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State of the Art

Engineering Ceramics

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Abstract

The field of engineering ceramics (structural ceramics) is much more limited in volume than functional ceramics. Engineering ceramics are often subject to high thermal and high mechanical loadings including severe multiaxial stressing. These materials, their properties and the principal design aspects are outlined. Some examples are given and important testing methods are described. For many actual or prospective applications it is difficult to meet the requirements with respect to reliability and cost. Nevertheless, much successful developmental work has taken place. A variety of engineering and wear parts for many applications is commercially manufactured and a slow but continuous growth can be expected. The introduction of ceramic parts for diesel and spark ignition engines, where extremely high reliability is required, is occurring step by step, especially in Japan and USA. The ceramic gas turbine will be a long-term project, however. Considerable progress in the use of engineering ceramics is expected in the future, when several requirements have been fulfilled, namely: a thorough application of the design principles for brittle materials; the generation of a database for more reliable ceramics, obtained by improvement of processing including using precisely controlled raw materials; better understanding of long-term degradation phenomena; development and use of composites with high fracture toughness and, last but not least, motivation of engineers to utilize the technical and economical possibilities on the existing level of materials development.

Der Bereich der Ingenieurkeramiken (Strukturkeramiken) ist vom Volumen her viel begrenzter als der Funktionskeramiken. Ingenieurkeramiken werden oft hohen thermischen und mechanischen Belastungen mit mehrachsigen Beanspruchungen ausgesetzt. Diese Werkstoffe, ihre Eigenschaften und die Hauptkriterien der Konstruktion mit diesen Werbstuffen sollen umrissen werden. Es werden einige Beispiele gegeben und wichtige Untersuchungsmethoden beschrieben. Bei vielen aktuellen oder zukünftigen Anwendungen ist es schwierig, den Anforderungen bezüglich der Zuverlässigkeit und Kosten zu entsprechen. Nichtsdestoweniger wurde viel erfolgreiche Entwicklungsarbeit geleistet. Für viele Anwendungen werden eine Reihe von Ingenieur- und Verschleißteilen kommerziell hergestellt und man erwartet einen langsamen aber kontinuierlichen Bedarfsanstieg. Die Einführung von Keramikteilen für Diesel- und Ottomotoren, wo eine sehr hohe Zuverlässigkeit gefordert wird, erfolgt Schritt für Schritt, speziell in Japan und den USA. Die Entwicklung der Keramischen Gasturbine ist ein langfristiger Ansatz. Man erwartet für die Zukunft einen beträchtlichen Fortschritt in der Anwendung der Ingenieurkeramik, wenn verschiedene Bedingungen erfüllt werden und zwar: eine sorgfältige Anwendung der Konstruktionskriterien für spröde Werkstoffe; die Erstellung einer Datenbasis für zuverlässige Keramiken, die durch verbesserte Herstellungsmethoden und genau kontrollierte Rohstoffe erreicht werden; ein besseres Verständnis der langfristigen Degradations erscheinungen; die Entwicklung und Anwendung von Verbundwerkstoffen mit hoher Bruchzähighkeit und schliesslich müssen Ingenieure motiviert werden, sich die technischen und ökonomischen Möglichkeiten auf dem derzeitigen Stand der Werkstoffentwicklung zunutze zu machen.

Le domaine des céramiques structurales présente moins de débouchés que celui des céramiques fonctionnelles. Les céramiques structurales sont souvent soumises à des contraintes thermiques et mécaniques

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(y compris multiaxiales) élevées. On donne ici un aperçu de ces matériaux, de leurs propriétés et des principes de conception des pièces. Pour beaucoup d'applications présentes et futures, il est difficile de remplir les conditions de fiabilité et de coûts. Néanmoins, de nombreux développements ont été fructueux. Une gamme de pièces mécaniques d'applications variées est déjà produite commercialement et l'ont peut espérer une croissance lente mais continue. L'intoduction de composants céramiques dans les moteurs diesel et à explosion pour lesquels une très grande fiabilité est exigée se développe peu à peu, particulièrement au Japon et aux USA. Cependant la turbine à gaz céramique reste un projet à long terme. On attend des progrès considérables dans l'utilisation de ces céramiques, lorsque les exigences suivantes seront satisfaites, à savoir: une application rigoureuse des principes de conception des pièces fragiles; la création d'une base de données pour obtenir des céramiques plus fiables par amélioration des procédés, notamment en utilisant des matières premières sévèrement contrôlées; une meilleure compréhension des phénomènes de dégradation à long terme; le développement et la mise en oeuvre de composites de ténacité élevée; et enfin la mise en valeur par les concepteurs des possibilités techniques et économiques offertes par les matériaux déjà existants.

1 Introduction

The main applications of advanced ceramics manufactured in mass production are in electronic, telecommunication and electroengineering industries. Ceramics for these applications represent about 70 or even 80% of the entire field of advanced ceramics. The field is normally defined as excluding classical refractories and insulators. Several reviews can be found in the literature, e.g. Refs 1 and 2. The growth rate per year in Japan is claimed to be about 10% at present.[3] Structural ceramics, which are used as components in engines, in chemical devices, as wear parts, high temperature parts, etc., represent about 10–20%, depending on the country. The growth rate in Japan is reported as being 0·4%[3], in Europe somewhat more, perhaps 5%.

When the classification of advanced ceramics is examined as in Table 1, the engineering ceramics are seen to be concentrated in the upper part of the Table. They are often subject to high mechanical and high thermal loading. The load mostly leads to long-term multiaxial stresses which change with time. In the case of high temperature application, the mechanical stresses are superimposed by thermal stresses, while the materials properties are changing with temperature and time. Problems relating to such complex and severe loadings under long-term conditions are difficult to solve. This is one of the reasons why the progress in introducing engineering ceramics in technology is slower than formerly expected. Furthermore, many possible applications in engineering are not yet thoroughly evaluated, because brittle materials design is much less developed than design with metals and alloys.

