VERLAG MODERNE INDUSTRIE

Technical Ceramics

The material of choice for the most demanding applications

mi

CeramTec

verlag moderne industrie

Technical Ceramics

The material of choice for the most demanding applications

Klaus-Dieter Linsmeier

This book was produced with the technical collaboration
of CeramTec GmbH.

Translation: Intercontact GmbH, Willich

Second, revised edition, 2015

First published in the series
Die Bibliothek der Technik
Original title: *Technische Keramik*
First edition (2000) © verlag moderne industrie, Landsberg am Lech
Second, revised and enlarged edition (2010) © Süddeutscher Verlag
onpact GmbH, Munich
Third, revised edition (2015) © Süddeutscher Verlag onpact GmbH,
Munich

Illustrations: No. 4 Uwe Happel, Institut für Mineralogie
und Lagerstättenlehre, RWTH Aachen; No. 44 Fotolia;
all others CeramTec GmbH, Plochingen
Typesetting: JournalMedia GmbH, 85540 Munich-Haar
Printing and binding: Kösel GmbH & Co. KG, 87452 Altusried-Krugzell
Printed in Germany 236639

Contents

Technical ceramics – the material of choice for the most demanding applications

It is a scene from everyday life: When drawing a bath, we lift the lever of the combination faucet and adjust its position until we find the right water temperature. This mixer is expected to do its job thousands of times. Even in household plumbing fixtures, this can only be accomplished using an extremely wear- and corrosion-resistant material. Technical ceramics offer one solution to this challenge (Fig. 1).

Fields of application

Very few people are aware of all the applications in which these materials work behind the scenes to meet the most exacting requirements, for example in electronics, electrical engineering, mechanical engineering, textile manufacturing, medical products or automotive manufacturing. For instance, the miniaturization of electronic circuits is not based solely on silicon as a semiconductor material, but also on substrates made from alumina (aluminum oxide) ceramics that enable compact circuit design.

Properties

Technical ceramics have long replaced metals and plastics in many areas, because they are extremely hard and highly resistant to wear. They are not susceptible to extreme temperatures or aggressive media, they insulate against electrical voltage and are generally effective thermal insulators. There are also special types of ceramics that demonstrate the exact opposite characteristics.

In summary, it can be said that: Technical ceramics are especially useful in areas where

Fig. 1:
Hidden helpers: Seal and regulator discs made from technical ceramics installed in sanitary fittings control the temperature and flow of water.

other materials reach their limits or where the goal is to improve system efficiency. Conventional arguments against the use of ceramics such as “brittleness” and “expense” no longer apply today as they did in the past. Growing expertise regarding the influence of microstructure on ceramic characteristics has helped to further develop the various types of ceramics. This has made it possible to significantly increase the mechanical strength and reliability of modern ceramic materials compared to earlier ceramics. Moreover, today’s simulation technology enables engineers to design components effective enough to avoid voltage peaks altogether.

Tremendous potential for innovation

Today’s ceramic components are often still more expensive than those made of metal or synthetics. Considering the cost-effectiveness of the system as a whole in which ceramics are used, however, ceramic solutions often possess the most advantages because they require less maintenance and fewer repairs, thereby raising productivity. Thus, the individual types of technical ceramics form a family of materials with a tremendous potential for innovation that is far from exhausted.

Not all ceramics are created equal

Definition

Works of art and goods made of fired clay or porcelain have been a part of human life for thousands of years. Archaeological finds confirm that small clay sculptures and animal figures were made over 24,000 years ago, and pottery vessels were crafted around 8000 years ago. The discovery of electricity and the invention of the light bulb in the mid-nineteenth century marked the first use of ceramics in the field of technology due to their suitability as an insulation material. Since then, engineers have been researching, detailing and systematically enhancing ceramic materials.

Family of ceramics

Our ability to provide a definitive explanation of the term "ceramics" is limited because there is an entire family of ceramics made

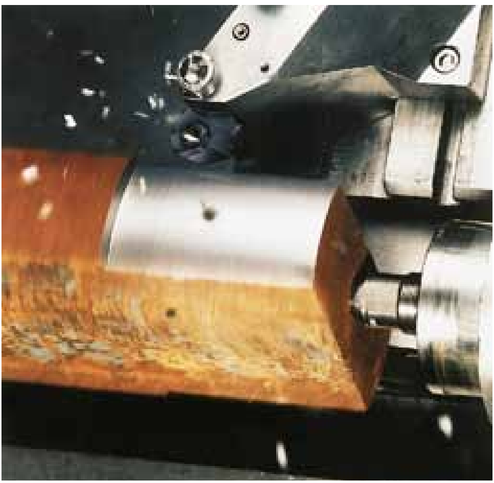


Fig. 2: Proof of superior performance capability: By the time an edge of a cutting insert reaches the end of its service life, it has withstood an average of 125,000 strikes. Based on these figures, the overall performance of an octagonal insert can reach around one million strikes.

from various chemical substances, which in some cases possess distinctly different properties. A popular definition states that ceramic is a non-metallic, inorganic, temperature-resistant material that is at least 30% crystalline and is difficult or impossible to dissolve in water.

Production

In general, ceramics are manufactured as follows: At room temperature a raw mass – composed mainly of ceramic powder and a bonding agent – is molded into a semi-solid blank still incapable of bearing any load; it then thickens to form a hard solid during a process known as sintering, thereby obtaining its typical material properties.

Materials with microstructural components measuring less than 0.1 mm in diameter are considered fine ceramics (all other types are considered heavy ceramics). This includes porcelain and wall tiles, art ceramics, abrasives and technical ceramics. As the name suggests, this group comprises all fine ceramic materials and products that are used in technical applications.

Structural ceramics

This group can be further divided into subgroups. Structural ceramics are used whenever there are exceptionally high mechanical loads to bear, as is the case with ceramic inserts, which are used for machining metal components (Fig. 2). Therefore, these materials must be very hard, dimensionally stable and strong; depending on the application, they should demonstrate these properties even under high temperatures, and they should also be physiologically compatible in medical applications (hip joint replacements are an example of this).

Functional ceramics

Materials known as functional ceramics are used because of their special functional characteristics, for example due to their excellent insulating properties. The functional ceramics group includes piezoceramics introduced in the chapter on "Electrical engineering and electronics" (see p. 63 et seq.).

Advanced ceramics

Advanced ceramics demonstrate the characteristics of structural and functional ceramics outlined above and must meet extraordinarily high demands, e.g. they must demonstrate exceptional wear and heat resistance (cutting ceramics) or a high level of leakage current resistance (e.g. switching devices, insulators, etc.). They must also be suitable as a replacement material for bones or for dental implants (bioceramics).

Overview: major groups

Currently there are four major groups of ceramic materials: silicate, oxide and non-oxide ceramics and piezoceramics. Table 1 presents a rough overview of the properties of oxide and non-oxide ceramics. It uses typical representatives of each group above all to illustrate that: Selecting the right material for the application requires experience and intuition.

Technical ceramics are very hard and resistant to high temperatures, but components made from these materials break when they are subject to conditions that exceed threshold values, while components made of metal may undergo plastic deformation before breaking. These differences are already present at an atomic level: In ceramics, ionic or covalent bonds occur between the atoms; they are stronger than metallic bonds, but only permit a low level of ductility.

Table 1 (opposite): A simplified comparison of the most important advanced ceramics

Mixed ionic-covalent compounds play a dominant role in oxide ceramics. The most impor-

	Unit	Silicates	Alumina		Zirconium oxide		Silicon carbide	Silicon nitride
Fundamental properties		High insulating properties, low thermal conductivity	High hardness, good wear resistance under abrasion, low electrical conductivity, good value for money		Similar mechanical properties (Young's modulus, thermal longitudinal direction) to steel, making it especially suitable for composite steel/ceramic components; harder than steel, low thermal conductivity, good tribology		Extremely hard, relatively light, good heat-conducting properties, good tribology, resistant to thermal shock	Maximum mechanical strength, extremely fracture resistant, high hardness, relatively light, resistant to thermal shock
Main component		SiO_2 – MgO	96 – 99.1 % Al_2O_3	99.8 % Al_2O_3	ZrO_2-MgO	ZrO_2-Y_2O_3	SiC	Si_3N_4-Y_2O_3
Gross density	g/cm^3	2.2 – 2.8	3.80 – 3.82	3.96	5.74	6.08	3.10	3.21
Flexural strength	MPa	110 – 180	280 – 350	500	500	1000	350	750
Compressive strength	MPa	–	2000	4000	1600	2200	2000	3000
Fracture toughness K_{1C}	Mpa $m^{1/2}$	–	4	4.3	8.1	10	3.8	7.0
Young's modulus (dynamic)	GPa	70 – 120	270 – 340	380	210	210	350	305
Vickers hardness	GPa	–	14 – 17	18	13	13	25	16
Thermal conductivity	W/mK	2 – 5	24 – 28	30	3	2.5	100	21
Coefficient of linear expansion (20 – 400°C)	10^{-6} K^{-1}	4 – 7	7.1 – 7.3	7.5	10.2	10.4	3.5	3.2
Maximum operating temperature	°C	1000	1400	1500	850	1000	1800	1600

tant of these materials is aluminum oxide (Al_2O_3), also known as alumina. It is the material of choice in over 80% of all applications, whether in its purest form or in combination with other oxides, such as silicates. Al_2O_3 plays such a key role thanks not only to its outstanding properties – for example, it is wear-resistant, electrically insulating and corrosion-resistant – but also because it is the third-most abundant compound in the earth's crust, after bound oxygen and silicon (8.23 mass percentage). Moreover, people have known since 1928 that it can be manufactured from the raw material bauxite, and process quality has improved steadily ever since.

Properties of alumina …

But silicates are the oldest material representatives for technical ceramics. These are made primarily from natural raw materials in conjunction with alumina to form materials such as steatite, cordierite, mullite and many other variations of these substances. These types of materials are characterized by their extremely low thermal conductivity and high electrical insulation levels. Above all, they are opti-

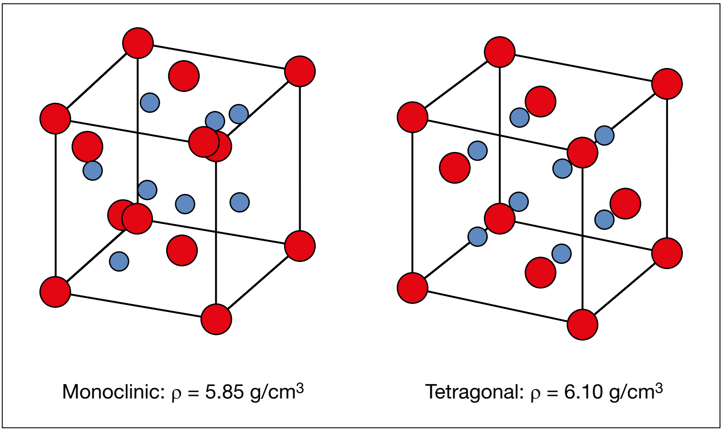


Fig. 3: Monoclinic and tetragonal structures of zirconium oxide (red: zirconium ions; blue: oxygen ions)

mized to deliver outstanding process capability and, thanks to their siliceous raw material basis, offer excellent value for manufacturing switching devices, regulator casings or electrothermal applications.

... silicate ceramic ...

The addition of foreign substances and the conditions selected during further processing have an impact on the microstructure of ceramic materials. One example of this is zirconium oxide (ZrO_2), in which ionic bonds also play a dominant role. Depending on the temperature, it appears in three different crystal structures, which differ in their respective volumes. Below 1175°C, ZrO_2 has a monoclinic crystal structure, it then transitions to tetragonal (Fig. 3), and from 2300°C, it is cubic (these technical terms describe three of the seven basic symmetries of a crystal lattice).

