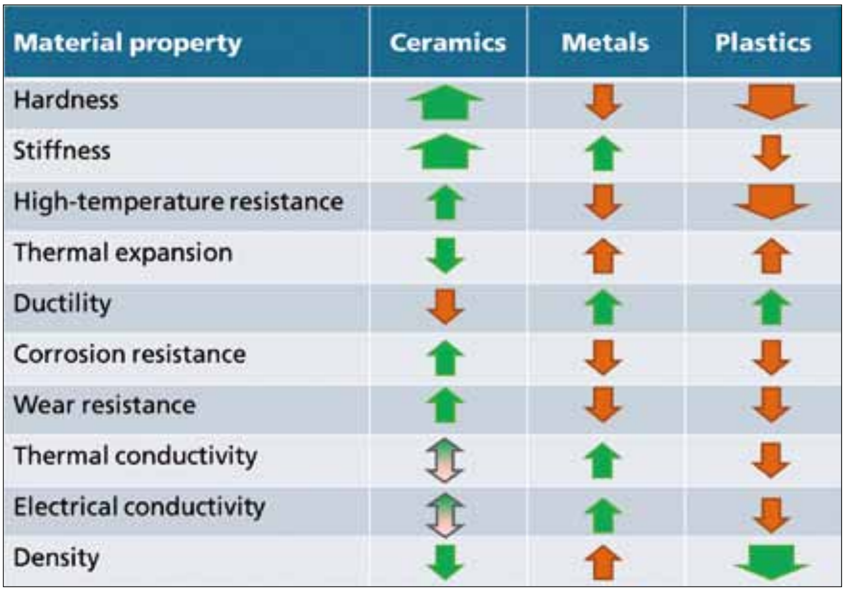
Ceramics Facing Competition with other Materials

Higher stiffness and hardness as well as better corrosion and abrasion resistance of ceramics are valuable advantages in its use as engineering material. Its excellent high-temperature resistance offers additional value for various applications. But still technical challenges for ceramic materials have to be solved.

Introduction

Compared to the huge markets of metal or plastic components technical ceramics are a niche product. Accordingly, they are rarely considered in the curriculum of mechanical engineers. As a consequence, the use of ceramics may simply fail in the design of new products, because the engineers involved are not familiar with it. However, as indicated in Fig. 1, many material properties of ceramics are clearly superior to plastics and metals. Especially the higher stiffness and hardness as well as better corrosion and abrasion resistance of ceramics are valuable advantages in its use as engineering material. In addition, its excellent high-temperature resistance is crucial for many refractory applications. The small coefficient of thermal expansion of many ceramics is helpful in its use with thermal loads or in precision mechanics.

Compared to most metals, ceramics have a smaller density, making them superior in lightweight design. Thermal and electrical conductivity of ceramics can be selected in a very wide range – depending on their composition and microstructure. Together with other properties, not mentioned in Fig. 1, like electrical permittivity, dielectric strength, piezoelectric coefficients, transparency, refractive index or biocompatibility ceramic properties can be exactly matched to the requirements of a specific application.



Material property	Ceramics	Metals	Plastics
Hardness	⬆	↓	⬇
Stiffness	⬆	↑	↓
High-temperature resistance	↑	↓	⬇
Thermal expansion	↓	↑	↑
Ductility	↓	↑	↑
Corrosion resistance	↑	↓	↓
Wear resistance	↑	↓	↓
Thermal conductivity	↕	↑	↓
Electrical conductivity	↕	↑	↓
Density	↓	↑	⬇

Fig. 1
Comparison of ceramic, metallic and plastic material properties: upward arrow indicates larger, downward arrow smaller magnitude; width of arrow indicates order of effect; colour of arrow indicates assessment: green means in general beneficial, orange means in general detrimental (according to [1])

Yet, in competition with plastics and metals one has also to address disadvantages of ceramics. Compared to high-volume production of iron based metals and plastics, ceramic manufacturing is rather expensive resulting in higher prices of ceramic products. Unlike most plastics and metals, ceramics are inherently brittle. Brittleness can lead to a risk of failure, which is not acceptable according to present-day manufacturing standards. So the decision in favour of ceramics is not easy in the design of new products. It becomes even more complex, because it depends on the interplay of many factors beyond material properties as illustrated in Fig. 2. Due to this difficulty, there is a strong motivation to avoid any risk by using traditional material solutions – which is a serious barrier for new ceramic applications.

