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# CERAMICS IN ENGINES
# PAST - PRESENT - FUTURE

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SUMMARY

The application of different ceramic components in engines together with the relevant materials properties will be discussed.

The present state of the development will be outlined and a future outlook will be given.

## INTRODUCTION

Ceramics have played an important role in technology since decades but in the past 10-15 years the interest in this class of materials has risen sharply due to the fact, that ceramics do play an increasing significant role in high-technology areas. In the most general definition ceramics are inorganic non-metallic materials and are based on oxides, carbides, nitrides etc. and related compounds (Table 1).

TABLE 1

| Oxide Ceramics | | Non-Oxide Ceramics | | |
|---|---|---|---|---|
| $Al_2O_3$ | | C | | |
| $ZrO_2$ | | SiC | $B_4C$ | WC |
| $TiO_2$ | Silicates | $Si_3N_4$ | BN | AIN |
| MgO | Titanates | $MoSi_2$ | | |
| BeO | Ferrites | $TiB_2$ | | |
| $UO_2$ | Actinides | | | |
| $Y_2O_3$ | Phosphates | | | |
| $Eu_2O_3$ | | | | |
| ZnO | | | | |

Most traditional ceramics (e. g. porcelain, steatite etc.) are silicates and are produced from natural raw materials, whereas the production of high-performance ceramics requires synthetic chemicals of high purity and some significant changes in fabrication technology. Nevertheless it should be recalled, that there are also many examples of traditional ceramics, such as insulators, catalyst carriers etc. which are used in modern technology.

Ceramics are used or are under consideration as system components by the

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automotive industry due to a number of their attractive properties, e. g. excellent thermal stability, high wear- and corrosion resistance, special electrical properties etc. Their brittleness is a disadvantage and a reason, that many design engineers are reluctant to use ceramics even when their application would be attractive due to other desirable materials properties. This conflicting situation becomes especially evident in the development of ceramic materials for engines. For each case a careful selection of a special material is necessary in order to achieve the required performance and in most instances not one single but a combination of different desired properties is decisive for the final choice. In the paper examples for already existing or possible future applications of ceramics as engine components will be discussed.

## APPLICATIONS BASED ON ELECTRICAL PROPERTIES OF CERAMICS

Probably the oldest application of a ceramic part in an engine is the spark plug (Fig. 1).

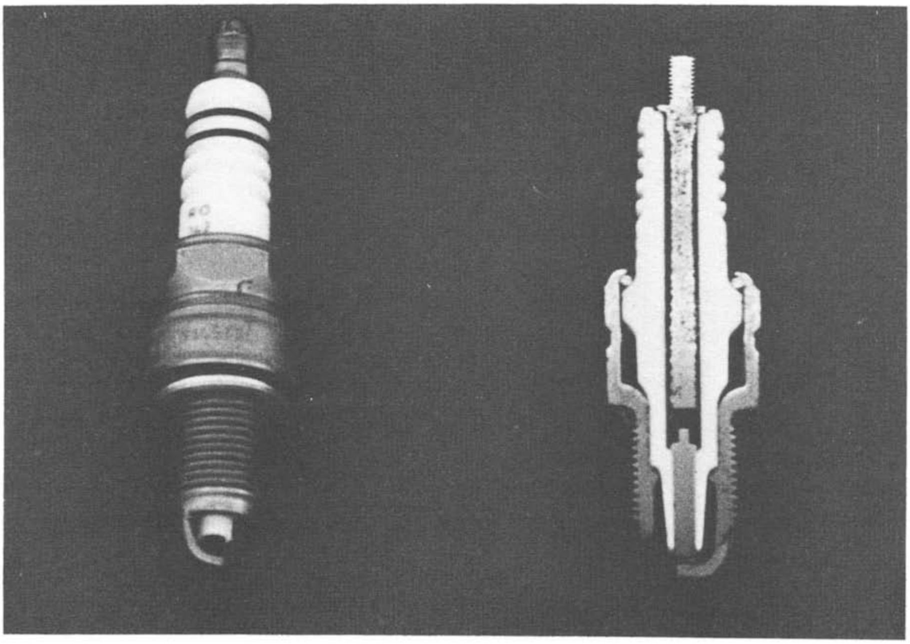

Fig. 1 Spark plug

The necessity to use a material with a high electrical resistivity combined with a high corrosion resistance and a good thermal shock behaviour resulted in the development of aluminum oxide spark plugs. In Fig. 2 the electrical conductivity of two ceramic materials is shown as an example for the widespread electrical properties of ceramics.