... zirconium oxide ...

Practical applications benefit from the fact that monoclinic ZrO_2 has a somewhat larger volume, or rather a lower density ρ than the other two modifications. If a crack that runs through the ceramic reaches a tetragonal crystal, it prompts a conversion to the monoclinic form. This process is known as transformation toughening; it absorbs part of the energy of the crack and also causes it to branch off into different directions, thereby increasing fracture toughness.

In order to utilize this mechanism, it is necessary to prevent the tetragonal form from reconverting into the monoclinic form during cooling. This is where admixtures (dopants) come into play, for example from magnesium oxide (MgO) or yttrium oxide (Y_2O_3), which stabilize the cubic and tetragonal modification.

... silicon nitride ...

The behavior of the non-oxide ceramic silicon nitride (Si_3N_4), the most important representative of nitrogen compounds among ceramic materials, is almost exclusively dictated by covalent bonds. This results in low density, high mechanical strength at temperatures above 1000°C and both thermal and chemical stability. A crystal modification of Si_3N_4 is indicated by needle-like grains that hook together, thus creating greater resistance against a crack.

… and silicon carbide

Only diamonds or the more exotic types of ceramic boron carbide (B_4C) and cubic boron nitride (BN) surpass the synthetic material silicon carbide (SiC) when it comes to hardness. Additional outstanding properties of ceramics, which count among the members of the non-oxide group, include extraordinary resistance to extremely high temperatures, acids and alkaline solutions, minimal expansion when exposed to heat, their low density and a thermal conductivity similar to that of aluminum.

Manufacturing raw materials

To ensure that ceramics deliver the precisely specified properties, extremely chemically pure raw materials with the finest possible granular structure are used.

Alumina

Bauxite, a yellow-brown sedimentary rock named after the village where it was first discovered, Les Baux de Provence in southern France, forms the basis for aluminum production. It is generally strip-mined in Africa, Australia, Asia, Central and South America (Fig. 4). In 1888, the Austrian Karl Josef

Fig. 4:
Following intense chemical conversion processes, the desired alumina is obtained from the raw material bauxite.

Bayer method

Bayer (1847 to 1904) developed the multi-stage process named after him that makes it possible to manufacture aluminum hydroxide inexpensively and which is still in use today. In this process, bauxite is mixed with a sodium hydroxide solution, finely ground and heated with steam; the aluminum bond from the mineral is dissolved.

Aluminum hydroxide precipitates from this alkaline solution. Filtering is used to separate the solid from the alkaline solution. Heating the precipitate to 1200°C removes the water and the hydroxide is converted to an oxide; this process is called calcination. What remains is the desired oxide (Al_2O_3) in the form of a very fine powder, called argillaceous

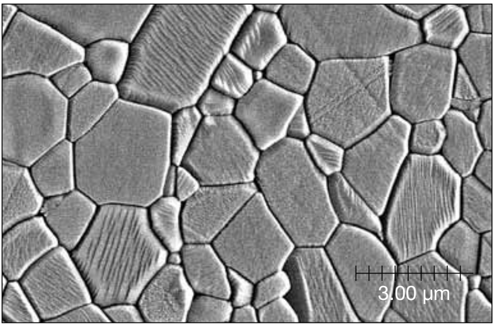


Fig. 5: Electron microscopic image of the microstructure of an Al_2O_3 ceramic

earth or corundum (this can be used to produce pure aluminum through igneous electrolysis). However, residues from foreign oxides remain, such as silicon dioxide (SiO_2), iron oxide (Fe_2O_3), sodium oxide (Na_2O), magnesium oxide (MgO) and calcium oxide (CaO). Their ratio is determined by the subsequent use of Al_2O_3 ceramic; this means that materials for sealing discs can contain up to 0.5% impurities, while bioceramics have considerably less (very few ppm).

Foreign oxides

Figure 5 shows the typical microstructure of an Al_2O_3 ceramic.
There are other methods of obtaining alumina, including the alum, chloride and alkoxide processes, in which the interfering impurities in bauxite can be more easily separated by producing defined, well-crystallizing aluminum bonds.

Zirconium oxide

Crucibles for the refractory industry and wire drawing cones are just some of the products zirconium oxide ceramics can be used for. Figure 6 shows the microstructure of a nanoscale Y-TZP ceramic used for ceramic cutters.

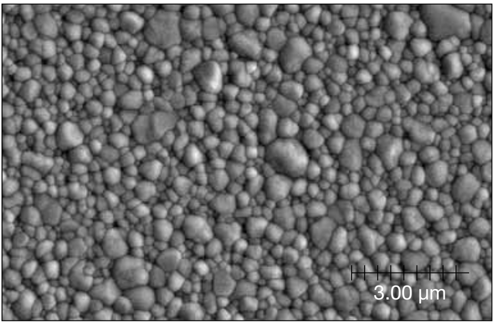


Fig. 6: Electron microscopic image of the microstructure of a ZrO_2 ceramic

Sources of raw materials

Sources of raw materials used in pulverization are minerals that are mainly present in Australia and South Africa: Baddeleyite, a pure form of ZrO_2 (also known as zirconia) and zircon ($ZrSiO_4$), a compound of the desired oxide and silicon dioxide. Both minerals are impure due to the chemically very similar hafnium oxide as well as other foreign substances, in particular radioactive oxides. This specifically applies to baddeleyite, meaning that zirconium oxide obtained from this material is less expensive, but is not suitable for medical products, for instance. Costly purification steps are required in order to remove most of the radioactive substances. The purer the powders are, the higher the quality of components which may be manufactured with them.

Methods of extraction

But how does one obtain the desired powder from the purified zircon? There are a number of different methods, which differ in terms of economic viability: For example, $ZrSiO_4$ separates into simpler compounds at around 1775°C – generally accomplished with a plasma flame – and during cooling the desired zirconium oxide precipitates, followed by the silicon dioxide; the latter is removed using sodium hydroxide or hydrofluoric acid. The method of extraction using a sodium hydroxide solution requires the least energy expenditure, i.e. only a temperature of 600°C; first sodium zirconate is formed and after additional, in some cases thermal steps, the desired ZrO_2 is obtained. An especially fine powder results when the $ZrSiO_4$ reacts with carbon and chlorine at temperatures between 800 and 1200°C. One of several reaction products is zirconium tetrachloride, which then serves as a precursor for further synthetic steps.

Silicon nitride

The direct method of producing powder for silicon nitride ceramics (Fig. 7) is to use the reaction between pure silicon with nitrogen or ammonia at 1000 to 1400°C. The silicon is obtained from quartz sand (SiO_2) beforehand, usually through the process of reduction with carbon in an electric arc at 2000°C. However, quartz sand can be converted to the desired substance more economically with carbon and nitrogen or ammonia. In both cases the

Reduction of quartz sand in an electric arc

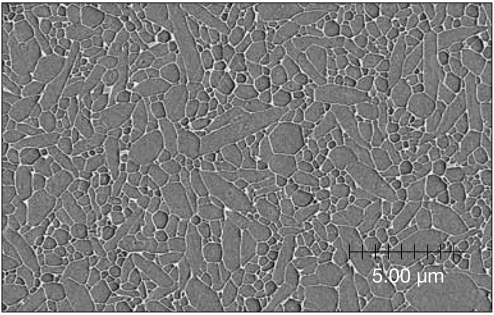


Fig. 7: Electron microscopic image of the microstructure of an Si_3N_4 ceramic

reaction product Si_3N_4 is then chemically purified – of unreacted carbon in the second reaction pathway, for example – and then ground into powder. Very pure and sinter-active silicon nitride powder is obtained through the chemical decomposition of silicon diimide ($Si(NH)_2$).

Silicon carbide

Manufacturing at temperatures ranging from 1600 to 2500°C

Approaching diamond in terms of hardness and temperature resistance, silicon carbide is the material of choice for extremely demanding applications. The powder originates from coke and quartz sand at temperatures between 1600 and 2500°C; so its production requires significant energy expenditure. The raw materials are combined and accumulate around a graphite core. A high electric current is used to heat this core to the required temperature. In reactors up to 9 m long and 3 m high, the zone of pure SiC slowly wanders outward during a period of up to 50 hours, while impurities in the reaction front also move along with it in dissolved form. The reaction product obtained in this way is then thoroughly ground and acids are used to wash the dust out of the grinding medium, which is generally made of steel.

From raw material to granulate

Raw materials in powder form

The raw materials are ground multiple times in order to modify their size (Fig. 8); typical diameters range from 0.1 to 10 µm. But powders can also reach up to 50 µm or, for specialized, high-end products, powders are processed that are only a few nanometers in size. However, since the material does not flow well when ground this way – in this respect it can be compared to flour– it is not possible to introduce it homogeneously in tool molds for further processing. Therefore, it is combined with bonding agents and other organic additives to form a granulate. To accomplish this, the fine powder is placed in an aqueous suspension, which is then atomized with a hot air flow. During this process, droplets – very precisely adjustable spherical particles – are formed and are also dried in the same

Fig. 8:
The ceramic powder before further processing into a green body component

processing step; their diameters range from 50 to a maximum of 150 µm. Due to their spherical shape, the granulates behave much better than the pure raw material during the tool mold filling process. They flow just as well as fine sand, which also enables automatic dispensing.

Stringent incoming materials inspection

To guarantee the highest quality, raw materials are subject to stringent testing by the processing company's incoming materials inspection department. The chemical composition, the crystal structure and the size distribution are closely examined using physical measuring methods. Excited by x-rays, the atoms fluoresce with a spectrum characteristic of the respective element, thereby revealing the exact composition of the materials. x-ray diffraction shows which crystalline structures are present – these are important for the microstructures on the final ceramic. Laser light diffraction helps determine the size distribution of the powder particles and sieve analysis is used to assess the size distribution of the granulates.

Production processes

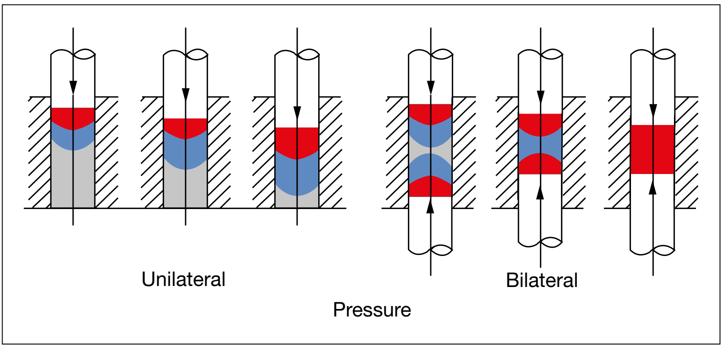
Pressing

Uniaxial pressing

Pressing techniques have obtained the most important status among all of the different production processes. In particular pressing with a rigid punch, known as uniaxial pressing (Fig. 9), is well-suited for large-scale production. In this process, the granulate is poured into a steel die in the shape of the part that is being manufactured. The size distribution of the starting material is a key factor in this method: Large spheres flow better into the mold and fill it more evenly than small ones; nevertheless, finer powder particles are necessary to fill the interstitial spaces.

Because dry granulates with very minimal residual moisture are used instead of plastic bodies or liquid slips, this technique is also known as dry pressing. Applied from one or two sides under high pressure, usually 1500 bar, the material is compressed to between 50 and 60% of the original volume. Higher pressure would not improve the pro-

Fig. 9:
Two versions of uniaxial pressing
Left: Unilateral pressure
Right: Bilateral pressure
Red/blue: Areas with varying compression levels



cess, because unlike metal particles, ceramic particles are not malleable. The costs of precise tooling geometries are indeed quite high; however, for large production runs this straightforward manufacturing method is well worth the expense.

