Oxide Ceramics – Working Materials for High-Stress Applications

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Following a general overview, this paper highlights the properties of working materials which have a decisive influence on the manufacture of component parts made from ceramics. Manufacturing processes and their significance in design are described. The range of applications in different technological areas is illustrated by a number of practical examples.

The requirements placed on mechanical components, special-purpose machinery and mass-produced articles are constantly increasing as technological concepts progress. Once the possibilities for making improvements in design and structural aspects are exhausted, research concentrates on the different properties of working materials. Much wider use is being made of ceramics in new applications, since these working materials possess a range of extraordinary properties. With them, it is often possible to realise a concept which would not be possible with metal components, for example. In such cases, oxide ceramics have a decisive effect on the design and construction process. The physical working material specifications given in the table below have to be interpreted correctly, in order to find the best solution for the problem in hand.

Finding the appropriate techniques of fastening ceramics to the mostly metal components of a device often places heavy demands on structural aspects. Different heat expansion coefficients of metals and ceramics and the brittleness resulting from the high degree of hardness of ceramics also have to be incorporated into the design concept.

Properties of oxide ceramics (aluminium oxide)

Taking oxide ceramics as an example, the outstanding properties of high-efficiency ceramics are as follows:

– Wear resistance – for example, bearings in chemical pumps subject to a high degree of mechanical stress usually run lubricated by the pumped medium alone.
– Extreme hardness – as a single crystal, aluminium oxide is on the level of the sapphire, which has a degree of hardness only negligibly less than that of a diamond.
– Friction – excellent friction values are obtained even without lubrication with grease, for example with high-pressure pistons.
– Low density – with ball valves, the lighter weight of the ball compared to a metal ball of the same size can be decisive in performance.
– Resistance to corrosion – usually, working materials with extremely high degrees of corrosion resistance are required for apparatus and plant construction.
– High-temperature resistance – means that the material can be used for all sorts of applications in furnace construction, for crucibles, and in temperature measurement technology.
– Electrical properties – the electrical insulating properties are exploited in high-vacuum sealed electric applications, protective sheaths for thermoelements, and chip carriers.

These properties, however, only come at a higher price level, and structural adaptation is necessary. The important thing is to find the right combination of properties for a working material. These comparatively expensive working materials are usually only successful in an application with a wide range of requirements. Several of the outstanding properties of the ceramic material must be required by the application, which limits the range of alternative materials. For example, low friction values, wear resistance and corrosion resistance are required for pumps in the chemical industry. There are cheap working materials that offer low friction values. There are also cheap materials that offer adequate resistance to corrosion. There are few, however, which combine outstanding resistance to corrosion with very low friction values, and this at high temperatures too, as in this example. And if electrical insulation is also required, then there is no alternative to a ceramic component.

Fig. 1: Miniature bead mill for the laboratory. The rotor, cooled grinding basket and lid are made of ceramics, thus avoiding any contact of the grinding stock with metal. (Works photo Friatec AG Division Frialit-Degussit)

Structural considerations

The design and structure of machine components made from ceramic materi-

Fig. 2: Compression moulds for the high-pressure compaction of powders into solid shapes. K (?) (Works photo Friatec AG Division Frialit-Degussit)

als is usually different from the same components when made from metal. Rigidly adhering to the typical structure of a wooden bridge when using concrete as a construction material would do as little justice to the innate properties of the working material as simply making a ceramic copy of a metal component. The properties of a working material always have a considerable influence on structural considerations and it is no different for ceramic materials. Since the designing of structures appropriate for ceramics is often uncharted territory for users, the ceramics manufacturer has to establish exactly what the specific requirements of the customer are for new components. The aim of this is ensure that the construction is suited to the properties of ceramic materials so that the required function is fulfilled and the component can be manufactured at a reasonable price level. This means that applications technologists in the ceramics industry often have to invest considerable time and effort in establishing a customer's exact structural requirements.

