High-Performance Ceramics for Mobility, Electrical Engineering/ Optics and Life Sciences

As the result of an intensive dialogue between 60 professionals from industry and research institutes, which had been organized on the initiative of the Joint Committee on High-Performance Ceramics of the DKG (German Ceramic Society) and the DGM (German Material Science Society) in collaboration with the VKI (Association of the German Ceramic Industry), the expert study "Future Potential of High-Performance Ceramics" was published. This summary is reviewing those findings.

Fig. 1
Wide-ranging applications of ceramic components in automotive engineering [1]

High-performance ceramic materials for future applications in mobility

High-performance ceramics with outstanding functional and structural properties have been successfully used in large volumes in automotive engineering for many years. Prominent examples of this are piezo-ceramics for distance and knock sensors, ceramic tapes for the production of hybrids in electronic control systems, components for cooling water and fuel pumps, just to name a few.

In the context of this study, the attention of the experts focuses on the future potential of high-performance ceramics, especially for conventional drive engineering in road vehicles (combustion engines, power electronics).

Keywords
combustion engines, mobile power electronics, battery systems, passive electrical components, lightning technology

The study (German language) can be downloaded from www.dkg.de

Ceramics in combustion engines

Focus on materials and production processes – reliability concepts

To counter the increasing pressure take action, which results from the stricter emission targets for combustion engines

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for motorized vehicles, it seems appropriate to reassess ceramic solution concepts developed earlier with today's knowledge of materials and production processes, so as to determine the benefits from a technical and especially economic perspective in consideration of the general conditions that apply today.

On the material side, the requirements of today's applications can be fulfilled and realized in laboratory conditions. However, it has not yet proved possible to effectively transfer such developments into series production. For a comprehensive technical and economic reassessment, it is necessary to examine the entire value creation chain, starting with the raw materials to certification of the reliability and lifetime of the components including the possibilities for their improvement.

For this purpose, advanced simulation techniques must be better utilized. To break down the barriers of the vehicle manufacturers with regard to making radical changes to the highly developed system that is the combustion engine, one promising approach could be to first develop and elaborate the benefits of ceramic components and then demonstrate these with prototypes.

With proven reliable components, the integration of these components in a new development, like, for example, a single-cylinder engine, produced in small numbers, is feasible. In this way, practical experience with series production of the components and their integration in the engine can be collected and processes qualified for use in large series production. Crucial for success is cooperation

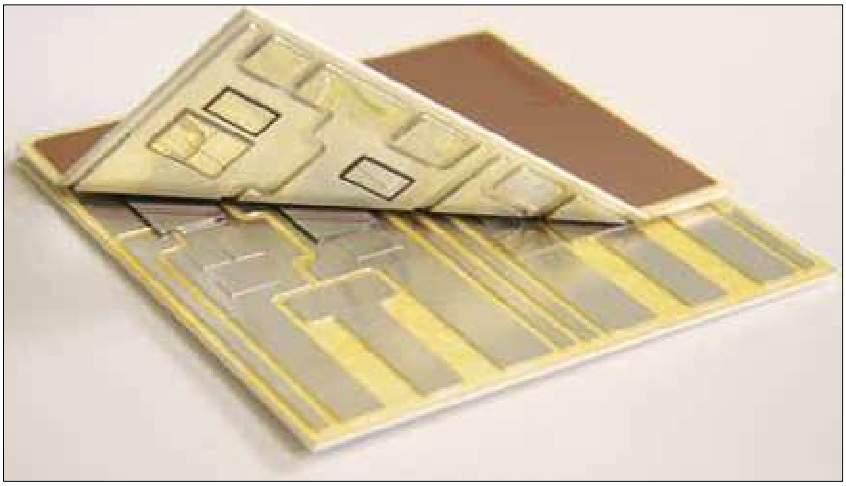

Fig. 2
Double-sided cooling of power semiconductor devices with ceramic carriers [2]

