Association of the German Ceramics Industry

Breviary
TECHNICAL CERAMICS

think
ceramics
TECHNICAL CERAMICS

Imprint:

Edited by: Informationszentrum Technische Keramik (IZTK)
in co-operation with member firms of the Technical
Ceramics Section (Fachgruppe Technische Keramik)
in the Verband der Keramischen Industrie e.V.

Contact: Verband der Keramischen Industrie e.V.
Informationszentrum Technische Keramik
Schillerstraße 17, 95100 Selb
Telephone: +49 (0) 92 87 - 9 12 34
Fax: +49 (0) 92 87 - 7 04 92
E-mail: info@keramverband.de
http://www.keramverband.de

Published by: Fahner Verlag, Lauf
ISBN 3-924158-57-6

Printed by: Fahner Druck GmbH, Lauf
December 2004

Preface

This guide is intended as a companion for the practical engineer, regardless of whether he or she is a user or manufacturer of ceramics. It has therefore been designed as a practical aid for everyday use. To this end, it offers an overview of ceramic materials, their properties, manufacturing and processing methods, and describes the basic rules for construction using ceramics as well as bonding and joining techniques. This does not, however, mean that it replaces definitive manufacturers' data. We also refer the reader to the large quantity of specialist literature available for the scientific background.

The guide also restricts itself, in the field of applications of technical ceramics, to the tabulation of examples and the presentation of typical components, since information on these matters can be found in the literature that is available free from the Informationszentrums Technische Keramik.

This guide is a result of suggestions and cooperation with the Technical Commission of the Technical Ceramics Section of the Association of Ceramics Industries (VKI). This 4th edition has been carefully reworked throughout.

Our sincere thanks for close cooperation and committed work go to:

- all the members of the commission,
- all the specialists at the members factories and
- Roger Morell.

Verband der Keramischen Industrie e.V.
- Informationszentrum Technische Keramik -

Selb, 15th December 2004

Table of Contents

1 Introduction

Science and technology are in continuous development. This leads to ever more demanding and intelligent technology.

The demands made on modern materials are increasing with the same dynamism. The features that are demanded include greater strengths for material-saving constructions, lighter components for energy saving, higher quality for more security and longer service life. After all, cost-effectiveness plays a crucial role.

Ceramic materials have in the past made an important contribution to this process of innovation.

Requirements for the successful application of ceramics include constructions that are appropriate to the materials and the manufacturing processes, as well as appropriate applications. The point is not that common materials can be displaced, but rather that customised products allow completely new solutions.

The road to the ceramic component

In order to make intelligent and effective use of the properties of ceramics, it is not sufficient simply to take an existing structural component and to replace it in every detail with a ceramic part. A drawing of the component used so far, however, together with a great deal of supplementary information, can show the way to the mass-produced ceramic component.

Thermal, electrical, mechanical loading and the chemical environment must all be taken into account in this process. Appropriate criteria relevant to each particular case mean that one or more suitable materials out of the wide range of available ceramics can be identified. The materials tables and associated descriptions in the following chapters will be helpful in this process.

The ceramic material for the new application must satisfy the technical analysis of the particular problem, must also offer an appropriate price/performance ratio throughout its service life, and may have to offer additional benefits.

The drawing is then checked for feasibility of implementation, and optimised for manufacture.
The tolerances required are often typical of those for metals, i.e. relatively close for all surfaces. In order to optimise costs it is necessary to distinguish between the general tolerances typical for ceramics, and special tolerances that may be needed for functional surfaces.
In a few cases it may also be necessary to consider the functional principles, and therefore perhaps a new design for the assembly.
The user will be steered through the process described above by the ceramics manufacturer.

After clarifying the technical details, the ceramics manufacturer can choose the optimum production procedure, bearing in mind the length of the production run, and can make a quotation.

Ceramics today

Ceramics have already proven themselves in a wide variety of applications, and are being considered for others where high hardness, wear resistance, corrosion resistance and high temperature stability, combined with low specific weight, are necessary. The new high-tech materials achieve high levels of strength. Their figures are comparable with those for metals, and generally exceed those of any polymer.
The properties of the ceramic material are heavily influenced by those of the particular microstructure. The mechanical and physical properties can be influenced in different ways through the deliberate creation of particular microstructures, a process referred to as "microstructure design".

An important point always to bear in mind when applying ceramics is this - ceramics are brittle! The ductility of metal construction materials make them "good-tempered and well-behaved". They are able to forgive small errors of construction (incorrect tolerance), because they are able to disperse local stress peaks through elastic and plastic deformation.

Other features typical of metals include good electrical and thermal conductivity, and characteristics that are independent of orientation.

Ceramic materials, on the other hand, are usually electrically and thermally insulating, have high hardness figures, and may have very low thermal expansion. Their shape is, furthermore, extremely stable due to the absence of a capacity for plastic deformation. Compression strengths ten times greater than the bending or tensile strengths can be achieved. In comparison with metals, ceramics are particularly suitable for application at high temperatures, since the characteristics of ceramic materials are altogether less strongly influenced by temperature than metals and even then only at particularly high temperatures. Ceramics offer equally high benefits in terms of corrosion and abrasion resistance.

Because of these advantages, we find technical ceramics wherever we go. Without ceramic insulators, many household devices would not function. Likewise, without insulators and safety devices made of technical ceramics, a reliable electricity supply would be unthinkable. Ceramic substrates and parts are the basis for components and modules in all areas of electronics, while in machine and plant construction sliding and bearing elements provide low wear, corrosion-free function. Ceramic construction and insulation materials are indispensable to the industrial furnaces used in high-temperature technology. Even these few examples make clear that technical ceramics have an important role to play in today's world.

Ceramic components are often, however, not visible at the first glance. Nevertheless they play a crucial role, both in conventional applications and in innovative products.

The potential of technical ceramics has not yet been exhausted.

2 The History of Technical Ceramics

The use of ceramics can be traced back to the early history of mankind. Reliable archaeological research has shown that the first ceramic figures were formed from malleable ceramic material and hardened by fire more than 24,000 years ago. Almost 10,000 years later, as our ancestors developed settled communities, tiles were first manufactured in Mesopotamia and India. The first useful vessels were then produced in Central Europe between 7,000 and 8,000 years ago.

Until the end of the Middle Ages, the smelting and process furnaces of the early metal industry were constructed using natural sandstone bonded with kaolinite or siliceous material. The development of synthetic refractory materials (Agricola, Freiberg around 1550) was one of the foundation stones of the industrial revolution, and created the necessary conditions for melting metals and glass on an industrial scale, and for the manufacture of coke, cement and ceramics.

The ceramics industry was an important partner to the chemical industry. Acid-resistant stoneware and porcelain were for a long time the most important materials available for corrosion protection. Nowadays they have largely been replaced by acid-resistant steels and enamels, but also by ceramics based on oxides, nitrides and carbides.

Beginning in the second half of the 19th century, electro-ceramics provided the momentum for industrial development. During this time, basic solutions for electrical insulation based on porcelain were developed.

It is difficult to determine the precise beginning of modern, high-performance ceramic materials. Until the turn of the 20th century, the development of ceramic materials had a primarily empirical character. Scientific methods were first applied to ceramics in the course of the 20th century.

The development of manufacturing technologies using quartz-enriched porcelain achieved bending strengths of more than 100 MPa for the first time. It was only in the 1960s, with the systematic development of alumina porcelain, that marked increases in strength, especially in large insulators for voltages over 220 kV, resulted in considerable weight reductions.

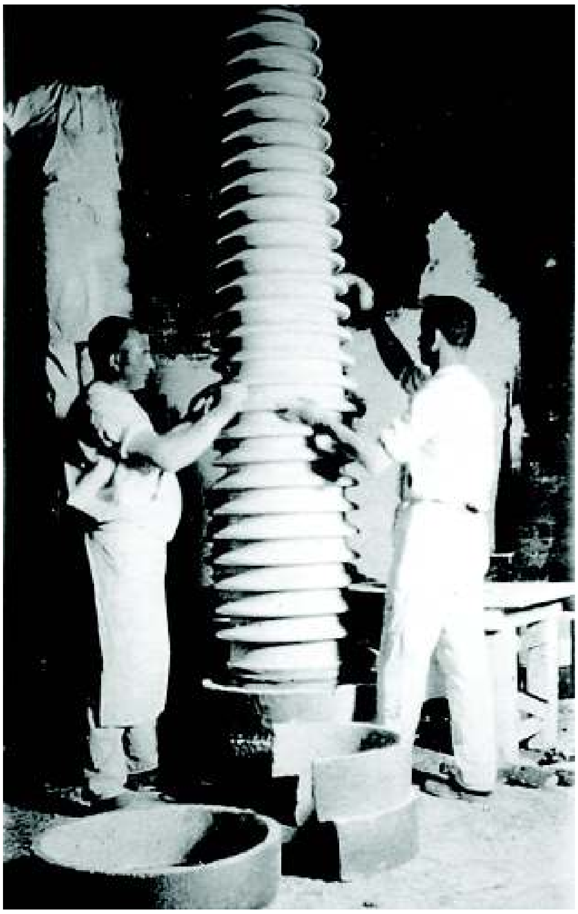


Figure 1: Manufacture of insulators around 1920.

The growth of broadcast radio in the 1920s led to the need for special ceramic insulation materials that did not heat up under the influence of high-frequency electromagnetic fields. This led to the development of steatite and forsterite, both of which are still in use today. Research on oxide magnetic materials began in the 1940s (hard ferrites, soft ferrites). At this time, capacitor materials based on titanium oxide were also developed, and research began on the ferroelectric and piezoelectric properties of perovskite ($BaTiO_3$). This made a wide palette of materials available – some even with semiconducting properties – for sensors, frequency selective components (filters) and capacitors with high storage capacity. Theoretical considerations are derived from basic research by Heisenberg, Dirac, Heitler, Londas, Hartre and Fock, among others.

A further important milestone was the introduction of sparkplugs made of sintered alumina (Siemens, 1929). The development of microelectronics increased the demand for aluminium oxide materials, for example, as a material for substrates and housings. An important property of this material, in addition to high electrical resistance, low dielectric losses, high thermal conductivity, high mechanical strength and thermal shock resistance, is the vacuum tightness offered by these new types of material.

While the thermal properties were sufficiently well explained by the theories of Debye, it was necessary to develop a theory of fracture mechanics in order to explain mechanical properties. Whereas initially aluminium oxide and later zirconium oxide, were first used as ceramic construction materials, the outstanding properties of covalently bonded materials based on silicon (silicon carbide, silicon nitride, SIALONe etc.) were recognised and exploited at the end of the 1960s. Research into all these materials continues today. In addition to the approaches of fracture mechanics, new mathematical methods and computer simulations have been developed in order to understand the relationship between microstructure and properties through modelling. In parallel with the theoretical developments, process technologies have been optimised, extending as far as the introduction of completely new process sequences and sintering methods.

Known materials continue to be improved, new materials are being developed, and new applications are being found. The materials of today can no longer be compared with those that were on the market ten or twenty years ago. Scientific research is increasing our understanding of materials. New and improved manufacturing technologies have brought progress in the areas of quality, reproducibility and operating safety.

3 Ceramic Materials

3.1 Definitions

The terminology currently in general use in ceramic engineering and having industrial significance will be presented here.

Ceramic, as a materials definition, involves concepts that have developed over history due to the diversity of the applications and raw materials used. Many systematic national definitions are slowly beginning to find a common basis as a result of international scientific cooperation, industrial standardisation and international business statistics.

Very generally defined:
Ceramic materials are inorganic and non-metallic. They are generally moulded from a mass of raw material at room temperature, and gain their typical physical properties through a high temperature firing process. (See also "High-performance ceramics".)
In contrast, the Anglo-Saxon term **"ceramics"** also often includes glass, enamel, glass-ceramic, and inorganic cementitious materials (cement, plaster and lime).

The German ceramics industry also distinguishes between **coarse** and **fine ceramics**, depending on the particle size in the raw material. The definition according to Hausner applies to the structure of the fired ceramic, specifically to the grain structure. The boundary is considered to lie at grain sizes of between about 0.1 and 0.2 mm. If the elements of the microstructure are smaller than 0.1 mm, which means that they can no longer be detected with the naked eye, the German usage then refers to fine ceramics – regardless of the material.

Technical ceramics, tableware, decorative ceramics, ceramic sanitary ware, wall and floor tiles and ceramic abrasives belong to the fine ceramics category.

The category of coarse ceramics includes, for example, brick or conventional refractory materials.

Technical ceramics refers to ceramic products for engineering applications.

Terms commonly seen in literature such as:

- high performance ceramics
- structural ceramics
- construction ceramics
- industrial ceramics
- engineering ceramics
- functional ceramics
- electrical ceramics
- cutting ceramics and
- medical ceramics

describe special aspects of technical ceramics. A categorisation along these lines is not very useful, since in some cases they overlap significantly.

High-performance ceramic is defined in **DIN V ENV 12 212** as a "highly-developed, high-strength ceramic material, which is primarily non-metallic and inorganic and possesses specific functional attributes."

The concept **high-performance ceramics** is primarily used to distinguish them from traditional ceramics based on clay, including tableware, sanitary ware, walls and floor tiles as well as ceramics for civil engineering. This definition agrees with that of the "Japanese Fine Ceramics Association".

Structural or **construction ceramics** are terms that have not yet been standardised, referring to materials that in some way must withstand mechanical stresses, bending or pressure for example. The concepts **industrial** and **engineering ceramics** have practically identical meanings.

Functional ceramics are high-performance ceramics in which the inherent characteristics of the material play an active role, for example ceramic parts which possess specific electric, magnetic, dielectric or optical properties.

Electrical ceramics are high-performance ceramics that are applied because of their specific electric or electronic characteristics. Electrical engineering applications make use primarily of the excellent insulating characteristics and mechanical strength. The electronics industry also takes advantage of characteristics such as ferroelectric behaviour, semiconductivity, non-linear resistance, ionic conduction, and superconductivity.

Cutting tool ceramics are high-performance ceramics that are applied in machining processes (lathe bits, drilling, milling) due to their excellent wear and high-temperature resistance.

Medical ceramics are high-performance ceramics for medical applications, in other words within the human body, and are represented by products that repair or replace bone, teeth or other hard tissues.

Further definitions are contained in DIN EN 12 212.

3.2 Materials Groups

Technical ceramics are often subdivided into groups in accordance with the definitions mentioned above. However since this does not permit unambiguous classification, they are alternatively grouped according to their mineralogical or chemical composition.

The following groups belong to the materials defined as technical ceramics:

- silicate ceramics
- oxide ceramics
- non-oxide ceramics

Silicate ceramics, as the oldest group amongst all the ceramics, represent the largest proportion of fine ceramic products. The major components of these polyphase materials are clay and kaolin, feldspar and soapstone as silicate sources. Additionally such components as alumina and zircon are used to achieve special properties such as higher strength. During sintering a large proportion (> 20%) of glass phase material, with silicon dioxide (SiO_2) as the major component, is formed in addition to the crystalline phases.

Included in the silicate ceramic materials category are:

- porcelain,
- steatite,
- cordierite and
- mullite.

Due to the relatively low sintering temperatures, the good understanding of how to control the process, and the ready availability of the natural raw materials, silicate ceramics are much cheaper than the oxide or non-oxide ceramics. The latter require expensive synthetic powders and high sintering temperatures.

Silicate ceramics are found, for example, in heat engineering applications, measurement and control engineering, process and environmental technologies, high and low voltage applications with typical uses such as insulators, fuse cartridges, catalysts, enclosures and in a wide range of applications in the electrical equipment industry. Silicate ceramics also continue to be used as refractory materials.

Oxide ceramics are defined as all materials that are principally composed of a single phase and a single component (>90 %) metal oxide. These materials have little or no glass phase. The raw materials are synthetic products with a high purity. At very high sintering temperatures a uniform microstructure is created which is responsible for the improved properties.

Some examples of oxide ceramics include

- as a single-material system
    - aluminium oxide,
    - magnesium oxide

        - zirconium oxide,
        - titanium dioxide (as a capacitor material)
- and as a multi-material system
    - mixed oxide ceramics
        - aluminium titanate
        - lead zirconium titanate (piezo-ceramics)
    - and dispersion ceramics
        - aluminium oxide reinforced with zirconium oxide (ZTA - Al_2O_3/ZrO_2).

Oxide ceramics are found in the electrical and electronics industries, and often as structural ceramics, i.e. for non-electrical applications. They offer the typical properties suited to these applications, such as high fracture toughness, wear resistance, high-temperature resistance and corrosion resistance.

