies, like chambers, channels and membranes by using sacrificial materials.

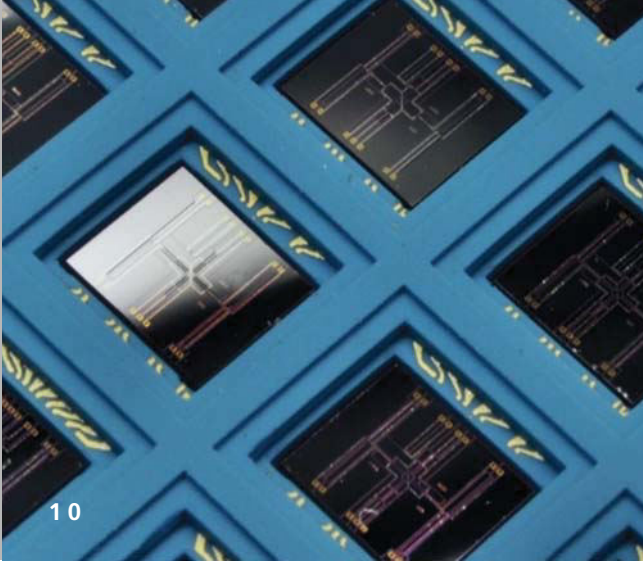
Combining laminated object manufacturing with other shaping techniques established at Fraunhofer IKTS (for instance ceramic injection molding) offers additional chances for production of complex shaped, multifunctional, miniaturized and customized ceramic 3D components.

Key technologies for functionalization of above-mentioned 3D components are digital printing methods, which allow providing free-formed surfaces with desired functional structures in high resolution. For that purpose at Fraunhofer IKTS, different microextrusion and dispenser methods, such as ink-jet and aerosol-jet technologies, are available. Especially the aerosol-jet technology is suited for coating of 3D and free-formed surfaces with functional structures, e.g. conducting paths, R, L, C, sensors, etc.. This method bases on atomizing particle-containing and particle-free inks in microscale. The droplet flow generated in this way is focused in the printer head (diameter $< 10 \mu\text{m}$). Due to the comparatively high waist length of 1–3 mm, geometrical steps can be overprinted, functional structures can be written and fibers can be coated.

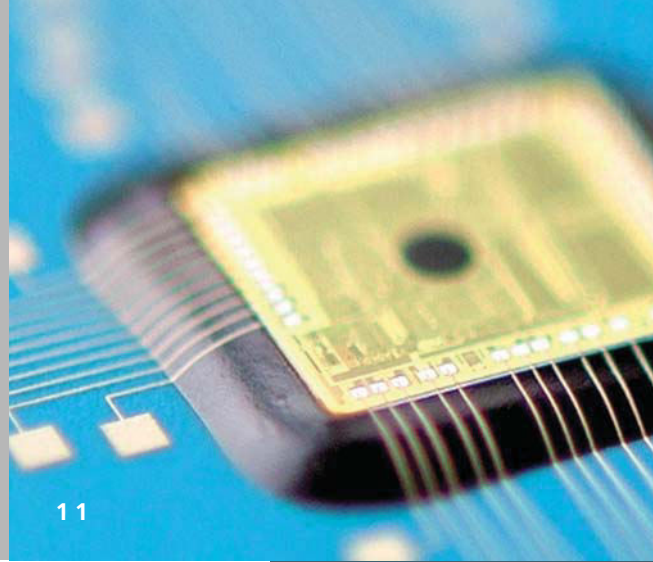


Conclusion and outline

Additive manufacturing methods open new horizons in design and construction of ceramic components. Due to the tool-free shaping technology and the layer-wise assembly of components, additive manufacturing methods are working especially



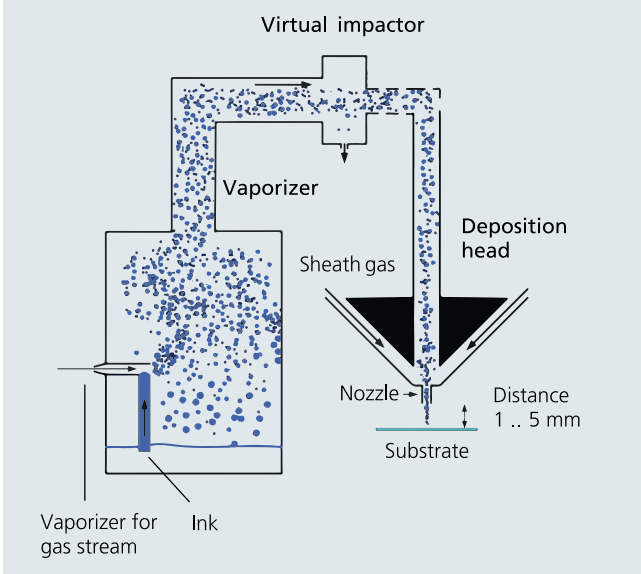
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Schematic sketch of the aerosol-jet method



resource- and cost-efficient and almost without waste. These are the reasons for an increasing interest in using additive manufacturing methods for production of individualized components, single parts or small series. The possible applications are manifold ranging from medical, patient-specific instruments or implants to special tools or customized jewelry and luxury goods. The trend in the field of ceramic materials goes to increasing the material portfolio, enlarging the dimensions of the manufactured products by increasing the building area of the AM machines and improving the properties of the manufactured components, i.e. improved surface quality and enhanced mechanical properties. For an increasing multifunctionality of ceramic components multi-material applications for the combination of different properties will play a growing role.

By further work on material and technological development, it will be possible to exploit the huge innovation potential of additive manufacturing also for ceramics and to foster its industrial application. In this development process, Fraunhofer IKTS will be a competent and innovative research partner for both ceramic component producers and applicants.

- 7 LCM method: Al_2O_3 mixing structure.
- 8 3D printing: Demonstration component (petrous part) from hydroxylapatite, data of Phacon GmbH.
- 9 Selective laser sintering: Detailed picture of SiSiC tool usage.
- 10 MEMS packages on wafer level.
- 11 Chip bonding via aerosol-jet printing.