Ceramic Components and their Implementation in Industrial Applications

The current status and future challenges in the production of the most important engineering ceramic materials (Al_2O_3, SiC, Si_3N_4, ZrO_2) is outlined. Their specific properties to be considered for the design of ceramic components are discussed.

The most important engineering ceramic materials and their characteristic properties were introduced, which determine their main applications. Progress made within the last decades is demonstrated by the size and complexity of ceramic components, which can be fabricated nowadays at reasonable costs by applying appropriate and modern technologies. While a further increase in size seems to touch limits, even higher complexities appear to be possible by the application of modular designs and further new technologies, partially still under development.

Introduction

Engineering ceramic components like the four most important ones Al_2O_3, SiC, Si_3N_4 or ZrO_2/Y-TZP are already used in broad technical applications, where conventional materials reach their performance limits. For such established applications, matured material grades are used, which are commercially available from various suppliers in the market. The choice of the appropriate ceramic material is determined by the combination of its properties, which is certain for each individual ceramic [1]. A kind of visual survey of important properties of the mentioned four ceramic materials is given in Fig. 1.

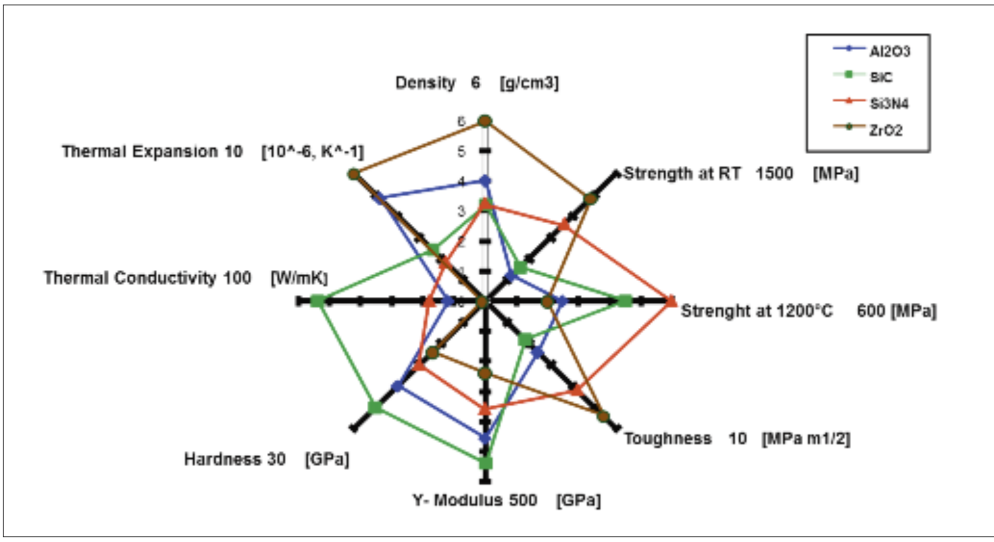

Fig. 1
Comparison of important design properties of four representative engineering ceramic materials

Starting with the axis for density in Fig. 1, already marked differences in the density of the materials are seen, favoring Al_2O_3, SiC and Si_3N_4 for lightweight constructions, in opposite to ZrO_2/Y-TZP. Looking for strength at room-temperature, ZrO_2/Y-TZP is at the top, followed by Si_3N_4. This situation changes with increasing temperatures, at 1200 °C Si_3N_4 and SiC show the highest values, predestining them for high-temperature applications. On the other hand, toughness is highest and Youngs-modulus is lowest for ZrO_2/Y-TZP, indicating a low brittleness and high impact resistance. In opposite, the very high Youngs-modulus and hardness of SiC provides a high stiffness and abrasion resistance. Concerning hardness SiC is only excelled by B_4C, c-BN and diamond. Besides this, SiC also shows a very high thermal conductivity; except some metals, only AlN, BeO and diamond exhibit better ones.