Table 1. Classification of advanced ceramics

Main function	*Properties required*	*Applications (examples)*
Thermal	High-temperature and thermal shock resistance, thermal conductivity (high or low, respectively)	High-temperature components, burner nozzles, heat exchangers heating elements, non-iron metallurgy, insulating parts, thermal barrier coatings
Mechanical	Long-term, high-temperature resistance, fatigue, thermal shock, wear resistance	Wear parts, sealings, bearings, cutting tools, engine, motor and gas turbine parts, thermal barrier coatings
Chemical, biological	Corrosion resistance, bio-compatibility	Corrosion protection, catalyst carriers, environmental protection, sensors, implants (joints, teeth, etc.)
Electrical, magnetic	Electrical conductivity (high or low, respectively), semi-conducting, piezo-, thermoelectricity, dielectrical properties	Heating elements, insulators, magnets, sensors, IC-packages, substrates, solid electrolytes, piezoelectrics, dielectrics, super conductors
Optical	Low absorption coefficient	Lamps, windows, fibre optics, IR-optics
Nuclear	Irradiation resistance, high absorption coefficient, high-temperature resistance, corrosion resistance	Fuel and breeding elements, absorbers, shields, waste conditioning

2 The Materials Used

Most of the engineering ceramic parts used at the present time are monolithic, either oxides or non-oxides. Important oxide ceramics are Al_2O_3 and ZrO_2, for special applications also Al_2TiO_5, while non-oxidic ceramic parts are mainly based on Si_3N_4

Table 2. Selection of monolithic and composite advanced ceramics

Material or matrix (vol.%)	*Theoretical density (g/cm³)*	*Young's modulus (GPa)*	*Bend strength (MPa)*	*Fracture toughness (K_{IC}) (MPa $\sqrt{m}$)*
Monolithic				
Si_3N_4	3·19	160–300	250–1 000	2–8
SiC	3·21	300–400	400–800	3
Al_2O_3	3·98	400	400 (1 000)[a]	3–4
Al_2TiO_5	3·77	13	40	—
Monolithic or reinforced				
ZrO_2	5·56	205[b]	600–900 (1 500)[a,b]	3–9
Reinforced				
Al_2O_3–SiC, 20–30[c]	3·6	400	850	8·5
C–C, 30[d,e]	1·9	70	1 000	—
SiC–SiC, 45[d,f]	2·9	250–270	580	12–18
Glass–SiC, 30–65[d,e]	2·6	120–140	600–900	10–35

[a] Peak values.
[b] Partially stabilized.
[c] Whisker.
[d] Fibre.
[e] One-dimensionally reinforced.
[f] Two-dimensionally reinforced.

or SiC (Table 2). Each formula in this table represents a group of materials, their microstructural and mechanical properties depending on single composition, consolidation method, porosity, etc. The properties of some of these products have been improved continuously during the last two decades. A large increase in strength and fracture toughness has been achieved by developing composite materials, namely transformation-toughened ZrO_2 and Al_2O_3, SiC-whisker (and platelet) reinforced ceramics (mainly Al_2O_3) and fibre-reinforced products (e.g. C–C and SiC–SiC). The transformation-toughened ceramics provide a considerably higher strength and toughness than comparable monolithics, but so far only at lower temperatures. The continuous fibre-reinforcement leads to a substantially increased toughness, non-catastrophic fracture behaviour and to the possibility of application at high temperatures. These materials, however, are in a less-developed state and are very expensive, but provide the highest potential in principle.

3 Principal Design Aspects and Properties Required

For manufacturing engineering parts from these materials the principal design aspects have to be considered, the most important aspects of which are collected in Table 3. The more complicated and expensive a part is the higher the reliability has to be, and the more design effort is necessary. Only some of these aspects are discussed in this paper.

3.1 Basic Evaluations and Short-Term Behaviour

A basic requirement is a complete stress analysis in the ceramic component by finite element analysis including the joining interfaces. To this end, the

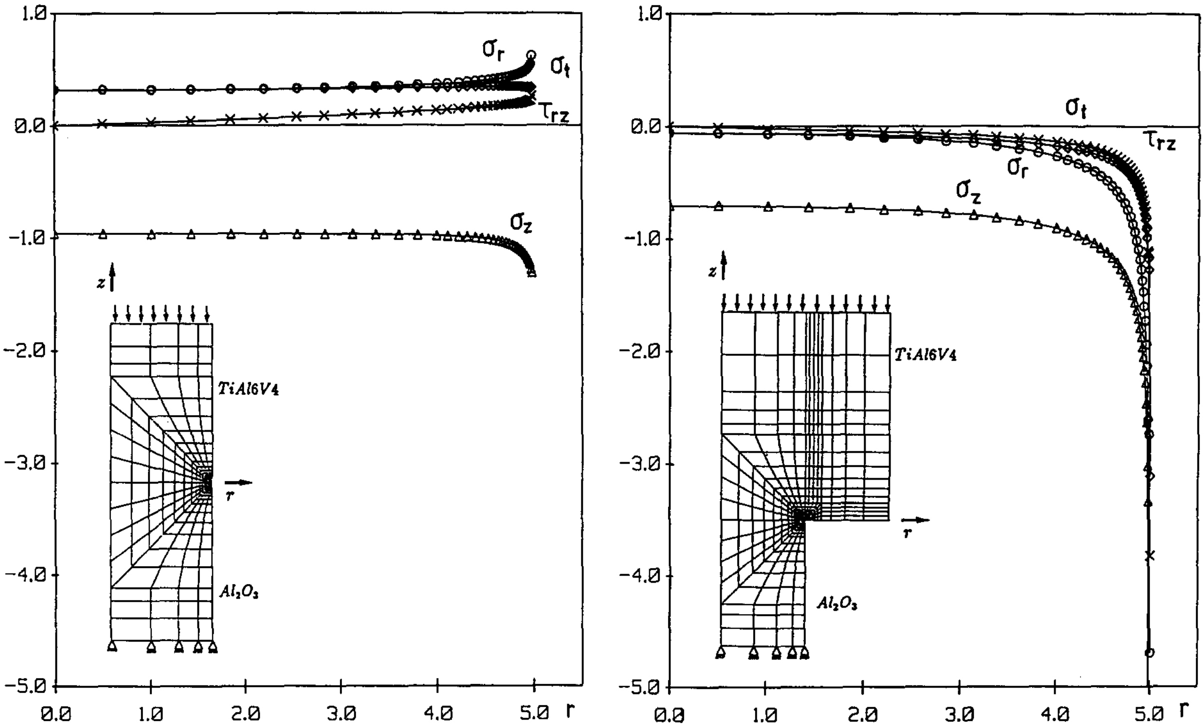
Table 3. Brittle material design for engineering components