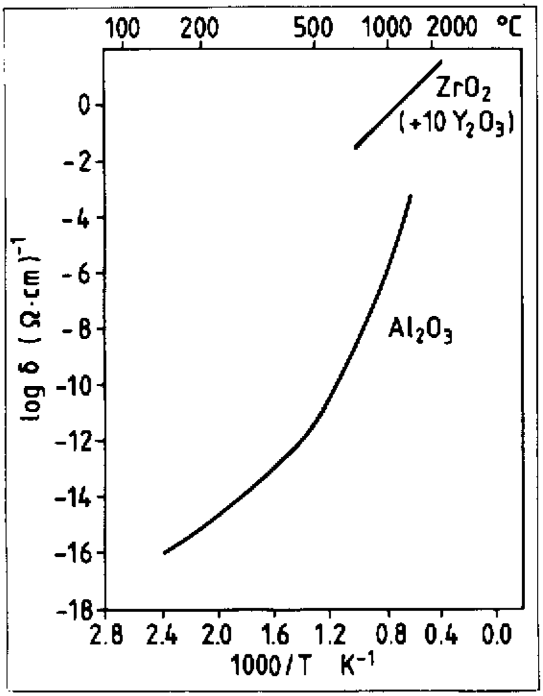


Fig. 2 Electrical conductivity of $Al_2O_3$ and $ZrO_2$(10 $Y_2O_3$)

Aluminum oxide is an excellent electrical insulator in contrast to zirconium oxide ceramics being ion conductors. The high electrical conductivity of the latter is caused by the presence of oxygen vacancies resulting from the addition of lower valent oxides to the zirconia, e. g. CaO or $Y_2O_3$. The charge carriers are oxygen ions, their diffusion rate is dependent on the temperature and the oxygen partial pressure in the surrounding atmosphere. Therefore the material can be used for the determination of oxygen in gases according to

$$E = \frac{RT}{4F} \cdot \ln \frac{Po_2}{Po_2^*} \qquad (1)$$

E = electrical potential

F = Faraday number

$Po_2$ = oxygen partial pressure

$Po_2^*$ = reference oxygen partial pressure

A schematic drawing of such a sensor ( λ-Sonde) is shown in Fig. 3. The oxygen content in the exhaust gas is monitored and the obtained signal is used to control the fuel-air mixture in the combustion process (Fig. 4).

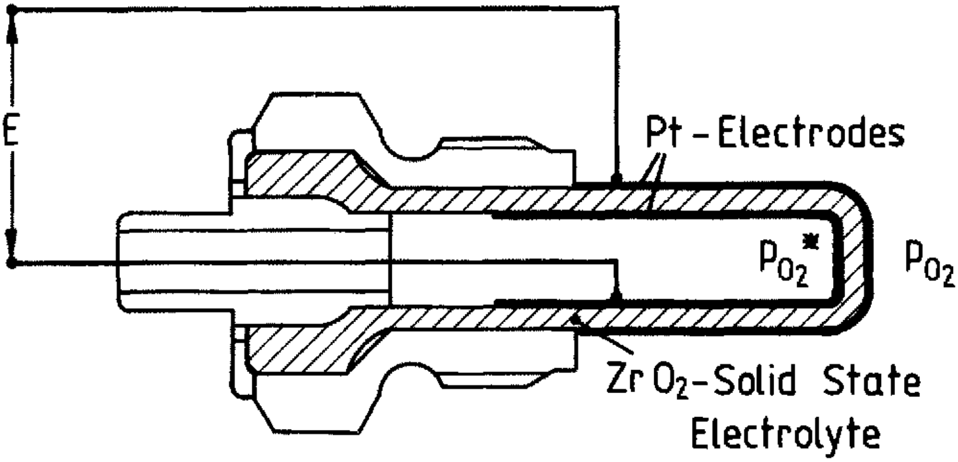


Fig. 3 λ -Sensor (schematic)