Non-oxide ceramics include ceramic materials based on compounds of boron, carbon, nitrogen and silicon. (Products made of amorphous graphite do **not** belong to this category!)

Non-oxide ceramics usually contain a high proportion of covalent compounds. This allows their use at very high temperatures, results in a very high elastic modulus, and provides high strength and hardness combined with excellent resistance to corrosion and wear.

The most important non-oxide ceramics are:

- silicon carbide,
- silicon nitride,
- aluminium nitride,
- boron carbide and
- boron nitride.

3.3 Classification

Early standardisation

The fundamental need of application engineers to consider matters of safety and reliability led at a very early stage to the standardisation of ceramic materials by the Association of German Electrical Engineers (VDE). Only materials that fulfilled these specifications were certified for applications in electrical engineering.

The importance of this "Ceramic Materials for Electronics" standard is emphasised by the fact that the German regulatory standard DIN IEC 40 685 / VDE 0335 was accepted as binding, both nationally and internationally, for decades. The reworked standard has been published as **DIN EN 60 672**. The materials standardised there are categorised into groups (100, 200 etc.) and are identified by type numbers (C...)[1].

Since these and other materials also became very important outside electronics, a standard for the classification of the features of technical ceramics was developed by the "European Committee for Standardisation" (CEN) as EN 12 212. The German version was published as **DIN EN 12 212**.

The two standards are fundamentally different. DIN EN 60 672 assigns brief type identifiers to defined ceramic materials and describes their minimum requirements. These material identifiers (e.g. C 799) are frequently entered on technical drawings. DIN EN 12 212 on the other hand is a flexible system through which individual identifiers can be encoded immediately.

The preliminary European standard, **prENV 14 232,** moreover, defines important basic terms related to high-performance ceramics and formulaic short identifiers for ceramic materials, frequently containing indications to the manufacturing technique.

In Table 1 the materials used for insulation purposes in accordance with DIN EN 60 672 are shown with their corresponding material identifier (C...), and materials according to manufacturers' specification marked wherever possible with abbreviations according to DIN ENV 14 232.

---

[1] The old KER… identifiers according to VDE 0335 are no longer valid!

Silicate ceramics

Alkali aluminosilicates .... *(C 100)*

Quartz porcelain, plastically formed	C 110
Quartz porcelain, pressed	C 111
Cristobalite porcelain, plastically formed	C 112
Alumina porcelain	C 120
Alumina porcelain, high strength	C 130
Lithium porcelain	C 140

Magnesia silicates .... *(C 200)*

Low voltage steatite	C 210
Standard steatite	C 220
Steatite, low loss angle	C 221
Porous steatite	C 230
Forsterite, porous	C 240
Forsterite, dense	C 250

Alkaline earth – aluminosilicates and zircon porcelain ..... *(C 400)*

Cordierite, dense	C 410
Celsian, dense	C 420
Basic calcium oxide, dense	C 430
Basic zircon, dense	C 440

Porous aluminosilicates and magnesium-aluminosilicates ... *(C 500)*

Aluminosilicate based	C 510
Magnesium-aluminosilicate based	C 511
Magnesium-aluminosilicate based	C 512
Cordierite based	C 520
Aluminosilicate based	C 530

Mullite ceramic with low alkali content .... *(C 600)*

Mullite ceramics with 50 % to 65 % Al_2O_3	C 610
Mullite ceramics with 65 % to 80 % Al_2O_3	C 620

Oxide ceramics

Titanates and other ceramics with high permittivity .... *(C 300)*

Titanium dioxide based	C 310
Magnesium titanate based	C 320
Titanium dioxide and other oxides	C 330
Titanium dioxide and other oxides	C 331
Calcium and strontium bismuth titanate based	C 340
Ferroelectric perovskites based	C 350
Ferroelectric perovskite based	C 351

Ceramic materials with high alumina content …………… *(C 700)*

High Al_2O_3 content ceramics; > 80 % to 86 % Al_2O_3	C 780	
High Al_2O_3 content ceramics; > 86 % to 95 % Al_2O_3	C 786	
High Al_2O_3 content ceramics; > 95 % to 99 % Al_2O_3	C 795	
High Al_2O_3 content ceramics; > 99 % Al_2O_3	C 799	

Other oxide ceramics materials …………………………… *(C 800)*

Beryllium oxide, dense	C 810	
Magnesium oxide (MgO), porous	C 820	
Magnesium oxide	MgO	*
Zirconium oxide (ZrO_2)	(C 830)[2]	
partially stabilised zirconium oxide	PSZ	*
fully stabilised zirconium oxide	FSZ	*
tetragonal polycrystalline zirconium oxide	TZP	*
Aluminium titanate	ATI	*
Lead zirconium titanate (piezo-ceramics)	PZT	*
Fused silica ceramic (SiO_2)	SiO_2	*
Spinel ($MgO \cdot Al_2O_3$)	Spinel	**
Mullite ($Al_2O_3 \cdot SiO_2$)[3]	Mullite	**
Titanium dioxide (TiO_2)	TiO_2	*

Non-oxide ceramics

Carbides

Silicon carbide (SiC)	SiC	*
re-crystallised silicon carbide	RSIC	*
nitride-bonded silicon carbide	NSIC	*
(non-pressurised) sintered silicon carbide	SSIC	*
silicon infiltrated silicon carbide	SISIC	*
liquid-phase sintered silicon carbide	LPSIC	*
hot-pressed silicon carbide	HPSIC	*
isostatic hot-pressed silicon carbide	HIPSIC	*
silicate-bonded silicon carbide	SiC	*
Boron carbide (B_4C)	BC	*

Nitrides and "non-oxide ceramic insulators" …………… *(C900)*

Aluminium nitride (AlN)	C 910	
Aluminium nitride	ALN	*
Boron nitride (BN)	C 920	
cubic boron nitride	CBN	*
hexagonal boron nitride	HBN	*
Silicon nitride, reaction-bonded, porous (RBSN)	C 930	

---

[2] Standardised up to 1996.

[3] As a material with little or no glass phase.

Silicon nitride, dense	C 935	
Silicon nitride (SN)	SN	*
sintered silicon nitride	SSN	*
reaction-bonded silicon nitride	RBSN	*
hot-pressed silicon nitride	HPSN	*
isostatic hot-pressed silicon nitride	HIPSN	*
Silicon aluminium oxynitride	SIALON	*
Titanium nitride (TiN)	TiN	*

Caption: Material according to DIN EN 60 672 in the form of C...
* Material according to DIN ENV 14 242 as abbreviation
** Material name in common speech

Table 1: Technical ceramics materials

3.4 Material Descriptions

Figure 2: Products made from technical ceramics.

3.4.1 Silicate Ceramics

3.4.1.1 Technical Porcelain

Technical porcelains are understood to be materials in the "alkaline alumina silicate porcelain" (C 100) group, which find diverse applications in electronics.

As electricity began to be used in the home and industry, many types of porcelain were already available, offering excellent properties such as

- high mechanical strength,
- excellent electrical insulation properties and
- outstanding resistance to chemical attack.

As energy consumption rapidly increased so did the needs of electrical technology, and the properties of porcelain were continually developed and improved. This led to today’s **alumina porcelain**, which exhibited noticeably greater strength and reliability even under extreme thermal stress (for example, -50 °C to 550 °C) or sudden temperature changes (during a short circuit for example), and was clearly superior to quartz porcelain. Even the long-term behaviour under open air conditions (ageing) of alumina porcelain is superior to that of quartz porcelain, and it is therefore used primarily in open air switching stations and for open-wire insulators (e.g., high tension or train insulators and supports) by quality-conscious users.

More recent developments indicate that hydrophobic surfaces improve the electrical properties of the outer layer, and permit simplified structural forms. The replacement of alumina with bauxite is a further innovation. This new and significantly more economical material offers comparable technical properties.

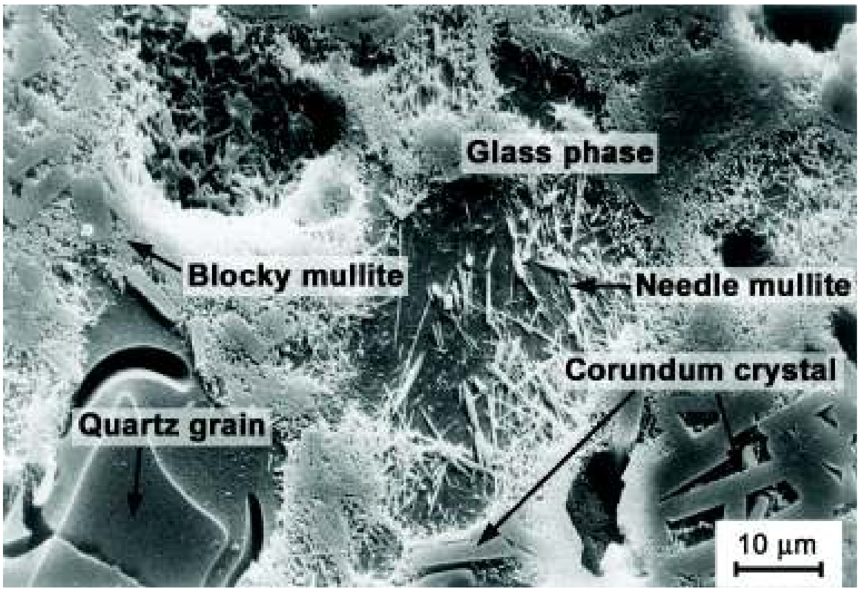


Figure 3: Microstructure of an alumina porcelain, ground and etched, under a scanning electron microscope

The difference between quartz porcelain and alumina porcelain lies in the exchangeable raw material, i.e. the more economical quartz (SiO_2) and the relatively expensive alumina (Al_2O_3). For this reason, and because of the lower production costs, traditional **quartz porcelain** represents an economic alternative for moderate load applications. For a significant number of applications, this is thus a factor in quartz porcelain retaining market share and improving competitiveness.

3.4.1.2 Steatite

Steatite is a ceramic material based on natural raw materials and consists mainly of soapstone ($Mg(Si_4O_{10})(OH)_2$), a natural magnesium silicate, with the addition of clay and feldspar or barium carbonate. Steatite is usually sintered to a high density.
The type of flux used influences the electrical properties of this material, leading to a distinction between normal steatite and special steatite, also known as high-frequency steatite.

Special steatite is defined in international standards as steatite with a low loss factor, and is not only used in low-loss high-frequency parts, but because of its excellent workability it is also used for the manufacture of components with thin, constant thickness. This allows thermally induced mechanical stresses to be controlled.

This material also permits the economical manufacture of products with very small tolerances due to its low shrinkage during sintering. It is also less abrasive to tools than any other ceramic, making it particularly suited to dry pressing.

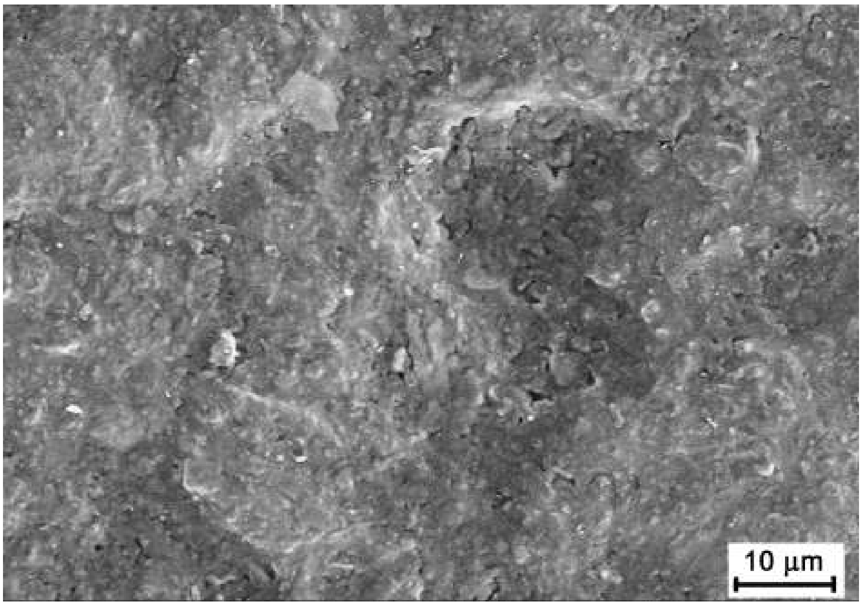


Figure 4: Steatite (C 221) surface with firing skin

Special steatite possesses excellent mechanical and dielectric properties, and has been used for more than 90 years in various applications in electrical engineering, for electronic parts and in heat engineering. Typical applications include sockets, control housings, insulating beads, low-voltage power fuses and base plates.

For special applications such as heating cartridges, porous steatite is often used, since it can be easily machined even after sintering, and has a very good thermal shock resistance.

3.4.1.3 Cordierite

Cordierite materials and others based on it are magnesium aluminosilicates, fabricated by sintering soapstone or talcum with the addition of clay, kaolin, fireclay, corundum and mullite. A simplified approximation to the composition of pure ceramic cordierite is approx. 14 % MgO, 35 % Al_2O_3 and 51 % SiO_2.

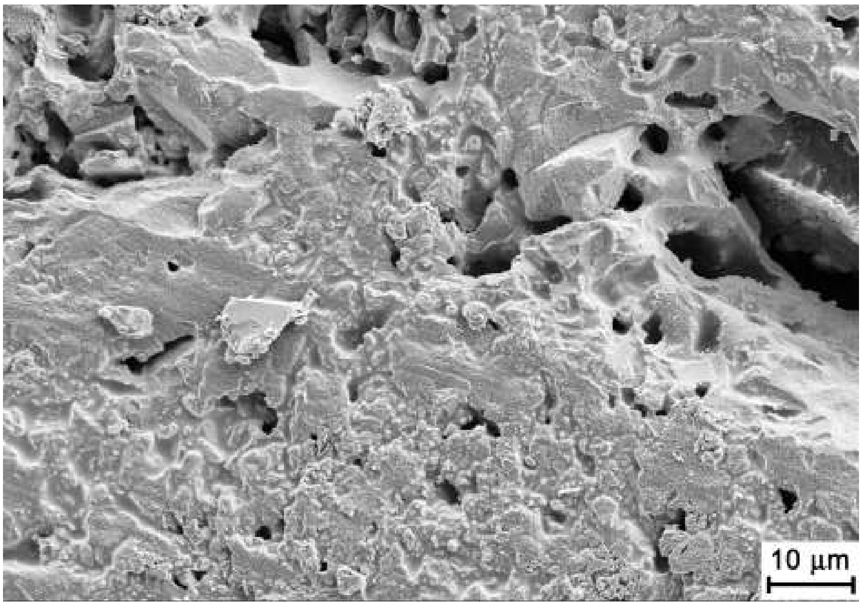


Figure 5: Microstructure of a porous cordierite (C 520)

Cordierite materials have a low coefficient of thermal expansion. This is the reason for their outstanding thermal shock resistance combined with good mechanical strength. Two types of cordierite, porous and dense, are distinguished. The porous type has a low bending strength but even higher thermal shock resistance than the dense type, since it can absorb mechanical stresses in its porous structure.
Cordierite materials, moreover, behave inertly towards heating element alloys at temperatures up to 1,000°C or even 1,200 °C (there is no reaction between the heating element and the ceramic).

For this reason, cordierites are often found in electric heating applications, and in heat engineering in general.
Applications include, for example, insulators for continuous flow electric water heaters, heating element pipes, heating element supports in furnaces, link heaters, heating cartridges for soldering irons, gas heater inserts, spark protectors and catalyst carriers in automobiles.

For special purposes a material is available containing cordierite and mullite and having a high aluminium oxide content (C 530) which, for instance, permits higher application temperatures.

3.4.1.4 Mullite Ceramics

By varying the chemical and mineralogical composition of the Al_2O_3–SiO_2 system, specific modifications to the properties of the mullite ceramic can be achieved. Pure mullite ($3Al_2O_3 \cdot 2SiO_2$) consists of 82.7 % Al_2O_3 by mass and 17.3 % SiO_2. Dense sintering of pure mullite cannot be achieved with conventional sintering techniques.
Mullite ceramics have a microstructure whose mineral phases consist of mullite, corundum (Al_2O_3) and glass (SiO_2).

Sintered mullite usually contains up to 10 % glass phase material. The overall porosity, however, is still around 10 % by volume. M72 and M85 are typical of these materials. They are compared in the following table.