Definition of service conditions

Basic evaluations
  Stress analysis in ceramics and ceramic–metal interfaces
  —Load stresses
  —Thermal stresses
  —Residual stresses
  Multiaxial stress criteria application
  Evaluation of other influences than mechanical stresses
  Geometrical optimization
  Definition of materials specifications required

Database for materials
  Mechanical properties under short-term conditions with respect to failure probability
  —Strength distribution (bending, tensile, ring test)
  —Fracture toughness (K_{IC})
  —Thermal shock resistance
  Materials behaviour and degradation under long-term conditions with respect to lifetime predictions
  —Fatigue (sub-critical crack growth)
    —thermal
    —static
    —cyclic
  —Creep and creep fracture
  —Friction and wear
  Thermophysical and chemical properties

Evaluation of special procedures
  —Hard machining, including surface finishing
  —Joining



(a) (b)

Fig. 1. Metal–ceramic contact under pressure; stresses in the contact plane of the ceramic cylinder (related to pressure of 1 N/mm^2). Metal/ceramic diameter ratio: (a) 1, (b) 2.[4]

service conditions have to be defined as well as possible. For comprehensive estimation load, thermal and residual stresses have to be considered likewise.

A principal aspect is the load stress distribution in contact planes of axially symmetrical parts of materials with different Young's moduli under pressure.[4] Due to the different transverse strain behaviour, radial tensile stresses occur in the ceramic part, although the nominal stress is only by pressure. Stress concentrations are observed at the edges of the contact plane. Figure 1 shows this situation for pressing cylinders of Ti-alloy on Al_2O_3, assuming no sliding in the contact plane. Tensile stresses in the ceramic part can be reduced or even avoided, when the diameter ratio of metal to ceramic part increases from 1 to 2, but in this case high compressive stress peaks occur. They can be reduced by avoiding sharp edges.

In Fig. 2 the FEM-mesh and the load–stress analysis is shown as an example with curved contacts for the development of a ceramic joint bearing.[5] They have a potential for applications at high temperatures and under severe environmental conditions. The outer ring is stressed in tension circumferentially and high modulus ceramics (SiC) lead to higher tensile stresses than low modulus ones (ZrO_2). Optimization requires that the tensile stress level is minimized as well as stress peaks by

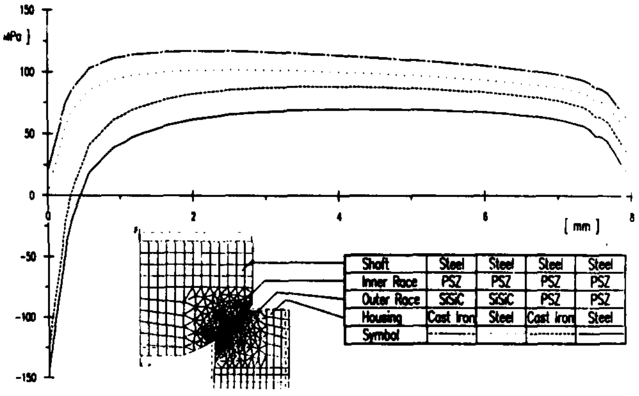


Fig. 2. FEM-mesh and circumferential tensile stresses in the outer race contact area of a ceramic joint bearing.[5]

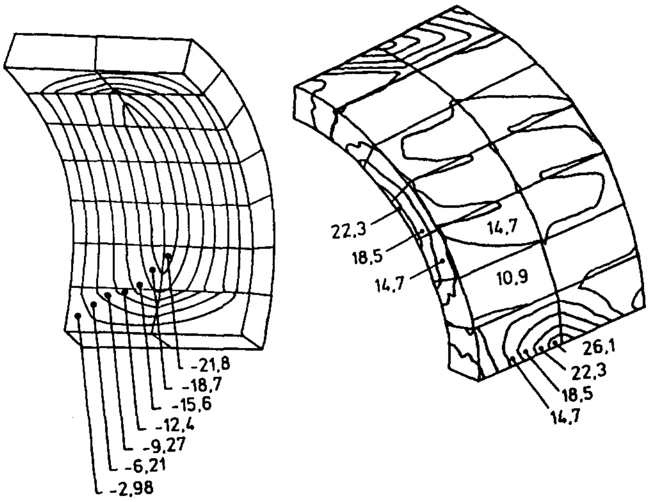


Fig. 3. Stress distribution (MPa) in a flame tube segment.[6]

improving contact geometries with equalizing local pressures and, consequently, local elastic deformation. This is even more important with ceramics than in metallic design, as is well known.

Figure 3 shows, as an example of thermal stresses in the field of turbine combustor development,[6] the stress distribution of a flame tube segment. The analysis shows the highest tensile stress values on the outer surface of the sintered SiC part due to the calculated temperature distribution. The highest compressive stresses occur in the middle of the inner surface. As a result of these investigations the geometrical dimensions of a ceramic part are shown to be of major importance. Thickness, curvature, length to width ratios and radii must be carefully adjusted to the load conditions, and subdividing into segments is advisable.

Remembering the well-known qualitative design rules, namely: avoiding tensile stresses, stress concentrations, thin local cross-sections, sharp edges, etc., nevertheless it is often impossible to avoid the stresses mentioned. Therefore a quantitative stress analysis is necessary. Residual stresses in ceramics may be a result of manufacturing, machining and joining. Because they can reach considerably high values and superimpose external stresses they have to be considered for strength and lifetime considerations. Residual stress depth profiles, measured by X-ray analysis, are available from several sources[7-9] and are especially important for machined surfaces and interfaces after joining. In machined surfaces compression stresses are often introduced, but their beneficial effect can be offset by increasing the surface flaws, resulting possibly in an effective decrease of strength. Figure 4 is an example for a soldered ceramic tip on a steel surface for a rocker arm. Measurement as well as calculation[8,10] show complicated profiles of residual tensile and compressive stresses, which can be controlled by geometrical optimization and by adjusting soldering material and processing.