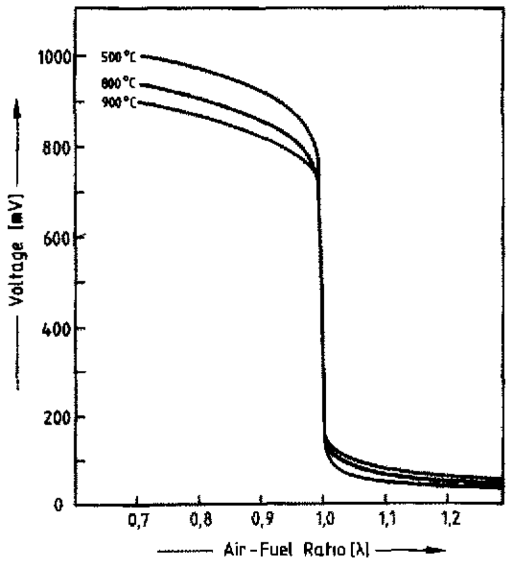


Fig. 4 Electrical characteristics of λ -Sensor

## APPLICATIONS BASED ON THERMAL AND MECHANICAL PROPERTIES OF CERAMICS

In order to control automotive exhaust emissions cordierite honeycomb substrates coated with catalysts are in use (Fig. 5). Cordierite (MAS, Table 4) a magnesium aluminum silicate has a low thermal expansion. In addition, due to the extrusion process used in fabrication the crystallites have a preferred orientation with the low expansion direction parallel to the plane of extrusion. In this way an expansion coefficient of ~ $1.0 \times 10^{-6}\ K^{-1}$ can be achieved in the temperature range 20-1000°C, which is important for the excellent thermal-shock restistance of the ceramic. Furthermore cordierite shows good compatibility with the oxide coatings and the catalysts which are part of the final device.

The most challenging part of the R & D worldwide in the field of engine ceramics during the past 15 years was probably the attempt to build a ceramic gas turbine. In order to achieve the necessary efficieny for the turbine size under consideration, one must have turbine inlet temperatures in the range of 1370°C which excludes the use of metallic alloys. Whereas some turbine components, such as the combustion chamber, the stator or the heat exchanger are only exposed to high temperature gradients or a high gas pressure, the turbine rotor (Fig. 6) has to withstand additional dynamic stresses and becomes the most critical component of the whole development. Turbine rotors with a rotational speed of 700 m/s (100.000 rpm) were envisaged. Although prototypes were built and tested much further work is necessary to achieve the envisaged goal. Here the already mentioned disadvantage of ceramic materials, their brittleness, is responsible for the delay encountered.

In contrast to the ceramic gas turbine a number of ceramic components for conventional engines are being used either already commercially or undergo at least extensive field testing. Ceramic glow plugs and swirl chambers based on silicon nitride are used in diesel engines with a resulting improvement of the cold start performance of the engine. Aluminum titanate has found its application as thermal insulating material in form of the portliner (Fig. 7) with the result, that the exhaust gas temperature is higher, when it reaches the catalyst. The aluminum titanate parts are fixed in their predetermined position before the metallic structure is cast around them. With this design the low mechanical strength of the aluminum titanate (Table 4) can be tolerated. Silicon carbide turbochargers (Fig. 8) have been developed and are tested under severe conditions (e. g. 950°C, 150.000 rpm). In addition there are other examples, where the use of ceramic parts in engines is being considered, e. g. cylinder liners, valve guides, valve tappets etc.: in these latter applications the high wear resistance of ceramics could be of advantage in comparison to metallic parts.