Setting tolerance levels has a considerable influence on the extent of precision finishing required for a component. For example, manufacturing tolerance levels of ±2–5 % can be achieved without cost-intensive finishing. With carefully optimised construction designs, tolerance levels and surface requirements are chosen which fulfil the requirements of the application with minimal grinding and polishing. It is often worthwhile scrutinising the construction to see where savings can be made on grinding and polishing work. For high-precision parts, the costs of grinding and polishing may be many time higher than the material costs themselves.

The number of parts required also affects the choice of manufacturing process. For batches larger than 500, automatic compression or injection moulding are the methods of choice. The investment in equipment and tools is not worthwhile for smaller batches. The possibilities offered by moulding, and therefore also aspects of design and construction, depend on the process used. In the same way, the properties of a metal component differ depending on whether it was cast, milled or turned. It is therefore important that the user or manufacturer knows the different manufacturing possibilities, so that they can agree on an economic manufacturing process in line with requirements.

Manufacturing process

Powder: Aluminium oxide powder is extracted from bauxite using the Bayer procedure. The pure powder is ground down by the ceramics manufacturer, mixed with organic fixing agents and then usually spray dried, since pourable granules are generally required for further processing.

Shaping

Dry compression – the granules are compressed in moulds by a counter die and a bottom-force die to form a green compact, which has a consistency similar to chalk. The green compact is usually fired without any further processing, and this is what gives it the extraordinary degree of hardness. This is the process chosen for large batches and simple product geometry for sealing discs, rings and plates. Using the tools available, there are no restrictions on the design of the exterior contours or drill holes. With this process, however, undercutting is not possible. When designing the component, the usual limitations when using compression moulding have to be taken into account.

Isostatic compression – granules are also compressed using this technique. A rubber mould designed for the desired component is filled with granules. It is carefully sealed and placed in a high-pressure container filled with liquid. The liquid transfers the pressure to the granules via the rubber mould. This technique is used for large components. The process is also suitable for manufacturing small batches and prototypes. Further finishing work on the green compact (green = before firing) is usually necessary.

Extrusion – organic glues mixed with the powder are used for extrusion. The result is a softish, mouldable, dough-like mass, which is forced through an extruder. The emerging billet is dried and sintered (fired). This process is used to manufacture pipes, rods and capillaries.

Injection moulding – the process is very similar to the familiar injection moulding process used for filled plastics. After injection, however, the plastic component is removed chemically or by heat. The "filling agent" remaining is fired, and consolidates in this way into a dense ceramic component. This process is suitable for the manufacture of large numbers of small components with complex shapes.

Slip casting – the ceramic powder is poured into a plaster of Paris mould in the required shape in an aqueous suspension. The plaster of Paris absorbs the water from the suspension and, rather like a filter cake, the remaining powder settles in a layer on the walls of the mould forming a component in the shape of the mould. Crucibles and boats for high-temperature applications are manufactured this way.

Finishing before firing – components manufactured using the process described above have a consistency similar to that of chalk. They can be further processed in this state, and this is often done for small batches. Swarf removing processes known from metal processing such as turning, milling and drilling are used. Every effort is made to manufacture parts at this stage very close to their final shape, to reduce the amount of grinding and polishing work later (processing after firing).

Tab.1: Comparison of physical properties of different Frialit-Degussit working materials