The complexity of material selection can be reduced using systematic methods. Dissemination of these methods is help-

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Fig. 2
Criteria for material selection

ful to support decision-making and to promote the use of new materials. Some systematic methods for material selection are outlined in this paper. Some examples of successful substitutions of other materials by ceramics are given. General obstacles impeding a wider use of ceramics as engineering material are given and an outlook regarding global trends is provided.

Material selection

Before a systematic decision for a specific material can be started, a careful analysis of the customer requirements is necessary. Usually several material properties affect the performance for the planned use. They can interact in a complex manner. E.g., if a light-weight construction is required, material stiffness and density are strongly correlated in reducing weight. In addition, there are constraints, e.g. dimensional limitations from the construction, and optimization items, e.g. price reduction. This leads to a multidimensional decision space where each material is represented by a point. In more than two dimensions often spider graphs are used for this purpose and materials are represented by polygons. In any case, a ranking of materials – in order to make the best choice – becomes very difficult, because the trade-off between different axes is complex.

The second challenge is to obtain the required data. There are numerous material data bases available – many of them free of charge on the internet. Yet, the majority of databases is restricted to a specific material class: either metals or polymers or ceramics. Comparing material data from different databases is difficult because listed properties differ by type and measuring conditions. Examples for general cross-material databases are listed in reference [2–4]. MATWEB [2] is a very large database containing 110 000 data records which is close to the estimated number of 130 000 materials commercially available [5]. However, it contains only the trade names and data sheets of the material producers making cross-material searches difficult. Reference [3] points to an ambitious Japanese database on inorganic materials containing 82 000 crystal structures, 15 000 phase diagrams and 55 000 material property records. Yet, polymers are listed in a separate database and the material property records are not complete.

Another approach is realized with the CES selector database of Granta [4]. It contains only 3500 material data records of metals, polymers and ceramics but these records enable a systematic material selection. With 60 properties per material, numerical as well as categorical data, this database is rather complete. An advantage of the CES selector database is the consistency checking of data excluding rough mistakes. However, as with other data bases the quality of the data is not sufficient to replace careful investigations on material properties of selected candidates. Also few high temperature data are available. On the other hand, the CES selector enables material selection via material indices, which is a powerful tool to reduce the number of dimensions in the decision space.

Material indices combine material properties with optimization targets of the construction. Their use can be illustrated in a simple example: consider a rod designed for the transmission of tensile forces. The weight of the rod shall be minimized. The tensile force F and the length of the rod L are preset whereas its cross section A is variable. It is clear that a low material density ρ and a high tensile strength σ_T are favourable to fulfil the requirements. But how to evaluate materials if one has the better density and the other the better strength? This requires a simple calculation. The weight M of the rod is given by:

$$M = A\,L\,\rho. \tag{1}$$

To avoid fracture, the tensile stresses σ within the rod have to be smaller than the tensile strength:

$$\sigma = \frac{F}{A} < \sigma_T\ . \tag{2}$$

Combining both equations gives:

$$M > F\,L\,MI; \quad MI = \frac{\rho}{\sigma_T}. \tag{3}$$

Since F and L are set, the ratio MI between density ρ and tensile strength σ_T has to be minimized to obtain minimum weight. This ratio is the material index related to the specific engineering task. If instead of weight M cost has to be minimized, the corresponding material index for the example above is:

$$MI = \frac{\rho\,p}{\sigma_T}, \tag{4}$$

with p = material price per kilogram. Using material indices a rational ranking between various material candidates becomes possible. If two independent indices are required for a material choice, candidate materials can be plotted with one material index as x- and the other as y-axis. Then a trade-off surface can be constructed showing the best materials lined up at the surface. This is demonstrated in Fig. 3 for the light and cheap connecting rod. Steel is the best choice – if a low price is very important – and a unidirectional carbon fiber reinforced polymer if weight is more relevant. All other materials are located in the upper right section of Fig. 3 compared to the trade-off surface.