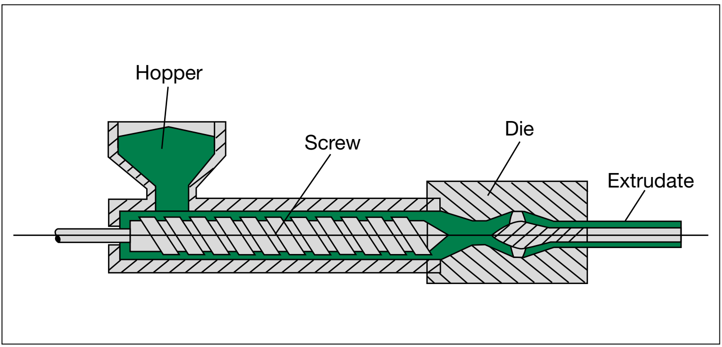
Isostatic pressing

Isostatic pressing is recommended in cases where products place higher demands on material homogeneity, for example due to their size or geometry. Here, the shape is elastic and is made of rubber or latex. As the name implies, an ambient fluid exerts pressure evenly and from all sides. Above all, this method is suited to manufacturing rotationally symmetrical parts with complex geometries. One good example of this type of part is the spark plug, with its shaft spline extending in longitudinal direction.

Plastic method

Mixing the powder with water, thermoplastics and/or lubricants results in a plastic mass which is also shaped under pressure. Two methods are used here that are common in the plastics processing industry: Extrusion and injection molding.

Fig. 10: The extrusion process is highly suitable for manufacturing rotationally symmetrical components in particular.



Extrusion …

The extrusion process is suitable for rotationally symmetric components with a minimal cross section relative to their length – i.e. tubes, rods, honeycombs and the like (Fig. 10). First, the plastic mass is fed into what is known as an extruder. The screw rotates, pushing the mass toward the die and pressing it through. The nozzle geometry then determines the shape of the workpiece.

… and injection molding

In contrast, in the injection molding process, e.g. for thread guides in the textile industry, the mass is injected into a metallic die and hardens into a solid workpiece. This is a reliable method used chiefly for complex geometries with undercuts.

Tradition and innovation: casting

Slip casting

Slip casting is a conventional production method. As in the production of porcelain, the suspension is poured into a porous plaster mold, generally having multiple parts. The capillary action of the pores removes the water from the slip. A solid mass forms on the surface of the plaster mold, called the body, which can be removed after drying. The problem with plaster molds is that the surface begins to clog with continued use. Thus, this method is used infrequently in the field of technical ceramics. Similarly, plastic molds used in the porcelain industry that can be rinsed are seldom utilized, except for instance when manufacturing sample workpieces.

Tape casting method

Tape casting continues to be the preferred method for manufacturing planar components. In this process a homogeneous mixture of ceramic, organic auxiliary materials and liquid portions, called slips in scientific nomenclature, is very precisely applied to a sub-

Fig. 11:
The leather-like tapes are cut to size and rolled up after leaving the casting belt.

strate material using a blade at a defined layer thickness and then dried. Substrate materials can be continuous, polished, endless steel strips or even polymer tapes. The material then is transported through the tape casting machine drying channel on a continuous conveyor belt. Once the ceramic slip has dried, i.e. the liquid portions have been removed, a ceramic tape is obtained with a leather-like consistency (Fig. 11). In this state, the organic auxiliary materials play a dominant role, as they contain the finely distributed ceramic powder particles. This is an important aspect of further processes in that the ceramic tape is now wound up on a roll and can subsequently be cut or punched.

Leather-like ceramic tape

Cast tape thicknesses have decreased thanks to the continued miniaturization in the field of electronic circuits. Today they lie between 100 and 1500 µm.

From green body to finished part

Green body machining

Compressing the blank

Once plastic production processes such as extrusion or slip casting are complete, high water ratios that may have built up must be expelled from the blank, also known as a green body. Because the powder particles move closer together as their water sheath opens, the volume of the blank begins to shrink. Since mechanical stress can build up during inhomogeneous drying, this phase is often very precisely controlled in drying chambers. No additional drying steps are required for methods such as dry pressing or injection molding.
After drying, the relatively soft, chalk-like green body is formed and can still be easily mechanically processed. For example, the green body can be sawed, milled or turned (Fig. 12). Tapes are punched before curing.

Fig. 12: Hip joint ball heads obtain their spherical contour by turning the dried, green body.

After bonding agents and other additives have burnt out and prefiring has been completed, an additional opportunity presents itself to optimally shape complicated geometries using conventional tools without generating significant wear or expense. This is called white machining. In general, however: Ceramic products should correspond as closely as possible to the final shape before firing; otherwise the following processes will become expensive.

Coking organic additives

At the end of this process, any remaining additives are annealed or coked. This is how plastic content in silicon carbide is converted into carbon, which remains in the microstructure of the material and later fulfills its purpose.

Sintering

The final heat treatment plays a decisive role in the development of the part's characteristic features. The term sintering refers not only to this process, but to all of the physical and chemical reactions that take place during the process

Fig. 13: A comparison of the production stages of a hip joint ball head: Green body (back left), sintered ball head (front), hard-machined ball head (back right)

as well. A dense, hard material is obtained from the green body (Fig. 13). In the field of technical ceramics, sintering temperatures range from 1200 to 2200°C. If the raw mass only consists of one component, it is heated to between 70 and 80% of the melting temperature, so the material remains solid. This is referred to as solid-phase sintering. Another sintering method is liquid-phase sintering. Additives are introduced, creating a liquid phase at a low melting temperature, which in turn produces a vitreous bond phase between the crystal grains. For example, solid-phase sintering of pure Al_2O_3 takes place at just below 1700°C, while liquid-phase sintering of Si_3N_4 ceramics is performed at nearly 1900°C.

Solid- and liquid-phase sintering

Temperature control, possibly achieved by applying pressure (referred to as hot pressing or hot isostatic pressing), and the selection of suitable atmospheres make it possible to positively influence the resulting microstructure. Chemical additives are also common. Magnesium oxide (MgO) is typically used to inhibit grain growth in Al_2O_3, since smaller microstructures increase tensile strength.

Volume shrinkage of up to 50%

When developing the tools used to manufacture parts, engineers should consider volume shrinkage levels of up to 50% which occur during material compression. Nevertheless, there are certain materials that do not demonstrate any shrinkage whatsoever. One example is reaction sintering of silicon-infiltrated silicon carbide. Here, the blank is made of silicon carbide and carbon. During heat treatment, molten or gaseous silicon penetrates the pores and bonds with the carbon to form new carbide. The result: While the component compresses, the material increase compensates for the shrinkage.

Finishing

Unfortunately, parts are often still not in optimum shape after firing: Due to volume shrinkage their dimensions are accurate to a maximum of 0.5 to 1%, depending on the material and the manufacturing process. Surfaces and edge zones exhibit roughness and

Fig. 14: Components undergoing the lapping process

in some cases even flaws. However, functional surfaces must either be extremely smooth or profiled, making the dimensional stability insufficient for precision applications. Finishing – grinding, lapping (Fig. 14), polishing, drilling, etc. – then becomes imperative (Table 2). Due to the hardness and wear resistance of the material, diamond tools are often the only tools used in this process. It is an expensive endeavor, yet necessary in or-

Method	Processing material	Objective
Grinding	• Loose or bonded abrasive grain, wet • Diamond grinding wheel (diamond grit bound in metal or plastic) • Use of cooling lubricants	• Rough and/or precision finishing (e.g. of profile and bearing surfaces) • Processing functional surfaces while adhering to required tolerances
Disc cutting	• Loose or bonded abrasive grain, wet; • Diamond saw • Diamond grinding wheel	Blank cutting
Honing	• Diamond honing stones • Use of cooling lubricants	Improvement in dimensional accuracy and surface quality (e.g. of sliding surfaces)
Lapping, polishing	• Loose grain, wet • Diamond lapping mixture or B_4C	Improvement in dimensional accuracy and surface quality (e.g. preparation of polished sections, sealing surfaces)
Ultrasonic machining	• Loose grain, wet • Diamond lapping mixture or B_4C	• Boring • Engraving
Water-jet cutting	Loose grain, wet	Cutting
Sand blasting	Loose grain, dry	• Removal of soft elements on the surface • Roughening surfaces
Electrical discharge machining	Electrical, with a copper-tungsten or graphite electrode	Complex shapes, virtually only on SiC
Lasering	Thermal, with a CO_2 laser	• Boring • Separating • Cutting

Table 2: Overview of techniques used for finishing ceramic products

der to deliver the high performance these applications demand. Thorough planning and process controlling help keep the required expenditure as low as possible.

Final quality inspection

Dimensional stability and surface quality are the key parameters that are analyzed in the final quality inspection; for functional ceramics, this of course also includes testing the relevant characteristic values.

Fig. 15:
During the final quality control test the entire contour of the hip joint ball head is inspected again.

Sample quality control testing …

For example, random checks are carried out in a test laboratory to determine whether an insert meets the required specifications, e.g. inserts made of silicon nitride must be able to turn a shaft that is flattened on both sides and rotates at 1500 rpm without sustaining any damage. In this highly intermittent cutting, one of the shaft's edges continuously impacts the insert with tremendous force at intervals of fractions of a second. Only when the tool is capable of withstanding a load of 35,000 hits without damage is the corresponding production batch considered to be of high quality and is approved for delivery.

… and the 100% test

Hip joint ball heads are even subject to a 100% test, meaning that each individual head is precisely measured (Fig. 15) and undergoes a variety of different tests. For example, the conical bore in the ball heads is placed under a specific hydrostatic pressure that exceeds the expected physiological forces. If the ball is flawed it will break under the compression load. Flawless hip joint balls that have passed the test are cleared for approval. Laser engraving a number on the joint ball ensures seamless documentation.

Suitable construction design for ceramics

Basic guidelines

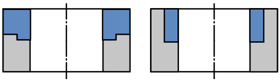
Search for the ideal compromise

The design engineer's task is to solve a technical problem. In order to do this, design engineers seek not just the best, but also the most economical solution, i.e. the solution that meets the application's functional specifications at the lowest possible production costs. This requires a knowledge of the advantageous properties of the possible materials and collaboration with ceramics experts to choose a design that solves the problem, and finally, the selection of a production process that can be implemented in the planned production chain environment in a cost-effective manner.

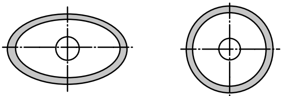
Rules of ceramic-oriented design

Optimally utilising the strengths and potential of the material by selecting a construction design that is suitable for ceramics presents a unique challenge (Fig. 16). Because ceramic behavior is marked by brittleness and not plasticity, it is absolutely essential to avoid tensile and shear stress concentration. This precludes areas with small radii, sharp edges, steps and breaks, as well as linear and especially punctiform load application. Another advantage lies in designing the part in a manner that subjects it to compressive rather than tensile stress, because the compressive strength of ceramic materials is much higher than the tensile strength. Observing these guidelines, it is not possible to simply replace a metallic component with one made from ceramic. On the contrary, a new design is nearly always necessary, as is the adaptation of the immediate operational environment.

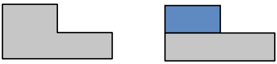
Fig. 16 (opposite): Improper (left partial images) and ceramic-oriented construction designs: Ceramic component design must be aligned with the special properties of the material.



