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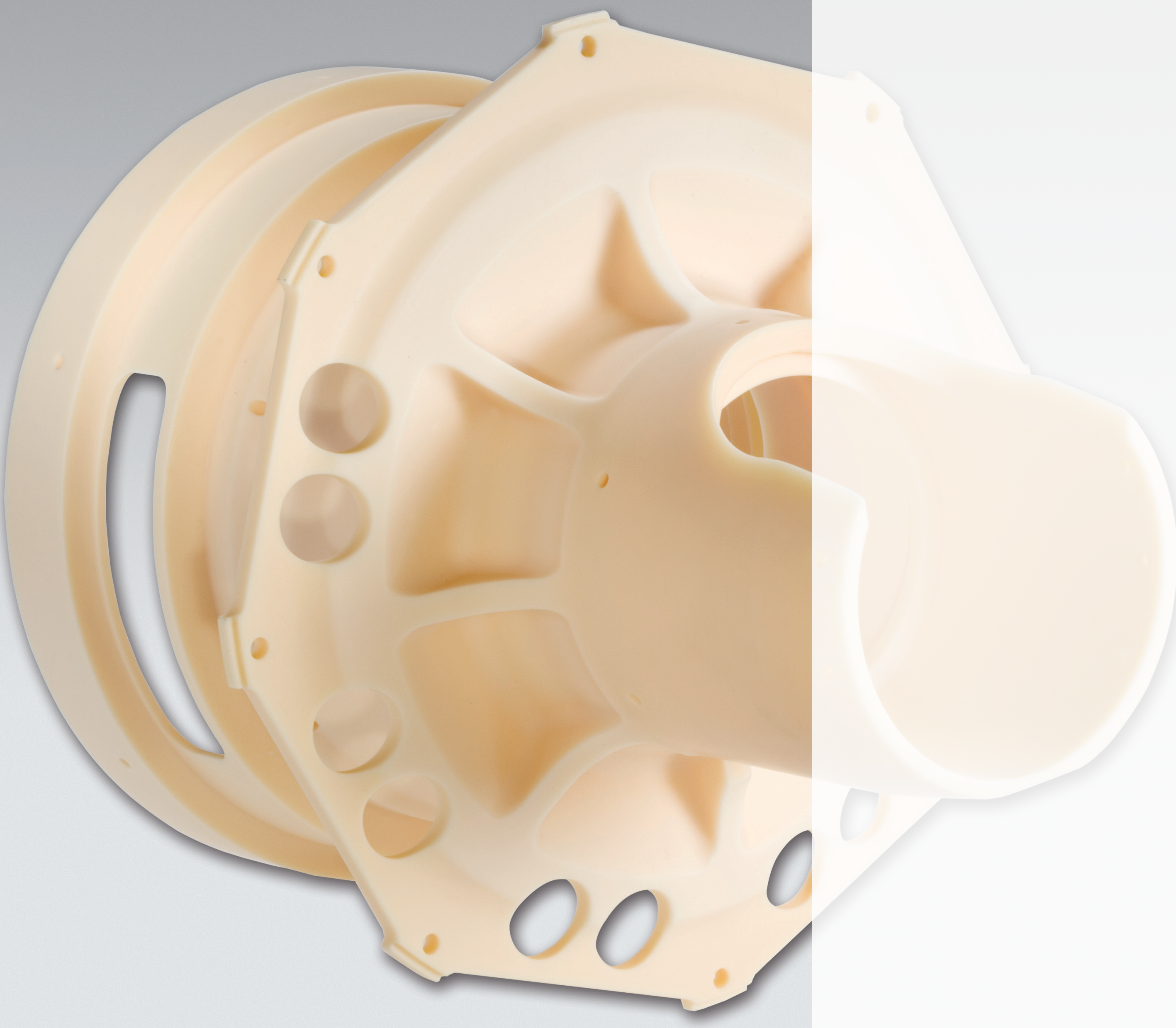
Construction with ceramics - Manufacturing and dimensional stability without finishing



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1. Introduction

Products made from ceramic materials are often used as components in mechanical and plant engineering that require particular mechanical, thermal and chemical resistance. As a result, construction engineers are often confronted by materials with which they have little or no experience. This paper will provide an overview that will contribute towards overcoming this deficit in knowledge.