Ceramics are inferior by an order of magnitude. Note, that a constraint on maximum service temperature – being above 1000 °C – completely changes the competition. Now ceramics become the best choice – as indicated by a second trade-off surface in Fig. 3. Many examples of material indices are given in the book of Ashby covering also thermal and electrical material use [5]. Additional examples will be presented in the next section.

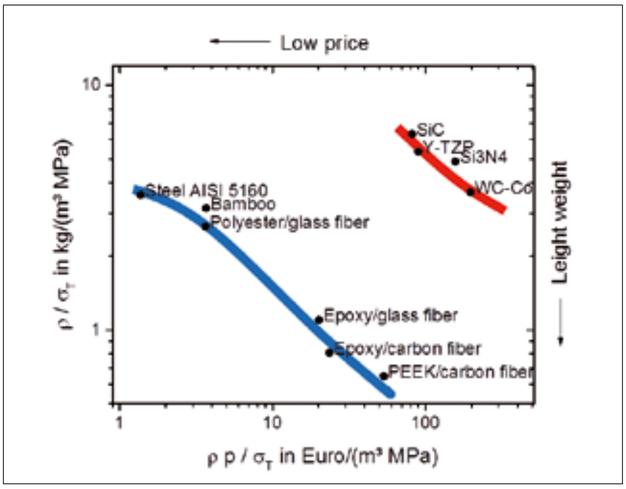

Fig. 3
Material selection for a lightweight and cheap connecting rod using material indices, blue and red line are trade-off surfaces for ambient and high temperature application respectively (material data from [4], explanations see text)

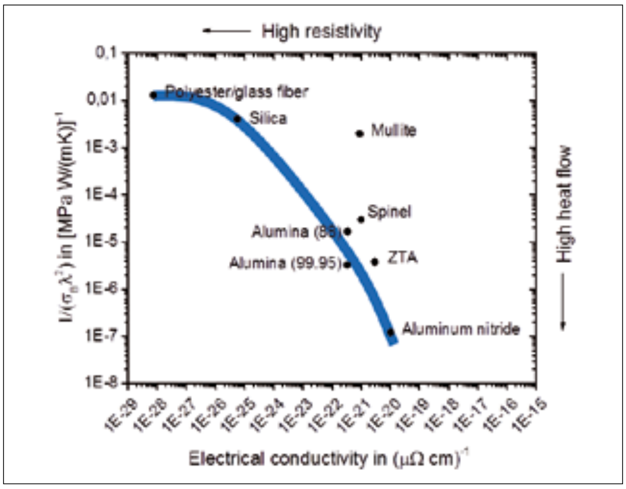

Fig. 4
Material selection for substrates used in heat sinks using material indices (material data from [4], explanations see text)

Ceramic success stories

Usually ceramics are superior to metals and plastics if additional demands, besides construction properties, are to be fulfilled – e.g. thermal, electrical or optical properties. As first example heat sinks for micro- or power electronics are discussed. The power consumed by the electronics is dissipated to heat and the heat has to be transferred to a fluid cooling medium to prevent overheating of the electronics. Therefore electronic components are mounted on substrates separating e.g. chips from the cooling liquid. These substrates have to be electrically isolating – excluding metals for this purpose. They require high thermal conductivity λ and low thickness to maximize heat flow. On the other hand mechanical integrity during assembly and use of the heat sinks require a minimum thickness of the substrates depending on materials strength σ_B. The material index combining these two requirements is:

$$MI = \frac{1}{\sigma_B \, \lambda^2}. \qquad (5)$$

Fig. 4 shows this material index versus specific electrical conductivity for several materials. It can be seen that ceramic substrates are clearly superior to polymers – with aluminum nitride being the best – but also most expensive – choice. Using tape casting, substrates can be manufactured to a minimum thickness of 300 µm. Consequently, very thin and strong ceramic substrates have been developed using e.g. zirconia toughened alumina (ZTA) ceramics (Fig. 5). In addition, other – electrical – requirements have to be met by the substrates. A detailed discussion on microstructure design is presented in [6].