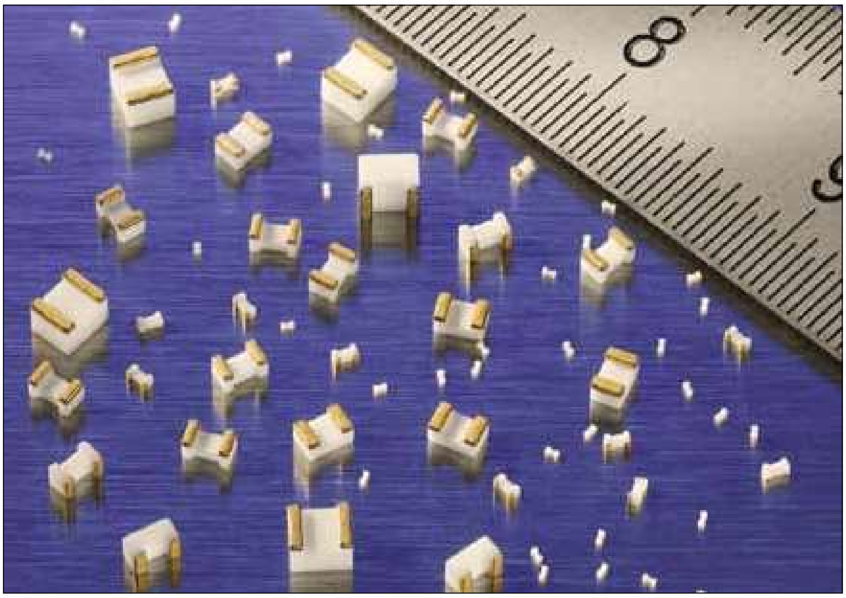

Fig. 3
Ceramic coil formers [3]

between material and engine experts as well as continuous process development.

Focus on thermomanagement in the power train and exhaust gas system

Starting from increasing requirements for the reduction of CO_2 emissions, experts see potential for different applications of ceramics in fossil-fuel propulsion systems. Central starting points for significant efficiency improvements are in the view of the experts in the reduction of frictional and heat losses. With costs of around EUR 20–100 per gramme CO_2 emission reduction for petrol or diesel engines respectively, the industry is, however, facing immense cost pressure.

With regard to the changing conditions and the pressure resulting from this, the application of innovative materials is gaining more and more importance for further increasing efficiency and reducing emissions. Ceramics provide a promising option to realize the potential for efficiency increases that have been frequently limited owing to material-related aspects.

In fossil fuel propulsion, applications are seen especially in the selective insulation of certain areas of the exhaust gas system with the aim of realizing higher exhaust gas temperatures during after-treatment. Moreover, the application of such components or coatings for insulation of the combustion chamber is a promising avenue with regard to achieving significant improvements in the efficiency of fossil-fuel drives with an adiabatic combustion chamber. New materials for components or coatings of this type need to exhibit particularly low thermal conductivity and heat capacity to pave the way to so-called "temperature swing insulation", which on the one hand has especially good thermal insulation properties and on other hand can cope with high-frequency temperature changes. The effects of such a solution offer a potential of 3–4 % in performance improvement.

Further insulation of the engine-mounted exhaust gas system would not only lead to a reduction of the load on the cooling system, into which currently 30–40 % of the total heat from the combustion area is introduced, but also to a significant improvement in the exhaust gas after-treatment, because the enthalpy of the exhaust gas would not be lost to the engine compartment and would therefore be available for the exhaust gas after-treatment. As a large part of the emissions are output before the operating temperature of the catalytic converter is reached, this aspect holds key potential for reducing harmful emissions.

In electromobility, the use of new coatings to encase the battery is feasible. To enable optimum cooling of the battery, such a coating should exhibit good thermal conductivity and particularly low electrical conductivity.

Focus on cleaning exhaust gases from commercial vehicle diesel engines

Especially with regard to commercial vehicles, the subject of exhaust gas after-treatment is assigned great importance as for engines with higher capacity, the costs of the exhaust gas system can already exceed the costs of the actual engine.