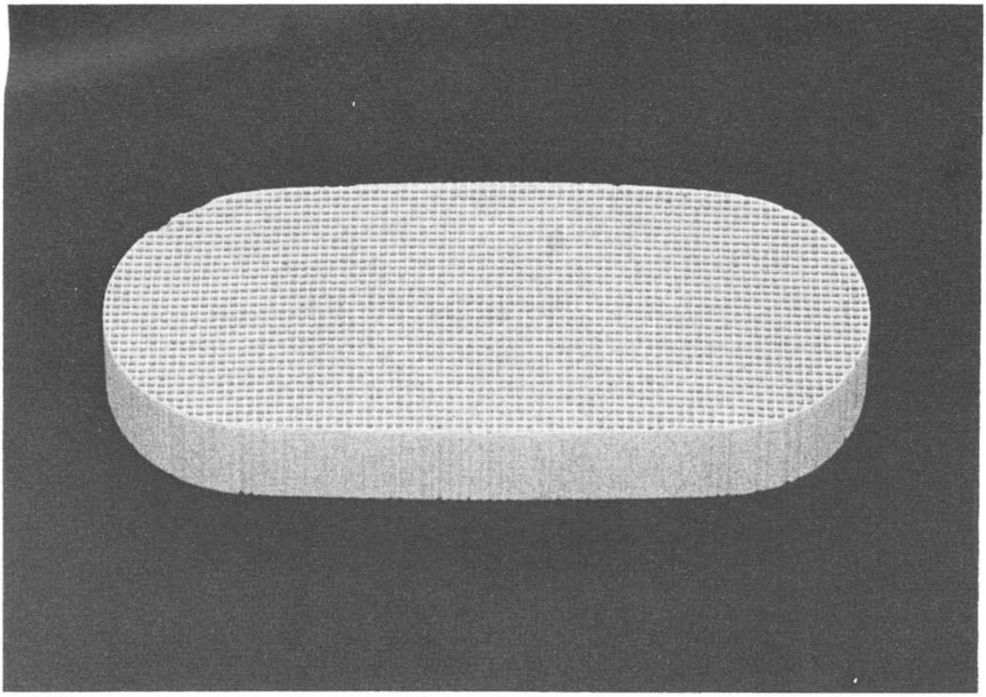

Fig. 5 Cordierite monolith (Court. Corning Keramik)

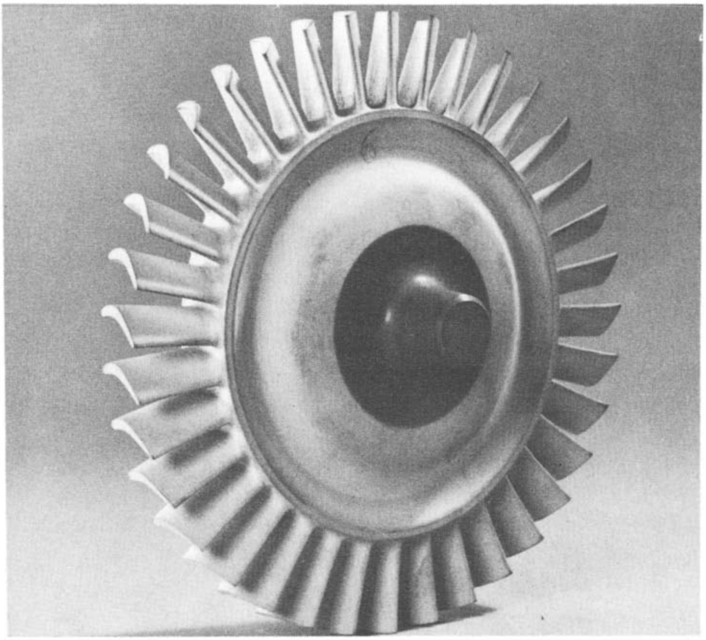

Fig. 6 $Si_3N_4$ - Turbine rotor (Court. Volkswagen AG)

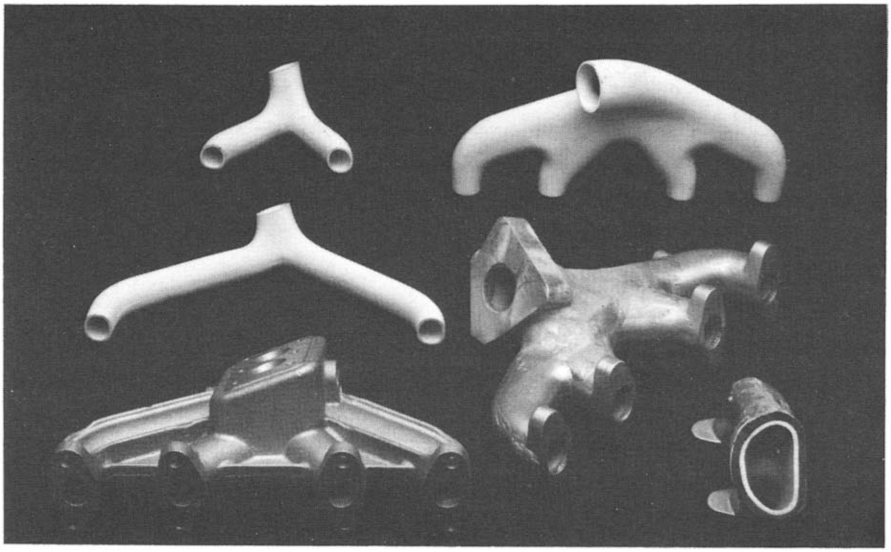

Fig. 7 $Al_2TiO_5$ insulating parts (Court. Hoechst CeramTec)