Fig. 4. Rocker arm with Si_3N_4 tip, soldered structure (Daimler Benz).

Calculated and measured stresses under service conditions have to be used to define specifications required for the materials and have to be correlated with the properties of the materials available. In the case where the material response is purely elastic under short-term conditions, linear–elastic fracture mechanics and Weibull distribution data of inert strength can be applied for failure probability analysis, where the strength dependence on size has to be considered. However, surface failures often become effective and determine the strength of the part. In order to have the full benefit from bulk strength properties, a rigid control of surface quality including grinding or other machining effects is abolutely necessary.

The loading under service conditions is seldom of pure bending, compression or tension, respectively. Consequently, the conventional four-point bending test is often of limited value for the design engineer, although it is widely used. Thus, correlation of bending to tensile data[11] and tensile tests are necessary. In many cases, multiaxial stress criteria have to be applied, otherwise the calculation of applicable stresses is too optimistic. Experimentally, the double ring test[12] on disks with biaxial stresses is advisable, resulting in lower strength values than four-point bending tests on bars. (Experimental results with this test are shown later in Fig. 8 for long-term strength.)

Based on the ideas of Weibull, Batdorf and Heinisch,[13] Evans[14] and, in Germany, Munz and Fett[15] have developed sophisticated multiaxial failure criteria. The flaws causing failure are considered as randomly orientated cracks. Local fracture mechanics failure criteria taking into account mixed mode stress-intensity factors are applied. For homogeneous stress distribution the results of these calculations can be plotted in a modified Mohr biaxial stress diagram, where the result depends on the Weibull parameter m. For inhomogeneous stress states, where the degree of multiaxiality can also vary within a component, the principal calculation procedure is shown in Fig. 5. Firstly from the external loadings, the multiaxial stress distribution in the components is calculated. For a given crack, whose orientation is characterized by two angles Ψ and Φ, the normal stress σ_n and the shear stress τ are important. The stress intensity

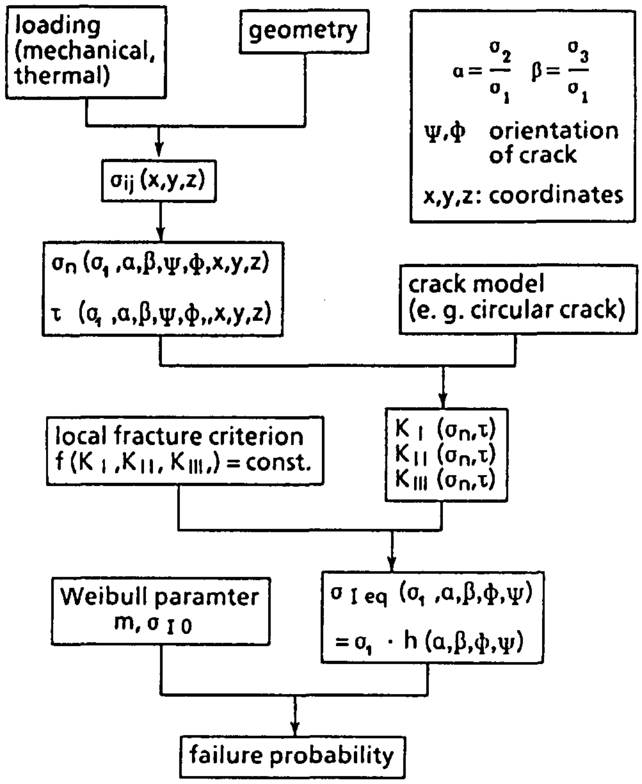


Fig. 5. Steps for multiaxial stress design procedure.[15]

factors K_I, K_{II} and K_{III} for different loading modes are calculated, and by applying a local mixed mode fracture criterion an equivalent stress σ_{Ieq}. is obtained.

Failure occurs for all cracks for which the equivalent stress exceeds a critical stress. The failure probability is obtained from the two-parametric Weibull relation with the reference stress σ^*, geometrical function g, and the function h:

$$P = 1 - \exp\left[-\frac{1}{2\pi}\left(\frac{\sigma^*}{\sigma_{10}}\right)^m \times \int_V g^m \int_0^{2\pi} \int_0^{\pi/2} h^m \sin\Phi \, \mathrm{d}\Phi \, \mathrm{d}\Psi \, \mathrm{d}V\right]$$

Design with brittle materials is facilitated considerably when materials of high toughness are available. Although there is some potential in improving monolithic ceramics, a drastically improved toughness can be achieved mainly by continuous fibre-reinforcement. For high-temperature applications the solution of the oxidation problem is critical. In Fig. 6, a stress–strain diagram of a 'modern brittle matrix material' is shown, where the continuous fibres inhibit catastrophic failure, as demonstrated in a SiC fibre-reinforced glass. Also, parts manufactured from SiC fibre-reinforced SiC exhibit fracture toughness data, which can never be achieved in monolithic SiC (see Table 2) (Experimental product of SEP, Paris, France).

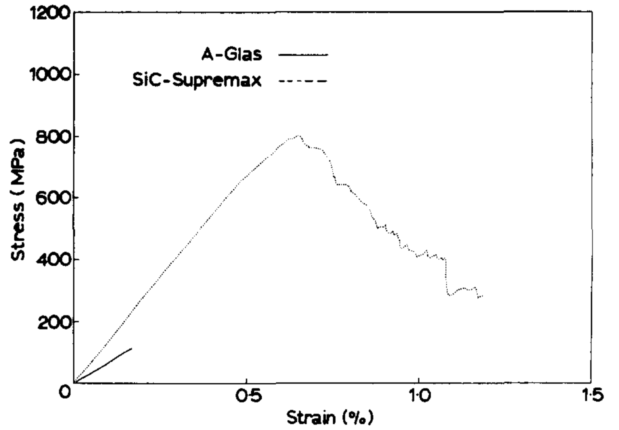


Fig. 6. Stress–strain diagram of SiC fibre-reinforced supremax glass (Grathwohl, G., unpublished).