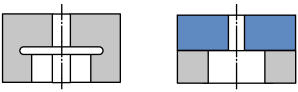
Avoid breaks



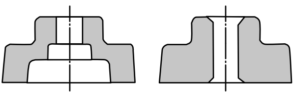
Avoid oval parts



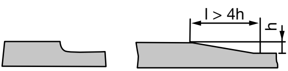
Favor modular design



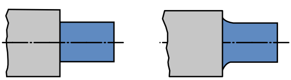
Avoid undercuts, favor modular design



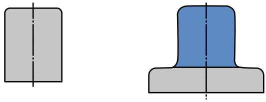
Avoid complicated wall designs and shapes



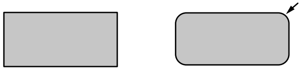
Avoid sudden cross-section changes



Minimize stress concentration

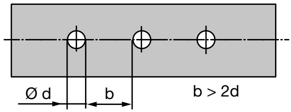


Plan in large bearing areas

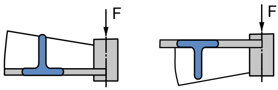


Avoid corners and sharp edges, round inside edges and breakthroughs

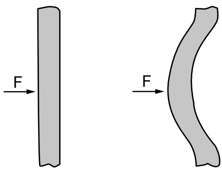
Avoid long, pointed edges



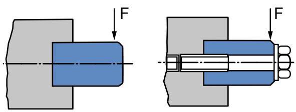
Ensure hole distance is not too small



Select a profile that minimizes tensile stress



Conversion of tensile stress into compression stress



Introduce pre-compression

During sintering, parts generally shrink linearly by up to 25%. Ceramics manufacturers compensate for this by designing larger shapes for manufacturing green bodies. In order to accomplish this task, manufacturers naturally need a broad range of knowledge and experience: How homogeneously does the respective powder used distribute during the production process selected for its particular suitability, and how does the powder behave later on during sintering?

In addition, ceramics experts also take into consideration particularities of the manufacturing process. If the green body is to be extruded, i.e. pressed from the machine in a strand, its geometry must be designed in such a way that the cross section does not change when the strand flexes. Manufacturing thin wall sections and webs is often problematic; undercuts can only be made using injection molding and isostatic pressing. If molds are used, it must be easy to eject the product from them. If the surface still requires finishing, a good support and clamping fixture should be part of the design concept right from the start.

Adapting to the manufacturing process …

In addition, the forming process works together with the ceramic starting powder, the additives and the sintering process to influence the part's microstructure and properties.

Moreover, the ideal method in terms of materials and design is not necessarily the most economical one. Some methods are only worth considering for large quantities. But if a customer only requires small quantities, a short production run on an existing production line may be more cost-effective.

… and the customer order volume

All of the factors that through the complexity of their interaction ultimately determine the microstructure and dimensions of a ceramic part cause the geometry and mechanical strength of the part to scatter around a mean value. For instance, if the dimensions must be rendered precisely to less than one percent, this can only be accomplished with the appropriate finishing techniques. This brings us full circle, because these types of requirements must already be taken into account in the design phase. With proper design, forming and finishing, it is possible to fully exploit the advantages the material has to offer. Therefore, design engineers and users should cooperate closely, always with an eye for the system as a whole in which the part is to be integrated.

Comprehensive procedural method

Joining techniques for modules

The more complex the design geometry, the more difficult it is to affordably implement the design with a production process. It often makes more sense to pursue a construction design that consists of simpler modules. Another reason for modular construction may be the customer's desire to be able to occasionally replace components that are subject to wear. Various methods for joining modules have already been proven in practical applications. For example, components are combined in their green state and then fired together or previously fired modules are bonded together.

Advantages of modular design

Joining ceramic components with non-ceramic components is especially challenging. The behavior of the various materials under the expected working conditions must be accurately calculated, for example to prevent damage resulting from highly varying thermal expansion coefficients that may occur.

Form fit …

"Form-fit joining" techniques require that the parts to be joined fit together seamlessly. The plug-and-socket connection is an example of this. Loads must never bear down on the connection's axis. Instead, they should always approach it at a transverse angle. One of the benefits of this method: The plugged part is easier to remove and replace.

… frictional …

Related to this method is the frictional joining technique, in which one of the two components presses or clamps the other into its fixed position. An example of this is shrinkage in forming tools: A matrix made of silicon nitride is to be shrunk in a steel ring. To accomplish this, either the metal is heated so that it expands or the ceramic is cooled so that it contracts. Afterward, both components can be interjoined. A temperature balance creates compressive stress which holds the assembly together, but it should not be allowed to become too large.

… and adhesive joining methods

In adhesive joining methods, the bond between the various materials extends all the way down to the atomic level. For instance, ceramic materials can be poured into aluminum; in the process a transition zone comprised of both materials is created in the border area. Soldering and brazing are also part of the same method group. To use solder, the ceramic is first metalized. This means that a thin metal layer is applied, for example by means of a galvanization process.

Specially designed metalization systems

Corresponding thermally adapted metalization systems were developed to ensure that no internal stress occurs during cooling. Common metalizations consist of tungsten or molybdenum. The metallic layers applied to the ceramic material make the component suitable for further processing by means of both brazing and soft soldering. A thin layer of nickel is deposited on the tungsten layer to achieve the required wettability of the solder on the metalization. A layer of gold is applied to the nickel for corrosion protection. An additional layer of tin is applied when soft solder is used. These two methods enable engineers to join metal and ceramic, and result in components that are ready to install such as ceramic surge arrestor tubes with metallic caps.

Bonding technique in use

Like solder, adhesives that harden at room temperature also create an adhesive bond. The advantage of this method is that no major temperature-related internal stress occurs. However, it is important to note the temperatures that the compound is exposed to in practical applications. Due to their varying thermal expansion, ceramic-metal pairings in particular can develop mechanical stresses that lead to damage.

These types of joining techniques are gaining importance – especially with respect to their modular construction, which helps expensive machinery to be operated for longer periods by facilitating the exchange of used and defective parts. Which method is the most suitable depends on the respective application. New materials and applications also provide room for fresh ideas and concepts.

Ceramics in practical applications

Textile industry

Ceramic thread guides

Around 40 years ago, yarn manufacturers and processors began replacing thread guides in their machines made of surface-treated steel with slower wearing elements made of advanced ceramics. This is because the high-speed thread acts like a saw; then, oils and lubricants were necessary in order to provide adequate lubrication, and this made it essential to clean the yarn once the process was complete. Today, the use of ceramics helps the textile industry achieve anywhere from double to ten times the normal service life of their machinery.

Texturizing synthetic fibers

Having said that, yarns made from natural fibers are not the only ones employed in the clothing industry. Synthetic fibers created by the extrusion of endless filaments are also commonly used. In order to give these fibers a natural feel, a friction disc is used to nap the surface of the material (Fig. 17). There are two competing materials here: Polyurethane (PU) as a tough synthetic, and technical ceramics. Here as well, the advantages of ceramics are apparent. The surface of the friction discs can be easily adjusted in its microstructure and finishing in order to determine the texture of the synthetic fibers. The high wear resistance of alumina, for example, enables yarn speeds of 1200 to 1400 m/min while maintaining a service life of several years. PU only lasts a few months when subjected to these kinds of loads. Another advantage lies in the ionic-covalent bonds in the material, as they contain

Fig. 17: Ceramic friction discs are key components of the friction texturing process.

large oxygen ions that keep the passing synthetic fibers in the processing and guide system by means of electrostatic attraction without slowing them down.

There are many other applications in these fields, such as air blasting. In order to uniformly align and bundle batches of synthetic fibers, a jet of air is blown onto them from the side of the ceramic guide assembly. In recent years, zirconium oxide splicer shears have also proven themselves in winders. They use optics to identify and cut out sections that are too thick or too thin. An air flow joins the ends together with a jet of air. The sections must be guided very smoothly to ensure that the linked ends hold. Under practical tests, ceramic splicer shears last around four times as long as shears made from hard metal.

Zirconium oxide splicer shears

Zirconium oxide ceramic blades for looms are also available in the marketplace. While winder blades must only withstand a few cuts per minute, loom blades can spring into action up to ten times per second.

Metalworking

Shaping non-ferrous metal wires
It is safe to say that no one is capable of measuring how many kilometers of power lines traverse the Federal Republic of Germany alone. The spectrum of cable and wire products ranges from high-voltage lines and telephone lines to the finest wires in electrical appliances that supply everything from circuits all the way to chips with electrical power. These wires consist almost exclusively of copper and its alloys – non-ferrous metals that combine minimal electrical impedance with low manufacturing costs.

The more or less fine wire variants all start out as raw wire. In the foundry a bar is cast from the liquid metal in a continuous process; the bar is then rolled into a blank. The resulting cast wire rod has a diameter of 8 mm. The temperature reaches 800°C during this process. Advanced ceramics can successfully handle these rough conditions while maintaining an economical tool service life. This is why the guide rolls that the raw wire passes through are made of zirconium oxide or silicon nitride, i.e. materials that possess a high temperature strength. This property, along with wear resistance, demonstrates yet another strong point of ceramic compared to metal: At these temperatures, the semi-finished product that is guided through the machine could easily fuse with the metal guide rolls; this, in turn, would damage the coating on the rolls, leading to breakdowns.

Guide rolls …

To create a copper wire that is often only a fraction of a millimeter thick from the cast wire rod, wire drawing machines pull the soft material until the desired end thickness is achieved. The trick here is to guide the wire

Fig. 18: A look inside a multiple wire drawing machine: The forming rolls used here are made of zirconium oxide ceramic.

like the rope of a hoist through the many capstans, thereby transferring force for shaping onto the wire (Fig. 18). This is where technical ceramics are able to fully play out their advantages. Navels for centering and guiding the raw wire into the machine, guides and guide rolls resist wear longer when they are manufactured from zirconium oxide or silicon nitride. Even lower-cost alumina is suitable for this purpose.

… and navels made of ZrO_2 and Si_3N_4

An intelligent solution that specialists take for granted today is a type of conical drawing winch called a drawing cone. Rings of different diameters compensate the changes in wire length that occur after every pull. Thus it is possible to achieve a number of different shaping speeds on a drawing shaft without using expensive gears that take up a great deal of space. This enables engineers to build small and compact machines with many shaping speeds.

Drawing cones made from ceramic composite

Manufacturers produce these drawing cones from ceramic composites to meet the high mechanical demands placed on them. The functional element is made from technical ceramics

that are clamped to a metal carrier. In other words, ceramic is only used when it is required for direct contact with the wire itself. Once the copper product has reached its final dimensions, it may require a visit to the paint shop. In order to send multiple wires through the paint bath simultaneously, specialists use ceramic plates with parallel guides as spacers.
Finally, the copper product is packed into a batch. Depending on the machinery available, there are three possible methods:

- Rolling the wire onto a solid core, which is sold with the wire
- Rolling the wire onto a splittable core, which can later be removed
- Bundling wire without a core

Coreless bundling uses a ceramic arc over which the wire spans and from which it falls at a specified curve.
The processes described here require the use of cooling agents and lubricants to reduce wear and overheating due to friction. Experienced wire drawers understand the tribochemical reactions that occur under such high pressure and high temperatures. In the process, sticky copper residues enriched with wire abrasion particles build up, causing the machine components to soil and wear, thus promoting wire breakage. With ceramics, it is possible to reduce the amount and concentration of cooling agents and lubricants and, beyond this, to use types that can be disposed of in a more eco-friendly manner.

Fewer cooling agents and lubricants required

Machining with cutting ceramics
Turning, milling and drilling are some of the typical processing methods in the metalworking industry and are grouped together

using the term "machining". The machining process transforms unmachined blanks into workpieces that are ready to install and can be used in the automotive industry as brake discs, clutch pressure plates, differential casings, flywheel discs or cylinder blocks, or in general mechanical engineering applications such as bearings or drive elements, for instance.