Core components such as diesel particle filters and SCR catalytic converters (selective catalytic reaction) are based on monolithic ceramic honeycomb elements. As substrate for the active material, currently made mainly of cordierite, aluminium titanate and silicon carbide honeycombs as well as sintered metals are used. Compared to conventional cordierite filters, silicon carbide filters feature certain advantages, for example a four-times-higher capacity for soot load, 21-times-higher thermal conductivity as well as higher mechanical and temperature resistance. These properties enable development goals to be met, avoidance of filter damage caused by fracture or cracking and the guarantee of a worldwide risk-free engine and filter operation.

A major challenge is in the design of the ceramic monoliths to ensure high flow-through and reduce through-flow losses. Key criterion is the work deficiency of the engine during clearing of the cylinders caused by the counterpressure of the exhaust gas system. 100 mbar counterpressure already leads to 1 %-higher fuel consumption. Also relevant are the reduction of the specific filter weight and construction volume.

Approaches for this are based on the one hand on an increase in the number of cells per cross-sectional area in the catalytic converter in order to increase the contact area of exhaust gas and active material and on the other hand on a reduction of the wall thickness.

Extruded catalytic converters that consist exclusively of active material exhibit a higher activity for the same flow-through rate compared to catalytic converters consisting of a base structure with a washcoat.

Another possibility is the use of ceramics with higher porosity, which enables higher washcoat load of the substrate or thinner cell walls with the same washcoat load. The resulting effects are in this case much improved performance in lower temperature ranges with around 15 % reduction in the counterpressure.

Ceramics for mobile power electronics

Requirements for decreasingly lower pollutant emissions and fuel consumption are leading to increasing electrification of cars and commercial vehicles. This applies equally to ancillary components such as steering assistance and the propulsion system and extends over a wide range of different electric outputs. The polymer-based circuit boards used for low power outputs below a few kilowatts reach their thermal limits above this power range. Here, special ceramics with good electric insulator properties combined with excellent thermal conductivity and resistance can play on their good performance and are key elements for the steadily growing market for power electronics.

Future challenges with regard to circuit carriers result from the optimization to moderate thermal conductivity combined with good fracture toughness and thermal shock resistance. Mixed ceramics can offer a solution still at a low price. Function- and system-optimized combinations of metallization and ceramic are a promising approach. Three-dimensionalized and metallized cooling elements open up unexpected possibilities in technological and economic optimization. The maximum disruptive strength and the partial discharge resistance define the insulation properties of the circuit carrier, which is why these parameters are coming increasingly to the fore, especially for relatively high voltages.

For soft magnetic ferrites for transformers and storage throttle, energy density is one of the most important parameters. Key factors are the permeability and the maximum magnetic flux density, which has a quadratic rather than linear influence on the energy density. Any improvement would have direct impact on the size of the finished components.

Another important parameter are the magnetization losses, which can be minimized with modified material composition and higher purity materials. Another aspect is the shifting of the loss minimum to higher temperatures, which would allow lower cost cooling concepts.

For dielectric materials for capacitors, the energy density is the most important parameter. Permittivity has a linear influence on the energy density, while the maximum field strength has a quadratic influence. The focus should therefore be on increasing the field strength.

Currently all applied field strengths in ceramic capacitors are one order of magnitude below the possible material properties. Reduction or avoidance of pores would be one solution approach.

Furthermore, according to the state of the art, the capacity of ceramic capacitors is highly dependent on the temperature and the applied field strength. New material formulations with less pronounced dependence would be a starting point here.

E-mobility – focus on battery systems

The biggest lever for successful development of electromobility is seen in the increase in the energy density of batteries, as this is the key to realizing longer operating distances. In view of the considerable additional costs of electrically powered vehicles compared to conventional vehicles, which are largely down to the battery, cost pressure also plays a significant role.

With a view to quality, it should be noted that higher lifetime requirements are demanded of E-drives than of conventional drives and safety-relevant aspects play an important role with regard to the consequences in the event of battery failure. With the application of ceramic components inside the batteries, approaches to lengthening the lifetime of electrolytes and electrodes as well as safety-relevant aspects are explicitly addressed.