Materials		M 72	M 85
Al_2O_3	Mass %	72	85.5
SiO_2	Mass %	26.5	13.5
Mullite	Mass %	90 - 95	50 - 55
Corundum	Mass %	1	45 - 50
Glass phase	Mass %	5 - 10	0.5
Density	g/cm³	2.85	3.2
Porosity	Volume %	9	10

Table 2: Chemical composition and mineral phases

Porous mullite ceramics containing little glass phase material have a relatively high strength, comparatively low thermal expansion, and are therefore highly resistant to thermal shock. Resistance to creep at high temperatures is superior to that of pure aluminium oxide ceramic.
Applications include kiln furniture for temperatures up to 1,700°C – even in oxidising atmospheres – and carrier rollers in high-temperature furnaces. Because of its low thermal conductivity and high resistance to corrosion, porous mullite is also used as an industrial refractory material.

The porosity can be significantly reduced by increasing the proportion of glass phase material (> 10 %). Densely sintered mullite ceramic combines high-strength, good thermal shock resistance and a useful resistance to creep. One important application, for instance, is protective tubes for thermocouples.

3.4.2 Oxide Ceramics

3.4.2.1 Aluminium oxide

Aluminium oxide (Al_2O_3) is the most important technical oxide ceramic material and has the widest range of applications. Densely sintered aluminium oxide is characterised by

- high strength and hardness,
- temperature stability,
- high wear resistance and corrosion resistance even at high temperatures.

These synthetically manufactured materials with aluminium oxide contents ranging from 80 % to more than 99 %, have been proven in practice. The choice of this material is determined by technical and economic criteria. A material with higher aluminium oxide content does not necessarily fulfil the needs of an application best.

It is also possible for the mechanical properties of aluminium oxides from different manufacturers to vary, even when the aluminium oxide content is the same, due to different powder formulations.

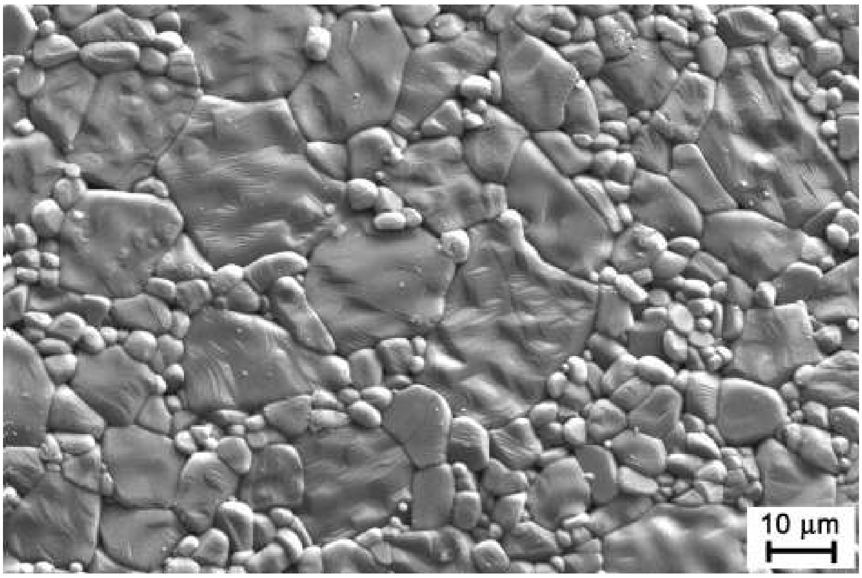


Figure 6: Surface of an aluminium oxide "as fired"

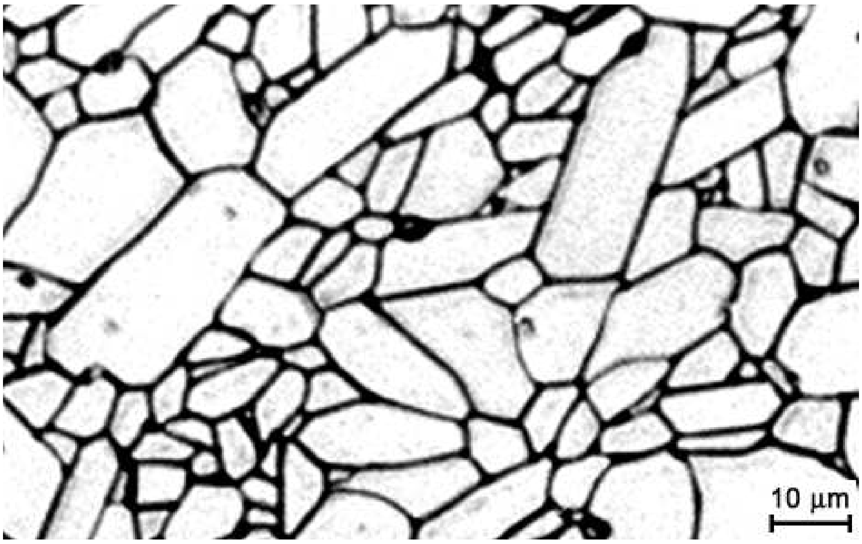


Figure 7: Microstructure of an aluminium oxide ceramic (99.7 %)

Aluminium oxide materials satisfy all the requirements of insulation materials for applications in electrical engineering. Outstanding values for bending strength and for resistance to wear and to high temperatures suit the material to mechanical applications.

The microstructure, and therefore the other properties, of aluminium oxide ceramics can differ markedly (see Figures 8 and 9).

Figure 8: Microstructure of a micro-crystalline aluminium oxide

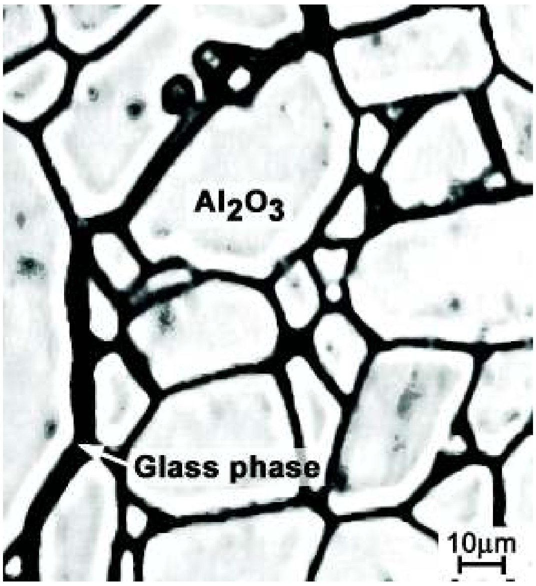


Figure 9: Microstructure of a coarse-crystal aluminium oxide

Surfaces with the highest possible bearing area[4] are not always either necessary or desirable. Thread guides used in the textile industry, for instance, should have a small contact area with the thread and should not have any sharp edges, whereas sealing plates require a material proportion of approx. 80 %.

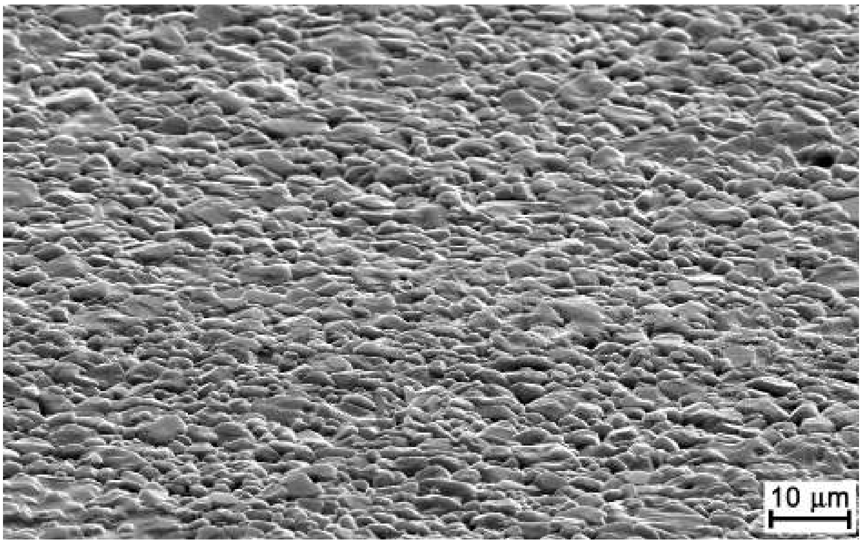


Figure 10: "As fired" surface of a extruded aluminium oxide

Due to their good price/performance ratio and their generally useful properties, aluminium oxide ceramics are used

• in the sanitary industry	as a sealing element,
• in electrical engineering	as insulation,
• in electronics	as a substrate,
• in machine and plant construction	as wear protection (wear-resistant material),
• in the chemical industry	as corrosion protection (corrosion-resistant material, highly resistant to vapours, melting and slag up to high temperatures) and as a filter,
• in instrumentation	as a protective tube for thermocouples used for high temperature measurements

---

[4] See pages 231 and 236 for details of the bearing area.

• in human medicine	as an implant, and
• in high temperature applications	as a burner nozzle or as a support tube for heat conductors.

3.4.2.2 Magnesium Oxide

Magnesium oxide (MgO) ceramic is mostly manufactured in high purity as a *single component ceramic* in porous or gas-tight forms.

Particular characteristics are

- good electrical insulation and
- good thermal conductivity.

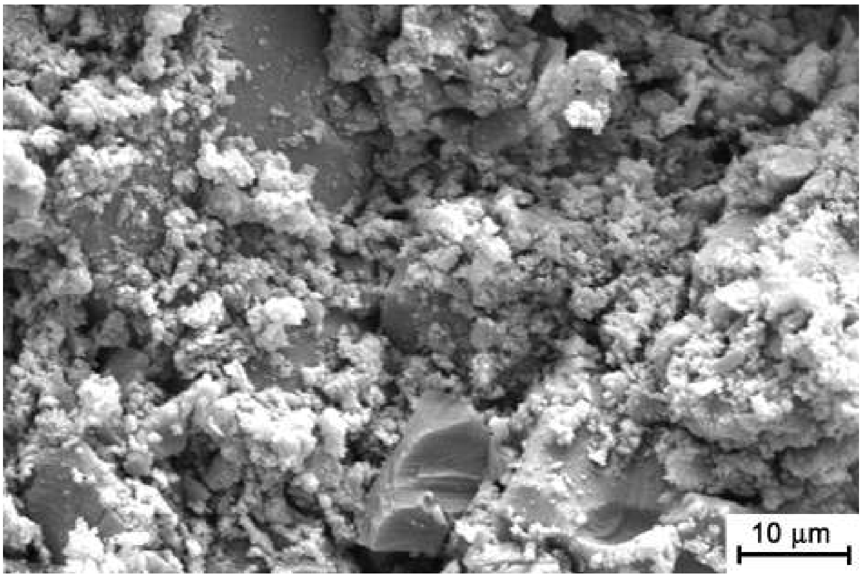


Figure 11: Fracture surface of a porous magnesium oxide

This material is used in heat engineering primarily for small tubes with a precisely defined strength. These are slipped over heating wires and then inserted into metal tubes. Through subsequent hammering, rolling or drawing, the ceramic is reduced in size. The insulation material is crushed and adapts itself to the form given to the metal tube. This production technique makes it possible to manufacture curved tubular heating elements as used, for instance, in immersion heaters and heating cartridges, and for thermocouples.

3.4.2.3 Zirconium Oxide

Zirconium oxide (ZrO_2) has gained importance in the last few years due to its

- high fracture toughness,
- thermal expansion similar to cast iron,
- extremely high bending strength and tensile strength,
- high resistance to wear and to corrosion,
- low thermal conductivity,
- oxygen ion conductivity and
- very good tribological properties (it is very well suited for slide rings).

Zirconium oxide occurs as monoclinic, tetragonal and cubic crystal forms. Densely sintered parts can be manufactured as cubic and/or tetragonal crystal forms. In order to stabilise these crystal structures, stabilisers such as magnesium oxide (MgO), calcium oxide (CaO) or yttrium oxide (Y_2O_3) need to be added to the ZrO_2. Other stabilisers sometimes used are cerium oxide (CeO_2), scandium oxide (Sc_2O_3) or ytterbium oxide (Yb_2O_3).

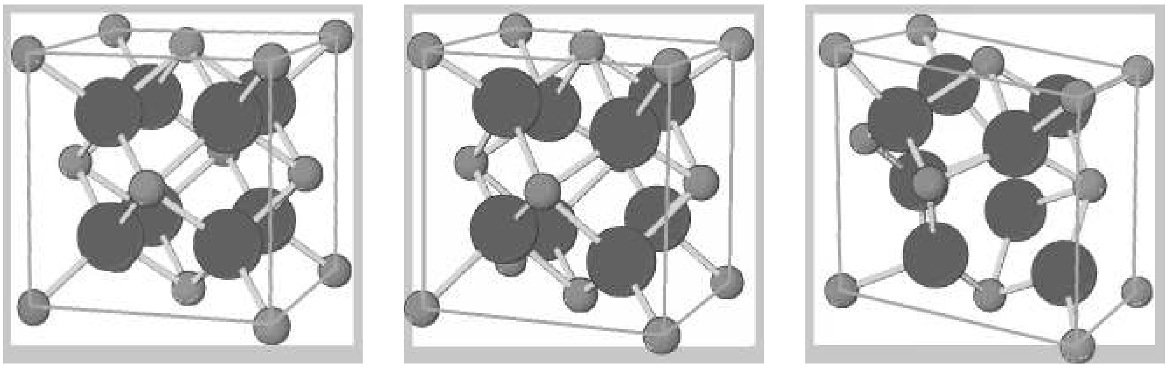


Figure 12: Zirconium oxide: cubic, tetragonal and monoclinic crystal lattices
light spheres = Zr dark spheres = O

In **fully stabilised zirconium oxide (FSZ – fully stabilised zirconia)** the high-temperature cubic structure is preserved even after cooling due to the addition of the other oxides into the crystal structure. The increase in volume, undesirable for technical applications, does not take place in FSZ.

Partially stabilised zirconium oxide (PSZ – partly stabilised zirconia) is of great technical significance. At room temperature, the substance includes a coarse cubic phase with tetragonal regions. This state can be retained in a metastable form through appropriate process control or annealing techniques. This prevents transformation of the tetragonal phase to the monoclinic phase, and the microstructure is "pre-stressed"; this is associated with an increase in strength and toughness.

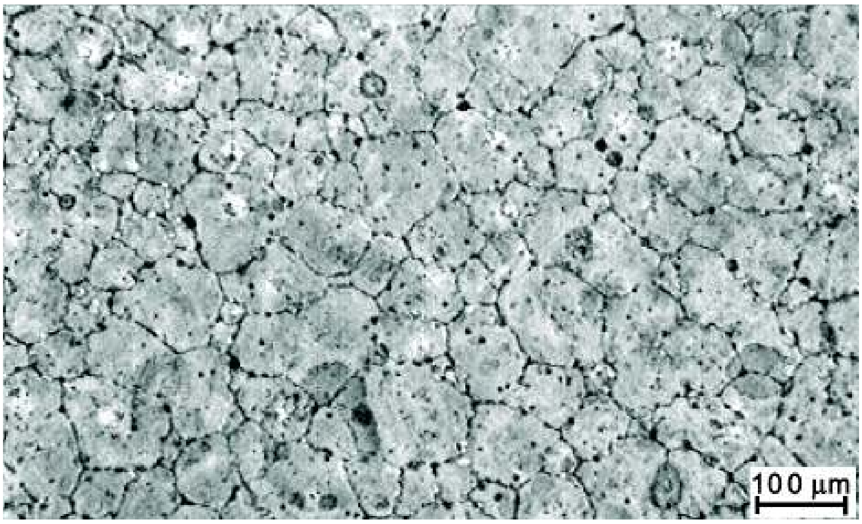


Figure 13: Microstructure of a partially stabilised zirconium oxide (PSZ)

In **polycrystalline tetragonal zirconium oxide (TZP – tetragonal zirconia polycrystal)** the use of extremely fine initial powders, and the application of low sintering temperatures, achieves an extremely fine-grained microstructure. Due to its extremely fine microstructure (grain size < 100 µm) and the metastable tetragonal structure, this material is characterised by extraordinary high mechanical strength, possibly even exceeding 1,500 MPa.

The very finely developed tetragonal crystal phase in PSZ and in TZP displays a phenomenon unique to high-performance ceramics: transformation of the tetragonal phase into the monoclinic phase can be prevented by pressure. When the pressure is released, e.g. through crack tips or internal tensile stress, the transformation then occurs. The pressure-controlled increase in volume involved in the metamorphosis of the crystal phases closes cracks, slowing or deflecting their growth. This behaviour is exploited technically, and is known as transformation reinforcement. In PSZ ceramics, and in particular in TZP ceramics, it leads to extremely high component strength. Depending on the stabilisation method, it can be exploited at application temperatures between 600°C and 1,100°C. Zirconium oxide ceramics are therefore favoured for use in components that are subject to high mechanical stress.