High cutting speeds

The tools used in the processing methods mentioned above are equipped with ceramic inserts, as they ensure the highest possible processing speeds while maintaining maximum productivity and economy (Fig. 19). Ceramic cutting materials used in machining have a long history. The first alumina ceramics for high-performance finishing of cast iron materials were introduced as early as 1957. In the years and decades that followed, both oxide ceramics and other types of ceramics established themselves as cutting materials. These include cermets, silicon nitride and SiAlON cutting materials, a ceramic ma-

Fig. 19: Cutting tool with ceramic insert

terials group in its own right that reflects the advances in the field of silicon nitride ceramics. Coated ceramics (Si-based cutting materials) have also been in use for quite some time. They complete the spectrum of use for ceramic cutting materials and also open up additional fields of application.

Each of these cutting ceramics is characterized by its own specific property profile. They are found in applications such as high-speed and high-performance machining of cast iron materials such as gray cast iron (cast iron with lamellar graphite) and ductile cast iron (cast iron with spherical graphite). Additionally, cermets are used to turn hardened steel and chilled cast iron.

In summary, the following can be said of cutting ceramics:

Ceramic cutting materials

- Oxide ceramics that use alumina with zirconium oxide particle deposits as a basis to increase toughness are preferred for turning and grooving under uniform conditions.
- Due to their increased ratio of additional hard materials such as TiCN, mixed ceramics demonstrate improved hardness and hot hardness and are viewed as superior for the final finishing steps of the turning process.
- Si-based materials, silicon nitride and α-/β-SiAlON, are characterized by a microstructure featuring needle-like Si_3N_4 or SiAlON grains. This helps them achieve remarkable toughness characteristics while retaining their exceptional wear resistance. These cutting materials have now become established in the field of high-performance finishing in turning and milling cast iron materials, even under very unfavorable and rough working conditions.

- Polycrystalline cubic boron nitride is distinguished by extreme hardness and superior wear resistance. In practical applications, these cutting materials offer convincing performance thanks to their ability to meet the highest demands with regard to dimensional stability and surface quality during hard turning.
- Coatings containing alumina and/or titanium carbon nitride generally consisting of multiple layers increase wear resistance and decrease friction during machining. This helps further improve the already excellent application qualities of ceramic cutting materials.

Brake discs are a typical example of an area where cutting ceramics are used (Fig. 20). Brake discs are manufactured using CNC lathes in multiple settings to produce a ready-to-use workpiece from the cast-iron blank through the various machining operations. The machining speed is a benchmark for the manufactured parts per unit of time and the resulting costs per unit. The Si-

Fig. 20:
Turning a brake disc with a ceramic insert

based cutting ceramic used in this example, α-/β-SiAlON, works at such high machining speeds that it takes less than 30 seconds for each of the (under normal conditions) three settings, despite reaching speeds of 1000 m/min and more. Conventional cutting materials such as hard metals cannot reach these speeds because they have a lower temperature strength. Furthermore, the use of cutting ceramics renders cooling lubricants unnecessary. This has a positive impact on acquisition and disposal costs and expenditure overall.

Significant time savings

In transmission technology, processed parts such as hardened gear wheels and shafts (hardness range of 58 to 62 HRC) are often subject to a costly and time-consuming grinding process in order to achieve the specified surface qualities and part tolerances. Using mixed ceramics during this final processing step allows manufacturers to replace conventional grinding with the less costly and more flexible "hard-fine turning" method. Substituting the methods in this way is enabled by the fine-grained, extraordinarily firm, hard and hot strength mixed ceramics.

Mixed ceramics enable hard-fine turning

Welding with ceramics

Welding is among the standard procedures for joining metal parts. The materials used on the machine end of this joining process are exposed to extreme levels of stress. When selecting the right material, engineers must take a number of different criteria into consideration in order to fulfill the high demands with regard to wear resistance, service life and economy. In this domain, ceramic has repeatedly proven itself a worthy material based on its extraordinary hardness, outstanding ther-

Fig. 21:
Ceramic components used in the welding process: Gas nozzles, centering pins and welding rollers

mal shock resistance, excellent electrical insulation capability, high temperature resistance as well as its high compressive strength and toughness.

Three ceramics

Three different types of ceramics are used here: Alumina is used for plasma gas nozzles in particular. Yttrium-stabilized zirconium oxide, on the other hand, is the standard material for welding pins. The third, most recently introduced material is silicon nitride. Silicon nitride is capable of significantly reducing wear in tools subject to extreme levels of stress during the welding process, such as welding rollers (longitudinal seam welding on pipes), welding pins (projection welding) or gas nozzles (MIG/MAG welding) (Fig. 21). This brings the following advantages to the welding process:

- Much longer tool life
- Reduction in total set-up times
- Increase in machine running times
- Avoiding cold shuts
- Improvements in welding seam quality

Advanced ceramics in the casting process
Aggressive melts, temperatures surpassing 1000°C and temperature differences of several hundred degrees – ensuring reliable process controlling, maximum system availability and high melt purity under such extreme conditions overextends the capabilities of most materials, but not aluminum titanate, a mixed ceramic made of high-purity alumina and titanium oxide. A special reaction sintering process ensures a microstructure with microfine pores and cracks, distinguished by a unique property profile:

Properties of aluminum titanate

- Low thermal conductivity
- Minimal thermal expansion
- High corrosion resistance
- Excellent thermal shock behavior
- Outstanding temperature resistance
- No or very little wetting with most molten metals

Armed with these characteristics, the material is highly suited for work with non-ferrous metal melts such as those made from aluminum, magnesium, zinc, tin, brass or gold. Above all, aluminum titanate has effectively proven itself in low-pressure aluminum casting as a material for risers and nozzles (Fig. 22).

Thermal shock resistance

Since they are resistant to thermal shock, components made from aluminum titanate do not require preheating; instead they can come into direct contact with the melt – a huge advantage in practical applications. The low thermal conductivity of the material reduces the temperature gradient in the melt, thereby decelerating its solidification; moreover, heat dissipation remains low, which also conserves energy. The chemical resistance not

Fig. 22:
Aluminum titanate risers and nozzles can even withstand aluminum melts.

only extends the service life of ceramic components; it also prevents impurities in the melt. Since most metal materials cannot be wetted, they do not bake on and components require less frequent cleaning. Finally, aluminum titanate components weigh only half as much as gray cast iron components with the same dimensions; this simplifies handling considerably.

Wear protection in plant engineering

Plant component wear and corrosion are key factors that influence the cost-effectiveness of production. Plants that can no longer guarantee flawless operation incur downtime and repair costs. Systems that convey or process highly abrasive and aggressive substances are impacted most. Linings made from technical ceramics minimize wear and corrosion in areas subject to high stress. Some application fields for wear-resistant ceramics are machines and plant equipment, for example in steel mills, in the chemical, food and beverage and pharmaceutical industries, in power plants, in the cement and concrete industry and in the preparation of mineral-based raw materials. Solutions that feature advanced ceramics ensure longer service life, are lower in maintenance and are thus more economical overall.

Use of alumina

Alumina is the chief material used in plant engineering, as it features high hardness and wear resistance, consistently low erosion levels, high temperature resistance of up to 1000°C and beyond, corrosion resistance, bioinertness and a low specific weight. The decisive factor in ensuring that these advantages are fully exploited, however, is the optimum integration of ceramic in existing systems combined with a custom-fit, permanent bond with other materials such as steel, rubber or synthetics.

Application examples

Due to the myriad utilization possibilities, only a few sample applications are listed here. Ceramic linings are used in transport chutes and slides, oscillating conveyors, drum mills, mixers, ball valves (Fig. 23) and in compact bends. When transporting blast-furnace (metallurgical) coke, ceramic linings can achieve a service life up to 12 times that of steel linings.

In mineral technology, ceramic mill and separator linings also enable contamination-free operation in addition to longer service life.

Fig. 23:
Ball valve with a steel valve ball; the steel valve ball passage has a ceramic lining to minimize wear.

Further, their bioinert properties make them suitable for use in the pharmaceutical and food and beverage industries. Ceramics are just as suitable for processes where high impact load plays a role, e.g. transfer hoppers, funnel tubes or skip cars for blast furnace feeding. In pneumatic pipe systems, especially in highly turbulent areas, in arcs, manifolds, inlet pipe ends and ball valves, alumina boasts service lives of up to 10 times that of steel.

Advanced ceramics are used in innovative ways to protect against wear in large ski jump

Fig. 24:
Left: Ski jumping without ice
Right: The applied ceramic nubs have the same glide properties as ice.

Innovative use of ceramic nubs

installations. Ceramic nubs are applied to the inrun track systems on ski jumps, allowing ski jumpers to glide toward the ramp (Fig. 24). These ceramic nubs are used in summer ski jumping events and whenever athletes are required to train in non-snow conditions. Ceramic nub glide properties are adapted to imitate those of ice, ensuring ideal conditions for ski jumpers.

Optical technologies

Transparent ceramics

A new material in the technical ceramics market is a transparent ceramic, branded Perlucor® (Fig. 25). It combines the optical characteristics of transparent materials with the mechanical properties of advanced ceramics, creating a mechanically, chemically, thermally and optically optimized solution for extreme applications in transparency.

Physical and …

Thanks to the high hardness of transparent ceramic components, there is virtually no natural substance that can scratch the surface of this material. This makes it a very good

Fig. 25: Transparent ceramics open up new perspectives in optical technologies.

choice for use in extreme wear conditions, for example as panes in blasting cubicles. While conventional glass panes can become completely opaque after only a few blasting operations, panes made from transparent ceramics continue to enable clear viewing. The excellent scratch resistance makes it ideal for use in watch faces or display panels, for instance. The high thermal stability makes it suitable for use as an inspection window in furnaces at temperatures of up to 1600°C. Since the material is highly transparent right through to the infrared range, it can also be implemented in a variety of optical sensors. Its outstanding chemical resistance against acids and lyes makes it possible to use the material as an inspection window or tube for highly corrosive fluids in industrial plants. Applied as safety glass, weight and volume savings of up to 50% are achievable thanks to these unique characteristics (see also p. 67).

… chemical properties

Chemical, energy and environmental technologies

Conventional applications: technical porcelain

Powerful interatomic bonds not only give ceramic materials hardness and wear resistance, but also a resistance to corrosion. Put simply, a great deal of energy is required to free individual atoms from the crystal lattice; consequently, these materials stand up well to the aggressive effects of any number of different media. Since they also tolerate high temperatures, ceramics have obtained a permanent place in the world of chemical, energy and environmental technologies. For instance, crucibles made of high-grade la-

Fig. 26:
Dipping formers for synthetic gloves for industry, household and surgical use

boratory porcelain are part of every chemist's toolkit.
Yet another area of application is the manufacture of dipping formers for latex, vinyl and PVC gloves (Fig. 26). The hand mold is dipped in the liquid plastic molding compound; the plastic adheres evenly to the dipping former, dries and, following several other processing steps, the glove can be removed from the mold. Properties such as thermal shock resistance, resistance to corrosive media and a low expansion coefficient are just some of the advantages of technical porcelain in these kinds of applications.

Ceramic bearings, seal and regulator discs

Transporting abrasive, corrosive media

Today, technical ceramics are used in bearings as well as other pump components such as shafts, bushings and seals whenever pumps are required to convey corrosive and abrasive media.
The chemical industry places particularly high demands on materials. Here they are expected to transport acids or alkalis through pipes to the reaction vessels. These media often contain solids that would have a devastating impact on conventional materials under conditions involving high pressure and speed in bearing and/or sealing gaps. The food and beverage and cosmetics industries also have exacting requirements. For example, pump component corrosion is completely unacceptable in these industries. The physiological soundness of ceramic materials is opening up new avenues in mechanical engineering (Fig. 27). For instance, highly viscous media such as all types of dough, sausages and/or pastes, jams and creams are

Physiologically safe

Fig. 27:
Nozzles, seal rings and tubes made of silicon carbide for machine and plant engineering

pulverized with ceramic grinding tools and liners made from silicon carbide and transported through pumps fitted with ceramic bearings and seals.