3.2 Long-term Behaviour

Under long-term conditions, a time dependence of strength due to subcritical crack growth is observed in most of the ceramics in a wide temperature range. The laws for these processes are well developed[16,17] and generally accepted. It seems to be established that slow crack growth is normally a grain boundary process, preferably occurring when amorphous layers between the grains are present. Amorphous material (glasses) also undergoes these processes, and is strongly influenced by environmental conditions. Different types of stress, namely by thermal cycling, static, dynamic or cyclic loading, lead to similar phenomena and have to be considered for long-term applications.

In high-temperature applications where no external stresses are expected, thermal fatigue[18] experiments for lifetime considerations are advisable. (They should be distinguished from thermal degradation effects, where no temperature cycling is involved.) Results of thermal cycling are very dependent on cycling conditions, geometry and materials properties, because very different stresses and stress gradients may occur. An example is shown in Fig. 7, where a considerable strength decrease is observed after repeated thermal cycling.

Delayed fracture experiments have been performed by many authors normally as bend tests, with most of the interesting advanced ceramics.[19-22] The straight lines follow the equation

$$t_B \cdot \sigma_T^n = K(T) \cdot \sigma_{RT}^{n-2} = \text{const.}$$

with the characteristic parameters n and $K(T)$ and the time at fracture t_B. A high n value, i.e. a flat line, is

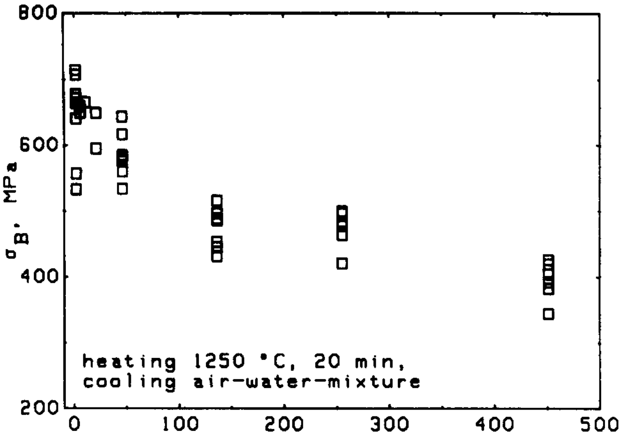


Fig. 7. Strength at room temperature of HPSN after thermal cycling.[18]

a criterion for resistance to slow crack growth (SCG). Different ceramics may behave very differently, however, mainly depending on the state of grain boundaries. Si_3N_4 with a crystallized grain boundary phase and some SiC grades belong to the more 'resistant' ceramics. Materials development during the last few years has shown interesting progress. Thresholds in SCG have been observed in HPSN at certain stresses due to relaxation and creep.[21] Experimental data are shown in Fig. 8,[20] the main result being drastically reduced lifetime when biaxial testing by a ring-on-ring test is used, compared with the conventional bend test. This seems to be extremely important for practical use. For theoretical considerations see also Ref. 23.

A most challenging field with respect to long-term performance is cyclic fatigue, which received little attention in ceramics up to five years ago. However, currently many laboratories have entered this field.[24,26] The principal question, of whether ceramics undergo cyclic effects at all, has to be answered positively, but depends strongly on microstructure and crack configuration. Some high strength ceramics particularly show specific cyclic effects due to continuous interaction of crack flanks, formation of micro-debris, etc., increasing stress intensity at crack tips. Figure 9 shows the results of cyclic fatigue of ZrO_2 (3% Y_2O_3)–20% Al_2O_3 **72**(10) (1989). After cyclic tests, survivors may exhibit even higher strength than before.

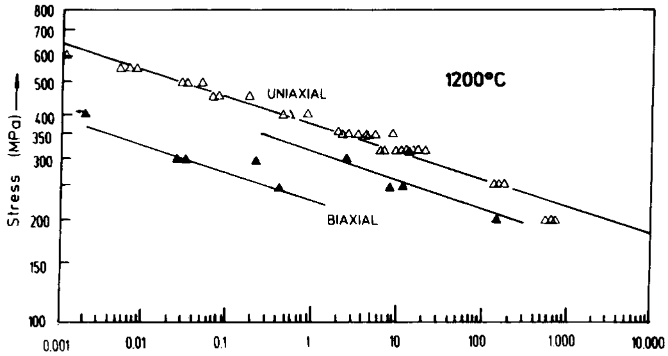


Fig. 8. Static fatigue of HPSN in uniaxial and biaxial (ring-on-ring) tests.[20]

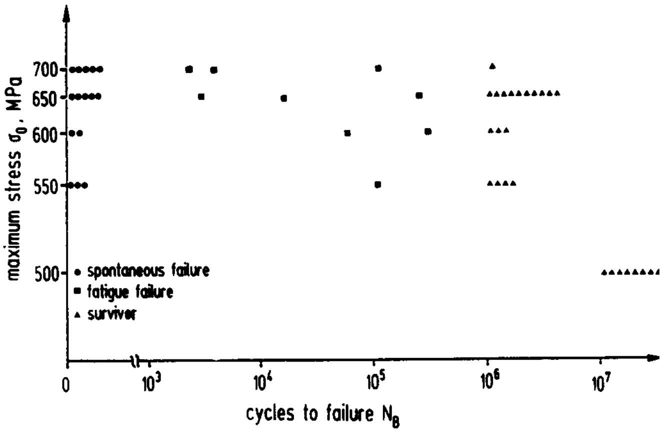


Fig. 9. Cyclic fatigue behaviour of TZ (3Y)-20A (200 Hz) (Grathwohl, G., unpublished results in Grathwohl, G. & Liu, T. S., Strengthening of Zirconia-Alumina during cyclic fatigue testing. *J. Am. Ceram. Soc.*, **72**(10) (1989).