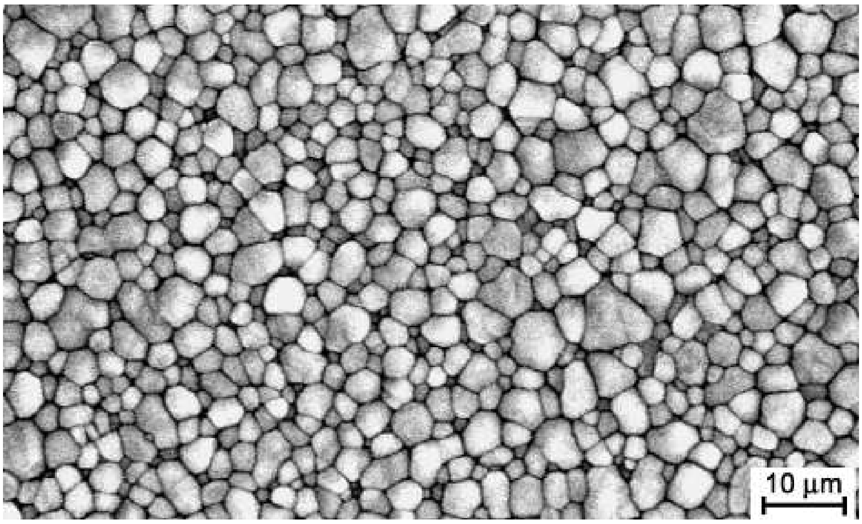


Figure 14: Microstructure of a polycrystalline tetragonal zirconium oxide (TZP)

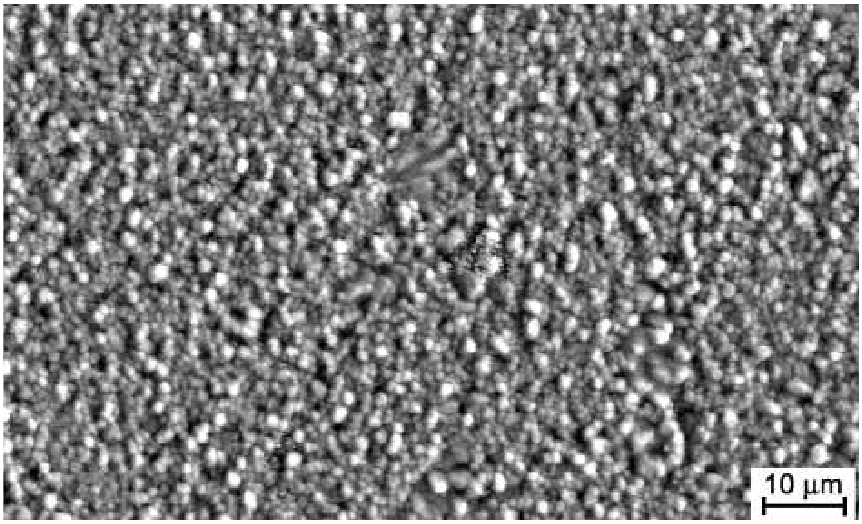


Figure 15: Nanostructure of a polycrystalline tetragonal zirconium oxide (TZP)

Another property specific to this material is its oxygen ion conductivity. This phenomenon is used to measure the partial pressure of oxygen. Zirconium oxide is therefore the basis, for example, of the "lambda sensors" used to regulate petrol engine exhausts.

3.4.2.4 Zirconium Oxide Toughend Aluminium Oxide

In practice, this is usually simply known as ZTA (**z**irconia **t**oughened **a**lumina). Its properties depend strongly on the mixing ratio of aluminium oxide to zirconium oxide, and on the details of the processing.

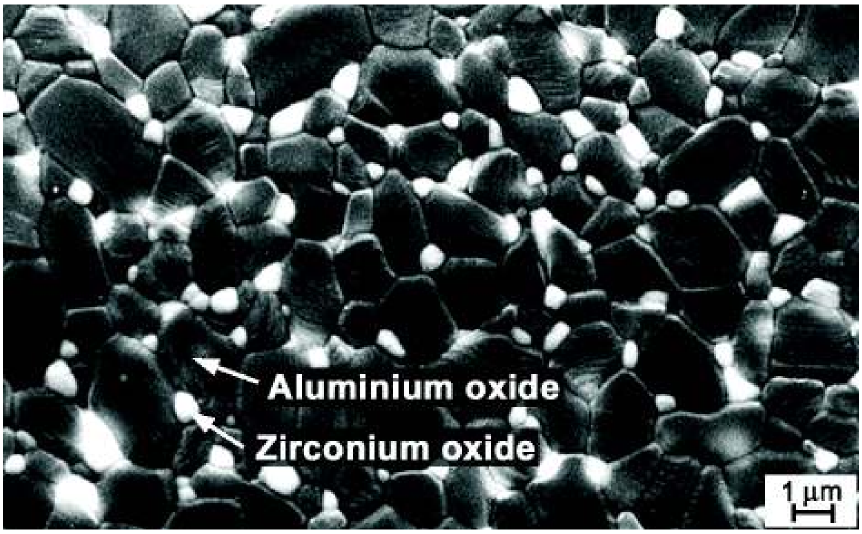


Figure 16: Microstructure of a ZTA with a low proportion of zirconium oxide

Low proportions of zirconium oxide, up to approx. 10% by volume, allow improved values, in comparison with aluminium oxide, for

- bending strength
- K_{IC} factor,
- modulus of elasticity and
- larger coefficients of linear expansion to be achieved.

Versions of the material containing higher concentrations of zirconium oxide, if appropriately processed, develop platelets in the microstructure, which contributes to an improvement in some material properties (ZPTA ceramics). These and other measures taken to optimise properties permit the achievement of outstanding figures for

- bending strength
- modulus of elasticity and
- thermal behaviour

that are superior to those of Y-ZTP (tetragonal zirconium oxide stabilised with yttrium oxide).

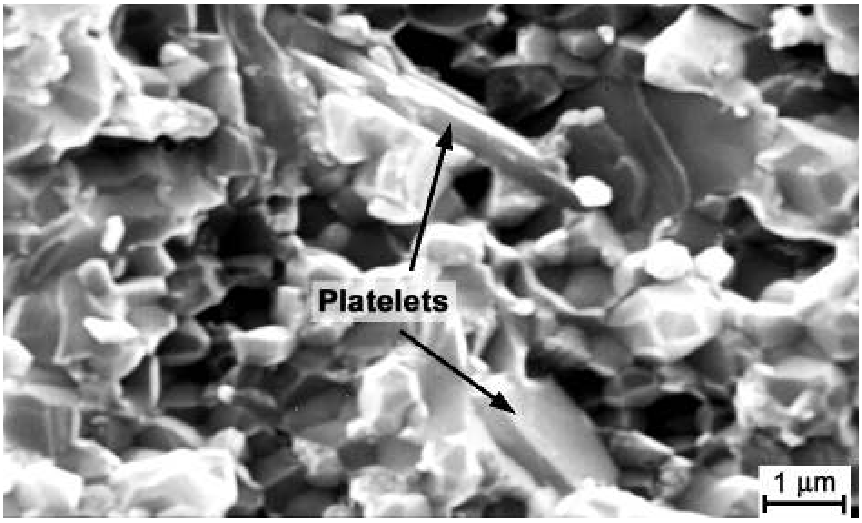


Figure 17: ZTA with a high proportion of zirconium oxide, shown as a breakage microstructure in order to reveal the platelets

3.4.2.5 Aluminium Titanate

Aluminium titanate (ATI) ceramic is the stoichiometric solid solution of aluminium oxide and titanium dioxide ($Al_2O_3 \cdot TiO_2$), and is distinguished by:

- low modulus of elasticity
- low thermal conductivity,
- very low coefficients of thermal expansion, leading to excellent thermal shock resistance and to
- low wettability by molten non-ferrous metals

These properties result from a high a residual porosity and from micro-cracks resulting from highly anisotropic thermal expansion in the individual ATI crystals. These crystals display very different coefficients of thermal expansion along their three primary axes. In two directions it is positive, i.e. there is an expansion as the temperature rises, but along the third axis it is negative, generating a contraction. As a result of this, during manufacture, and in particular during cooling, tensions develop on a microscopic scale, the consequence of which is the formation of micro-cracks in the microstructure.
In terms of the macroscopic expansion, due to the anisotropic thermal expansion of the individual crystals, the material yields a very low

thermal expansion, since this initially involves the micro-cracks; in other words, the cracks close.

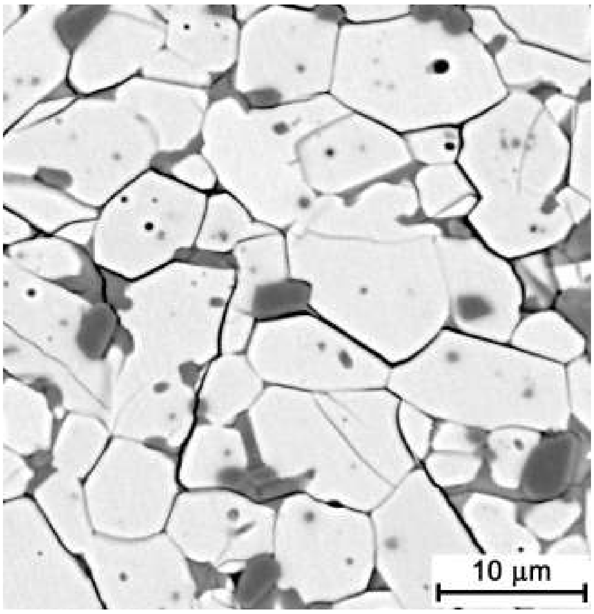


Figure 18: Microstructure of an aluminium titanate

The outstanding thermal shock resistance of ATI results from the low coefficient of thermal expansion on the macroscopic scale, in combination with the low modulus of elasticity. The dependency of the strength and of the modulus of elasticity on temperature also have what for ceramics are unusual curves. Both values increase as the temperature rises, effects that are again due to the closing of the micro-cracks at higher temperatures. The low mechanical strength specific to this material can be compensated for through composite structures.

The material is used, for instance, in portliners, cylinder liners and vehicle engines, in the spacing rings of catalytic converters, as kiln furniture and in foundry engineering. Here it is particularly found in aluminium smelting works where it is used for rising pipes and proportioning pipes, nozzles, crucibles, flow regulators and so forth.

3.4.2.6 Titanium Dioxide

Titanium dioxide materials consist of titanium dioxide or titanates, and are used for capacitors in high-frequency electronics. They are distinguished by a wide range of controllable permittivities and temperature coefficients, as well as very low loss factors.

Additionally, titanium dioxide is the primary raw material for modern catalysts used to reduce nitrous oxide emissions from coal burning power plants.

3.4.2.7 Barium Titanate

Barium titanates are amongst the materials used as **functional ceramics**. They possess extremely high permittivities, therefore finding application as capacitor dielectrics. They are also used as piezoelectric ceramic materials.

Barium carbonate, titanium dioxide and other raw materials for doping purposes are sintered at between 1,200°C and 1,400°C to form polycrystalline barium titanate. This exhibits semiconducting properties together with a positive temperature coefficient of the ohmic resistance, for which reason it is used as a positive temperature coefficient resistor (PTC). This effect is characterised by a very sharp rise of electrical resistance – several powers of ten – starting at a reference temperature (T_b).

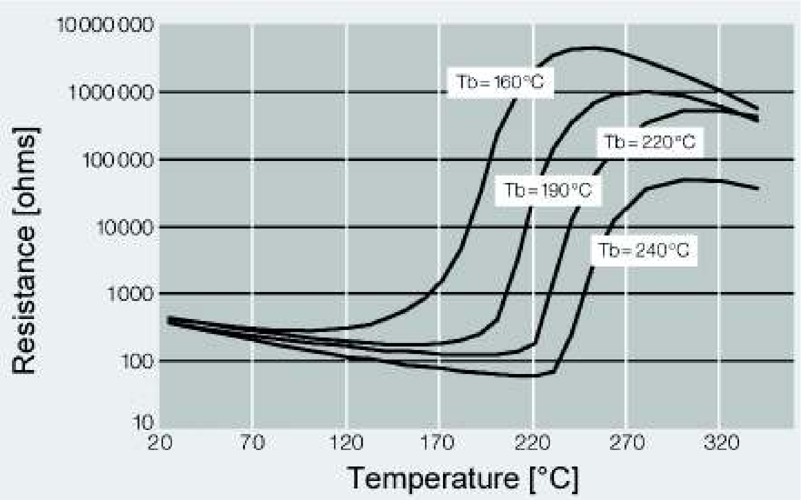


Figure 19: Resistance curves of PTC ceramics

PTC ceramics are used as temperature sensors in instrumentation and control technology, and as limit sensors for motor and machine protection. The material is also applied for self-regulating heating elements operating from low and mains voltage, as switching delay elements (for electric motor starting and de-magnetisation), and for overload protection.

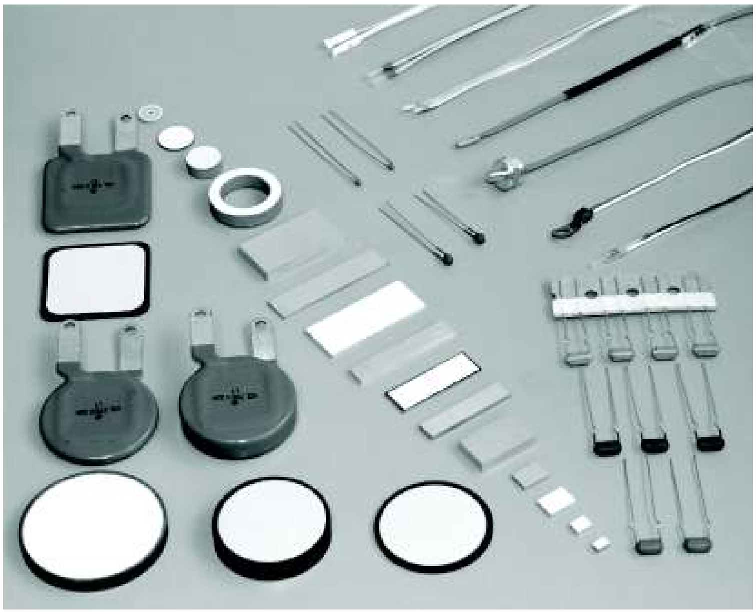


Figure 20: Components manufactured from PTC ceramics

3.4.2.8 Lead zirconate titanate

Currently the most important ***piezoelectric ceramic materials*** are based on mixed oxide crystal system consisting of lead zirconate and lead titanate known as **lead zirconate titanate (PZT)**.

The specific properties of these ceramics, such as the high dielectric constant, are dependent on the molar ratio of lead zirconate to lead titanate as well as on substitution and doping with additional elements. A wide range of modifications can be implemented in this way, creating materials with highly varied specifications.

The piezoelectric effect

The piezoelectric effect links both electrical and mechanical properties.

Piezoelectricity refers to a linear electro-mechanical interplay between the mechanical and electrical states of a crystal.

The **direct piezoelectric effect** refers to an electrical charge, detectable as a voltage, being created in proportion to mechanical deformation of the crystal.

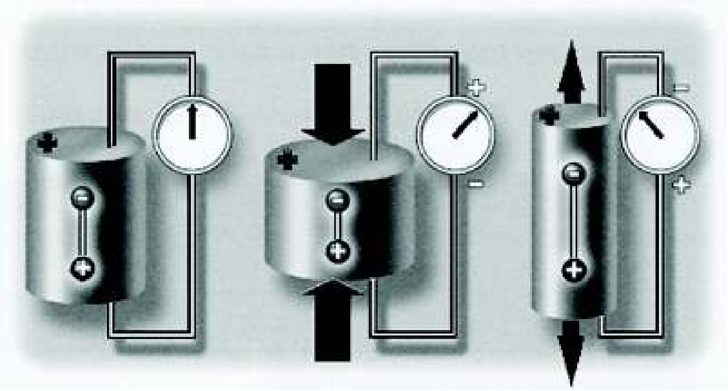


Figure 21: Piezoelectric effect resulting from an external force. The polarity of the electric charge depends on the direction of the applied force.

The **reciprocal** or **inverse piezoelectric** effect refers to a deformation that arises in proportion to an external electrical field created by the application of an electrical voltage.