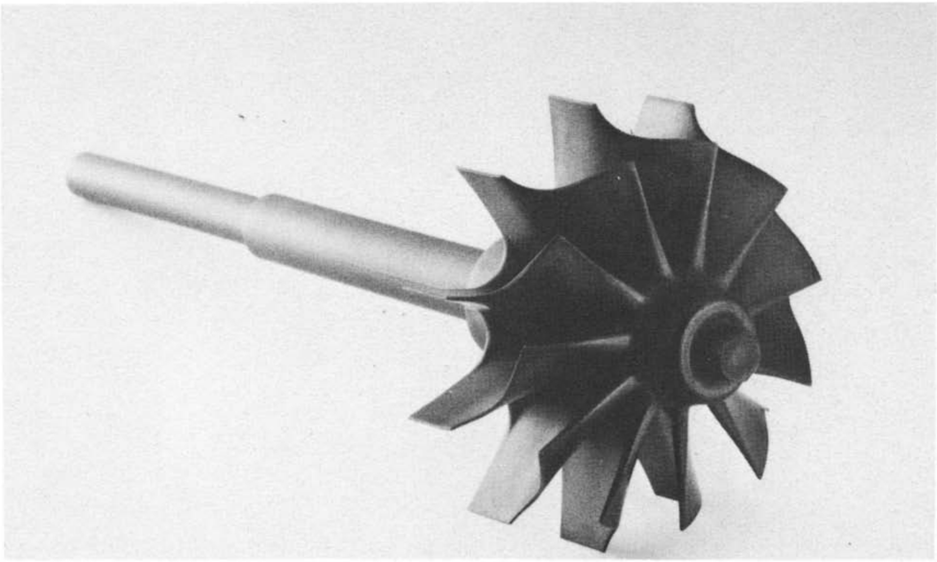

Fig. 8  SiC-Turbocharger (Court. Volkswagen AG)

A number of different ceramic materials has been developed and tested (Table 2 and 3).

TABLE 2

Ceramic materials for vehicular gas turbines

| Component | Material | |
|---|---|---|
| Combustion chamber | Si-infiltrated silicon carbide | (SiSiC) |
| | Sintered silicon carbide | (SSiC) |
| Stator | Reaction bonded silicon nitride | (RBSN) |
| | Si-infiltrated silicon carbide | (SiSiC) |
| | Sintered silicon carbide | (SSiC) |
| Heat exchanger | Magnesium-aluminum-silicate (cordierite) | (MAS) |
| Turbine rotor | Hot-pressed silicon nitride | (HPSN) |
| | Post-sintered RBSN | (SRBSN) |
| | Sintered silicon nitride | (SSN) |
| | Sintered silicon carbide | (SSiC) |

TABLE 3

Ceramic materials for diesel engines

| Component | Material | |
|---|---|---|
| Parts for piston and cylinder | Partially stabilized zirconia | (PSZ)* |
| | Sintered silicon nitride | (SSN) |
| Exhaust lines | Aluminum titanate | ($Al_2TiO_5$) |
| Turbocharger | Sintered silicon carbide | (SSiC) |
| | Sintered silicon nitride | (SSN) |

* or TZP (Tetragonal $ZrO_2$ Polycrystals) if HT-strength can be improved.

For application in gas turbines silicon carbide and silicon nitride ceramics have to be used due to the high system temperatures up to 1400°C. In the uncooled engine, temperatures are lower and caused by additional requirements with regard to thermal expansion or thermal conductivity partially stabilized zirconium oxide or aluminum titanate are used. In Table 4 properties of the materials mentioned above are indicated and in Fig. 9 their bend strength at various temperatures is shown. In principle two classes can be distinguished with regard to the high-temperature mechanical properties. Ceramics like reaction bonded silicon nitride (RBSN), sintered silicon carbide (SSiC), hotpressed silicon carbide (HPSiC) and Si-infiltrated silicon carbide (SiSiC)