Creep including creep fracture have to be considered as lifetime criteria in long-term high-temperature applications, e.g. for gas turbine development. Bend-test creep data have been measured during the last two decades for many ceramics.[27–29] Non-oxide ceramics, especially high-quality RBSN and SiC, belong to the most creep-resistant materials, ranging between $\dot{\varepsilon} = 10^{-5}$ and 10^{-6}/h at 1300–1400°C. In these materials creep deformation is hardly a life-limiting factor, but possibly creep fracture may be, because only small creep deformation can be sustained. Oxide ceramics are generally somewhat less creep resistant. Creep properties of dense Si_3N_4 qualities are very dependent on composition, crystalline state and the amount of grain boundary phases arising from sintering additives. SSN-materials, which can be sintered to high densities and homogeneity in larger volumes, are not very creep resistant, unless the glassy phase can be crystallized to a great extent. In non-oxide ceramics it is often not possible to define a wider range of steady-state creep because transient creep is very extended.[30] Generally, bending creep data are often not sufficient for design purposes, but tensile creep data are much less available. In Fig. 10 a few results are given. As expected, creep strain under tension is generally higher than under bending load at the same nominal conditions. For long lifetimes, a continuous decrease of creep rate with time, as observed with several Si_3N_4 qualities,[30] is favourable, but the conditions to achieve this cannot yet be clearly defined.

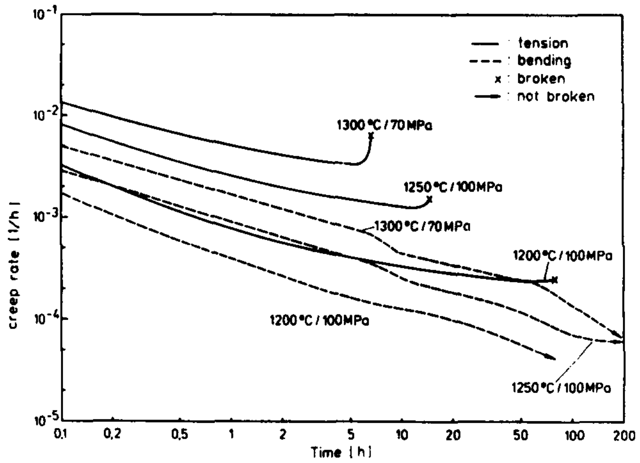


Fig. 10. Comparison of creep curves in tension and bending of SSN.[31]

The friction and wear properties are of general importance for the design of components with sliding functions, like bearings, sealing rings, joints, etc. Because tribological properties are related to the system and not primarily to the material itself, factors like materials combination, surface finishing, lubrication, sliding speed and environment, are important in addition to time, temperature and pressure.[32] Although friction coefficients and wear have been measured in many ceramic–ceramic and ceramic–metal combinations,[33] each prospective application should be handled as a 'new problem'. Dry friction between ceramics can lead to disastrous results under high loading conditions.[34] A generally improved behaviour should be achieved, when 'internal lubrication' (e.g. graphite-containing SiC) and very good surface finishing can be applied.

For several applications, especially at high temperatures and under corrosive environmental influences, thermophysical and chemical properties should be known, including degradation effects during long service, but are not discussed in this paper.

3.3 Special Procedures

Many applications of ceramics require special procedures like surface finishing, hard machining,[35,37] joining,[38,39] etc. (see Table 3). Although hard machining generally increases cost, it is unavoidable, when real net shape manufacturing is impossible or when the required surface quality cannot be achieved by other means. While mechanical surface finishing is (partly) established and is used for a lot of mass-produced parts, methods like electroerosive or ultrasonic machining are in a more developmental state. Electroerosion with an acceptable speed is only possible when the electrical conductivity exceeds a certain value, as in the case of special grades of SiC[36] or in ceramics with larger additives of high conductivity material. Ultrasonic machining is a universal method in principle, but becomes more difficult with ceramics of high toughness and special tooling and processing have to be adapted for complicated geometries.

The reliability of joints is as important as that of the ceramics themselves. When joining is necessary for a special design, the problem has to be handled for each geometry and each case separately, although brazing alloys are known in principle and are partly optimized for several ceramic–metal and ceramic–ceramic combinations. Bonding, thermal expansion misfit, residual stresses and long-term stability even under thermal cycling conditions are of major importance.

4 Engineering Ceramics in Practice

High hardness, wear and corrosion resistance are inherent properties of ceramics. Consequently, many applications have been realized based on these properties. Alumina pairs are widely used as sealing disks in hot and cold water taps, where low friction has been achieved by specification of surface roughness as low as 0·6 μm or less. Sand-blast nozzles of B_4C or SiC, sealing rings for pumps and equipment for transporting corrosive or abrasive liquids are the subject of mass production. Oxide as well as non-oxide ceramics are used. Pump and pipe liners are especially important for transporting abrasive slurries and dry abrasives; SiC seems to be the favoured material.

A field of prospective growth is that of roller and ball bearing[40] and shaft protection sleeve production. Fully dense silicon nitride particularly can obviously improve the performance of antifriction bearings. Ceramic bearings provide the possibility of operation at high temperatures ($\geq$800°C) and under severe environmental conditions. A most intriguing benefit of ceramic bearings is their ability to tolerate starvation of lubrication. A relatively new application is in parts for big valves like cones and ball plugs, e.g. in coal liquefaction plants and for gas desulphurization. Products of general interest are knives and scissors manufactured from transformation-toughened zirconia in Japan, by e.g. Jaguar, Solingen, in Germany, and perhaps also in other countries. The prospective importance of these products is in housekeeping and hair cutting, as well as in craft and industrial applications.

Manufacture of heat-resistant structural parts is much less than of corrosion and wear resistant parts. Important products are kiln furniture from SiC, a product which requires much less space than conventional kiln furniture and other furnace parts. SiC burners including heat exchangers and nozzles for gas and oil burners (products of several German ceramic manufacturers, e.g. Hoechst-CeramTec, Selb) may develop into a substantial market. A commercial product is TiB_2 evaporators (product of Elektroschmelzwerk Kempten, FRG) and rings of hexagonal BN for horizontal casting. The welding and steel hardening industry perhaps represent a future potential market for application of Si_3N_4 materials because of their good thermal shock resistance. In industrial heat exchangers advanced ceramics permit higher operating temperatures (1300–1350°C) than metallic alloys, resulting in energy saving during heat recovery. Favoured materials for application in recuperators are SiC and perhaps also Si_3N_4.