With regard to lengthening lifetime, it is necessary to highlight the need to develop new approaches for protective coatings on the material side that effectively control material breakdown because of material migration from anode to cathode or, in the case of lithium-sulphur batteries, side reactions and morphology change of the metal anode.

The effective separation of the electrodes plays, however, a crucial role with regard

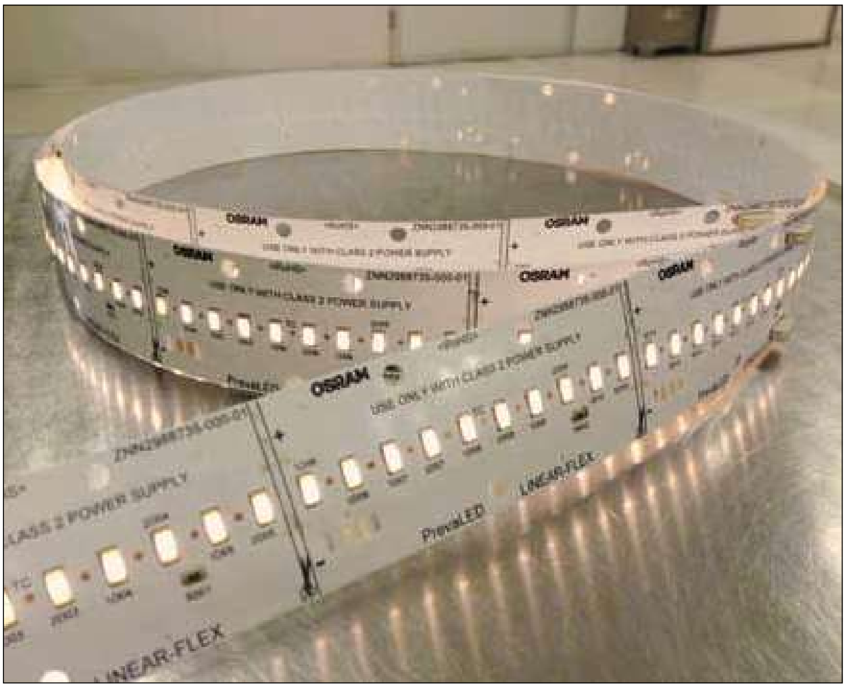

Fig. 4
Flex stripe with white light LEDs [4]

to safety and, in the industrial production of batteries, considerable requirements must be met in terms of their precision. To guarantee safe and stable battery operation over the battery lifetime, it is necessary to foster and develop engineering know-how for the design, construction and ultimately stable production of batteries.
The challenge here is to optimize the combination of ceramic materials for separator and protective coatings and the coating process for the individual cell layers in series production of the multimaterial system that constitutes a battery. Above all, the precision of the coating process must be improved with, at the same time, an increase in process reliability.
With regard to new materials, focus is on the development of new protective and separator coatings to reduce material breakdown of electrodes and electrolytes as well as for protection of the metal anodes against side reactions and morphology changes (in the case of cor-

responding material combinations, e.g. in lithium-sulphur batteries).

High-performance ceramics for electrical engineering and optics

Focus on passive electrical components

Daily life would be unthinkable without electronic components on the basis of oxide ceramics. They are used as protective elements, actuators, sensors, etc. in applications such as electronics, information and communications technology and energy engineering.

The variety of electrical components is based on an in-depth knowledge of materials, their properties and appropriate production technologies, which go far beyond the level of traditional ceramics. Driven by ever higher requirements for power density, miniaturization and narrow tolerances, a highly specialized industry has become established, which further develops these components and manufactures these in large unit numbers.

In future, the boundaries between active and passive components will become more fluid. With the combination of material expertise and the resulting physical characteristic values of passive components and with inclusion of highly integrated logic circuits (semi-conductors), there will be more integrated and intelligent passive components. From this result challenges with regard to the design of hybrid integrated manufacturing processes, the development of new measurement methods and manufacturing processes. This requires a production-related alliance of semi-conductor production and the diverse production possibilities for passive components and is a decided challenge for the know-how of the branches involved.