| | | RBSN | SSN | HPSN | SSiC | HPSiC | SiSiC | TZP | MAS | $Al_2TiO_5$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Density | ($g/cm^3$) | 2.7 | 3.2 | 3.3 | 3.1 | 3.2 | 3.1 | 5.9 | 2.1 | 3.0 |
| Therm. Exp. Coeff. (20 - 1000°C) | ($10^{-6}$/K) | 3.0 | 3.2 | 3.2 | 4.5 | 4.8 | 4.5 | 11.0 | 1.5 | 1.5 |
| Therm. Cond. (1000°C) | (W/mK) | 8 | 18 | 20 | 40 | 40 | 45 | 3.8 | 2.0 | 2.0 |
| Young's Modulus (20°C) | (GPa) | 200 | 320 | 320 | 400 | 440 | 340 | 180 | 60 | 13 |
| Flexural Strength (20°C) | (MPa) | 300 | 450 | 600 | 430 | 600 | 300 | 900 | 100 | 40 |
| Fracture Toughness (20°C) | (MPa m) | 3.5 | 6.5 | 7.0 | 4.8 | 5.5 | 4.0 | 12.0 | - | - |

TABLE 4 Properties of ceramic materials for engines and turbines

have an almost constant flexural strength up to 1200°C. In the case of RBSN, SSiC, HPSiC the same flexural strength is retained even at 1400°C, whereas the SiSiC, which contains free silicon with a melting point of 1410°C, shows a strong strength degradation at this temperature. In the second group a strength decrease can be observed at higher temperatures, although some of the compositions have excellent strength values in the lower temperature range. In the case of the sintered or hot-pressed silicon nitride the decrease is caused by the softening of a glassy phase, whereas in the case of PSZ the disappearance of internal stresses is the responsible mechanism. In all cases time-dependent phenomena must be taken into consideration, e. g. subcritical crack growth or high-temperature creep resulting in a further decrease in the maximum tolerable stresses. This is especially important for materials with a high amount of glassy phase.

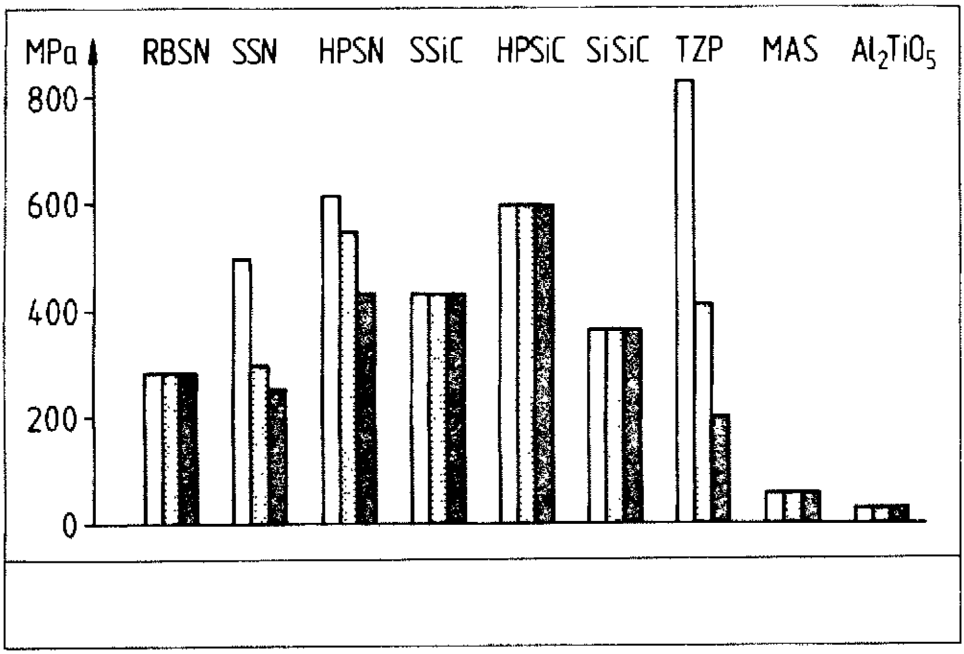


Fig. 9 Flexural strength of ceramic materials
(left 25°C, middle 1000°C, right 1200°C)

Despite the progress achieved a continuation in R & D is required to come to a breakthrough in the application of ceramics in engines or even turbines. Considering the materials development an increase in fracture toughness is necessary. Improvements in processing (powder synthesis, forming, sintering) will enable a reliable reproduction of a homogeneous microstructure and will reduce the strength variations of the materials encountered to-day. Non-destructive testing procedures must allow to detect defects in the micron size range and finally the knowledge about the optimum design with this class of brittle materials must be enlarged.

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