How to Choose Ceramic Materials?

Aerospace

Compared to other industries, the aerospace sector makes a rather small contribution to Germany's gross domestic product. However, precisely in this sector, economically and strategically important technology and know-how are developed that are then utilized in numerous industries and consequently play a key role in assuring industry's competitiveness.

At the focus of aerospace technology with regards to scientific, technical and environmentally relevant aspects are four system types:

- Aircraft
- Missiles
- Spacecraft
- Satellites

The technical requirements for such systems concentrate on:

- Low weight
- Good aerodynamics
- Efficient drives
- Power supply
- Control
- Data transfer and communications
- Safety
- Payload
- Thermal and dynamic resistance

From an ecological perspective, key factors are low noise generation and low fuel consumption.

In various positions in these complex structures, the use of components made of high-grade oxide and non-oxide ceramic materials and composites is recommended when high resilience is demanded in sometimes extreme operating conditions.

A rocket used to launch a satellite in orbit around the Earth has to reach a horizontal velocity of at least 7.8 km/s. To exit the Earth's gravitational field, more than 11 km/s are necessary. Machine and equipment components made of ceramic materials and composite components have to withstand a multiple of the Earth's acceleration, especially during lift-off, without incurring any damage. Besides the high technical resilience, an exceptionally high reliability of the ceramic components is a core requirement as the failure of even one component, which can be worth several thousand euros, can adversely impact an entire project costing many hundreds of millions of euros, and, in the case of manned space flights, endanger human life.

The use of high-purity, monolithic oxide and non-oxide ceramic materials and composites presents a potential solution when the specific requirements profiles demand the following properties from the components:

- Low density
- High mechanical strength
- High rigidity
- High toughness
- High wear resistance
- Resistance to high and low temperatures over a large range
- High thermal shock resistance
- Phase stability in the applicable pressure and temperature range
- Low thermal expansion
- High or low thermal conductivity, depending on the specific application
- Resistance to cosmic radiation
- High electrical insulating capacity
- Realizability of adhesively bonded, high-vacuum-tight ceramic-ceramic and ceramic-metal composite components also for temperatures near 0 K, with high thermal shock resistance and high mechanical strength
- No gas emission

Depending on the specific application, the requirement profiles are very different, and a correspondingly wide range of suitable high-grade ceramic materials is available for selection: Al_2O_3, ZrO_2, AlN, SiC, Si_3N_4, ferrites, piezoceramics and fibre composites.

In some cases, the materials are optimized for a specific application and consequently guarantee reliable function in long-term application.

Automotive Engineering

Motorized vehicles are manufactured in series production with a high degree of automation. With the variety of technical equipment, the numerous design variants and the high utility value for the customers, they are hardly surpassed by other technical products.

A large number of industries and technologies are involved in the manufacture of motorized vehicles: machine tool manufacturing, glass industry, plastics industry, ceramic and chemical industry, electrical engineering and electronics industries, textile industry, surface finishing and environmental engineering, just to name a few examples.

In a motorized vehicle, the following main component assemblies can be defined:

- Engine
- Power transmission / drive train
- Chassis
- Car body
- Vehicle electrics / electronics

Every component assembly has specific technical requirements for the materials used. The selection of certain materials is guided by the goal to maximize energy and cost efficiency combined with acceptable reliability.

As in the majority of applications in engineering, in motorized vehicles too, components made of high-quality technical ceramics are used to reliably meet requirements that materials on metal or plastic basis are hardly able to fulfil.