Eigenschaft	Einheit	Aluminiumoxid 99,70% F99,7	10%ZrO_2 FZT	Zirkonoxid MgO teilstab. FZM	Y2O3 stab. FZM/K	Siliziumkarbid SiC SiC 198	Siliziumnitrid Si_3N_4 HP 79
Dichte	g/cm⁄	3,9 - 3,95	4,10 - 4,15	5,7	6,0 - 6,1	3,1	3,2
Hrte (Knoop, 100 g)	N/mm^2	23000	23000	17000	18000	21000	17000
Druckfestigkeit	N/mm^2	3500	3000	2000	2200	1200	3000
Biegebruchfestigkeit (4-Punkt)	N/mm^2	350	450	500	800	350	750
Elastizittsmodul	10^5 N/mm^2	3,8	3,6	2	2	3,3	3,2
Weibull-Modul (m)	-	> 10	> 10	> 20	> 15	> 10	> 20
Poisson-Zahl	-	0,22	0,23	0,3	0,3	0,2	0,26
offene Porositt	%	0	0	0	0	< 1	0
Maximale Einsatztemperatur	¡C	1950	1700	900	1200	1400	1400
Ausdehnungekoeffizient	10^{-6}/K	8,5	8	10	11	4,4	3,2
Spezifische Wrme 20 ¡C	J/kgK	900	850	400	400	900	800
Wrmeleitfhigkeit 100 ¡C	W/mK	30	25	2,5	2,5	90	40
Spez. Widerstand 20 ¡C	Ω cm	10^{14}	10^{14}	10^{10}	10^{10}	10^{-1}	10^{14}
Farbe	-	weiß	weiß	gelb	weiß	schwarz	schwarz

Alle Werte beziehen sich auf eine Temperatur von 20°C.

Allgemeiner Hinweis:
Die in der Tabelle mitgeteilten Daten gelten fr Prfkrper, an denen sie ermittelt wurden. Eine bertragung auf andere Bauteile ist daher nur bedingt zulssig. Fr weitere Beratungen sowie zur Mitwirkung bei der Lsung Ihrer anwendungstechnischen Probleme stehen wir Ihnen

Sintering (firing) – this is where the actual densification occurs at a processing temperature below the melting point of the powder between 1600–1800 °C. Sintering results in shrinkage of 30-50 %. The extent of the shrinkage depends on the sintering temperature, sintering process, predensification and the composition of the granules. Sizes calculated in advance are achieved with an accuracy of ±2-5 %.

Finishing – sintering is the last step in the manufacturing process for oxide ceramic components. However, for many technological applications, parts are needed with a level of precision and surface texture which cannot be achieved without using finishing processes. For hard components, processes such as grinding, lapping, honing and polishing are available. Since finishing is time consuming and cost-intensive, the aim is to sinter parts as close as possible to their final shape.

Examples of applications “Mini”-mill with “maxi” effects

The grinfing stock is put into the grinding basket with water and (ceramic) grinding beads. The grinding basket is a very similar shape to a coffee cup. A ceramic cylinder then rotates at up to 10,000 rpm in the grinding basket. The ensuing friction grinds down the grinding stock. We are working on the manufacture of extremely fine powders and substance systems for a variety of different applications. For new developments, often only very small amounts of grinding stock obtained using very elaborate procedures are available, and correspondingly small mills are required. With such small amounts, every tiny piece of abraded material in the device is particularly disturbing and can easily have an influence on the result of an investigation. The amount of material abraded from a ceramic device is very small indeed and does not have any influence on the outcome of an investigation. The parts of the device which come into contact with the grinding stock are entirely made from ceramic material. Because it has a higher degree of mechanical strength, the fast-running rotor is made from zirconium oxide; the grinding basket, however, is made from aluminium oxide because of the heat conduction properties required.

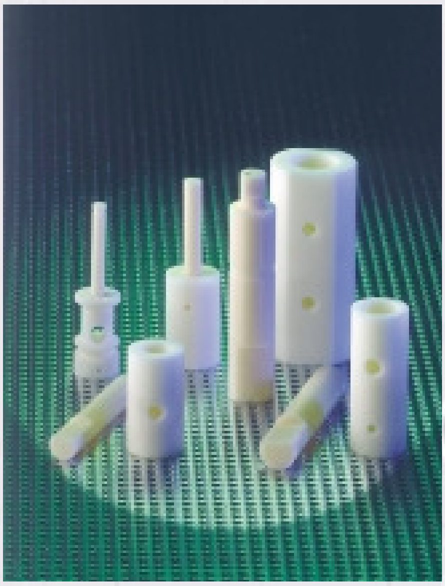

Fig. 3: Piston/cylinders sealed without rings for use in the food industry and pharmacy. Cleaning and sterilisation of the filling devices is made possible by the material properties. (Works photo Friatec AG Division Frialit-Degussit)

