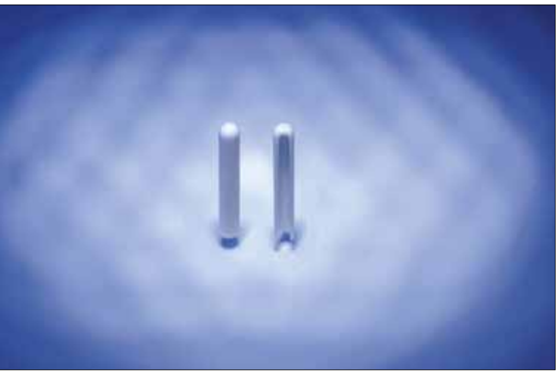

Fig. 3
Ceramic sleeve
(wall thickness: 0,2 mm; length: 18 mm)

ceramic injection moulding components in series. From development and simulation through design, the proprietary mouldmaking and the production up to adapted preliminary debinding, debinding and sintering. Whoever comes to Kläger with regard to powder processing, is given comprehensive support from the very beginning – to the finished component in series production!

Links between ceramics and plastic injection moulding are found in the process: Basically, plastic and ceramic materials can be processed in a similar way. The ceramic components have to be debinded after injection moulding and sintered to achieve their final shape and strength. Kläger has its origins in plastic injection moulding. Consequently, all customers can draw on sound knowledge and comprehensive engineering expertise from the two worlds for an ever individual process support.

In plastic injection moulding, Kläger currently processes over 300 different materials in over 2000 active articles. One focus are technical plastics, for which Kläger has a high material and process expertise, also for the substitution of metals with plastics. The injection weights range between 0,1 g – 450 g.

Fused Filament Fabrication (FFF) of Technical Ceramics

Fused Filament Fabrication (FFF), also known as FDM® is a thermoplastic Additive Manufacturing (AM) method in which an endless filament is used as a semi-finished product which is melted and deposited under a heated nozzle.

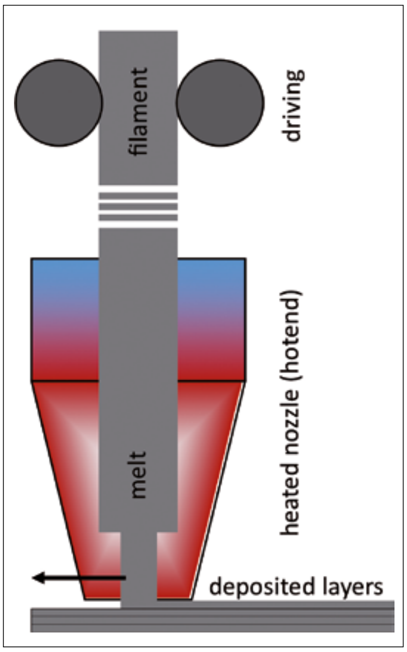

Fig. 1
Schematic view of the FFF process

Introduction

Components based on high-performance ceramics are applied in different areas of life as well as in science and technology. In all fields, a growing need for complex geometries with a wide range of individualization options and favourable manufacturing processes is identified. With the power of Additive Manufacturing (AM) completely new and highly complex geometries can be realized by selective adding of material to create undercuts or hollow structures. This possibility allows for shorter lead times and a rising efficiency as well. Strictly spoken: The way of thinking in today's fabrication guidelines has to be revised.

Fused-Filament-Fabrication (FFF), also known as FDM®, is a thermoplastic AM method in which an endless filament is used as a semi-finished product, which is melted and deposited under a heated nozzle. A scheme is shown in Fig. 1.

A component is imaged in accordance to computer-aided modeling, converted into the machine code (e.g. G-code), then transferred to the machine control and finally deposited layer by layer in a line-like manner. Through this method it is possible to produce large and complex components quickly and with high material efficiency.

Keywords
Additive Manufacturing (AM),
Fused Filament Fabrication (FFF)

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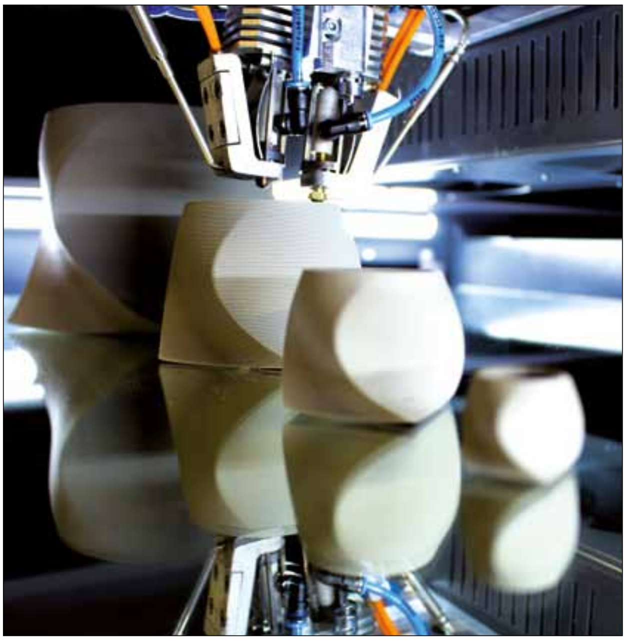