To remain competitive in international markets, from the trend towards higher power density, further miniaturization and cost reduction result challenges for the ceramics industry that can only be met in alliance with external/public research institutes.

Key aspects are the increase in the power density, the substitution of raw materials, process optimization and development, widening of the permissible application conditions in the direction of higher temperatures, process and component simulation as well as the minimization of defects on meso-, micro- and submicroscopic level. The need for basic and applied research derived from this covers material synthesis, simulation, design and manufacturing technology.

In the view of the experts, visionary goals for functional ceramic manufacturing of the future are seen, which themselves indicate complex material- and technology-specific approaches for appropriate fundamental and preliminary research. They concern innovative aspects of powder synthesis, component design, miniaturization as well as new applications.

Focus on lighting technology

Ceramic phosphors

New phosphors are a key part in modern light technology based on light-emitting diodes. They are used for the conversion of the blue radiation of InGaN-based LED light sources of different wavelength and are used in almost every white LED. The powder phosphor is generally introduced into organic matrix materials, like, for example, silicones or rarely epoxides, and positioned on the LED as a conversion coating.

Organic matrices have, however, low refractive indices, increase optical scatter and therefore reduce the efficiency of the LED. In applications with high luminous fluxes, they lead to a reduction in efficiency and colour index shifts owing to their low thermal conduction and chemical aging.

Basically, the use of ceramic phosphors in LEDs and lasers offers the enormous advantage of achieving higher efficiency at high luminous flux and high operating temperatures and reducing aging. With low-cost production processes, the crucial Lumens/EUR value could be increased as the useful light output increases.

To fully utilize the potential of ceramic converters, it is important to make the technology accessible to a wider spectrum of different phosphors and at the same time to develop lower cost production processes. As a basis for selective developments, better understanding of the relationship of phosphor properties, the

Fig. 5
Ceramic coil formers [3]

process parameters, and the microstructure of the ceramic is important. At the same time, methods have to be developed to precisely manufacture the very small pieces, e.g. 1 mm × 1 mm × 50 µm disks, without impairing the properties, and reliably guarantee their handling.

In multicomponent ceramic converters the challenge is to arrange different ceramic elements and connect with each other (e.g. co-sintering), so that the original properties of the individual components are preserved intact, which presents a great challenge especially in co-sintering.

The overall longer term research requirement resulting from this concerns production processes for phosphor ceramics suitable for the mass market, in-depth theoretical understanding of the relationship of phosphor properties, process parameters and microstructure of the ceramics, also with the application of simulations, process technologies for so far non-accessible phosphor compositions, new approaches for the production and processing of two- and three-component systems, 3D shaping of the ceramic elements for certain arrangements of light source to the phosphor ceramic as well as innovative joining techniques for ceramic elements and LED chip as well as additional optical components.

Ceramic substrates for lighting technology

The technical change from conventional to LED-based lighting technology demands competitive solutions on substrate and housing level. To thermally and electrically gate the LEDs, these are mounted to substrates. Different substrate materials, from organic to inorganic materials, are used here. Organic materials feature lower costs and easier processing.

The most frequently used ceramic substrates consist of aluminium oxide and aluminium nitride, which on account of their high thermal conduction, electrical insulating property, optical reflectivity and the coefficient of thermal expansion are ideally suitable for use as LED substrates.

The biggest challenge is the reduction of the high costs as well as the optimization of the system costs. To reduce the costs, new process technologies as well as materials have to be researched.

In material research, additives (for example zirconia) are introduced to further increase fracture toughness. With thinner substrates, the material consumption and the associated costs could be lowered and heat conduction increased. For process engineering, especially low-cost and mass-market-suitable production processes must be developed, e.g. with upscaling of the substrate tape width from 60–100 cm at present to a multiple of these dimensions.