Special caution is required when bearings run dry. Admittedly aluminum and zirconium oxide cannot cold-weld like metals do, but they may not be able to sustain the sudden temperature shifts that occur on re-entry of the liquid medium. In these cases, silicon carbide would be the best-suited material due to its low thermal expansion and high thermal conductivity.

Advanced ceramics in everyday households ...

But these high-tech components are not only present in industrial settings; they have also established themselves in everyday households. Now, every dishwasher comes with ceramic seal rings or axial bearings, which ensure quiet operation for long periods thanks to the low friction of ceramic components. Domestic water and heating circulating pumps are also equipped with ceramic bearings. Ceramic regulator discs are used in high-quality espresso machines as well. Manufacturers recently began producing ceramic grinding discs, as the constant fineness of the grounds determines the flavor of the coffee.

… and in plumbing fixtures

Advanced ceramics have been at home for years in bathrooms and kitchens, as seal and regulator discs in premium-quality single- or double-handle combination faucets, for example (Fig. 28 left). According to the cross-slide valve principle, a base disc sits firmly in the enclosure and is secured against twisting. The regulator disc is movable and situated above the base disc and connected to the control lever. Depending on both discs' positions in relation to one another, the openings for warm and/or cold water are either open or closed (Fig. 28 right). The ceramic discs can have a diameter of up to 60 mm. To ensure low-friction gliding and good leak tightness, their height is precisely adjusted to ±0.05 mm with a flatness requirement of 0.6 µm and a percentage of surface contact area between 50 and 80%. During finishing, micropores in

Fig. 28: Left: Ceramic seal and regulator discs ensure long-lasting functionality of single-handle combination faucets. Right: Schematic diagram of the regulating principle

the surface microstructure are introduced to house lubricant. They form a permanent reservoir for this purpose – adequate lubrication residue was detected even after two million actuation cycles under real operating conditions. Furthermore, the pores absorb solid particles carried by the water, thus minimizing wear; however, most of these particles are pulverized between the two discs and therefore rendered harmless.

Ceramic catalyst carriers

Today, many raw materials and products in the chemical industry can only be economically produced using catalytic methods. It is estimated that 70 to 80% of all large-scale synthesis methods use catalysts, i.e. substances that facilitate or accelerate a chemical reaction without being consumed in the process. Yet catalysts are often quite expensive. To manage with as little of the material required as possible, a thin layer of it is applied to a substrate. This is also necessary whenever the catalyst is not very mechanically stable or a thin layer is required anyway, for ex-

Fig. 29: Catalyst carriers play a key role in myriad chemical synthesis processes

ample to make the effective surface as large as possible.

Use in oxidation processes

Ceramic catalyst carriers form an important subgroup of commonly used materials. They are primarily used in selective oxidation processes, such as the manufacture of acrylic acid from propylene or ethylene oxide from ethylene. Depending on the application, dense or porous substrates may be used, usually designed as rings, balls or spherical granulates (Fig. 29). Steatite and alumina are used as ceramics.

Electrical engineering and electronics

Insulating components in electrical engineering

Hard, heat-resistant and corrosion-resistant – these are three essential features of ceramics that are joined by yet another property that

Fig. 30: Ceramics for electrical engineering: Casings, tubes, laminae and other insulation component geometries

plays a key role in electrical engineering and electronics: Ceramics insulate very well against electrical current flow. This is why insulating elements in electrical devices, regulators and lights are made from special ceramics (Fig. 30). This material is also used to manufacture fuses. Small, gas-filled tubes made of alumina protect electrical and electronic equipment against excess voltage. For example, when lightning strikes a telephone pole it is important that the excess voltage does not disrupt the entire system. In lightning/surge arrestors (Fig. 31), two metallic electrodes are separated by a gas that does not normally conduct electricity contained inside a ceramic insulating sleeve. The voltage pulse ignites an electric arc, which conducts electricity for a brief period, thereby diverting the excess voltage. Afterwards, the electric arc collapses and the component is ready for use again.

Use in circuit breakers

Fig. 31: Ceramic is used everywhere powerful currents flow, for example as surge arresters or casings for thyristors and diodes.

Beyond their uses in circuit breakers, specially designed ceramic-metal composite components are widely used as electrical feedthroughs, multi-pin connectors, coaxial connectors, thermal elements, insulators or sight glasses in technologically demanding fields such as aviation, medical technology, microwave technology, laser technology, oil production and telecommunications. In some cases, they are also present in space technology or in microscopy (scanning electron microscopes). These highly robust components are resistant to ultra-high

Fig. 32: Ultra-high-vacuum-capable brazed ceramic assemblies

vacuum (UHV) environments (Fig. 32), temperatures of around –273°C to +450°C, pressures of up to 1700 bar and highly corrosive and caustic atmospheres.

Leakage current resistance

Yet another advantage of ceramics is their leakage current resistance: When components made of other materials are exposed to moisture and corrosive agents, electrically conductive connections can form and “burn in”, so to speak. In contrast, advanced ceramics retain their insulating capacity even under adverse environmental conditions and high voltages.

This is one of the reasons why high-voltage transmission and distribution applications are often equipped with silicate ceramic insulators. To allow rain to run off and increase the creepage length, specially shaped outer forms are turned into the extruded tubes or rods. When installed on the towers, the conductor lines are hung onto the insulators; the ceramic products are often exposed to several tons of tensile stress. Engineers choose a different construction for transformer stations. Here, insulators support the lines from below. Supporting structures for antenna systems and their corresponding leads are traditionally insulated by ceramic – up to 1000 t of weight from one of these poles can rest on an insulator the size of a sheet of paper.

Mechanical stability

Technical ceramics for electronics

Electronic circuits can be constructed with a handful of primary components, such as circuit board materials, electrical conductors, active and passive components and areas for mechanical mounting. Today, modern advanced ceramic materials such as alumina, aluminum nitride, zirconia-toughened alumina, zirconium oxide and glass ceramics are used in these applications. Depending on the purpose of the application, these materials must possess characteristics such as thermal conductivity, mechanical strength, electrical insulation or electrical conductivity capabilities and corrosion resistance.

Flat ceramic circuit boards

The very flat and thin ceramic circuit boards are chiefly used whenever requirements dictate both a long lifetime and extremely high reliability on the one hand and difficult environmental conditions are present on the other, e.g. application temperatures exceeding 120°C, the occurrence of vibrations or thermal shock.

The metalization can be applied to the ceramic circuit boards in a number of different ways, depending on the requirements. The most commonly used method is known as thick-film technology.

Thick-film …

Here, a metallic paste is applied using the screen printing process and then fired at temperatures in excess of 400°C.

… or thin-film technology

Thin-film technologies such as sputtering are used in applications where the conductor path distances and conductor path widths are less than 80 μm. But these methods require significantly less surface roughness in the ceramic circuit boards, which are modified either by the selection of the material or through hard machining.

The bond between the metalization and ceramic achieves adhesion strengths of over 50 N/mm^2; this means that the peeling of the metalization similar to that which occurs on synthetic surfaces can be virtually ruled out.

Manufacturing using tape casting

The ceramic circuit boards or substrates are mainly produced using the tape casting process. The green body is processed using methods such as hacking, punching, stamping, perforating and laser treatment. If the substrates have been sintered, cracks and holes are generally added to the ceramic using lasers (Fig. 33). The most economical processing method is selected based on the quantity and geometry of the requested products.

In passive components such as electrical capacitors, resistors and inductor bodies, the core is also made of ceramic. This has helped in the miniaturization of regulators, cellular phones and everyday electronics such as

Fig. 33: Extremely thin ceramic substrates are finished with laser technology in order to achieve the finest possible bores and geometries.

notebooks, smartphones, navigation systems or DVD players, because the size of ceramic components has decreased exponentially while retaining the same functionality. Component sizes that once reached 2 × 2 × 4 mm have shrunk to 0.25 × 0.25 × 0.5 mm today.

Compatibility with a variety of materials

The demand for circuit systems featuring components with precisely matched material properties is also steadily increasing due to intensified working conditions. Thermal expansion is an example of this. When material is heated, it expands; when it cools, it contracts again. If the expansion behavior of different materials or components differs too much, strain occurs, which subsequently causes the different materials to separate. Thermal expansion now plays a significant role in that today's high integration densities boost the electrical power density and thus the temperature in the casing. Active components such as silicon semiconductors also generate heat that must dissipate so that the semiconductor does not self-destruct. Here as well, advanced ceramics contribute to longer life and improved reliability of electronic modules, as the silicon semiconductor can be directly joined with metalized regions of the ceramic material. This allows it to dissipate heat through the ceramic circuit board without encountering additional barriers.

Use of ceramic heat sinks

Semiconductor packages are rarely found in applications today. The same applies to electrical resistors. Now, these elements are usually printed and etched directly onto the circuit board. These types of concepts are executed using direct application onto ceramic, for instance with the help of a ceramic heat sink, which also functions as a circuit board at the same time.

Importance of functional properties

The newer ceramic materials are no longer defined exclusively by purely geometric dimensions; rather, their functional properties play an increasingly vital role. A good example of this is the one-piece ceramic pressure sensor, which is divided into rigid and flexible sections. During measuring, the outside pressure bearing on the element leads to deformation of the flexible ceramic section. A circuit mounted in this section transmits a signal in proportion to the pressure. This makes it possible to determine the difference between outside and inside pressure. Another example can be found in the manufacture of three-dimensional electrical circuits using glass ceramics (e.g. LTCC; Low Temperature Co-fired Ceramics). By intelligently combining ceramic and metalization, they make it possible to produce a multilayer circuit board with interior conductors and plated through-holes in one production step, thereby simultaneously achieving required inductance, capacitance and resistance in situ. Once the sintering process is complete, the three-dimensional electrical circuit is part of a one-piece component. It can then be populated with additional components and integrated into a complete system.

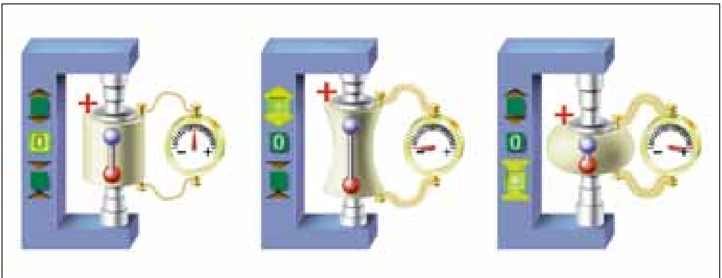
Ceramics also help regulate the process of combustion. For example, certain types of zirconium oxide are placed in lambda probes to measure oxygen concentrations in combustion gases and optimize them by regulating the air supply. The effect of oxygen ion conductivity also plays a key role in high-temperature fuel cells and is an important aspect of this technology's functionality.

Oxygen transferability

Sensors and actuators

The case studies mentioned above may give readers the impression that ceramic is only suitable as a material for passive components. In reality, ceramic is not only capable of withstanding extraordinarily difficult conditions, but special ceramics can also get things moving. This is due to what is known as the piezo effect (Fig. 34). In certain materials, positively and negatively electrically charged ions in the crystal lattice are not distributed evenly, but instead develop charge centers. Outwardly, the crystal normally appears electrically neutral. Nevertheless, a mechanical force stretches the lattice, thereby displacing

Fig. 34: When a piezoelectric component expands (middle), it emits electrical voltage. When it is compressed (right), the voltage polarity is reversed.



the mass centers and polarizing the crystal. Electrical voltage will then be produced on the outside of the crystal. The piezo effect also has an inverse counterpart. Voltage applied across the crystal distributes the charge centers evenly and the ceramic expands.