Keywords
Wear protection
Corrosion protection
High temperature application
Electrical characteristics
Lightweight construction
Materials: alumina (Al_2O_3), silicon carbide (SiC), silicon nitride (Si_3N_4), zirconia (ZrO_2)

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Marked differences again reveal concerning the thermal expansion. ZrO_2/Y-TZP shows a very high one, which approaches the one of steel and promotes joining of such material-pairs without the creation of high thermo-mechanical stresses. On the other hand, the relatively low thermal expansion coefficients of SiC and especially Si_3N_4 provide a very good thermal shock resistance.

This comparison, however, cannot cover all application-relevant properties; e.g. SiC possesses in addition excellent corrosion resistance and tribological properties, while Al_2O_3 has a favorable high electrical resistance. It is also important to know that in spite of their high strength and toughness, common ZrO_2/Y-TZP-grades suffer of a limited hydrothermal stability [2]. Thus, for each application with certain conditions, the most suitable material has to be selected. For very special conditions, there are also a variety of special material grades available, e.g. SiC-grades with specified electrical resistance from 10^8–10^{-1} Ω·cm [3]. On the other hand, the price of the material as well as the cost of components is a decisive factor, favoring the broad range of Al_2O_3-grades, which are till now by far the mostly applied engineering ceramics. One can find them in nearly every technological field: from spark plugs, wear protection parts to complex camera housings and vacuum devices. The further engineering ceramics were primarily chosen and applied, when certain properties are needed, which are no more fulfilled by Al_2O_3.

This description demonstrates that there are a variety of matured engineering ceramic materials in the market, which fulfill a broad range of technical demands. The main reasons for their use are collected once more in Tab. 1. For very certain applications and conditions, there are further very special ceramic materials available. Thus, customer and design engineers should talk with the ceramic companies, how to fulfill best their needs. Besides such specialties as well as commodities and serial products, however, there is a rising demand for large-sized ceramic components and rather complex shapes which are new challenges for producers. Accompanied with such types of components are very often questions, how to integrate these into machines and apparatus without severe changes of (existing) constructions. These points are outlined in more detail in the following.

Large-sized engineering ceramic components

Intensive developments in the past enable to fabricate a broad dimensional range of ceramic components today. This progress was made possible by a simultaneous development of material's technology and technological equipment, especially for the thermal treatment/sintering. Concerning SiC- and Si_3N_4-components, the capability of FCT ranges up to components of e.g. to Ø 650 mm × 1250 mm and a weight of up to 80 kg [4]. This, however, is not guilty for FCT's ZrO_2/Y-TZP, as this ceramic material provides enormous problems in sintering large-sized components due to its low thermal conductivity, high thermal expansion and high density. These characteristics lead to difficulties in heating up a green body sufficiently homogeneously, that sintering starts overall at the same time as well as to cool down the component quick enough to avoid destabilization and too high thermo-mechanical stresses. This is why the size of ZrO_2/Y-TZP-components currently appears to be limited to about Ø 300 mm × 400 mm and a weight of about 40 kg [5].

Producing such large-sized ceramic components of course affords appropriate technical equipment and handling devices. As in most cases, only a lower number of such components are needed, cold-isostatic pressing (CIP) and green machining is the preferred production route, as it gives best flexibility and relatively low tooling-cost. To fulfill this task, the following machinery is established at FCT (Tab. 2).

For further increased sizes, new equipment has to be installed; however, a thorough calculation is necessary as the market size diminishes for even larger sizes. Thus, other solutions should be kept in mind like modular constructions and/or joining of smaller parts, as will be outlined below.