Ceramic manufacturing technology can be compared to powder metallurgical technologies but causes more unfavourable conditions for dimensional stability and tolerances compared to metallic components. The common limits to dimensional and shape tolerances of components made from different materials and different shaping processes are presented.

2. Challenge and objective

Over the past decades, the use of ceramic materials has exceeded expectations because of their interesting technical properties such as outstanding hardness, excellent resistance to abrasive and erosive wear, high corrosion resistance at high heat resistance and the availability of the raw materials required. Ceramic materials are now used in mechanical and plant engineering, electric and medical engineering.

This paper does not discuss the ceramic materials, their properties or manufacture. The aim is to provide the user and the construction engineer in particular with information necessary for ceramic-oriented design. Furthermore, the limits that ceramic components are subject to when it comes to design and construction are described, making them easier to understand.

This paper presents the distinctive features of:

- the manufacturing and dimensional stability of ceramic components without finishing
- the realistic shape and dimensional tolerances that can be achieved through finishing
- the principles of construction, established through the manufacturing process and by brittleness or low resistance to crack evolution
- the formal approach to construction and design of ceramic components

3. Components

Ceramic components rarely fulfil their function in technical applications unless they are integrated into a system, such as spark plugs in combustion engines, insulators in electric switchboards or casings, ceramic thread guides in textile machinery, sealing discs inside a tap, endoprosthesis (bioceramics) inside the human body, etc.
Without referring to specific joining techniques, the knowledge of dimensional and shape tolerances usually applied to different ceramic materials is of fundamental importance for the design and construction of components. For this purpose, it is important to know the tolerances limits without machining in fired condition, i.e. without finishing and hard machining.

Ceramic components can be machined after firing (=sintering) but very often, this is only possible using diamond tools. This process is very time-consuming, labour- and cost-intensive [2-4]. Therefore, the finishing of ceramic components should be avoided or kept at least to a minimum.
The construction engineer must therefore take this into consideration during the draft phase. However, this can only be done correctly if the construction engineer knows the possibilities and limits of the tolerances of different materials and shaping processes.

4. Manufacturing techniques

Figure 1 shows terms used in the manufacturing techniques of metal and ceramics. It is assumed that the significance of these terms is known (for explanation of the most important terms used in the manufacturing technology of ceramic components, see 7. Appendix and [1, 10-12]).

A significantly different approach must be taken when manufacturing ceramic components than for metallic materials. These differences and the resulting limits with regard to the variety of shapes as well as shape and dimensional tolerances can be seen here.

Manufacturing technique	Commonly used with ceramics	Application
Primary shaping	Shaping, but needs additional process step "firing"	All ceramic products
Re-shaping	Not possible due to lack of plasticity	-------
Cutting	Sawing, grinding, polishing, lapping, honing	Always necessary if dimensional stability is required. Increase in application frequency with silicate, oxide and non-oxide ceramics
Joining [5-7]	When green (handling), only ceramics with ceramics (material bonded) When fired (material bonded) shrinking, plugging, sticking	Silicate ceramics (handle for cups, pots), sealing of pipes with caps, hard-soldering of oxide ceramics Ceramic-to-metal compounds Ceramics – other materials
Coating	Yes	Glaze, oxidation of von SiC-materials
Change material properties	Rarely	Na-ß aluminium oxide, annealing in O_2 atmosphere [9], partially stabilized zirconium oxide [13]

Table 1: Ceramic manufacturing processes

The manufacturing technology used with ceramic components is very similar to that used for powder metallurgical technologies. The main steps in the manufacturing process are raw material, preparation, shaping, drying, probably pre-firing, firing (sintering) and finishing.

Very often, the component is pre-fired and compressed. It can be finished using simple appliances (white machining) or coated (glazed). The components are then fired (=sintering process) and further compressed through shrinkage and increasing mechanical strength. Fired components are finished by sawing, grinding, polishing and lapping.