High-performance ceramics for life sciences

In the life sciences, especially in medical implantology and prosthetics, primarily structural ceramics, but also calcium-phosphate-based biomaterials as well as bioglasses play a significant role. Joint replacement in Germany is a contribution by medical technology to preserve mobility and quality of life at an advanced age. The implantation of a joint endoprosthesis is one of the most successful surgical procedures. Every year, around 400 000 Germans are given an artificial joint. Operative processes have become increasingly refined over the last 40 years, the implant systems technically ever better and with the use of ceramic continuously optimized in respect of wear. On account of the higher life expectation and the activity of the patients, the requirements for the materials for implants are, however, increasing.

For load-bearing ceramic components in joint endoprosthetics, the high fracture rates of the femoral heads suffered in the initial years have been reduced by several orders of magnitude. For ceramic balls made of mixed oxide ceramics, the problem of fracture is now regarded as resolved. The fracture rates of ceramic cup inserts, however, cannot be regarded as satisfactory. For this reason, the manufacturers continue to make efforts to increase the fracture strength of the components with further improvements to the materials, product design, instruments and training of the operating surgeons.

Another material-related problem affects especially the ceramic-ceramic wear couples. The occurrence of punctiform high surface pressure on sliding surfaces caused by so-called subluxation or microseparation can lead to surface roughening, which is a factor influencing undesirable noises in the artificial joint or additional crack formation and so-called chipping. Intelligent product design as well as corresponding instruments could help to avoid subluxation and microseparation.

On the material side, ceramic components could in future be designed to be safer for clinical application e.g. with tailored composite concepts. Especially with regard to improved long-term reliability (increase in the subcritical crack parameter n), mixed oxide ceramics present interesting further developments here too.

In dental applications, of the structural ceramics, especially zirconia (Y-TZP) is used as crown and bridge core material. First long-term studies confirm the reliability of these polymorphous structural ceramics in dental prosthetics. The research requirement for the coming years consists here in material optimization to meet the currently intensified demand for fully anatomical dental ceramic restoration with optimized materials. For example, possibilities must be found for avoiding abrasion of the natural antagonist when non-veneered full ceramic zirconia crowns and bridges are used. Also with fully anatomical zirconia restoration, subcritical crack propagation is accelerated as a result of the direct contact with saliva. Here too, ceramic further developments of tailored dispersion ceramics can be helpful in improving the mechanical long-term reliability of such restorations.

Non-oxide high-performance ceramics have so far not been in the focus of applications in life sciences. With their phase stability and their sometimes extreme mechanical loadability, they are, however, of particular interest for possible use as components for medical implants. In several scientific studies, it has been shown that especially silicon nitride, depending on the modification and production process, exhibits cytocompatible behaviour. For this reason, non-oxide high-performance ceramics hold great potential for medical applications and could in future contribute to improved clinical reliability in certain applications.

Besides the rising requirements for the properties of the ceramic materials for implantology, the cost aspect is playing an increasing role in the production of ceramic implant components. Increasing cost pressure conflicts with the rising costs of the manufacturers for product approval and documentation. At this point, in future the demand for efficient production technologies for ceramic components based on "near-net shape" process for shaping and for low-cost raw materials will grow.

Because of the potentially problematic raw material situation in the long term with regard to the availability of rare earths, possibilities must be sought to substitute these with elements that are commercially available in the long term.

Other innovative aspects for the use of inorganic non-metallic materials in life sciences also exist in synthetically prepared calcium phosphate materials as bone substitute for regenerative therapy as well as in biodegradable bioglasses.

Experts are focussing especially on the structuring/functionalisation of ceramic implant surfaces. In applications in which the ceramic is directly joined to the bone, e.g. in the case of zirconia dental implants, there remain considerable risks with regard to sufficient bone integration. To resolve the problem of insufficient osseointegration of full-ceramic implants, different concepts are currently pursued.
The variety of potential solutions ranges from barrier layers with graduated open porosity, selective microstructuring of the ceramic surface with innovative subtractive or even additive manufacturing processes to coating by means of plasma spraying, chemical functionalisation, self-organizing chemically or chemo-physically applied monolayers as well as antibacterial substances, sometimes in combination, to reduce the risk of implant-associated infections as well as to improve osseointegration.

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