Tab. 1
Characteristic properties of engineering ceramics and main reasons for their application

Characteristic properties
• Abrasion resistance (tribological properties)
• Corrosion resistance
• Electrical properties (insulation, conduction)
• High-temperature durability
• Light-weight (-constructions), stiffness

Tab. 2
Size/maximum dimensions of production equipment available at FCT

Technology	Technical parameters
Isostatic Pressing (CIP)	Ø 900 mm × 2500 mm, 1500 bar Ø 350 mm × 800 mm, 3500 bar
Axial Pressing	1000 mm × 500 mm, 1600 t
Green-Machining (max 5-Axis)	Turning: Ø 750 mm × 1100 mm Milling (L × W × H): 1000 mm × 600 mm × 400 mm
Sintering	Inert: 1000 l Air: 500 mm × 500 mm × 550 mm HP: up to Ø 380 mm HIP: Ø 300 mm × 650 mm, 1950 °C, 2 kb SPS/FAST
Hard-Machining Machining Center, max.	Round: Ø 800 mm × 1800 mm Flat: 600 mm × 1500 mm 1800 mm × 1000 mm × 1300 mm

Fig. 2
Green-machining of a near net-shaped Si_3N_4-blisk (source: Honeywell)

Fig. 3
Conveyor screws made of ZrO_2/Y-TZP (bright) and SiC (dark) with undercuts

Fig. 4
SiC pump wheel with optimized front- and back-side blades (Ø 360 mm)

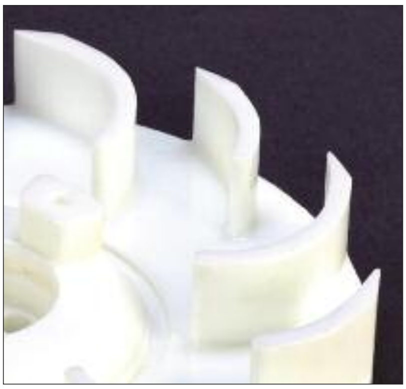

Fig. 5
Cross-sectioned view of a ZrO_2/Y-TZP-rotor with curved, undercut blades

Complexity and machining

Thanks to the enormous progress in numerical controlled machining (CNC) as well as 5-axis technology, the range of shapes of ceramic components which can be fabricated today economically is widened essentially. Remembering the former German Gas-Turbine Program in the 1980s, turbine rotors were prepared by ultrasonic machining of a hot-pressed Si_3N_4-disc, taking about one day per blade [6]. For demonstration purposes, this can be afforded, but it has not had a chance to become an economical process. The mentioned progress in machining technology now allows, however, to machine such near net-shaped components in the green state (Fig. 2), followed by sintering and residual hard-machining finishing to the final highly-precise dimensions and narrow shape tolerances. As this is only possible by use of diamond tools, near net-shaping in the green state is very important for a cost-effective fabrication of complex-shaped engineering ceramic components.

With these techniques, highly complicated shapes can be fabricated like screws and augers for pumps, compressors and extruders (Fig. 3). The difficulties to fabricate such shapes often results from a non-linearity of the geometry, combined with undercuts and variations in flank leads, affording 5-axis machining technology. Other examples are pump wheels with hydro-dynamically optimized blade shapes (Fig. 4) or highly complex designed air-classifier- and mill-rotors of up to nearly 400 mm in diameter, as shown cross-sectioned in Fig. 5 for visualization.

Further challenges in green-machining (but also sintering) are heat-exchanger components made preferably of SiC because of its high thermal conductivity associated with a nearly overall corrosion resistance. Examples shown in Fig. 6 of the CORRESIC®-series of *GAB Neumann GmbH* [7], with a diameter of 350 mm each, are challenging due to the high material's volume to be removed by green machining like turning, milling and/or drilling. The overall length of the bore holes of the heat-exchanger block of about 60 kg sums up to about 120 m, demonstrating the possibilities given by modern machining equipment and technology.