Application in motorized vehicles demands from components made of technical ceramics high reliability and cost efficiency in long-term operation. The application-specific requirements are therefore focussed on the following properties:

- Mechanical strength
- Density
- Achievable geometric precision and edge stability
- Tribological properties, e.g. coefficient of friction and abrasive behaviour even in emergency conditions
- Dimensional stability with changing thermal and mechanical loads
- Resistance to high temperatures and sudden temperature changes
- Insulating capacity and thermal conductivity
- Chemical corrosion resistance
- Electrical insulation and electrical conductivity
- Dielectric properties
- Magnetic properties
- Suitability for thin and thick film technologies
- Possibility to produce force-fit, form-fit and adhesively bonded ceramic-ceramic and ceramic-metal joints

Today, the manufacturers of motor vehicles use monolithic ceramic materials, composites, piezoceramics and magnetoceramics on oxide and non-oxide basis. The components made of these materials are often optimized for the specific application. As a result, they achieve high reliability and long-term durability in everyday operation.

In motor vehicles too, the typical characteristic of the applications of ceramic materials is their existence in positions within component assemblies that are generally not visually accessible. One exception in this connection is the brake disk made of a non-oxide ceramic fibre composite, the use of which brings key technical benefits compared with conventional brake disks, like, for example, high wear resistance and consequently an unusually long service lifetime in operating conditions.

Chemicals - Pharmaceuticals

Machines and equipment in chemical and pharmaceutical process engineering are often exposed to high stresses caused by temperature, pressure, corrosion and abrasion. Owing to the constantly rising requirements for the efficiency of the processes, the most frequently used metallic materials in the area in contact with the products are often exposed to such high stresses that they only reach uneconomically short service lifetimes in operation. The result is cost-driving downtime of machines and equipment.

In such cases, ceramic materials on oxide and non-oxide basis are often a suitable alternative for the designers. In this connection, an exact knowledge of the application conditions is crucial for selection of the right material.

The thermal strength of dense-sintered, high-purity oxide ceramics generally reaches the region of 2000 ℃. Non-oxide ceramic materials are less thermally resistant on account of the restriction of their oxidation stability in an oxygen-containing atmospheres. Depending on the type of material, oxidation reactions only become noticeable above 1500 ℃, such reactions can be slowed down substantially or even prevented completely with the formation of passivation layer. In non-oxidizing environment, these materials withstand a type-dependent temperature level, which reaches in the region of 2000 ℃.

An economically significant issue in chemical process engineering is corrosion resistance of the materials in apparatus and equipment engineering when these are in contact with different highly concentrated acid and basic aqueous solutions of varying purity. In this respect, oxide and non-oxide ceramic materials have proven effective components over decades, which, apart from few exceptions, have achieved extraordinarily long service lifetimes in use in contact with such media even under tough conditions in numerous applications.

The behaviour of the ceramic materials exposed to corrosive load is determined mainly by their chemical composition and their microstructure. They can reach high corrosion resistance especially when they are formed by means of solid phase sintering and therefore have only a low content of grain boundary phase.

Both for material separation and for material synthesis, in different process stages oxide and non-oxide ceramic machines and plant components are used very successfully today in sometimes extremely aggressive conditions, which, as well as demanding chemical corrosion resistance from the materials at high temperatures, require a high mechanical and tribological loadability and often high thermal conductivity. Under such conditions, the use of ceramic components is sometimes the last resort, making economic operation of machine or plant possible in the first place.

The processing of active ingredients in the pharmaceuticals industry usually requires verification of suitability for direct contact with pharmaceutical products. In this field, both oxide and non-oxide materials can generally be used without any reservations. Many producers of oxide and non-oxide ceramics have obtained appropriate certification for the materials that they offer for such applications from the responsible regulatory authorities.

Electrical Engineering, Electronics

Products made of technical ceramics are now proven components in the construction and control of sophisticated plants, machinery and equipment with electrotechnical component assemblies. Often, they make possible the function of such constructions in the first place. Typical examples include λ sensors in automotive engineering or in kiln and furnace engineering, the vacuum chambers of particle accelerators or actuators in motion detectors. The size of such components is typically in the region of a few millimetres up to several metres.