Piezo effect

Many sensors function based on this electromechanical conversion, crash sensors in automobiles being a notable example. The rapid decceleration on impact generates a voltage signal that is amplified and ultimately ignites airbags.

Actuators for fiber optics

Actuators that are expected to exert forces within micrometers of space are controlled down to the nanometer by placing the corresponding voltage on a piezo ceramic. This precision is necessary for adjusting optical fibers, for instance. Actuators like these usually consist of multiple ceramic layers of only 0.1 mm each, enabling them to work with low operating voltages and making it possible to realize actuation displacements of 50 µm with an actuator length of 30 mm.

Ferroelectric ceramics

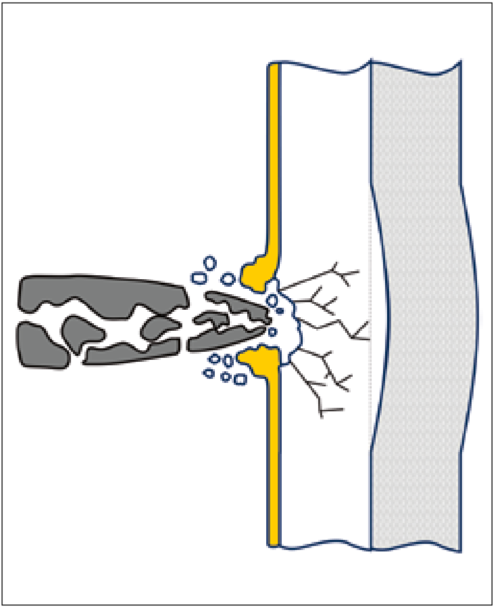
The corresponding ceramics are members of the ferroelectric material group. Today, lead zirconate titanate-based systems are used almost without exception. These are mixed crystals made of lead zirconate ($PbZrO_3$) and lead titanate ($PbTiO_3$). Their crystallites exhibit the charge separation referred to here; thus they work as dipoles. Following sintering, the directions of the dipoles are statistically distributed and would not demonstrate any piezo effect. Hence, they are aligned using an electrical field; i.e. the entire crystal is polarized. Heating them too much would reverse this orientation, as would too high a compression load; depending on the application, close attention must be paid to the design and operating conditions.

Ballistic protection

Advanced ceramics such as alumina and silicon carbide play an increasingly important role in the area of personal and vehicle protection. UN and NATO peacekeeping troops use ceramic-based supplementary armor plating on their vehicles that protects against artillery and mortar shrapnel and mine explosions (Fig. 35).
Ceramic per se is both brittle and sensitive to shock, and, when viewed individually, only offers minimal ballistic protection. As a composite, however, for example with polymers, it can comply with protection requirements with weight advantages of up to 50% compared to the steels used in these applications. The protective action of this ceramic-polymer composite armor plating is based on a highly specialized mechanism. The impact of am-

Fig. 35: Geometry specially adapted to the object being protected: Advanced ceramic components for vehicle protection.

Fig. 36:
The combination of protective ceramic and backing micronizes the projectile.



munition on the surface of the ceramic causes a deformation of the projectile tip. This enlarges the collision cross section. When it penetrates the ceramic layer, the projectile shatters into a number of small fragments, also called micronization (Fig. 36). The kinetic energy of the fragments is much lower due to their lower mass and is completely absorbed by elastic-plastic deformation in the synthetic layers (backing) located behind the ceramic shell.

Micronization

Body protection

Superior safety combined with reduced weight

The aim of personal protection is to boost the ballistic performance and wearing comfort of protective vests while at the same time reducing their weight. Nowadays, most bulletproof vests are equipped with monolithic ceramic plates. In addition to monolithic inserts, multi-tile versions are also available. In cases of impact, these inserts demonstrate heightened multi-hit capability because they minimize and control crack propagation in the armor system.

Vehicle and property protection
Composite armor systems based on advanced ceramics have frequently proven their efficiency in vehicle and property protection as "add-on armor" or as integrated interior protection. They are found not only in mobile containers but also in land- and aircraft as well as ships. In the latter three, the weight advantage of ceramic-polymer composite armor plays a crucial role in regards to mobility, payload and maintenance.

Transparent ceramics for ballistic protection
Non-transparent vehicle parts can also benefit from the impressive weight and volume savings resulting from the use of opaque ceramics in combination with fiber composites. Transparent ceramics also make it possible to achieve these savings in the field of transparent protection. They offer savings of 30 to 60% compared with conventional glass laminates. Here, ceramic replaces part of the glass panes within the system. Similar to opaque protection systems, the projectile is flattened or miniaturized when it impacts the transparent ceramic material, so that it can then be absorbed by the glass or plastic installed behind it. Alongside ballistic protection, ceramics also effectively shield against external influences such as impact from stones or sand abrasion.

Partial substitution of glass panes

Automotive technology

Almost no other products offer the cross section of state-of-the-art technology that motorized vehicles do, particularly passenger cars. Otherwise, it would be nearly impossible to fulfill the often conflicting demands of customers and manufacturers: Protecting the environment and the earth's natural resources, delivering performance and comfort, meeting high safety standards, offering reliability and cost-efficiency. Ceramic components are essential in meeting these requirements.

Wear- and corrosion-resistant alumina has been used in fuel delivery for gear pump end plates for years (Fig. 37). Further examples of alumina's efficacy include sensor components along with rotary gate valves and wear components for a broad range of pumps. Silicon carbide dominates the coolant pump market as a bearing and seal material due to its excellent thermal conductivity (see also the chapter on "Chemical, energy and envi-

Fig. 37: Alumina end plates for fuel pumps

ronmental technologies”, p. 51 et seq.). Here, this high-quality material’s mechanical and thermal properties offer more dependable operation than other solutions. In exhaust gas valves, part of the hot exhaust gas is fed back into the intake port and combusted in accordance with EU exhaust emission standards. Temperatures can exceed 450°C near the engine. Since zirconium oxide features thermal expansion coefficients similar to those of steel, i.e. it is easy to combine with this material, it is used to produce friction bearings. Temperature resistance and the positive tribological properties obtained through the coupling of zirconium oxide and steel enable high-temperature bearings to operate without lubrication. Another commonly used material is silicon nitride. Its outstanding mechanical properties (mechanical strength, toughness and tensile strength) allow this material to be used in applications with high or impact contact stress. Owing to its low density, it offers additional benefits, particularly in dynamic applications. These characteristics make silicon nitride the ideal material for executing automobile manufacturers’ downsizing strategies (reducing engine size while simultaneously increasing the power density).

Zirconium oxide for high-temperature bearings

Silicon nitride for dynamic applications

Computer-controlled catalytic converters are standard in exhaust gas purification. At temperatures surpassing 250°C and with a balanced ratio of air and fuel during combustion, catalytic converters effectively eliminate the majority of hydrocarbons, nitrous oxides and carbon monoxide. A “cat” comprises a silicate ceramic body containing thousands of fine channels that are flooded with exhaust gas. The catalytically effective layer of plati-

Catalytic converters made from silicate ceramic

Fig. 38: Piezoceramic components transmit and receive sound waves to help distance sensors determine distances.

num and rhodium is located on an alumina coating. Halogen lamp sockets are often made from silicate ceramics. Due to high temperatures, plastics can no longer be used for this purpose.

Piezoceramics are also prominently featured in vehicle engineering. Knock sensors made from this material register harmful knocks, a consequence of using improper fuel or altered operating conditions. The ignition characteristic map is readjusted accordingly. This keeps the combustions close to the knock limit, which lowers fuel consumption.

Piezoceramics for crash …

In the event of an accident, other piezo sensors trigger within fractions of a second to tighten seat belts and inflate airbags. This is accomplished by joining two piezoceramic beams of opposite polarization. When the vehicle decelerates very abruptly, this compound flexes, creating electrical voltage. When it exceeds a threshold value it triggers the vehicle safety systems. One technology that has rapidly gained popularity during the past few years is the use of ultrasound emitters to measure distances when driving in reverse. The delay from the reflected signal is used to measure the distance to the obstruction (Fig. 38).

… and distance sensors

Piezoceramics also serve well as actuators, controlling ABS, diesel or fuel injection valves, for example (Fig. 39). Because multilayer actuators are highly dynamic, they are even capable of delivering multi-stage cycles with pilot injection. In the process, the main injection quantity is regulated to allow for the engine's actual, present fuel requirements.

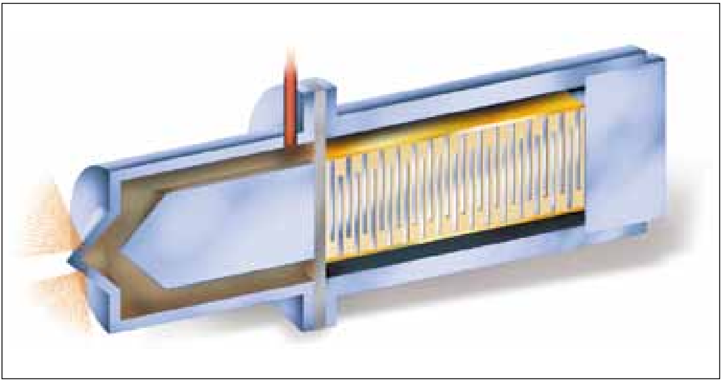
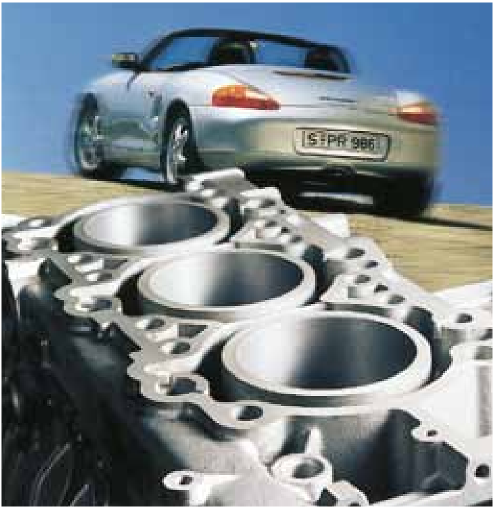


Fig. 39: Piezoceramic actuators control injection nozzles.

Preforms for cylinder liners in motor blocks are a special application (Fig. 40): A highly porous ceramic sleeve is infiltrated in the aluminum melt of a motor block in a pressure casting process, creating the running surface of the cylinder sleeve in the motor

Fig. 40:
Cylinder liners with cast silicon preforms combine maximum wear resistance and excellent tribology.



Metal-ceramic composite

block from a metal-ceramic composite with matchless tribological properties. This method results in remarkable weight reduction compared to conventional designs made from cast iron.

Medical products

Artificial hip joints

One out of every ten citizens in Germany suffers from hip problems: When walking, even when lying down, they experience hip pain and the flexibility of their joints is limited.

Arthrosis – a common ailment

This is often caused by arthrosis, a deterioration in the cartilage that provides coverage and padding for the surfaces of the joints. Age, excessive strain, lack of exercise or illness can cause this wear and a debilitating loss of quality of life is often the result. If the illness is very advanced, the patient's doctor will recommend an artificial hip joint – more than

1.5 million patients worldwide are advised to undergo the implant procedure each year.
The shape of the natural joint is conducive to prosthetics: A spherical head interconnects with a cupped joint socket.

The first functional prosthetics

After numerous failed attempts extending into the 19th century, the first somewhat functional prosthetics were developed in England toward the end of the 1940s: The stem and ball were made of stainless steel and produced from a single cast. At first, doctors did not replace the cup. Shortly thereafter, a prosthesis became available for this purpose. It was made from special polyethylene (ultra-high molecular weight polyethylene, PE-UHMW). The joint fluid generated naturally by the body lubricates the artificial joint as well.