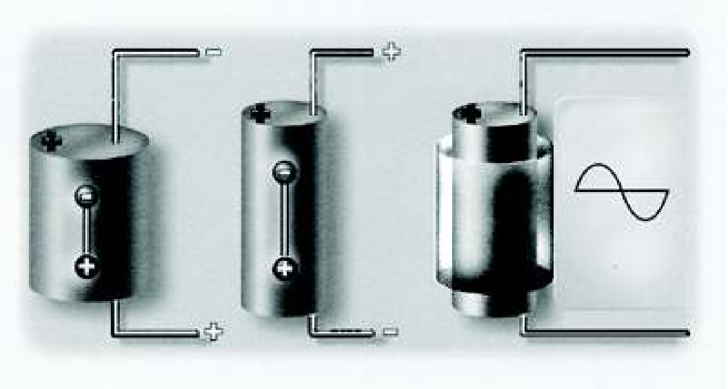


Figure 22: The inverse piezoelectric effect under the influence of external electric fields. The dimensions of the body vary with the change in voltage.

Principles

The piezoelectricity of ferroelectric materials is a consequence of the existence of polar areas (domains) whose orientation changes as result of the polarisation, i.e. of the application of an electrical voltage. The polarisation is associated with a change in length, ΔS.

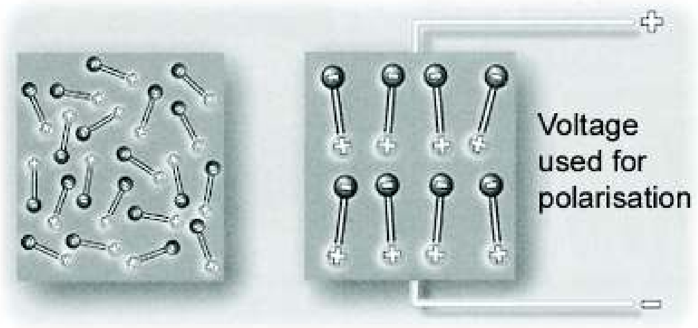


Figure 23: Electric dipoles in a piezoelectric material before and after polarisation.

Lead zirconium titanate $Pb(Zr_x Ti_{(1-x)}) O_3$ is processed in polycrystalline form. The two most common shaping methods are pressing and the tape casting process. The green body acquires its ceramic properties through firing.
The piezoceramic, however, only acquires its technically interesting piezoelectric properties through a **polarisation process**.

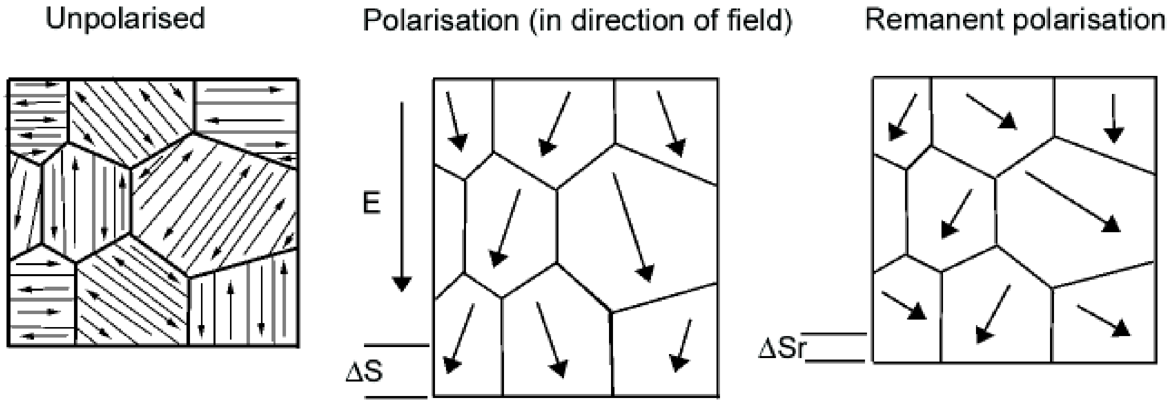


Figure 24: Diagram of the domains in lead zirconate titanate before, during and after polarisation
ΔS = change in length during polarisation
ΔS_r = residual changing length after the polarisation process

Resonance modes in piezoelectric components

All the components applied as sensors and actuators exploit the fundamental vibration modes.

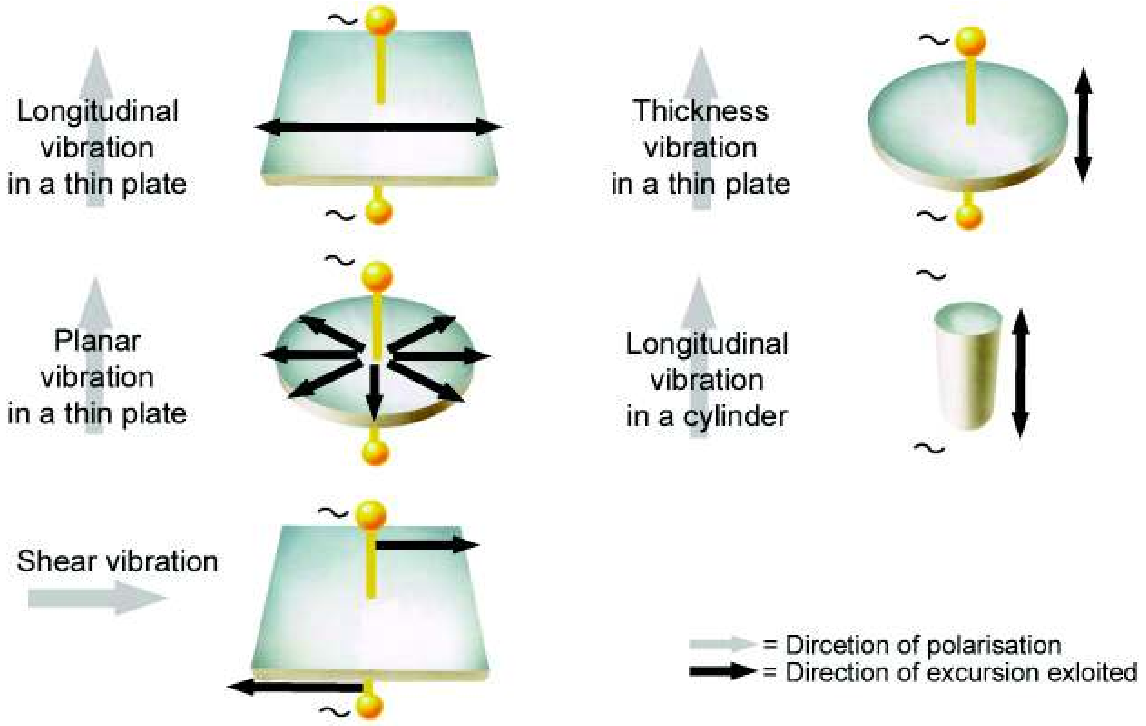


Figure 25: Fundamental vibration modes in piezoceramic components

Structural forms

If the piezo-ceramic consists of one layer, we speak of single layer technology. If the piezo-ceramic component consists of a number of active piezo-ceramic layers, we speak of multi-layer technology. Nowadays it is usual for piezo-ceramic plates, strips, rings, domes, small tubes and a large number of special geometries to be manufactured.

Their compact form means that piezo-ceramic transducers take up little space, and use little energy when used as actuators. **Multi-layer actuators** are used when large movements are required that can also create high forces.
The individual layers are connected electrically in parallel so that the external voltage remains small.

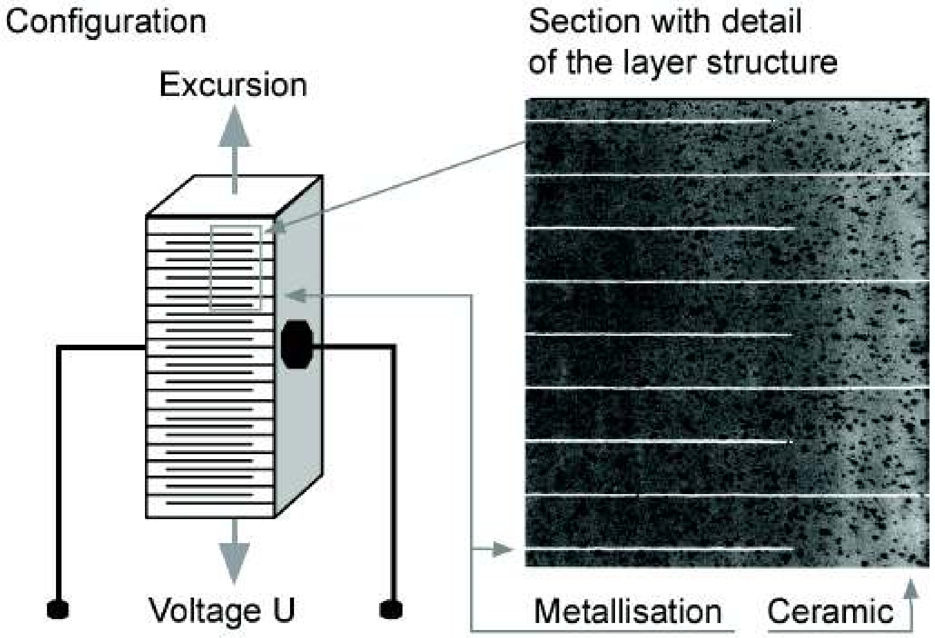


Figure 26: Configuration and sectional diagram of a monolithic multi-layer piezo-ceramic actuator.

Another variant is represented by the **bending transducer**. This is created if, for instance, piezo-ceramic elements are glued to a carrier material. The piezo-ceramic material reacts with a change in its length when electrically stimulated. The result, similar to that of a bimetal strip, is a large change in the shape of the composite material, depending on the voltage and its polarity, associated with moderate forces.

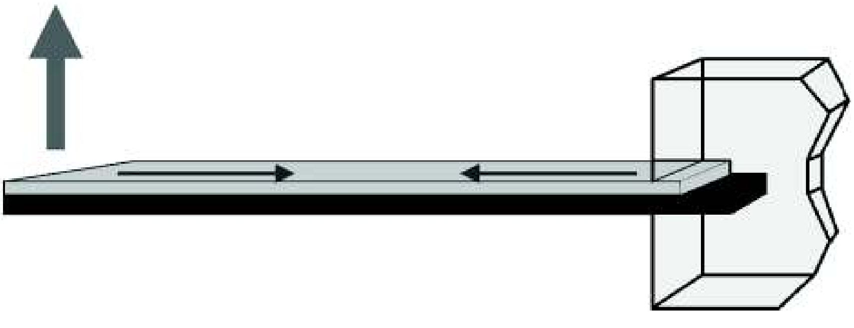


Figure 27: Application of the operating voltage causes the piezo-ceramic to contract, causing the pair to bend

Actuators with a passive layer and a piezo-ceramic component are called monomorphic. A bimorphic bending transducer consists of two piezo-ceramic elements without an intermediate passive layer. A system consisting of two piezo-ceramic components together with a passive intermediate layer is referred to as trimorphic. A multimorphic bending transducer consists of a large number of piezo-ceramic components, and does not have passive intermediate layers.

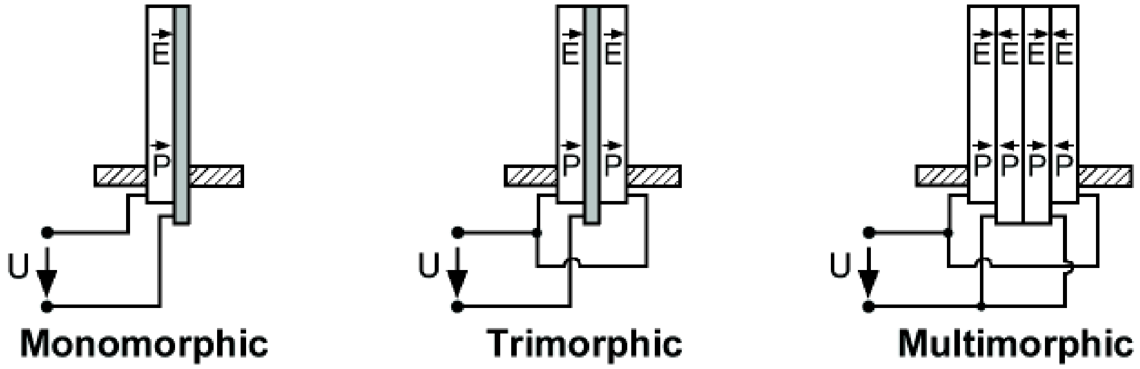


Figure 28: Structural variants of piezo-ceramic bending converters with P = polarisation direction and E = direction of the electrical field

Depending on the individual design of the bending transducer, movements of several millimetres, forces of up to a few newtons, and remarkably short movement times can be achieved. The bending transducer can therefore be used as a powerful and rapidly operating actuator.

Piezo-ceramics have won many applications in electronics, in the motor vehicle industry, in medical technology, in equipment and machine construction and consumer applications:
piezo-ceramic components are used as transducers in telecommunications, acoustics, hydro-acoustics, materials testing, ultrasonic processing, liquid atomisation, flow measurement, level measurement, distance measurement and medical technology. They are applied as actuators in micro-pumps, in optical systems, gas valves, low-pressure engineering, in inkjet printers, textile machines and in Braille modules (reading devices for the blind). Applied as sensors they react to force, pressure and acceleration, making it possible to monitor a wide range of processes.

3.4.2.9 Sintered fused silica

Silicon oxide ceramics (SiO_2) (also known as **fused silica ceramics or quarzware**[5]) are sintered from (amorphous) silicon dioxide powders. The goal is to obtain the typical properties of silicon dioxide, with its thermal expansion coefficient very close to zero, in ceramic components where those properties can be exploited. If the process is appropriately controlled, it is possible to retain the (amorphous) silicon dioxide phase in the sintered ceramic. The result is a ceramic with relatively low strength compared to the high strength oxide and non-oxide ceramics, but which has an extremely high thermal shock resistance as a direct result of the extremely low thermal expansion of the amorphous silicon dioxide phase.

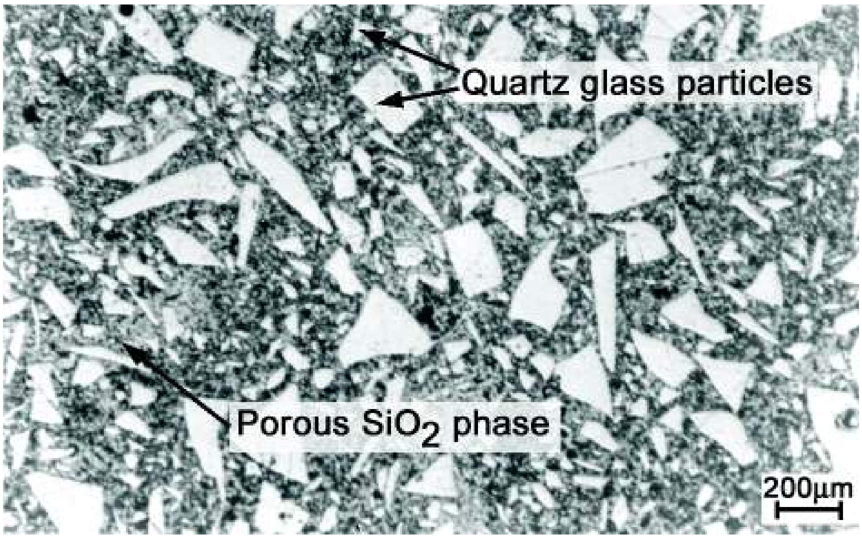


Figure 29: Microstructure of sintered fused silica

The maximum application temperature of 1,050° C should not be exceeded. Correspondingly, the application of these ceramics lies in areas where extreme thermal shocks are experienced and in the thermal treatment of glass products. In the latter case, the high purity

---

[5] The term ‘Quartzware’ originates from the manufacture of quartz glass. Due to the wide variety of methods used to manufacture more or less pure SiO_2 glasses, they are grouped nowadays from the scientific point of view under the general heading of silica glass. Chemically, transparent silica (quartz) glass, which is manufactured from a quartz sand or rock crystal, is practically identical to non-transparent quartzware ceramics. The primary difference between silica glass and quartzware is therefore just the different transparencies. From a scientific point of view, the term ceramic quartzware is wrong, since it does not contain crystalline phase SiO_2, but just particles of quartz glass.

and the compatibility of the silicon dioxide ceramics with the glass being processed prevents any contamination (such as discoloration). An other main application are casting cores for metal casting, especially nickel alloys.