A special feature of this class of materials is the wide range of electrical conductivity, which spans more than 15 orders of magnitude and cannot be matched by any other class of materials. It includes electrically insulating as well as semi-conducting, ionic-conducting and superconducting materials. On top of this come the dielectric properties, which can be used, for instance, in sensor technology and telecommunications.

Besides the electrical properties, magnetic properties are often required, The soft or hard magnetic ferrites have proven effective materials for decades. Compared with metallic materials, they often enable smaller product sizes and therefore more economically attractive products.

Typical for the applications of technical ceramic materials is a frequent requirement for other non-electrical properties such as:

- Mechanical strength
- Thermal resistance
- Thermal shock resistance
- Thermal conductivity
- Corrosion resistance
- Production of ultrahigh-vacuum-capable joints with metals

A key strength of this class of materials is the demand-driven combinations of the above-mentioned properties. In addition comes the possibility to optimize properties for a specific application by means of appropriate doping and therefore to tailor materials to requirements.

For instance, the zirconia ceramics used for λ sensors can be optimized to maximize their strength without compromising their suitability for use as oxygen sensors as only one electrical signal must be recorded, which can be evaluated on the basis of appropriate calibration. With the selective modification of the chemical composition of this material, maximized electrical conductivity can be obtained along with an acceptable level of strength. As a result, this anionic conductor can be efficiently used as electrolyte for SOFCs (high-temperature fuel cells).
The wide-ranging application of technical ceramic materials in electrical engineering and electronics has led over the past decades to a correspondingly high number of variants in electrically passive and active materials. Today a broad spectrum exists including insulators, dielectrics, piezoelectrics, NTC and PTC ceramics, varistors, cationic, anionic and electron conductors on oxide and non-oxide basis, superconductors as well as soft and hard magnetic ferrites.

The use of ceramic components in electrotechnical assemblies often demands material-to-material joints with one or more metallic components that can comprise different materials. Such joints are usually associated with the demand for high or ultrahigh vacuum tightness and acceptable mechanical strength for use in the field. Such ceramic – metal joints are generally realized by hard brazing based on MoMn procedures. For this purpose a thick film of molybdenum applied and then fired onto the ceramic is joined with the respective metal part with a silver-based solder as standard or, if corrosive attack is expected, with gold-based solder.

Optics

Thanks to their high refractive index, ceramic materials are interesting for optical applications as they enable comparatively small sizes in lenses and lens systems.

They are, however, not limited to applications as translucent and transparent components for special transmittance ranges, lighting purposes or high-precision connecting components for transmitting optical signals.

In their application in optical devices and equipment, other technical properties of oxide and non-oxide ceramic materials are effectively utilized, like, for example:

- Mechanical strength
- High modulus of elasticity
- Hardness
- Wear resistance
- Thermal stability
- Low thermal expansion
- Resistance to corrosion

In some cases, for optical systems, brazed high-vacuum-tight composites made of monocrystalline oxide materials, e.g. leuco-sapphire, with special crystallographically oriented sections with thermally adapted metals are fabricated.

For optically active components such as LEDs, ceramic phosphors on the basis of Y-Al-garnet ceramics are interesting as they can meet the high requirements with regard to durability in operating conditions that typically prevail in motorized vehicles.

Environmental Engineering

Environmental engineering concerns processes that serve to protect the biosphere and the regeneration of damaged ecosystems.

"Environmental protection" is an issue present directly and indirectly in all technical sectors in which equipment, plants and machinery are used, like, for example, in laboratories of research institutes or in companies in the ceramics, glass, plastics and metals industries.

A widely known example of the use of environmental engineering is the λ sensor that enables the control of optimum combustion of a fuel/air mix not only in the combustion engine of a motor vehicle, but also generally in firing systems.