More than 90% of the metal-working tool market is occupied by high-speed steels and cemented carbides, to a great extent with coated tips. Ceramic tool materials, especially Al_2O_3, Al_2O_3–ZrO_2, Si_3N_4 (HPSN or SSN), sialons, whisker-reinforced Al_2O_3, polycrystalline diamond (PKD) and cubic boron nitride (CBN) compete with metallic and cemented carbide tools. While Al_2O_3 and Al_2O_3–TiC materials have been used for special applications for about four decades, the others are products of more recent development. Si_3N_4 and sialons have been successful since the 1970s in turning and milling of cast-iron parts and Ni-based superalloys, with the result of dramatically increased productivity (up to 200%).[41] Si_3N_4 tool tips can be used for high-speed interrupted cutting operations due to their impressive fracture toughness and 'impact resistivity' under these conditions. Whisker-reinforced Al_2O_3 seems to be advantageous for superalloys. Figure 11 demonstrates the development of toughness of some tool materials since 1957.[42] The application of PKD is restricted to operation temperatures below 700°C and to materials having no carbon affinity (no steels), while these limitations are not valid for CBN. The excellent properties of advanced ceramic tools do not yet correspond at present to their introduction in practice, although for special machining operations in the car and aircraft and industry, ceramics are well established.

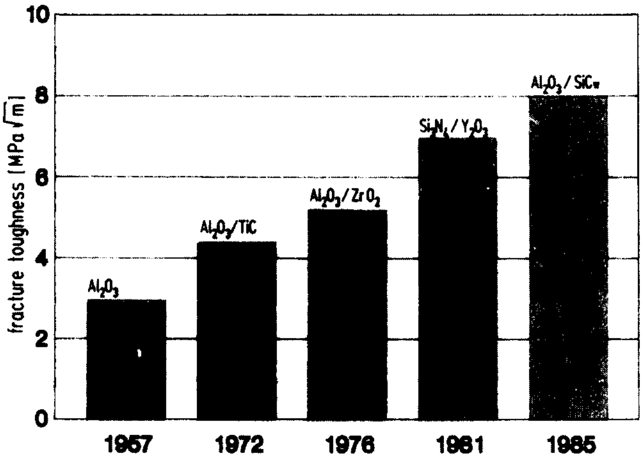


Fig. 11. Toughness development in ceramic tools since 1957.

The strong efforts to introduce ceramic parts in spark-ignition as well as in diesel engines during the last 10 years are aimed at increasing the performance of these engine types. Katz[41] has classified, especially for diesel technology, four levels of introduction of ceramics (Table 4) in order to achieve step-by-step benefits, according to the maturity and reliability of the mass production of the ceramic parts.

While the technical and economical realization of these concepts principally still lies in the future, considerable introduction of ceramics parts has been achieved at present in addition to the combustion area. Cordierite honeycomb catalyst carriers (products of several ceramic manufacturers, e.g. Hoechst-CeramTec and Selb, FRG) are now widely used in cars with gasoline-fuelled spark-ignition engines. Ceramic catalyst carriers are also very important in the chemical industries. The use of hotter exhaust gases is realized by the ceramic portliner, consisting of porous Al_2TiO_5. In the turbo-charged Porsche 944 engine, aluminium titanate portliners of about 3 mm thickness are reducing the heat flow from the exhaust port to the cooling system by up to 7 kW, causing a 13% decrease in cooling requirements.[43] Strong efforts are under way to introduce ceramic monolithic turbochargers for passenger cars, trucks, and armoured military vehicles as well. The favoured ceramic material is gas-pressure sintered Si_3N_4. The operation temperature can be considerably high, at the time being about 800–900°C and designed for about 1200°C. Mass production has been established first in Japan with 10 000 pieces per month, and up to 1988 amounts to 150 000 pieces for Toyota cars for the home market.

The swirl chamber from Si_3N_4 or Sialon was introduced in diesel cars, e.g. by Isuzu, Toyota and Mazda. A 10% improvement of output power without increase of fuel consumption has been reported.[2] The higher operating temperature compared with metallic swirl chamber may reduce also particle emission. The rocker arm insert is a typical ceramic wear part, obviously introduced as a Si_3N_4 tip in Mitsubishi cars. Sealing rings of SSiC, a mass product in conventional pumps, are now used in

Table 4. Future diesel engine technology development scenario.[41]

Technology level	*Engine configuration*	*Potential ceramic components*	*Potential pay-offs*
1	State-of-the-art engine turbocharged	Turbocharger Valve train components Pre-chamber, glow plugs	Improved performance Reduced cost? Early manufacturing experience
2	Uncooled, non-adiabatic (no water or air cooling) (no turbo-compounding)	Turbocharger Valve train components Piston, cap Cylinders, liners	Reduced weight—efficiency gain Gives option to improve aerodynamics—efficiency gain Reduced maintenance Reduced engine systems cost? Flexibility of engine placement
3	Adiabatic turbo-compound	Turbocharger Turbo-compound wheel Valve train components Piston, cap Cylinders, liners Exhaust train insulation	Very significant reduction in specific fuel consumption Improved aerodynamics Reduced maintenance
4	Minimum friction technology (could be combined with 1, 2 or 3)	Air bearings High temperature rings High temperature bearings Non-galling wear surfaces Low-friction liquid, lubricant-free bearings	Lower specific fuel consumption

cooling water pumps due to their superior friction behaviour, combined with less noise generation.

In Germany and—more generally—in Europe, the introduction of ceramic parts into passenger cars and trucks, especially in the hot zone, is not yet very advanced,[44] although substantial R and D activities are underway. An unlubricated ceramic intensive 20 kW motor is under development (Ficht-Motor; a common development of Ficht and Hoechst-CeramTec).