3.4.3 Non-oxide Ceramics

Analogous to the oxide ceramics, the non-oxide ceramics are made exclusively from synthetic raw materials. The term **non-oxide ceramics** generally refers to carbides, nitrides or oxynitrides. The non-oxide ceramics are characterised by their truly unusual properties, as will be seen in the following material descriptions. The high proportion of covalent bonds in the carbide and nitrides crystal structures is responsible for the remarkable combination of properties. Oxide crystal structures, in contrast, have a relatively high proportion of electrovalent bonds. This also implies that the process from raw material powder to manufactured part is more costly than for oxide ceramics. The raw materials generally have to be extremely fine-grained, and the sintering process requires an absolutely oxygen-free atmosphere. This implies firing in a vacuum or inert gas in a gas-tight furnace at temperatures that can reach well over 2,000° C![6]

3.4.3.1 Carbides

3.4.3.1.1 Silicon carbide

By far the most important carbide ceramics are materials based on **silicon carbide (SiC)**. Diverse types are manufactured, depending on the intended purpose, but all are characterised by the typical properties of silicon carbide, such as

- very high hardness,
- corrosion resistance, even at high temperatures,
- high resistance to wear,
- high strength, even at high temperatures,

---

[6] Further information may be found in Section 4, pp. 70–76, From Forming to Firing, and in Section 10, p. 209, Bonding and Strength.

- resistance to oxidation even at very high temperatures,
- good thermal shock resistance,
- low thermal expansion,
- very high thermal conductivity,
- good tribological properties and
- semiconductivity.

The typical properties mentioned above are more or less pronounced in the different varieties of the material. Depending on the manufacturing technique, it is necessary to distinguish between *self-bonded* and *second-phase bonded* silicon carbide ceramics, as well as between open porous and dense types.

Open porous silicon carbide:

- silicate-bonded silicon carbide
- recrystallized silicon carbide **(RSIC)**
- nitride or oxynitride bonded silicon carbide **(NSIC)**

Dense silicon carbide:

- reaction-bonded silicon carbide **(RBSIC)**
- silicon-infiltrated silicon carbide **(SISIC)**
- sintered silicon carbide **(SSIC)**
- hot [isostatic] pressed silicon carbide **(HPSIC, [HIPSIC])**
- liquid-phase sintered silicon carbide **(LPSIC)**

The type and proportion of the bonding are decisive in determining the corresponding characteristic properties of the silicon carbide ceramic.

Silicate bonded silicon carbide is manufactured from coarse and medium grained SiC powders, sintered with 5 to 15 % aluminosilicate binder in air. However, strength, corrosion resistance, and above all the high-temperature characteristics, are determined by the silicate binding matrix, and lie below those of non-oxide bonded SiC ceramics. The binding matrix begins to soften at very high application temperatures, and the material begins to deform under stress. The advantage lies in the comparatively low manufacturing cost. Applications for this material include, for example, plate stackers used in the manufacture of porcelain.

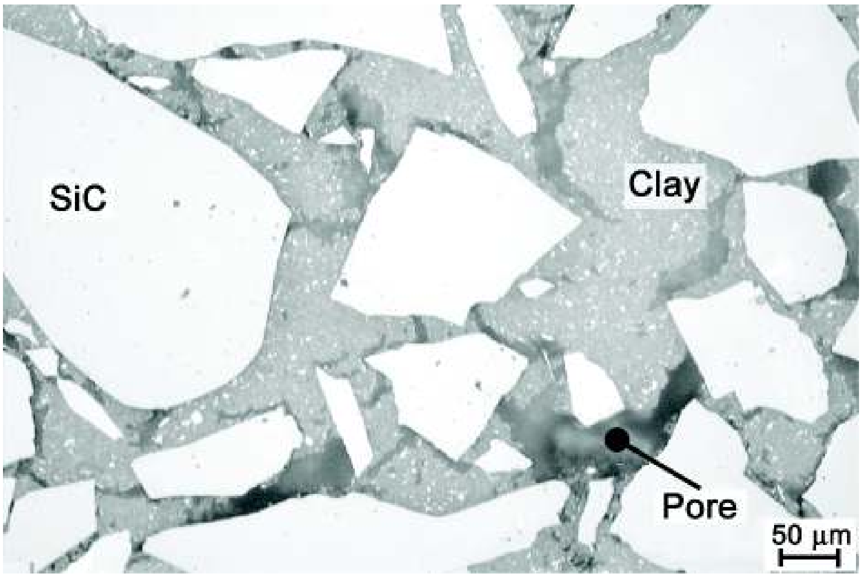


Figure 30: Microstructure of a coarse, silicate-bonded silicon carbide

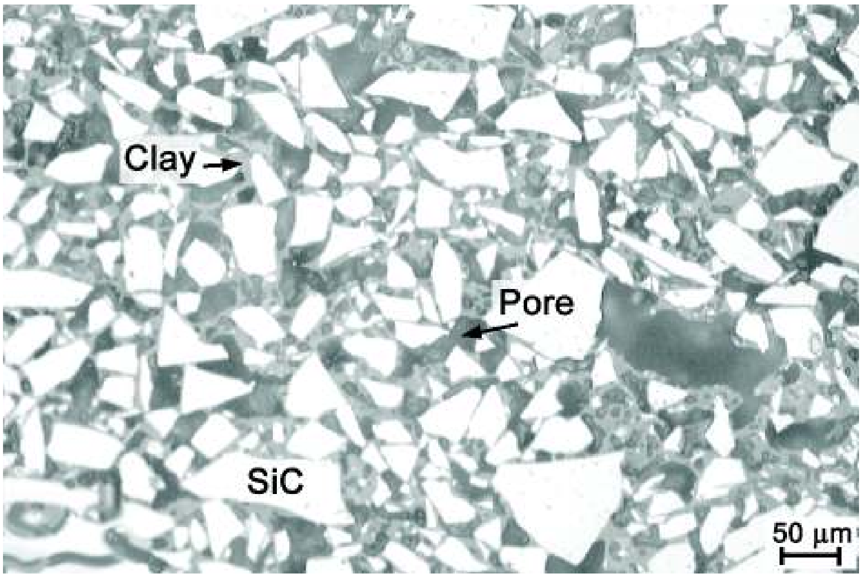


Figure 31: Microstructure of a fine-grained, silicate-bonded silicon carbide

Liquid-phase sintered silicon carbide (LPSIC) is a dense material containing SiC, a mixed oxynitride SiC phase, and an oxide secondary phase. The material is manufactured from silicon carbide powder and various mixtures of oxide ceramic powders, often based on aluminium oxide. The oxide components are responsible here for the density which, at approx. 3.24 g/cm^3, is somewhat higher than that of SSIC.

The components are compressed in a pressure sintering procedure at a pressure of 20-30 MPa and a temperature of more than 2,000°C.
The material is also characterised by a fine-grained matrix with grain sizes < 2 µm, by being almost entirely free from pores, by very high strength and fracture toughness.
LPSIC lies somewhere between SSIC and the high strength and toughness of Si_3N_4, from the point of view of mechanical properties,

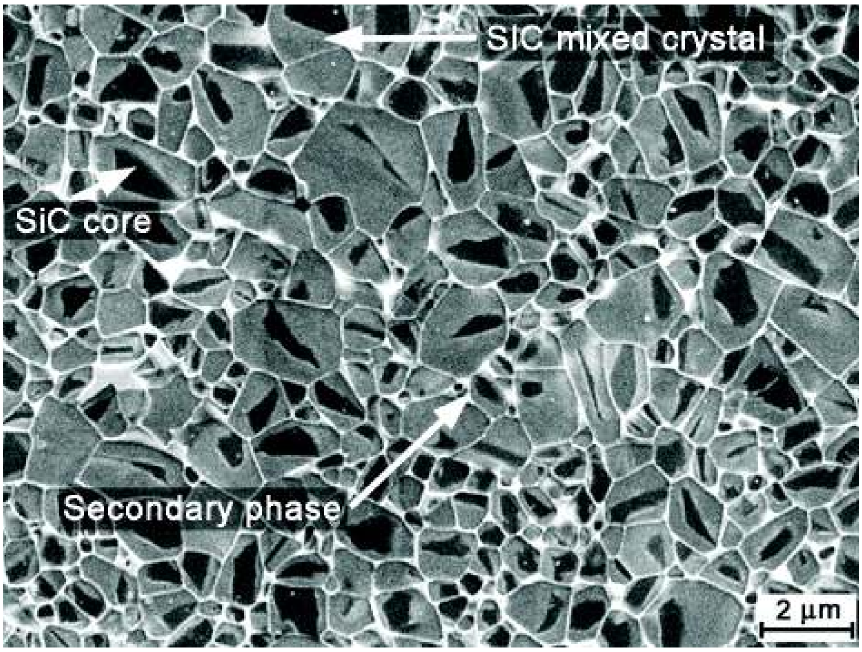


Figure 32: Microstructure of liquid-phase sintered silicon carbide

Pressureless sintered silicon carbide (SSIC) is produced using very fine SiC powder containing sintering additives. It is processed using forming methods typical for other ceramics and sintered at 2,000 to 2,200° C in an inert gas atmosphere. As well as fine-grained versions, with grain sizes < 5 µm, coarse-grained versions with grain sizes of up to 1.5 mm are available. SSIC is distinguished by high strength that stays nearly constant up to very high temperatures (approximately 1,600° C), maintaining that strength over long periods!

This material displays an extremely high corrosion resistance in acidic and basic media, and this too is maintained up to very high temperatures. The coarse-grained versions offer particular advantages. These properties are outstanding among high-temperature ceramics, and are complemented by high thermal shock resistance, high thermal conductivity, high resistance to wear, and a hardness close to that of diamond. Thus, SSIC is ideal for extremely demanding applications, for example, slip ring seals in chemical pumps, bearing bushes, high temperature burner nozzles, or as kiln furniture for very high application temperatures. The use of SSIC with graphite inclusions improves the performance of tribological systems.

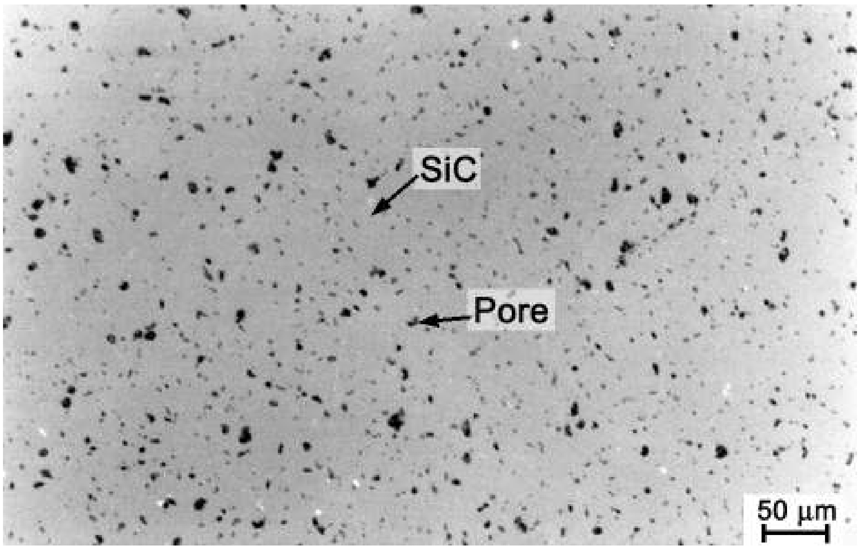


Figure 33: Microstructure of an SSIC (unetched)

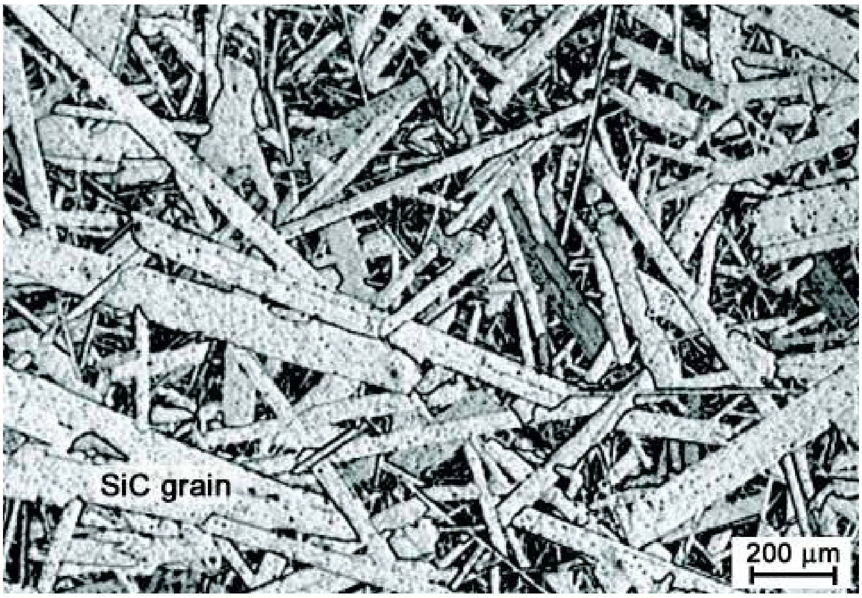


Figure 34: Microstructure of coarse-grained SSIC (etched)

Hot-pressed silicon carbide (HPSIC) and **hot isostatic pressed silicon carbide (HIPSIC)** exhibit even better mechanical specifications compared to pressureless sintered SSIC, since the products are nearly free of pores due to the application of mechanical pressures reaching up to about 2,000 bar. The axial (HP) and the isostatic (HIP) pressing techniques limit the parts to be made to relatively simple or small geometries, and involve greater expense compared with pressureless sintering. As a result, HPSIC and HIPSIC are used exclusively in the most demanding applications.

Reaction bonded silicon infiltrated silicon carbide (SISIC) is composed of approximately 85 to 94 % SiC and correspondingly 15 to 6 % metallic silicon (Si). SISIC has practically no residual porosity.

This is achieved by infiltrating a formed part of silicon carbide and carbon with metallic silicon. The reaction between the liquid silicon and the carbon leads to SiC bonding between SiC grains, and the remaining pore volume is filled with metallic silicon. The advantage of this technique is that, in contrast to powder sintering technologies, no shrinkage takes place during the infiltration process. In this way unusually large parts with very precise dimensions can be manufactured. The application of SISIC is limited to approximately 1,380° C due to the melting point of metallic silicon. Below this temperature, SISIC exhibits very high strength and corrosion resistance combined with good thermal shock resistance and wear resistance. SISIC is thus ideal as a material for highly stressed kiln furniture (beams, rolls, supports etc.) and various burner parts for direct and indirect combustion (flame tubes, recuperators and jet pipes).
It is also useful in machine construction for components that must be highly resistant to wear and to corrosion (slip ring seals).

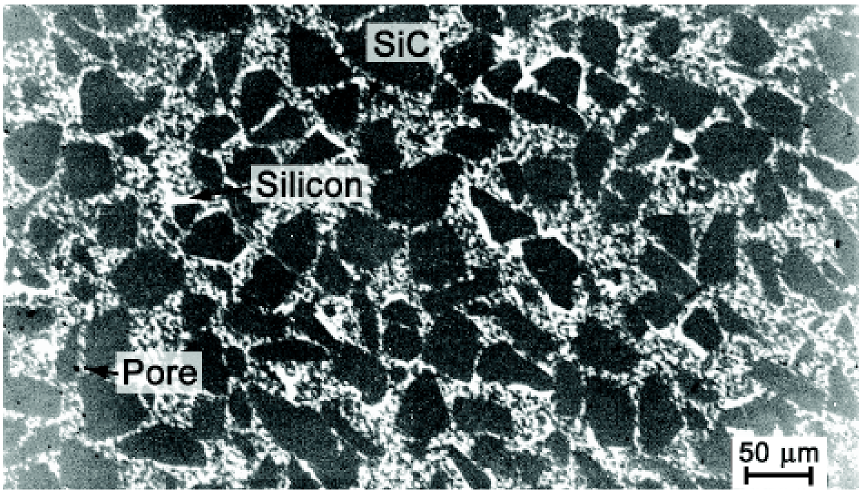


Figure 35: Microstructure of SISIC

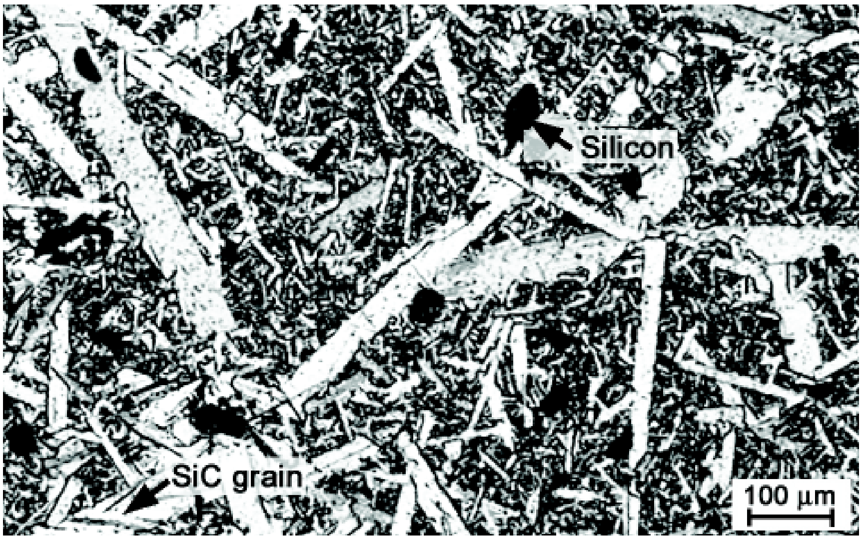


Figure 36: Microstructure of coarse-grained SISIC

Recrystallized silicon carbide (RSIC) is a pure silicon carbide material with approximately 11 to 15 % open porosity. This material is sintered at very high temperatures from 2,300 to 2,500° C, at which a mixture of extremely fine and coarse grains is converted to a compact SiC matrix without shrinkage. As a result of its open porosity, RSIC possesses lower strength in comparison to dense silicon carbide ceramics.