Finally, with DIN-ISO compliant gear wheels, examples are given for high-precision hard-machining in the sintered state (Fig. 7) [8]. Such gear wheels are applied in conveyor pumps and were tested for

Fig. 6
CORRESIC® SiC annular groove- and block heat-exchanger both with Ø 350 mm

Fig. 7
Highly precise (QK 5) ZrO_2/Y-TZP gear wheels for conveyor pumps and an example of a helical geared wheel for gear drives

gear drives with deficient- or media-lubrication. To enable such gears to transfer high torque, use is made of actual FEM-programs to calculate the optimum tooth-flank contour for highly stiff ceramics to provide best contact conditions. With the same machining technique, highly precise screw threads and even ceramic spiral springs can be fabricated.

For further design features like small bores, holes or oval slots, the application of ultrasonic-assisted machining proved to be very suitable. By use of this technique, structures can be realized which were not able to be fabricated economically by other machining techniques. A prominent example for this is the already often shown Si_3N_4 housing for extra-terrestrial surveillance cameras [9]. In order to realize the demanded high accuracy of such complex structures, increasingly machining centers are applied, which allow (nearly) all machining steps in one clamping. Additionally, they allow freeform-grinding, opening up new possibilities for even more complex parts like irregularly shaped molding tools [10].

Finer structures can be realized even in brittle ceramics by water-jet and laser machining, while, however, the thickness of parts is limited. The current status of micro water-jet machining is characterized by a repeat accuracy in the µm-range and smallest features of about 0,3 mm. With laser-machining, on the one hand, thicker parts can be machined but also smaller features can be realized down to 100 µm and less, as shown by a demo-machined Si_3N_4 disc in Fig. 8. One disadvantage is, however, that laser machining cannot be applied to each ceramic; with Si_3N_4 it works quite well, but with SiC and especially with ZrO_2/Y-TZP common techniques are not applicable.

A kind of renaissance experiences the electro-discharge machining (EDM). Though applied for metals for a long time, for ceramics it was more or less only used for Si-infiltrated SiC (SiSiC) with a very good electrical conductivity. Already some times ago, certain Si_3N_4-grades and more recently also special SiC- and ZrO_2-compositions were developed with an electrical conductivity suitable for the EDM-technique [11, 12]. However, there are also new interesting developments concerning the technique itself by applying it also for non-conductive ceramics [13], as well as ED-machining in air without electrolytic fluid, opening up much more variances with respect to the complexity of the machined ceramic parts.

Joining and system integration

As described above, meanwhile there are broad possibilities to fabricate large-sized, complex shaped engineering ceramic components. If they still are not sufficient to realize certain dimensions or structures demanded, one has to think about modular designs and joining. Ceramists would wish to have a kind of tool-box available to fulfill all wishes and requirements to fabricate such components. However, in spite of great progress made with this respect within the last years, such a tool-box is not yet available, but only some applicable individual solutions.

In general, the different joining methods are divided into form-, force- and matter-fitting. The first one means common devices like plug and socket fitted together and being resolvable, the second one uses stresses to fit the parts together, like tension bolts, shrink-fitting or press-fitting. Such techniques are used for e.g. extrusion screws [14], ceramic inserts in press-molds or for sliding-bearings (Fig. 9). With all these techniques, one has to keep in mind the principles of ceramic design [15, 16] as well as to set the ceramic component preferably under compression stress. On the other hand, different design solutions demonstrate that such constructions