The ceramic gas turbine, especially the 'all-ceramic' engine is undoubtedly the most challenging project in utilizing high-technology ceramics for industry. The expected benefits are the high turbine inlet temperatures, up to 1350°C, the multi-fuel capability and the potential of low environmental pollution. Most of the experts agree that the commercialization of a vehicular ceramic gas turbine (power between, say, 100 and 300 kW) is a long-term project and will not occur earlier than in the year 2000 or even 2015.[45] Encouraging results have been achieved with a Daimler-Benz engine (110 kW) with a monolithic ceramic Si_3N_4 rotor which is operating at about 1250°C and up to 63 000 rpm. The service life at the present time corresponds to 22 000 km on city and country roads (Daimler-Benz AG, Stuttgart, FRG, pers. commun.). Stators and rotors are components with the most complex geometry. When they are successful under realistic service conditions, the development of the other static parts can also be expected to be successful. The results achieved in the last 15 years demonstrate, in principle, the technical feasibility of a vehicular gas turbine. Therefore new R and D programmes are underway in several countries.[46]

5 The Lack of Knowledge and Future Requirements

The most essential need for prospective progress is the existence of an appropriate database for engineering ceramics, combined with high standard, reliable and reproducible manufacturing. Both are far from being established yet at a level needed for a larger breakthrough in engineering ceramics. The generation of a database is only of little value when the processing technology is in a 'preliminary' state and considerable batch-to-batch variations occur. Thus, a broadly based capability of properties measurement is preferably necessary for well-developed materials. For many prospective applications the important processing steps need to be improved, in order for clearly defined microstructures to be reached, physical and chemical failure minimization and optimization of homogeneity. New and optimized starting powders with improved cleanness will help to achieve this goal. Monosized powders, as claimed several years ago, are probably not an appropriate starting material, because they lead to ordered as well as disordered packing in neighbouring micro-volumes, leading to different shrinkage behaviour and failure generation. A blend of two monosized powders leads to a controllable disordered, but homogeneous particle distribution with 'homogeneous' sinterability.[47] This, together with optimized shaping and sintering procedures, e.g. with controlled densification rates[50] could be important steps to reach high-strength, high Weibull modulus materials. New possibilities, instead of using prefabricated powders, are possible by reactive processes, especially for manufacturing composite ceramics. Liquid, solid or gaseous precursors are used as starting materials which undergo a reaction process after shaping, resulting simultaneously in the formation of the ceramic compounds and their densification, as summarized in Ref. 51.

As stated previously, several properties are of basic importance for the lifetime of structural ceramic parts. A strength evaluation has to consider also residual stresses from different sources. Superimposed on external stresses, they can initiate subcritical crack growth and possibly lead to catastrophic failure. The investigation and understanding of cyclic fatigue is only at its beginning. This has to be investigated for monolithic as well as for composite materials and has to be considered for long-term performance evaluation. It is very important to provide strength data, not only by bending, but also by tensile tests, especially for fatigue and creep.[48] Multiaxial tests are of vital importance for practice and are necessary to help the designer. Comparative studies of materials' responses under bend and tensile stresses will also provide a deeper insight into materials' behaviours at high temperatures.

There is a principal lack of knowledge in correlations of microstructural parameters with the properties of ceramics. Very little is established with regard to quantitative correlations with respect to mechanical (strength and fatigue) properties; general trends only are known at present. More effort has to be spent by researchers and manufacturers to determine and to define microstructures chemically as well as physically, including the state of grain boundaries, and to investigate the correlations mentioned. During a recent conference[49] it was clear that many analytical methods are well established, but their application to properties and processing problem is still lacking.

Considerable breakthroughs in some 'difficult' fields of application, e.g. for car industry or gas turbines could certainly be achieved, when several requirements are fulfilled: Firstly, the definition of clear and approved specifications of properties, to be defined by the user; secondly, the existence of a manufacturing route which fulfils quality as well as economical criteria, including non-destructive testing methods; thirdly, the existence of a sufficient database for these 'reliable' ceramics and finally, when the manufacturers and the users of ceramic parts are willing to perform extensive long-term field tests.

6 Outlook

The long-range prospect for ceramics in engines has been assessed by Argonne National Laboratory.[45] Table 5 shows some of the data, which reflect the expected step-by-step introduction of structural ceramics in heat engines. The market introduction ranges from 1995 for diesel engines to beyond 2000 for gas turbines.

Success in this field will be closely related to the needs discussed in Section 5, focused on the problems of product reliability and cost. At present, the cost is the crucial point for potential applications in the automotive industry in cases when the

Table 5. Projected market development for ceramic intensive engines[45]

Type of engine	*Light duty*		*Heavy duty*	
	Introduction (1% market share)	*5% Market share*	*Introduction (1% market share)*	*5% Market share*
Diesel	1995	2005	1995	2005
Spark ignition	1996	2005	2000	2010
Rotary	2000	2005	2005	2010
Adiabatic	2000	2010	2005	2015
Gas turbine	2003	2025	2005	2015

reliability is considered as adequate (Daimler-Benz AG, Stuttgart, FRG, 1990, pers. commun.).

Several industries as well as the automotive industry have to be considered, however. There is no doubt that the market in engineering ceramics will grow continuously, but it is very difficult to make future estimates. Ceramics compete with parts manufactured from metals, which may result in special cases even in a replacement of ceramics by metals. (This eventually will take place in the field of catalyst carriers for personal cars.) The normal way is, as ceramists hope, the opposite! Many new applications of ceramics can be achieved in future simply due to their specific property advantages, because many potential applications with expected pay-offs are not yet thoroughly evaluated. Although it is extremely important to improve material quality as pointed out above, engineers should not wait for the 'ideal' ceramic material. Even the existing levels of properties in oxide and non-oxide ceramics would enable more application of structural ceramics to be achieved when the possibilities and principles of designing are properly applied. When material specialists, producers, designers and users face the technical and economic problems of reliability and cost on an interdisciplinary basis, the field of engineering ceramics should be considerably enlarged in the future.

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