Metal-ceramic bonded construction

Metal has a high degree of tensile strength, and ceramics are hard and resistant to corrosion. Extreme applications require that one working material has all these properties. Bonded components actually combine these contradictory properties in one component. Bonded components made from metal and ceramics combined in this way have much better properties than either of the working materials on their own. This is achieved by suiting the degree of stress of the application to the properties of each material.

Compression moulds

Juxtaposed dies compress powder into tablets in sheaths (moulds) under high pressure. The friction on the inside of the mould leads to a high degree of wear in the bore of the mould from the combined effects of corrosion and abrasion. Zirconium oxide withstands this wear and chemical attack much better than metal. The high internal pressure, however, can lead to a degree of explosive force that can cause pure ceramic sheaths to rupture. The solution here is to use the bonded approach. A densified ceramic sheath minimises the wear due to friction and corrosion, whilst high internal pressure resistance is achieved with a shrunk-on metal sheath. This 'job-sharing' approach by the two partners, ceramics and metal, has already established itself successfully in the battery manufacturing sector. Further applications are being tested at present in the pharmaceutical and food processing industries.

Tweezers

Tweezers made from high-efficiency ceramics are being increasingly used for technological applications and in medicine thanks to their outstanding properties. Physicians can work in the magnetic field of a tomograph with tweezers of this sort, without the usual interference from a metal instrument. There are no magnetic forces, as the crystalline ceramic working material is completely unmagnetic. In addition, unlike metallic working materials, the ceramic substance is nickel-free, which means that users also do not need to worry about nickel allergies. Electronics engineers also appreciate such tweezers when working on printed circuit boards. Electric currents and fields are not disturbed, which means that it is possible to carry out work on very sensitive settings.

Sealing rings

Rotating mechanical seals with ceramic sealing rings are now the standard method of sealing mechanical drive-shafts. Just like the rotor shaft of the lye pump in a washing machine, the stirrer and pump drive-shafts in the chemical industry and feed-water pumps in power stations are sealed with rotating mechanical seals with ceramic sealing rings. A rotating carbon ring is held against it using springs. The lapped sealing surfaces slide across one another and are lubricated by the material pumped. This means that some slight leakage is always unavoidable.

Spalttopf

Magnetic coupling is a more elaborate method of drive-shaft sealing, but needs hardly any maintenance and does not leak. The turning moment is transferred via magnets, which are separated by a ceramic Spalttopf. The housing is hermetically sealed.

Pistons/cylinder units

All types of different models and sizes of pistons/cylinder units made from ceramics are used for the transport, pumping and dosing of foods, cleaning materials, perfumes and pharmaceutical agents. The pistons are fitted into the cylinders – which are also made from ceramics – almost free from play. This means that all wearing parts which come into contact with the product are made from ceramics and there can be no contamination with toxic particles rubbing off. Thanks to their temperature and corrosion resistance, the ceramic parts can be cleaned with steam and the appropriate chemicals in the unmounted position. This means that deformation of these high precision components is as unlikely as corrosion or wear.

Conclusions

The applications presented demonstrate a small selection of the innumerable problems that high-efficiency ceramics can solve. Ceramics are a sensible and economical solution for many problems. It is usually necessary to design the components specially for the problem in hand. Knowledge of the problem to be solved, the different types of ceramic working materials and the possibilities for manufacturing ceramics are necessary to decide upon the ideal structure and manufacturing method. A prerequisite for successful production of ceramic components is that the user, designer and ceramics manufacturer work very closely together.

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