Due to the superior biocompatibility of ceramics, another successful market is medical application. Ceramics can be designed to easy biodegradability or long-term stability. They can be used for bone replacement, dental prostheses or implants. Besides biocompatibility, mechanical properties and reliability are decisive for selecting ceramics in this area. In addition, dental prostheses can require aesthetic properties hardly attainable by other materials (Fig. 6). A competitor of ceramics, e.g. with implants, is titanium which has a slightly inferior biocompatibility but very good reliability and a favourable price. The price of ceramic implants is pushed up by the expensive finishing processes required to meet their small dimensional tolerances. It was shown recently that production cost of dental implants can be reduced significantly substituting finishing by a very homogenous forming process and machining of green parts [7]. Due to the constant porosity sintering leads to a predictable shrinkage within 20 µm and ceramic implants can be used as sintered (Fig. 7).

Ceramics can be produced with very good transparency for visible light. A high refractive index and superior impact strength increase their competitiveness compared to plastics and glasses which are much cheaper on the other hand. Ceramic lenses successfully replaced glass lenses in consumer products, like cameras in mobile phones, due to their higher refractive index enabling smaller designs. High strength and stiffness make ceramics an interesting material for ballistic protec-

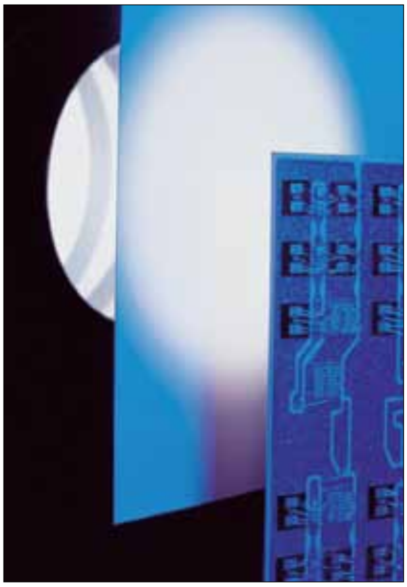

Fig. 5
Thin ZTA substrate for heat sinks produced by tape casting

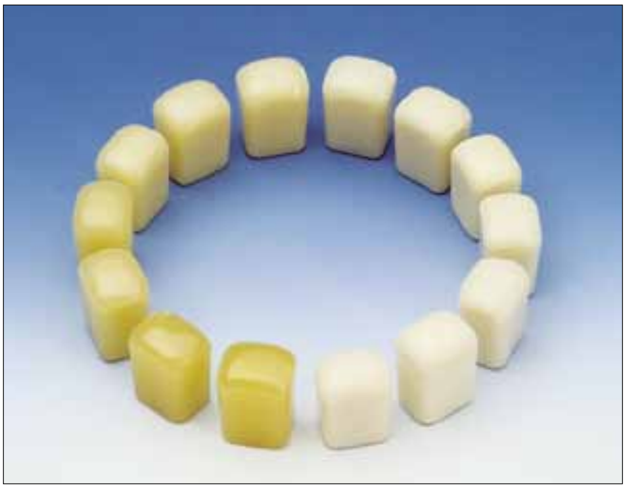

Fig. 6
Glass ceramics with adaptable translucency and colour for aesthetic dental restorations