Ceramics are very brittle. Therefore, they cannot be reshaped during the manufacturing process, i.e. after shaping, apart from finishing after firing; the outlines of a ceramic component cannot be modified. Finishing is time-consuming and diamond tools are often the only tools that can be used in this process. During constructive planning and design, it is therefore essential to look for options that avoid a finishing operation.

This is one of the reasons for there being little variety in the shape of ceramic components in comparison with metal parts. Joining techniques are well known for ceramic components, in particular techniques that are used to join green bodies (green = before firing) and techniques subsequent to firing. These techniques are increasing in importance [5-8].

The manufacturing step “Change material property” is significantly less important for ceramics than it is for metallic components. This manufacturing step is applied using solid electrolytes such as Na-ß-aluminium oxide [9] and multiphase materials such as partially stabilized zirconium oxide [13].

This shows that most of the decisive steps in the manufacture of ceramic components must be taken before firing. Green bodies (not fired) show little hardness and can only just be handled. In addition to the impossibility of re-shaping, the low hardness of green bodies is a second reason, why there are limits to the variety of shapes in ceramic components.

The component shrinks during shaping, drying and firing. Shrinkage is influenced by different manufacturing parameters such as grain size, green density, moisture content, temperature, time, heating-up rate, etc. The degree of shrinkage is for the most part still determined using empiric methods, i.e. serial tests. Values for linear shrinkage depend on the material and manufacturing method used and amounts to approx. 30%.

Ideally, the component shrinks while drying and firing according to an affine transformation; dimensional conditions, angles and parallelism are invariant. This can however never occur due to inhomogeneities and dispersion in the raw material, bodies, firing process, etc. We could go as far as to say that the warp in the component is uncontrolled. Therefore, close dimensional and shape tolerance can hardly be realized without finishing.

The common shaping processes are presented in table 2 according to the frequency of their application. Silicate ceramics are used mainly in batch production when using wet pressing and extrusion as well as slip casting; oxide ceramics are manufactured using dry pressing, extrusion and injection moulding. Application and demand have an increasing significance in the manufacture of non-oxide ceramics. This high-quality group of materials shows a trend towards dry and hot pressing as well as HIP (hot isostatic pressing).

Shaping process		Silicate ceramics (porcelain, stoneware)	Oxide ceramics (Al_2O_3, ZrO_2)	Non-oxide ceramics (SiC, Si_3N_4)
Wet pressing		XXX		
Casting		XXX	XX	XX
Dry pressing	with free-flowing granulate	X	XXX	XX
Isostatic pressing	with free-flowing granulate	X	XXX	XX
Extrusion		XXX	XXX	X
Injection moulding		X	XXX	XX
Hot pressing (incl. isostatic hot pressing)*			X	XX

Table 2: Ceramic shaping processes

Legend:

X = rarely used
XX = common process
XXX = used with batch production
* incl. sintering process (firing)

Besides the shaping process, the shrinkage caused by firing significantly influences the component properties (see table 4). Today, silicate and oxide ceramics can be fired economically mostly in gas-fired kilns. Silicate ceramics are fired at maximum temperatures of 1,500°C, oxide ceramics at 1,800°C.

In contrast, non-oxide ceramic components are always fired in electric kilns and in a reducing atmosphere using protective gas (hydrogen, nitrogen, argon) or vacuum. Temperatures up to 2,400°C are applied and partly sintered under high pressure. Among the non-oxide ceramics there are some materials that do not shrink during firing, therefore in principle it is possible to achieve higher dimensional and shape tolerances.

Group of materials	Heating	Max. temperature	Linear shrinking	Characteristic for firing	Features
Silicate ceramics	Mainly gas	1,500 °C	Up to 20%	Continuous firing (tunnel furnace) in batch quantities (holding furnace etc.)	
Oxide ceramics	Mainly gas	1,800 °C	Up to 20% 30% extreme cases	See above	HIP for high quality components
Non-oxide ceramics	Electric	2,400 °C	Up to 20% but also 0% possible in practice	Vacuum or protective gas firing in batch quantities	Reaction sintering without shrinkage of silicon nitride (RBSN) Reaction sintering without shrinkage at infiltration of silicium with SiSiC

Table 3: Ceramic firing techniques

5. Dimensional and shape tolerances

Dimensional and shape tolerances of ceramic components are determined mainly by the shaping, drying and firing production steps. The higher the degree of shrinkage, the more difficult it is to comply with close tolerances. The following determining factors in particular can be highlighted (see table 3).