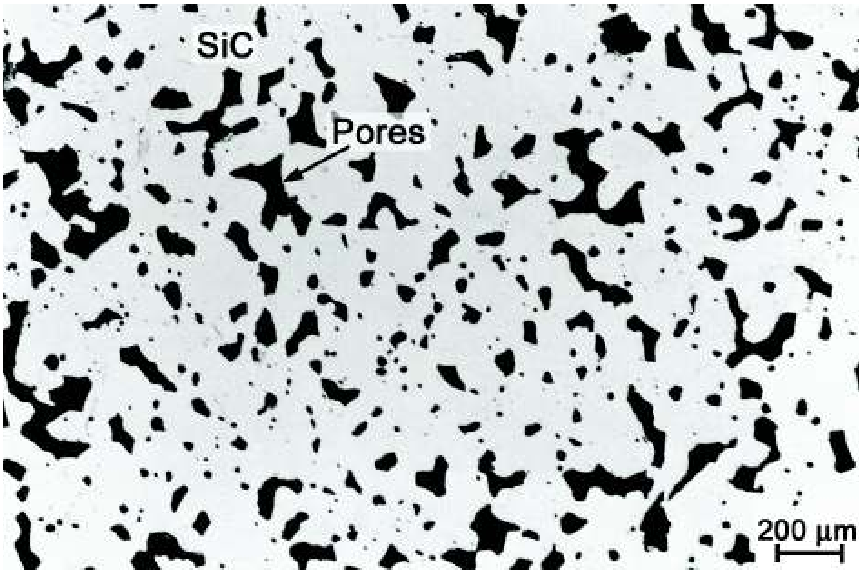


Figure 37: Microstructure of RSIC

Due to its porosity, RSIC demonstrates outstanding thermal shock resistance. Analogous to SISIC, this shrinkage-free sintering technique allows the manufacture of large parts that are used primarily as heavy duty kiln furniture (beams, rollers, supports etc.), for example in the porcelain industry. Due to its open porosity, this material does not resist oxidation over long periods, and is subject to a certain amount of corrosion when applied as kiln furniture or as a heating element. The maximum application temperature lies between 1,600 and 1,650° C.

Nitride bonded silicon carbide (NSIC) is a porous material, having a porosity of between 10 and 15 %, of which between 1 and 5 % is opened porosity. The manufacturing process is shrinkage-free, and involves a moulded body of silicon carbide granulate and metallic silicon powder being nitrided in an atmosphere of nitrogen at approx. 1,400 °C. The initially metallic silicon changes here to silicon nitride, creating a bond between the silicon carbide grains. The material is then exposed to an oxidising atmosphere at a temperature above 1,200 °C. In this way a thin oxidation layer of glass is created.

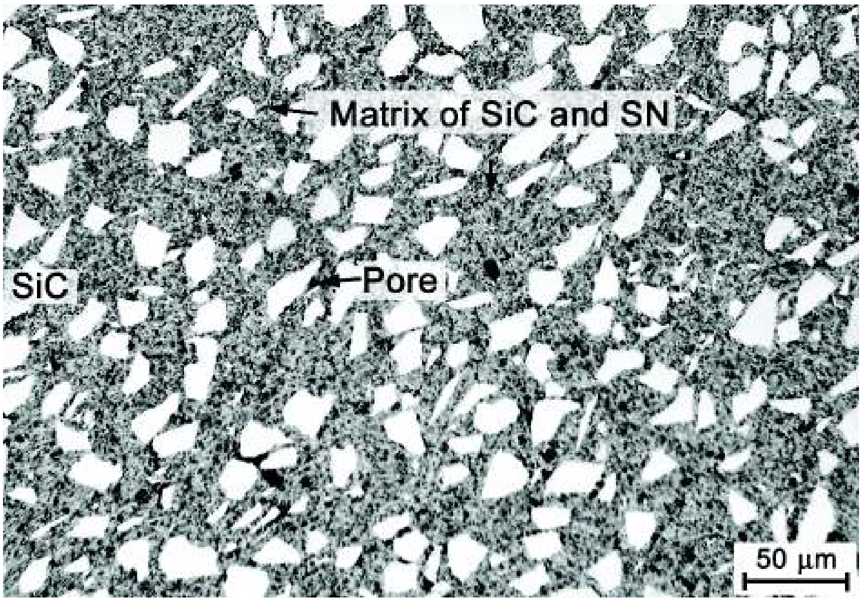


Figure 38: Microstructure of an NSIC

The effect of the matrix of silicon nitride is that workpieces made from NSIC are only wetted with great difficulty by molten non-ferrous metals. The bending strength of NSIC his greater by approx. 100%, because the pore size is smaller than that of RSIC. It is also more resistant to oxidisation, while the tougher surface means that it does not deform during its service life. This material is particularly suitable for use in highly stressed kiln furniture at up to 1,500°C.

3.4.3.1.2 Boron carbide

Boron carbide ceramics **(B_4C)** are manufactured, similarly to silicon carbide ceramics, from sub-micron B_4C powder in an inert gas atmosphere at temperatures above 2,000° C without pressure (SBC), hot pressed (HPBC), or hot isostatic pressed (HIPBC). Boron carbide ceramics are distinguished by their outstanding hardness, only exceeded by cubic boron nitrides and diamond. The mechanical properties of boron carbide ceramics are similar to those of silicon carbide, with the exception of comparatively high wear resistance. The combination of very low density (2.51 g/cm^3), high mechanical strength and high elastic modulus makes this type of ceramic particularly attractive in the field of ballistic protection. Boron carbide ceramics can only be used to a maximum of 1,000° C in oxidising atmospheres, since it oxidises very rapidly at higher temperatures.

3.4.3.2 Nitrides

3.4.3.2.1 Silicon nitride

Silicon nitride (Si_3N_4) plays at present a dominant role amongst nitride ceramics. It achieves a combination of outstanding material properties not yet reached by other ceramics, namely

- high toughness,
- high strength, even at high temperatures,
- outstanding thermal shock resistance,
- remarkable resistance to wear,
- low thermal expansion,
- medium thermal conductivity and
- good resistance to chemicals.

This combination of properties means that we have a ceramic that is appropriate for the toughest application conditions. Silicon nitride ceramics are therefore ideal for machine components with very high dynamic stresses and reliability requirements.

The manufacture of dense silicon nitride ceramic starts with sub-micron Si_3N_4 powder mixed with sintering additives (Al_2O_3, Y_2O_3, MgO etc.), and is sintered at temperatures between 1,750 and 1,950° C after moulding. Due to the decomposition of Si_3N_4 to Si and N_2 above approximately 1,700° C at atmospheric pressure, the N_2 pressure is increased during sintering in order to counteract this decomposition.

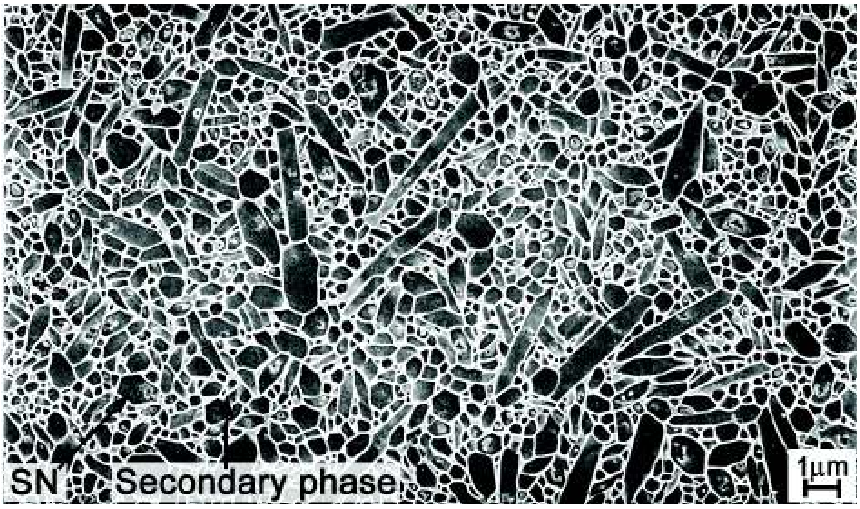


Figure 39: Microstructure of a gas-pressure sintered silicon nitride

A relatively economical version is that of **low-pressure sintered silicon nitride** (**SSN**), which has medium bending strength, and from which high-volume components (e.g. for metallurgical purposes) can be manufactured.

Gas pressure sintered silicon nitride (**GPSSN**) is sintered in a gas pressure sintering furnace with an excess N_2 pressure of up to 100 bar. This creates a high performance material suitable for high mechanical stresses.

Hot pressed and hot isostatic pressed silicon nitride (**HPSN** and **HIPSN**) undergo even higher pressures of up to 2000 bar during the sintering process. HPSN and HIPSN are distinguished by even greater mechanical strength, compared to GPSSN, because the remaining porosity is almost completely eliminated by the high mechanical pressures involved in the manufacturing process. The limited geometries available with axially pressed HPSN (due to the use of a mechanical pressing punch) and the high manufacturing costs of HIPSN are disadvantages associated with this ceramic.

Important fields of application for components made from this dense silicon nitride material are metal processing with cutting tools (indexable cutting inserts), roller bearing technology using balls, rollers or rings, and machine construction involving highly stressed machine elements. The inclusion of such parts also in the field of metal forming illustrates the capacities of the material.

Reaction bonded silicon nitride (**RBSN**) is manufactured using a completely different approach. As an alternative to the high priced Si_3N_4 powder, the relatively economical Si powder is used here as a raw material. It is formed and nitrided in an N_2 atmosphere at temperatures of approximately 1,400° C to form Si_3N_4 - and there is no shrinkage! The resulting ceramic displays good mechanical properties, but is prone to oxidation at high temperatures due to its very fine open porosity.

Examples of the application of RBSN include kiln furniture, melting crucibles and ingot moulds as used, for instance, in the manufacture of silicon components for solar technology.

The addition of additives to the Si powder allows the nitrided Si_3N_4 to be densely sintered (sintered RBSN = **SRBSN**). Both versions of the material are, only suitable for materials with thicknesses of up to 20 mm, depending on the particular process, however.

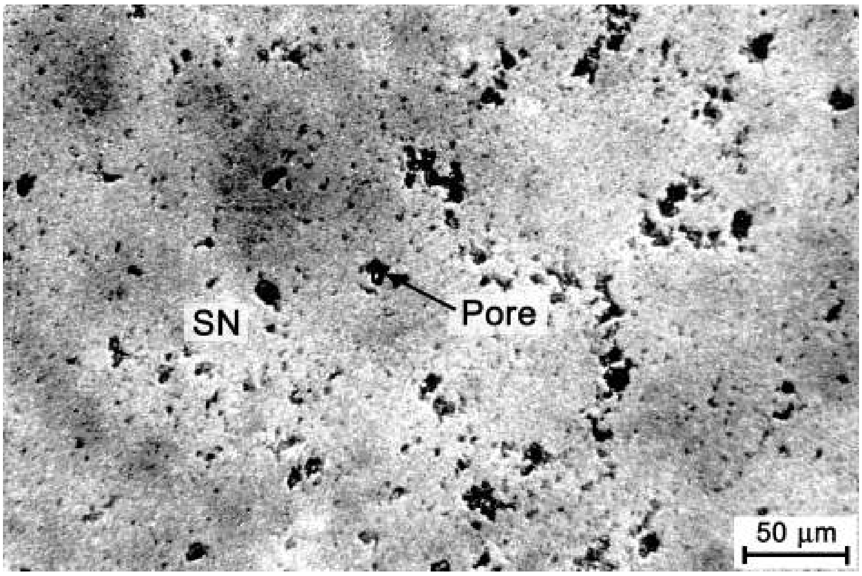


Figure 40: Surface of a reaction bonded silicon nitride

3.4.3.2.2 SIALONs

The **silicon aluminium oxynitrides** (**SIALON**) are versions of silicon nitride ceramics. The raw material is blended from silicon nitride, enriched with materials including the metal oxide Al_2O_3, in order to synthesise specific mixed crystal forms that achieve properties similar to those of silicon nitride but at lower sintering temperatures. The mechanical properties can be adjusted over a wide range by modifying the type and quantity of the additives. The relatively high fracture toughness should be noted. SIALONs are therefore frequently used for cutting tools. Their low wetting by aluminium and other molten non-ferrous metals has made the SIALONs the de facto standard material for thermocouple protection tubes in the smelting industry.

3.4.3.2.3 Aluminium Nitride

Aluminium nitride (AlN) has a remarkably high thermal conductivity, with 180 $Wm^{-1}K^{-1}$ being standard, and > 220 $Wm^{-1}K^{-1}$ being achievable. Because this is combined with good electrical insulating properties, aluminium nitride is exceptionally suitable for applications in electrical engineering. In addition to this, aluminium nitride ceramics can be metallised by any of the usual processes, and thus can be prepared for brazing or soft soldering. Because the thermal expansion of aluminium nitride is similar to that of silicon, mechanical stresses created between these two materials under conditions of thermal stresses remain particularly small.

Because the material is suitable for further processing with both thick and thin film technology, and because it can be coated with copper through both the DCB (direct copper bonding) and the AMB (active metal brazing) processes for tracks greater than 1 mm in height, aluminium nitride is an ideal material for applications in telecommunications technology.

Aluminium nitride ceramic is therefore used as a substrate for semiconductors, as well as for high-power electronic parts, housings and heat sinks.

High resistance to gases such as are used in the preparation of silicon wafers means that aluminium nitride ceramics are also widely used in this sector.

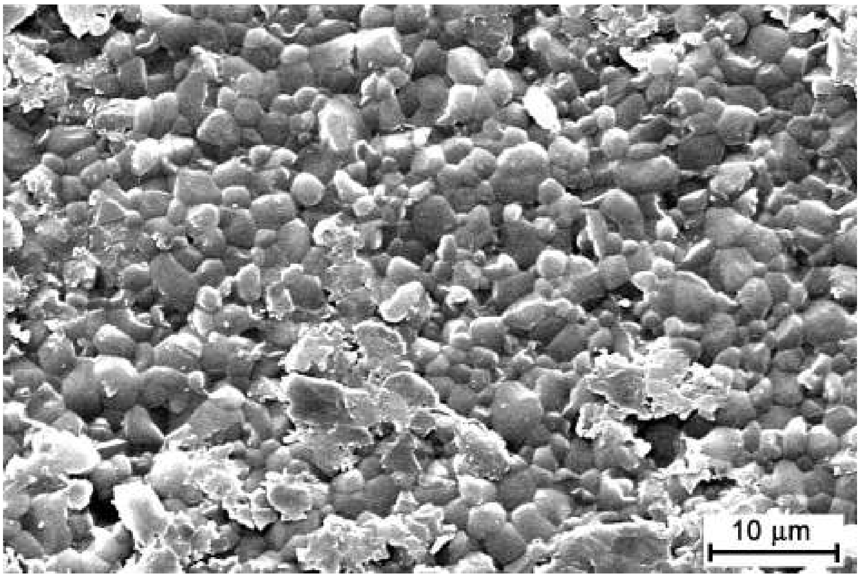


Figure 41: Surface of an aluminium nitride

Aluminium nitride ceramics are particularly suitable when the application requires

- very high thermal conductivity,
- high electrical insulation,
- thermal expansion similar to Si ($<Al_2O_3$) or
- inert behaviour in the presence of III-V compound melts.