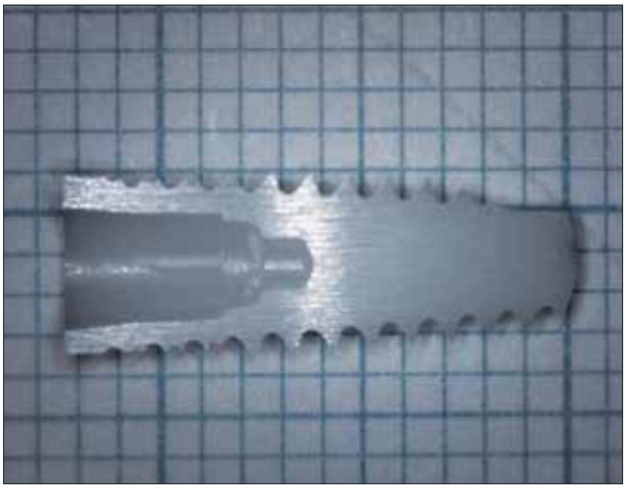

Fig. 7
Dental implant of zirconia produced within dimensional tolerances of ±20 µm without finishing
(Source: BCE Special Ceramics GmbH)

tion (Fig. 8). It is used in layered composites together with transparent polymers for bullet proof windowpanes. Manufacturing transparent ceramics requires very pure raw materials and expensive hot isostatic pressing processes. A decrease of production cost opens up many new applications. E.g. superior abrasion and corrosion resistance as well as high temperature stability of transparent ceramics allows its use as inspection glasses in harsh environments (Fig. 9).

There are numerous further successful applications of technical ceramics. All of them are based on specific material properties not attainable with metals or polymers. But a more comprehensive description is far beyond the scope of the present article. Instead some challenges are addressed in the next chapter.

Technical challenges and future trends

From the viewpoint of construction engineers ceramics are not as reliable as plastics or metals. This is a barrier for a wider use of ceramic components, which cannot be underestimated. It creates a driving force for circumventing use of ceramics by searching for other solutions, e.g. by changing the construction or by combining different materials. The customers view provides a strong reason to improve reliability of ceramic components. Much progress has been obtained in this field during the last two decades. So many construction engineers meanwhile accept the necessity of using special design rules compatible to ceramic properties. Automation level in ceramic production has been significantly increased leading to better reproducibility of critical process steps. Also process monitoring and quality control have been drastically improved. Note that special ceramic products have

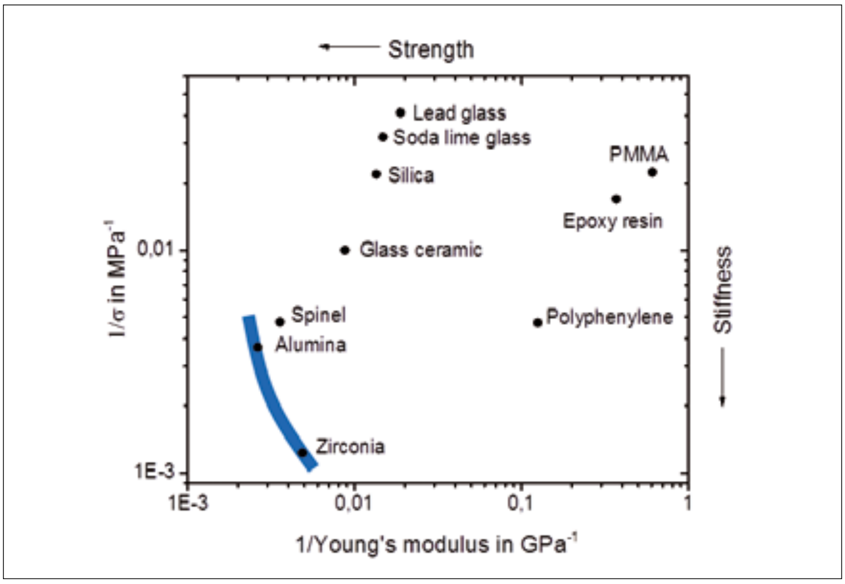

Fig. 8
Inverse strength versus inverse Young's modulus of transparent ceramics, glasses and polymers (material data from [4])

Fig. 9
Inspection glasses of transparent spinel ceramics for high temperature application
(Source: CeramTec-ETEC GmbH)