Shaping process	Tolerances	
	Standard	Possible today using precision methods
Casting	± 5% to ±3%	±0.5%
Dry pressing using free-flowing granulate	±2% to ±1%	±0.5%
Isostatic pressing using free-flowing granulate	±3%	±0.5%
Extrusion	±5% to ±3%	±1.5%
Injection moulding	±3%	±1.5%
Green and white machining	±3%	±0.5%

Table 4: Tolerances of fired components

5.1 Raw material, body or granulate

Purity, uniform grain size distribution also with mixes, as well as reproducibility are important factors. Close tolerances of ± 0.5% during dry pressing were reached only after successful manufacture of uniform spraying granulates.

5.2 Tooling tolerances and compressive processes in the tool

Uneven compression entails higher tolerances.

5.3 Drying

Uneven drying (in particular of extruded parts) causes green bodies to warp.

5.4 Green and white machining

Type of machining and stability of the body influence the accuracy of the process. (Parameters 5.1 and 5.4 determine dimensions and volume weight of the shaped component before firing).

5.5 Firing

To a very large extent, the temperature control inside the furnace affects the formation of the ceramic structure and the shrinkage quite considerably. Differences in the temperatures programmed might cause the component to warp.

Standard definitions and tolerances limits for ceramics are specified in DIN 40680 [14]; these relate mainly to ceramic materials used in electrical engineering (see also DIN 40685 [15]) but can also be applied to other materials. DIN 40680 provides general tolerances without finishing for dimensions and shapes, arranged according to material, manufacturing method and degree of accuracy.

The different degrees of accuracy are “coarse”, “medium” and “fine”. Components with dimensional and shape tolerances corresponding to “coarse” and “medium” are not usually suitable for mechanical engineering applications. Generally, manufacturers are able to achieve closer dimension and shape tolerances without finishing than those given in DIN 40680. However, significant increases can only be realized using finishing. Similar to the materials used in electrical ceramics, DIN 17410 applies to ceramic permanent magnets, known as hard ferrites, specifying the tolerated differences in press and vertical direction for pressed components. More precise tolerances can be achieved by grinding.

Table 4 shows common and realistic tolerances without finishing for ceramic components, specified according to the most important shaping processes. Generally, the tolerances for standard processes are significantly above ±1%. New precision processes are increasingly applied during shaping allowing for tolerances up to ±0.5%. This trend makes ceramic components more attractive even beyond their traditional application fields, such as mechanical engineering, and the research into alternative materials with high-temperature properties and/or good wear and corrosive resistance has contributed to this development [16, 17].

6. Conclusions for constructive planning

The manufacturing technology used for ceramic components involves larger dimensional and shape tolerances than for metal parts. Tolerances for batch production without finishing are often above ±1% (see table 4).

The tolerances to be reached depend on both the material and the manufacturing method used with the component. It has not been possible to establish generally accepted rules. There are no standard specifications or agreements in existence for materials and test methods or for tolerances achievable; these must be obtained from the manufacturer. However, the necessary information is generally available. There are two trends in the development of ceramic components and materials:

Finishing of ceramic components has increased despite high costs for oxide-ceramics materials, whereas the finishing of non-oxide ceramics has always been highly important to the manufacturing process.

Manufacturing methods allowing for tolerances of ±0.5% to ±1% have been tested and will be introduced. This will partly allow for sufficient tolerances in many applications and create the conditions for economic finishing.

7. Appendix

Definition of some important terms used in the ceramic manufacturing technology:

7.1 Raw materials and bodies

7.1.1 Powder processing raw material

Raw materials, i.e. basic materials for ceramic products, are generally used as grains or powders. They can come from natural deposits and are cleaned and prepared, however, they may also be synthesized. Chemical purity, (crystallographic) structure, grain size and distribution of synthetic raw materials are reproducible and the range of material properties can therefore be kept within limits.