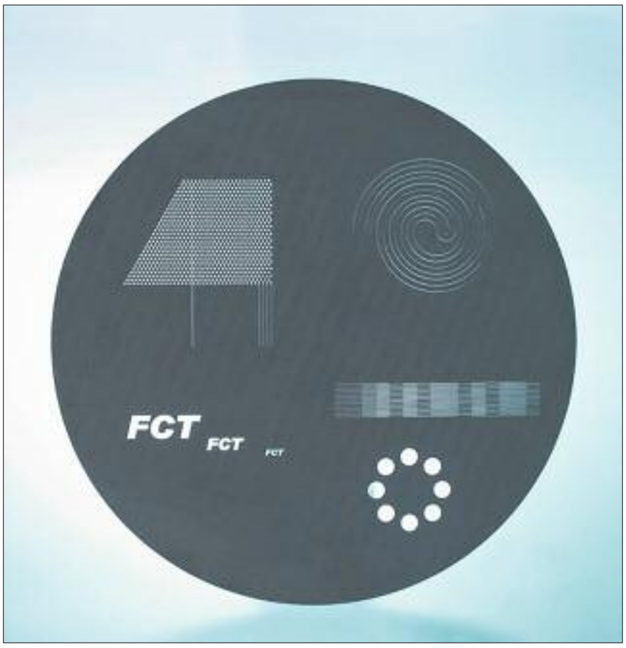

Fig. 8
Laser-machined Si_3N_4 demo-disk with structures down to 50 µm

Fig. 9
Shrink-fitted SiC journal sleeve

Fig. 10
Shrink-fitted Si_3N_4 pump-wheel (source: KTD, Uni Stuttgart)

also work reliably with the ceramic under (slight) tension stress. As an example, a shrink-fitted pump-wheel on a steel-axle is shown in Fig. 10 [17], further solutions for e.g. form-rolls for metal-molding are given in [18]. For the pump-wheel, a comprehensive calculation was performed for an optimized contour of the steel-axle to provide a constant stress-level within the hub-area of the ceramic and avoiding too high stresses at the edges. Such joining techniques also provide solutions for the integration of the ceramic components into technical systems.

Very different solutions are subsumed under the title matter-joining. This comprises gluing, brazing without or with metallization, reactive air brazing (RAB), joining with glass or glass solder, sinter-joining with ceramic slips, siliconizing, diffusion bonding etc. It is impossible to discuss all these techniques, which are very different with respect to the equipment needed as well as the strength and thermal-, abrasion- and corrosion-resistance of the joining area [19]. There have also to be considered the thermo-mechanical stresses, which develop at higher temperatures between joint parts of different materials. Basically, the joining region is the weakest part of such a construction, may be with the exception of diffusion bonding, where no joining area should remain. However, this is a very extensive technique, as the faces of the ceramic parts of identical material to be bonded have to be ideally flat and smooth to avoid residual gaps, resulting in scrap. This technique e.g. is applied for highly corrosion resistant SiC heat-exchangers and micro-reactors. As further promising techniques emerge joining by laser and RAB, as they can be performed outside of special furnaces and may provide a high flexibility in the future [20, 21].

With these techniques, on the one hand even more complex constructions can be realized; on the other hand they are necessary to integrate the ceramic components into technical systems. Designing such system integration affords high care to avoid damage in application due to e.g. thermal mismatch or punctual stress- or torque transfer, leading to a too high local stress for the ceramic component. This is especially the case with dynamically strained components like milling-, pump- or gas-turbine rotors. Though meanwhile also screw threads can be realized within the ceramic parts, they may only be used to fasten parts together but not to transfer load, due to the high stiffness of the ceramic materials. Due to the great variety of applications and operational conditions, only basic rules are available and each individual system has to be analyzed separately. There are several institutions in Germany, which are engaged in these issues and are able to provide numerically based solutions. It is highly advised to cooperate with the ceramic manufacturer as well as with these experts to find the best solution for a further successful application of engineering ceramic components instead to fail by applying trial and error.

Summary

Engineering ceramic materials and components have reached a high level of mature and reliability and are already used in broad ranges of technical applications. At the edge of technological developments, however, continuously new demands for ceramic components are rising, often associated with requests of rather large size and/or complex geometry. Such demands are still challenges for ceramists, as they are associated with a variety of questions concerning design, fabrication and integration into technical systems. Experience with this respect has widened essentially during the last decades so that today ceramic components can be offered and fabricated economically which were formerly not feasible. However, there are still a lot of challenging questions and problems, e.g. concerning joining, for which reliable solutions have to be developed in order to support implementation of engineering ceramics in new, innovative applications to enhance technical progress.

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