The competitive situations in industry often demand the reduction of production costs without any detriment to the quality of the products. Even if "environmental protection" is not always an express goal of entrepreneurial measures, improvement in the effectiveness and the energy efficiency of plants and machines generally leads to the reduction of the environmental impact by solid, liquid and gaseous waste materials produced in running production processes. For this reason, many industrial enterprises today see measures for protection of the environment as a strategic competitive advantage. Generally, in such companies, an environmental management system in compliance with ISO 14001 and / or the EMAS regulations is established as a permanent element of corporate policy.

The producing industrial companies pursue often typical environmentally relevant goals, such as:

- Increase of the efficiency of plants and machinery
- Increase of the production yield to the ideal of zero-error production
- Reduction in the number of process steps
- Optimization of energy-intensive process steps
- Reduction of the consumption of electrical energy, water and process gases
- Waste avoidance
- Optimum waste management based on recycling or environmentally compatible disposal

Technologies for the protection of natural resources and the environment have been developed and applied in some cases for decades in the following areas:

- Low-emission processes
- Renewable energy generation
- Storage systems for thermal, chemical and mechanical energy
- Mobility on water, land and in the air
- Building services engineering
- Reduction of air, water and soil pollution
- Protection against ionizing and non-ionizing radiation
- Air purification based on reduction of the dust and gas load, e.g. from mechanical and thermal process engineering
- Environmentally compatible waste management by means of recycling, cleaning processes, thermal processes and appropriate disposal
- Environment-specific measurement and analysis methods
- Control technology for waste recycling plants

Components made of high-grade ceramic materials often contribute considerably to the realization of environmentally friendly technologies. Sometimes they constitute a principal precondition when, for instance, the following properties are required:

- High mechanical stability at temperatures above 1000 ℃
- Thermal stability in oxidizing and reducing conditions as well as in a vacuum with temperatures sometimes well above 1500 ℃
- Resistance to thermal shock
- Resistance to corrosive attack by melts, solutions and gases, under reducing and oxidizing conditions, against supercritical fluids as well as in contact with solid bodies
- High wear resistance
- Depending on the specific application, a high or low thermal and electrical insulating capacity

- Realization of mechanically and thermally stable ceramic-ceramic and ceramic-metal composites by means of non-positive, positive and adhesive joining processes.

The spectrum of the materials used extends from high-quality ceramic refractories through filter ceramics to dense-sintered monolithic oxide and non-oxide ceramics, piezoceramics, magnetic ceramics and fibre-reinforced ceramics.

The components made from these materials are used primarily in positions exposed to high stresses in plants and machinery. Especially for extreme requirement profiles, such materials are, thanks to their unique combination of physical, chemical and biological properties, sometimes far superior to other non-ceramic materials with regard to their serviceability. They regularly reach reliably long service lifetimes in often very rough operating conditions.

Food processing technology

The process chain in food production begins with natural raw materials, which are subject to food-specific process steps such as separating and mixing, thermal, biological and chemical processes, and finally packaging in shelf-life-dependent storage materials before reaching the consumer. The machinery and equipment must be designed to ensure that no health hazard emanates from those areas in contact with the product. For the materials used, official approval is necessary at regular intervals. Other economically significant aspects are, for example, the requirement for wear resistance and high metering precision to minimize product losses.

For several decades now, high-quality ceramic materials have been used in reliable and long-life components with wide-ranging applications like, for example, material separation by means of micro- and ultrafiltration, filling of solid, paste and liquid foodstuffs up to atmosphere monitoring for film packaging and labelling of food containers.

Typical requirements for the properties of the ceramic materials depending on the specific application are:

- High geometric precision
- Mechanical strength
- Edge stability
- Wear resistance
- Superheated steam sterilizability
- Thermal shock resistance
- Compressive strength
- Non-magnetizability
- Easy cleaning after product changes

The specific requirement profiles are generally combinations of several of the above-mention properties. High-purity materials on oxide and non-oxide basis, sometimes even developed for specific applications, can easily meet such requirements.

Please visit https://www.preciseceramic.com/ for more information.