7.1.2 Preparation

Methods for the preparation of a body from a batch formula are grinding, granulating, mixing and spray drying.

7.1.3 Batch formula

The formula used for the manufacture of a ceramic material, specifying type and percentage of ceramic raw materials to be used as well as additives necessary for the process (water, specific additives etc.).

7.1.4 Body

The mix that has been prepared from a batch formula for a specific shaping process.

7.1.5 Granulate

A fluid, porous or powdery mix that transforms into a free-flowing condition.

The process aims to give the mixes used for processes such as dry pressing a good free-flowing capacity and a constant bulk density with the smallest possible bulk volume. The best possible granulate grain size distribution depends on the shaping process and the component shape; typical distributions range between 100µm and 2mm. The most important methods are spray drying of powder suspensions and pelletizing, i.e. further granulation of dry powder.

7.2 The shaping process

7.2.1 Dry pressing

The mix - a free flowing, non-clumping granulate - is fed into a mould and compressed on two sides (axial compaction) until the necessary raw density has been reached.

Advantage: Suitable for large quantities if used with automatic pressing units.

Disadvantage: The axial pressure only allows for sufficient compaction if the ratio of the height to diameter of the pressing body is within tolerable limits.

7.2.2 Isostatic pressing

The pressing mix is compacted from all sides; in the simplest case, the mix is filled and sealed in a container with elastic walls (e.g. rubber). This is then pressed in a container filled with water.

Advantages: Best possible compaction also for large-volume bodies, guarantees crack- and warp-free components due to even shrinkage in subsequent firing.

Disadvantages: Moulds are often complicated and subject to long cycles; green and white machining always required. (Small parts are automatically processed in large batches using the so-called dry bag pressing).

7.2.3 Extrusion

A plastic, mouldable body is made by mixing the powder with additives such as liquid (mainly water) and other additives, if necessary. The body is forced through a die and shaped into pipes or rods.

Advantage: Manufacturing of long axis-symmetrical parts.

Disadvantage: Simple shapes with rather high tolerances.

7.2.4 Slip casting

The powder is mixed with a liquid (mainly water) and the slip is cast into a porous mould that absorbs the water. The powder settles on the walls of the porous mould (mainly plaster) forming a solid body.

Advantage: Manufacture of particularly complicated large components, core and hollow casting.

Disadvantage: Complex process for large batches (automation only in few cases).

7.2.5 Injection moulding

The powder is mixed with a liquid (mainly water) and the slip is cast into a porous mould absorbing the water. The powder settles on the walls of the porous mould (mainly plaster) forming a solid body.

Advantage: Manufacture of particularly complicated large components, core and hollow casting.

Disadvantage: Complex process for large batches (automation only in few cases).

7.2.6 Green

In ceramic manufacturing technology, "green" is used to describe shaped bodies that have not been fired.

7.2.7 Green density

Volume weight of green bodies.

7.3 Drying / Firing

7.3.1 Drying

Removal of moisture (mainly water) from the shaped body.

7.3.2 Pre-firing (Biscuit firing)

Heating of the shaped body to the temperature at which the final ceramic structure develops.

7.3.3 Firing

Heating of the shaped body to a temperature and densification to the extent that the shaped body can be treated in the required manner.

7.3.4 Hot pressing

Heating and, at the same time, application of pressure allows for densification at lower temperatures compared to heating without pressure. For some special ceramic bodies, this is the only way to reach final high densities (raw densities).

7.3.5 HIP (Hot isostatic pressing)

The pressure transmitted by a gas that has been heated to the required temperature.

HIP-technology is used for redensification of pressureless pre-sintered components, given that open porosity does not exist. In this way, ideal material properties can be achieved.

7.4 Machining

7.4.1 Green machining

Machining after shaping and before firing.

7.4.2 White machining

Machining after pre-firing (biscuit firing) achieves the required minimum stability for machining. The temperature of pre-firing is set in such a way that firing shrinkage will not occur.

7.4.3 Finishing

Machining after the final firing (firing at high temperatures, sintering). For ceramics, tools based on diamond, boron or silicium carbide must be applied.

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