Rapid wear of synthetics

Unfortunately, synthetics wear rapidly in this combination of materials. After all, walking and running can have an impact of up to five times and stumbling can have an impact of up to ten times a person's body weight on joints; in a period of ten years, the gait cycle creates around 20 million load changes. Typical values of the wear that occurs here range from 0.2 to 0.5 mm per year (Table 3). This process also generates very large polyethylene particles that trigger an inflammation reaction. Often the prosthesis will loosen after a period of less than 10 years and will then

Material combination	Annual abrasion
Metal/polyethylene (PE-UHMW)	0.2 mm
Ceramic/polyethylene (PE-UHMW)	0.1 mm
Ceramic/ceramic	0.05 mm
Joint ball head and cup insert made of hot isostatic pressed Al_2O_3	< 0.001 mm

Table 3: Comparison of friction values of various material couplings for hip joint ball heads and cup inserts

require replacement, if still possible. These circumstances are unsatisfactory, especially since today, people under the age of 50 are receiving artificial hip joints and the life expectancy of the population is growing.
Replacing the metal head with one made from advanced ceramics offers a true improvement. Pure alumina ceramics and aluminum mixed-oxide ceramics are available options. Inserting

Fig. 41: Hip joint prosthetic with ceramic ball head and cup insert along with a hydroxylapatite-coated precious metal stem

the ceramic ball head necessitates a modular construction in which the ball is clamped onto a stem made of a titanium or cobalt-chrome steel alloy. Doctors began using these types of implants in the early 1970s. The acetabular cup is composed of titanium alloys, pure titanium or cobalt-chrome alloys. Ultra-high molecular weight polyethylene as insert material is generally used in these operations. Here, friction is reduced to less than 0.1 mm annually, cutting the loosening rate in half.

Ideal combination: Ceramic/ceramic

Nonetheless, the tribological pairing is not the optimum solution unless a ceramic cup insert is used, i.e. the coupling of materials is ceramic/ceramic (Fig. 41). When hot isostatic pressed alumina is used for both components, its fine microstructure reduces bioinert wear by orders of magnitude, namely to less than 0.001 mm annually. Moreover, the wear particles are much smaller; based on present experience, inflammation reactions do not occur. Another step forward is achieved through the use of aluminum mixed-oxide ceramics. Here, zirconium oxide is an additional component of the ceramic. The addition of this material makes it possible to further refine the microstructure compared to pure alumina ceramics. Furthermore, the zirconium oxide brings about crack-resistant mechanisms that more than double mechanical strength and resistance against crack propagation. Laboratory tests indicated that even under extreme experimental conditions, wear in a hard-hard (ceramic-ceramic) coupling made from aluminum mixed-oxide ceramic is reduced up to seven times as much compared to that of pure alumina ceramic.

Hydroxylapatite gives implants a secure hold

Coating the implants facilitates the fixation of the cup and stem. For almost 20 years, orthopedists have used implants coated with hydroxylapatite. This substance comprises 60 to 70% of bone material. During plasma spraying, a procedure used to coat metals with high-melting materials, hydroxlapatite forms an intricately interwoven lattice made of calcium phosphate crystals. New bone cells can grow rapidly in the interstitial spaces and give the prosthesis a secure hold within a matter of days.

Today, over six million people have ball joint heads made from alumina, and hundreds of thousands of patients have ceramic cups. Empirical values on hydroxylapatite coatings have been available for around 20 years. With these optimum material combinations featuring low wear and extended durability – and individually tailored planning and operation – physicians hope, especially for younger patients, that an operative replacement for the first hip prosthesis will not be required.

Application potential of knee endoprosthetics

Aluminum mixed-oxide ceramics are likewise the ideal material for enhancements and future innovations. This material enables lower wall thicknesses for hip components along with complex geometries, like those required in knee endoprosthetics, for instance. The clinical, functional and radiological behavior of a new knee prosthetic system with a ceramic femur or thigh bone component that runs against a polyethylene component in the lower leg is currently being evaluated in an international multi-center study – with excellent results thus far. Based on the tribological properties mentioned earlier, an option exists to reduce the generation of friction in joint replacements along with the risk of a "particle disease" with local osteolysis (resorption of bone tissue) and aseptic implant loosening.

Ceramics for patients who experience allergic reactions

Allergic reactions to metal are yet another aspect of implantation. If patients are allergic to metallic implant components, biologically inactive ceramic is a viable alternative to standard cobalt-chrome systems. Yet another development is the monoblock system, which consists of a pre-jointed composite comprising a ceramic insert and a metal cup and features a total wall thickness of only around 5 mm. Scientists are also developing artificial intervertebral discs that, when combined with the matching bone anchorage, do not produce any artifacts in magnetic resonance tomography (MRT).

Piezoceramics in medical technology

Generating ultrasound

Humans can hear sounds of up to 20 kHz; bats, on the other hand, use higher-frequency ultrasound to navigate their environments and find their prey with the help of reflections. Modern piezoceramics help humans tap the potential of ultrasound, too: Alternating voltages cause them to oscillate, which in turn sends off high-frequency acoustic signals.

Medicine is an important field of application for ultrasound technology. The different propagation velocities in the various body tissues cause changes in ultrasound signal run times. This enables medical professionals to find and display body structures from the signal reflections. Ultrasound diagnostics have long been a matter of course in prenatal exams and in cancer diagnostics.

Since the frequency with which sound is perceived and measured changes when the

Fig. 42: The technology used to break up kidney stones is based on ultrasound waves generated by piezoceramics.

sound source or reflector moves toward or away from the detector, and this effect is more powerful the greater the relative velocity is, it is possible to make deductions about the flow of blood in vessels based on the signal transmitted and received after reflection. This is called Doppler sonography, named after physicist Christian Johann Doppler (1803 to 1853), who discovered this effect.

Doppler sonography

Each sound wave is accompanied by a movement of molecules from the conductive media. The greater the amplitude of the wave, the more they oscillate from their resting position. A treatment known as shock wave lithotripsy takes advantage of this effect by coupling energy-laden ultrasound shock waves in the body. Focused on kidney stones or gall stones, they can painlessly break up these colic-inducing conglomerates into smaller fragments, which the body then passes (Fig. 42).

Ultrasound in medicine

Ultrasound is also effective in removing plaque and in atomized inhalers. The sound waves transfer energy to the fluid in which pharmacologically effective substances are dissolved, thus causing fine droplets to separate from the surface of the liquid. Ultrasound promotes the healing process in muscle damage treatment. In principle, all of these treatments are comparable, although the sound energy transferred is obviously lower than in lithotripsy.

Dental ceramics

Anyone who has ever accidentally bitten down on a cherry stone understands the kinds of forces that can impact teeth and dentures. Ceramic denture products need to withstand

Fig. 43:
Ceramic blank used as a primary product for manufacturing crowns and bridges used in dental medicine

these powerful forces. Manufacturers test the mechanical strength properties of their dental medicine materials for flexural strengths of up to 1500 MPa. This capability, along with additional characteristics such as biocompatibility, edge stability, toughness, hydrothermal resistance and flexural strength select ceramic materials for use in the field of dental medicine. Examples of use include dental implants, abutments (support for bridges), blanks as primary products for bridges and crowns (Fig. 43), in brackets for braces and as drill blanks.

Dental medicine applications

Two ceramic materials clearly distinguish themselves for use in dental ceramics thanks to their unique properties: yttrium-stabilized zirconium oxide and transparent (translucent) alumina.

Yttrium-stabilized zirconium oxide

Extremely fine-grained, yttrium-stabilized zirconium oxide (3Y-TZP) owes its use as a material for implants and blanks to its superb mechanical properties. In particular its potential for conversion from the tetragonal to monoclinic phase positively impacts these applications, because the induced conversion is linked to an increase in volume and thus the generation of compressive stress. The microstructure is strengthened under tensile load. Superior mechanical strength, toughness and durability and the ability to make a wide variety of color settings (dazzling white, translucent or adapted to one's own individual tooth color) are some of the distinguishing features of yttrium-stabilized zirconium oxide.

Translucent alumina

Translucent alumina, manufactured from nanoscale powders, is highly transparent and is therefore frequently used as a material for brackets to straighten teeth. This technology makes braces, which are frequently worn by adults today as well, virtually unnoticeable.

Composites ATZ and ZTA

Highly pure alumina, alumina-toughened zirconia (ATZ) as well as zirconia-toughened alumina (ZTA) are used for additional special treatments. ATZ is impressive because of its extreme toughness and excellent mechanical strength. It is used in drill blanks, for example. ZTA offers convincing performance thanks to its fracture toughness, a high level of hardness and superior mechanical properties. The basis for this material is a matrix made of alumina with a content by volume of 82%. A number of reinforcement mechanisms can be activated to further improve the excellent properties of this dental material.

Summary and outlook

Already today, ceramics are at work all day, every day, around the clock – whether as part of a machine or an appliance, or even inside the human body. Ceramic components are generally invisible to users, but most often the role they play is an important or even decisive one. The specific qualities of technical ceramics come to the fore when other materials such as metals or synthetics are unable to meet the specified requirements.
The examples listed in this book only reflect a small sample of the spectrum of applications in which ceramics are used. Momentum for new developments and further advances in the field of ceramic materials and process engineering for manufacturing the latest ceramic components has come mostly from the automotive industry, machine and equipment

Fig. 44: Environment and energy – technical ceramics will drive future technologies in this area as well.

construction and medical technology, measuring and sensor technology and electronics. These areas, alongside the growth market sectors energy and environmental technologies (Fig. 44), will also be the driving force behind the ceramics industry in the future. The use of ceramics as the material of choice will remain a necessity for many applications in the future as well in order to fulfill demands such as increasing miniaturization, process reliability, productivity, energy efficiency, wear resistance, lightweight construction and design and biocompatibility.

Each application and each ceramic component places individual demands on the capabilities of the material. Therefore, the successful employment of a product depends above all on selecting the correct material and fine-tuning it. Although the applications are extremely diverse, the common focus of further development of still more dependable ceramic materials with highly unique properties is placed on the manufacture of fine-grained, flawless and thus even more reliable materials and the targeted design of the microstructures. This requires a firm command of how to handle the finest, purest nanoscaled powders in order to avoid impurities during the manufacturing process.

Optimization in manufacturing

These advances in materials science will make many products and processes possible for the first time. Thus ceramic remains what it was at the dawn of its development in the midst of the industrial revolution: the material of choice for extremely demanding applications.

The company behind this book

CeramTec GmbH
CeramTec-Platz 1-9
73207 Plochingen
Phone: +49-7153-611-0
Fax: +49-7153-611-673
technische-keramik@ceramtec.de
www.ceramtec.com

CeramTec develops and manufactures products for nearly every sphere of life, work and technology using advanced ceramics – one of the most fascinating materials of our time. Applications range from ceramic components for artificial hip joints, seal and regulator discs for sanitary fittings, inserts for metalworking, substrates for electronic circuits, appliances and mechanical components, fuse components and protection components to piezoceramics as the key components of sensor technology products. From customized single-unit manufacturing to mass-production runs of millions of units, CeramTec supplies highest-quality products and is a leader in the design of new solutions for ever broader and more demanding application areas.
With annual sales of about 450 million euros and over 3,600 employees worldwide at production sites in Europe, the United States and Asia, CeramTec is one of the world's leading manufacturers of advanced ceramics. CeramTec has the highest level of expertise in the field of technical ceramics, backed by more than a century of development and production experience. The current portfolio comprises well over 10,000 different products, components and parts, and a wide variety of ceramic materials.
CeramTec's success is rooted in the formula: Continued development of new, innovative materials with a strong commitment to quality, a focus on customer-specific system solutions and dialog-based application consulting services that cover the entire product life cycle. This mission is what makes CeramTec a competent partner for a wide range of industries.

236639