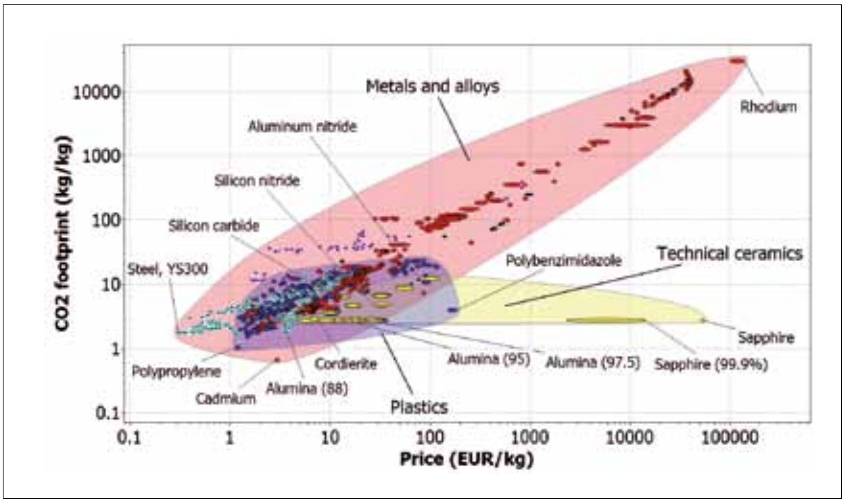

Fig. 10
CO_2 footprint and price of ceramics, metals and plastics (material data from [4])

been a driver for improving quality. E.g. with ceramic hip joints very high implantation cost led to an extraordinary high level of production control and with transparent ceramics, the visibility of each failure enforced special care but also provided additional options in failure detection.

However, the reliability of most ceramics is still inferior compared to competing materials. Reliability is measured by the Weibull modulus, which is in the range of 5 to 25 for technical ceramics. This means that large safety margins are necessary in ceramic designs. Moreover, fracture toughness of ceramics is typically lower by an order of magnitude compared to metals – leading to catastrophic failure if critical stresses exceed strength. Fracture toughness can be improved using special composites, e.g. ceramic matrix composites [8]. With these composites different mechanisms like crack deflection or fiber pullout increase fracture energy allowing for their use in security relevant areas. Yet, the improvement of the Weibull modulus is of general importance for new applications of all ceramics. It was shown recently that sintering can lead to increasing inhomogeneity of initially homogenous green compacts [9]. Better understanding and control of the thermodynamic driving forces responsible for this phenomenon are required. Inherently homogeneous sintering methods are to be implemented in ceramic production. Moreover, to cope with increasing use of finite element methods in construction, specification of ceramic products has to be completed with regard to computer simulations and the uncertainty of property data should be reduced.

In addition, the production costs of ceramics have to be further decreased to improve their competitive position (Fig. 10). More simple components should be identified which can be produced large scale by cheap processes. This requires further development of joining methods to construct complex systems from standardized semi-finished components. On the other hand, the global trend towards customized products and small series should be considered by establishing cheaper forming methods. Additive manufacturing methods are optimally suited to production on demand saving the high cost for moulding tools. Yet, they have to mature considerably to allow general use in small series production of ceramics [10]. Finally, more near net shape processing is required to save finishing cost as shown in the previous example on dental implants (compare Fig. 7).

Another global trend requires overall reduction of CO_2 emissions. At first sight one would assume that ceramics have disadvantages with respect to sustainability compared to other materials due to their high sintering temperatures. However, Fig. 10 shows that ceramics are in a middle region with regard to CO_2 footprint during production. It is important not to lose ground in the competition of different materials in terms of sustainability [7]. Due to the high public commitment, sustainability will become an important criterion for material selection in the future. Considering the long life span of production furnaces, present-day decisions affect carbon footprint of sintered ceramics during the next three decades. The reduction of CO_2 emissions can have a positive impact on ceramic market share, since ceramics have a unique position in their use in high temperature processes. Apart from some refractory metals, which need special atmospheres, there are no other materials with maximum service temperatures clearly above 1000 °C. In the effort to improve energy efficiency of high temperature processes, invest in high temperature materials will increase – giving new chances for high-performance ceramics with tailored material properties.

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