Fig. 2
SiC/SiC green samples made by FFF

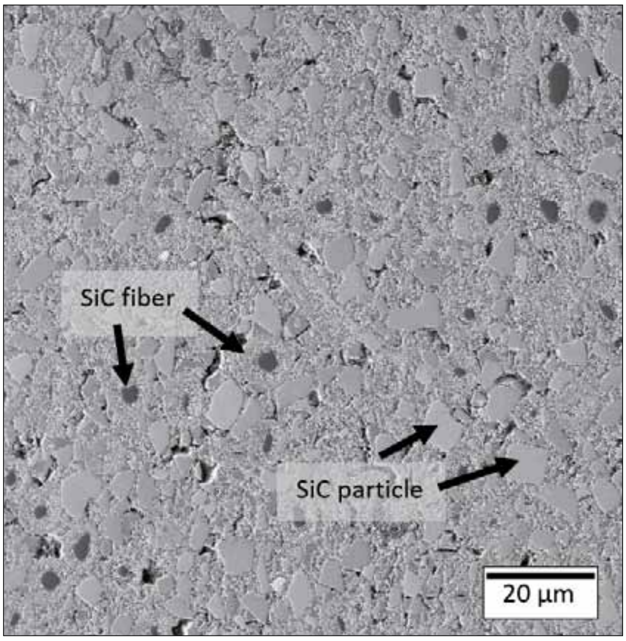

Fig. 3
Microstructure of an infiltrated and sintered SiC/SiC composite with aligned fibres (into the image plane) made by FFF

Among the AM technologies, FFF is one of the so called direct working processes, which means that a discreet element is deposited and solidified. In comparison to an indirect working process, e.g. powder bed methods such as binder jetting, where a discreet element is solidified within a continuously present material reservoir. The direct working processes are better suited for multi-material approaches [1]. The combination of materials enables individualization and functionalization at the same time. Obviously, AM will be the most suitable technology to make complex smart materials in the future. An overview about multi- material approaches is given in [2] and [3].

Within the commercial AM of components, FFF is the most widely used process. For less than EUR 500 devices can be purchased from different manufacturers. This applies not only to the production of polymer components such as PLA, ABS, PA, PET or even PEEK, but also elastic components consisting of TPE or TPU.

In the mid-nineties, Agarwala et. al. started to work with Si_3N_4, 17-4 PH metal filaments and other ceramic types [4, 5]. Now, two decades later, this topic comes up again. With enhanced materials and cheaper technologies, FFF becomes a competitive AM method.

Following benefits are most reasonable:

- low-cost standard devices available
- a broad variety of powders usable
- highly filled feedstocks allow the complete densification of the components during the sintering process (porosity <1 %)
- high productivity (up to 50 mm/s, e.g. 35 cm³/h using a 0,5 mm nozzle)
- theoretically no limitation in building space
- fibre reinforcement possible
- multi-material approach.

Fraunhofer IKTS investigates the suitability for the generative production of ceramic components using this method.

The main challenge is to compound a high amount of ceramic powder into the thermoplastic matrix (>40–60 vol.-%) and to provide a certain strength to the filament as well as a low viscosity during melting. Therefore, multi-component binder blends must be developed to maintain those properties.

For that purpose, measurements on a torque rheometer have to be applied to determine the correct melting behaviour.

To test the flexibility, filaments can be extruded by using a high pressure capillary viscosimeter equipped with a circular nozzle. The resulting filaments can be evaluated by a slip knot or bending test.

Initially, filaments based on a thermoplastic feedstock of SiC powders were successfully produced and processed in a standard printer 140L from Hage Sondermaschinenbau GmbH & Co. KG/AT. The solid loading can be adjusted between 42,5 vol.-% to 60 vol.-% by using different matrix polymers.

In the next step of the material development, reinforcement of the feedstock by SiC short fibres (Hydale Si-Tuff 7 Series) was applied. SiC materials with a SiC fibre content of up to 30 % by volume were successfully produced and processed. By a subsequent infiltration with ceramic polymers (precursors) and pyrolysis, the components could be compacted further. Depending on the solid loading and infiltration routine the remaining porosity in the shown case is about 15 – 30 vol.-%. Fig. 2 shows green parts made of SiC/SiC filaments in different scales.

A typical microstructure of the material deposited by FFF is shown in Fig. 3. Through the shear gradient in the nozzle of the extruding- and print head devices, the fibres are aligned in an unidirectional manner. This circumstance permits tailored properties in certain layers, which only can be generated in the x-y plane at the moment. By applying a further degree of freedom, e.g. 5-axis printing, the properties can be

Fig. 4
Endless filament for FFF made by extrusion at IKTS

implemented in a tailored way. Printing with 5-axis will boost the direct printing methods because it saves support material and rises the complexity, especially for hollow structures.

Fig. 5
Sintered Al_2O_3 part of a laval nozzle made by FFF

Based on this research, the high potential of this new additive manufacturing method for Ceramic Fibre Composite Materials (CMC) in various applications, e.g. in aerospace or energy engineering, is demonstrated. This can be a breakthrough compared to today's lamination or stack technologies, which were extensive and limited in complexity. Other approaches, using phenolic resins and silicon infiltration, are possible as well. In further development steps the production of components based on Al_2O_3, WC–Co and Si_3N_4 is investigated. An endless filament coil is shown in Fig. 4.

After the final sintering, materials with a relative density of >99 % were obtained. Fig. 5 shows a sintered Al_2O_3 part of a laval nozzle. This part was manufactured in a collaboration between Fraunhofer IKTS and INMATEC Technologies GmbH. The current results for the production and processing of filaments on the basis of a wide variety of ceramic powders open up completely new possibilities for the development of further fields of application.

As mentioned above, particular interest for FFF is focused on the simultaneous processing of several materials in order to functionalize components, or to provide them for decorative purposes. In this way, properties such as electrical conducting and insulation, toughness and ductility as well as different colours can be combined in a complex part by two component printing in the future.

As in all conventional shaping processes for ceramic components, the debinding and sintering of the shaped bodies must be applied subsequently, even using Additive Manufacturing.

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