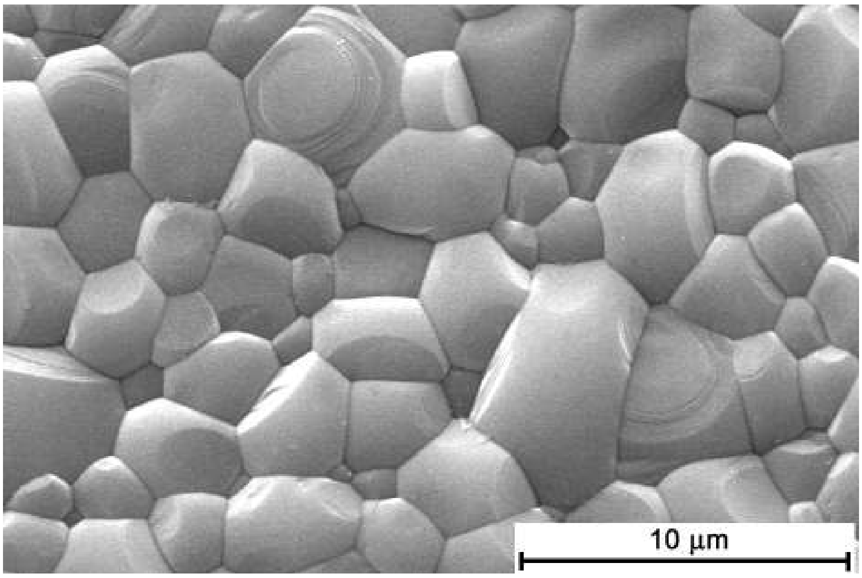


Figure 42: An aluminium nitride fracture surface

Aluminium nitride ceramics are less suitable for applications at temperatures above 1,000°C in environments containing water or oxygen, or under mechanical stress when simultaneously wetted by water.

3.4.4 Special materials

3.4.4.1 Composite fibre-ceramic materials

In contrast to monolithic ceramics, composite fibre-ceramic materials are characterised by quasi-ductile properties. This gives them a fracture behaviour somewhat like that of metals. Higher tolerance to damage is achieved due to their property of reacting to high stress with deformation instead of with brittle fracture. Stress concentrations do not lead to catastrophic failure of the component, since a number of energy-absorbing mechanisms such as micro-cracks or delamination allow them to be locally dispersed.
Due to the manufacturing costs, which at present are still high, composite fibre-ceramic materials have so far only found applications in special cases, such as high-performance brake discs for motor racing vehicles, or as a special component in aerospace applications.

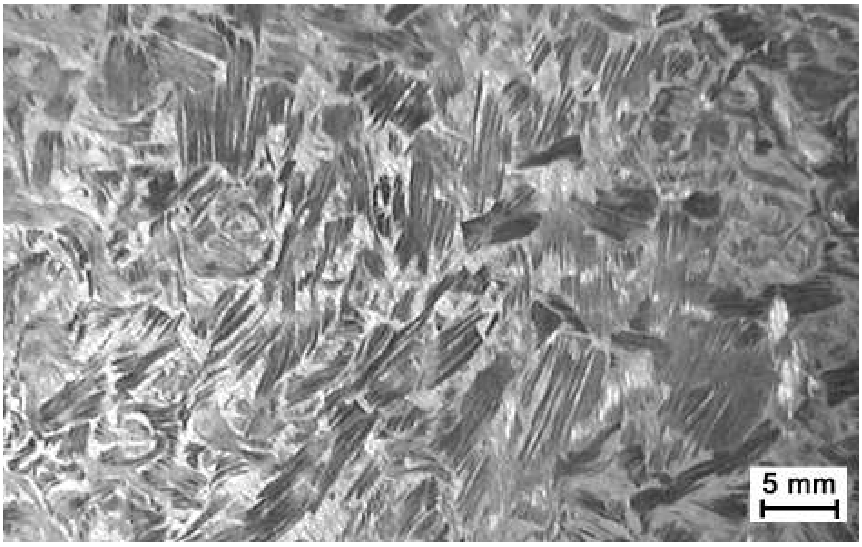


Figure 43: Microstructure of a composite fibre-ceramic material with random fibre orientation

3.4.4.2 Metal matrix composites

Metal matrix composites (MMCs) are compound materials whose microstructure consists of a metallic alloy into which a particular reinforcing component has been introduced.

MMC = metal + reinforcement

The metal alloys in the matrix can be reinforced with:

- particles (e.g. aluminium oxide, silicon carbide, ...)
- long fibres (e.g. aluminium oxide, silicon oxide, ...)
- short fibres (e.g. aluminium oxide, silicon oxide, carbon, ...)
- whiskers[7] (e.g. aluminium oxide, silicon carbide, ...)
- mixtures of particles and fibres (hybrid reinforcement)

An aluminium alloy is used most frequently as the metal matrix. Magnesium and copper are, however, finding increased use.

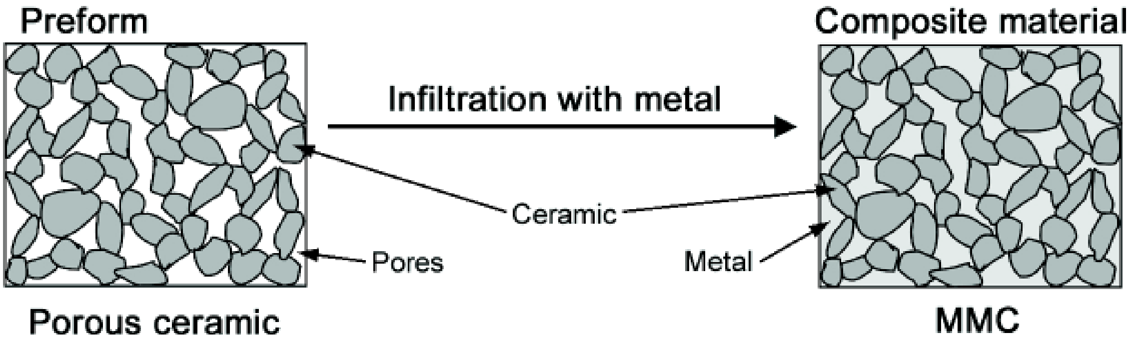


Figure 44: Manufacture of an interpenetrating structure

The first step of manufacture is to prepare porous ceramic pre-forms, whose open porosity is deliberately adjusted to values of between 25 and 75 per cent by volume. These pre-forms are then heated to above 500°C, and passed to the infiltration process. The molten metal then penetrates through the porous ceramic network, solidifies, and creates an interpenetrating structure with the reinforcing components. This makes it possible to manufacture components only part of which

---

[7] Whiskers are very thin crystal fibres or needle-like crystals with high tensile strength.

contains reinforcement – at precisely the locations where improved material properties are required.

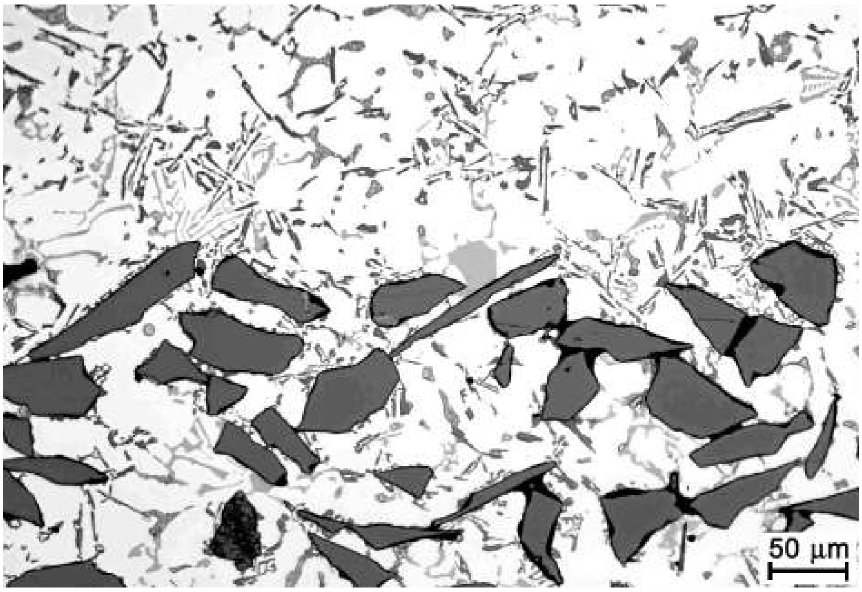
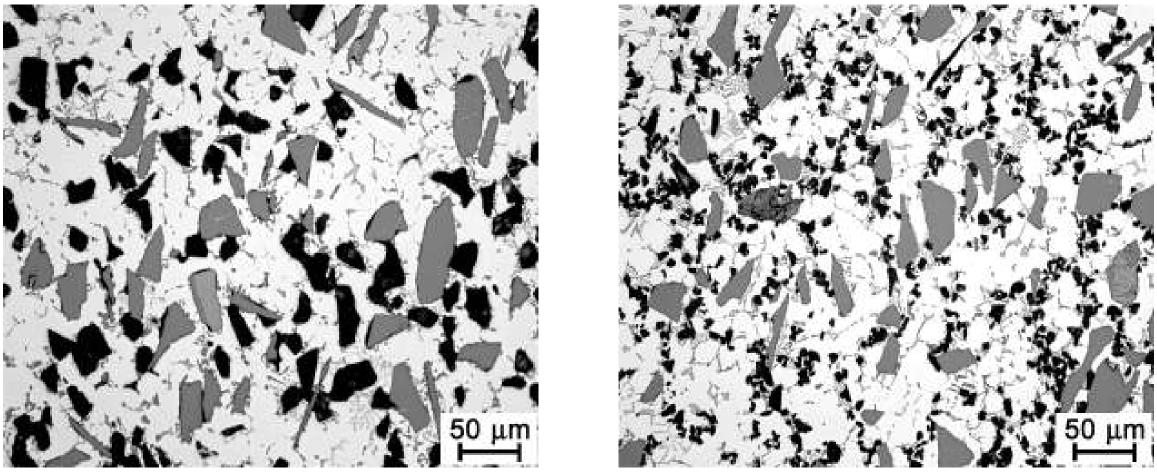


Figure 45: Microstructure showing partial reinforcement with a transition in the material

MMC materials are generally tailored precisely for the specific application. This is achieved by varying the type of particle or combinations of particles, the proportion by volume, the particle sizes and the porosity in order to meet the requirements of the infiltration process and of the composite material. Fibres can be included, as well as particles, particularly to increase the toughness of the material.



Figures 46 and 47: Examples of MMC microstructures

The goals of application-specific microstructure design may include:

- increasing the mechanical strength,
- affecting friction and wear (tribology),
- affecting the thermal expansion,
- improving thermal stability,
- retaining weight reduction through lightweight construction or achieving low density,
- permitting further processing and machining.

Possible applications for MMC materials include the running surfaces of cylinders in vehicle engines, cavity edges on engine pistons, brake ining carrier plates (weight), bearings (thermal expansion), connecting rods (weight), brake discs for motorbikes or railway applications, sports items such as golf club heads, tennis rackets or the frames of mountain bikes, and cooling plates in electronics.

4 From Powder to Part

4.1 Manufacture

The basic properties of the ceramic product are influenced by the selection of raw materials and the manufacturing process (see figure 48).

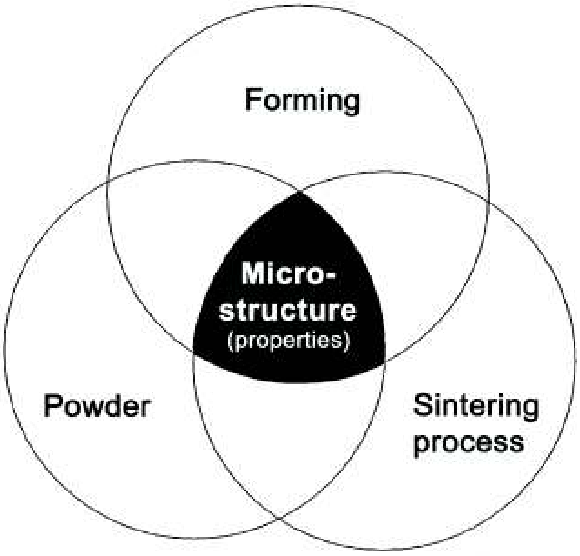
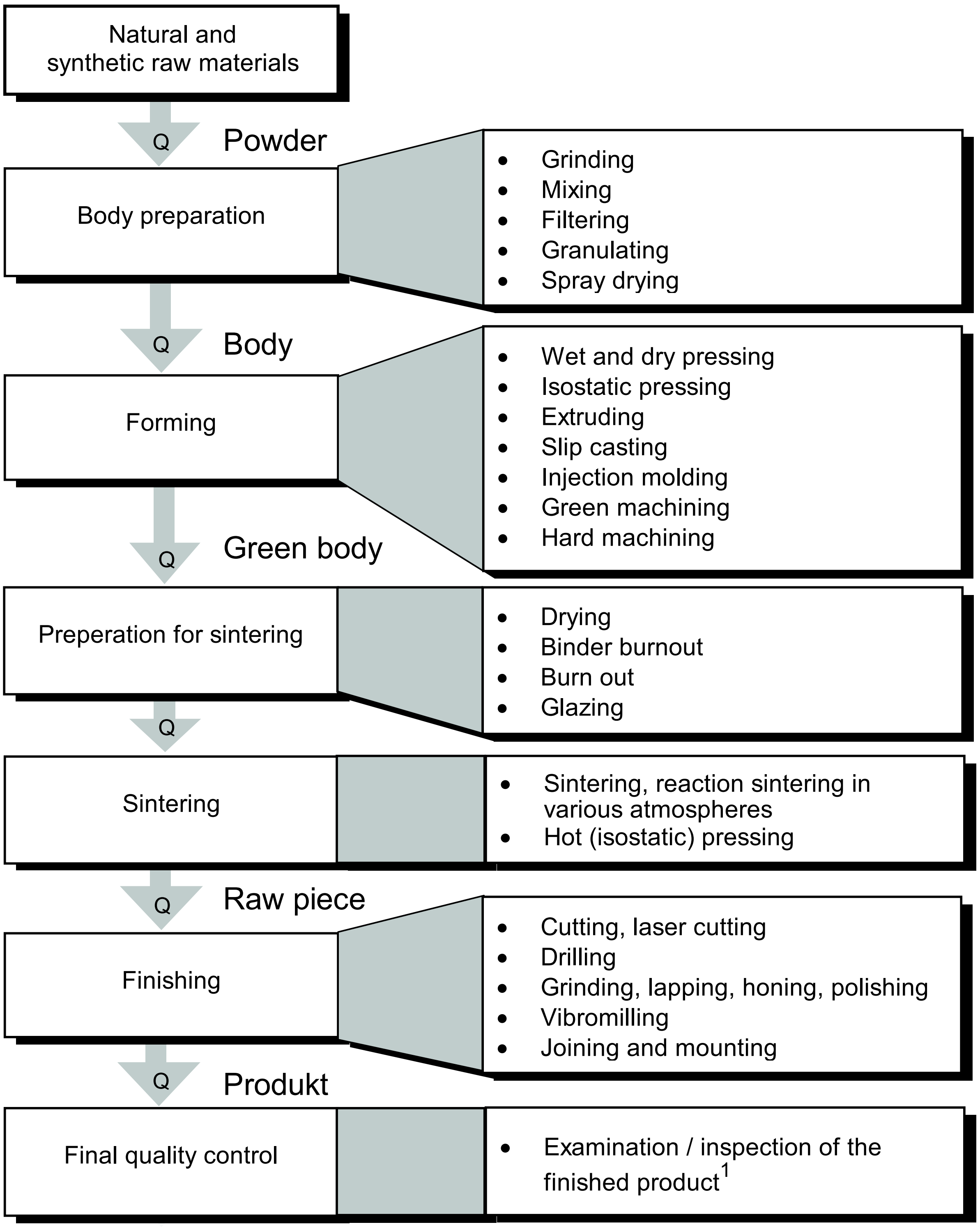


Figure 48: Influences on the microstructure

Throughout the entire complex manufacturing process (see Figure 49), the powder, forming and sintering processes together influence the formation of the crucially important microstructure and thereby the desired properties of the final product.

Particularly close dimensional tolerances in components are made possible through hard machining of the sintered ceramics.
Consistently high quality is based on proven, controlled manufacturing techniques, whose specifications and results are routinely monitored and recorded.



Q = Quality control measures
[1] Based on customer specifications

Figure 49: The ceramic manufacturing process

4.1.1 Raw Materials and Additives

The basic requirements of production and of using the most economic manufacturing process determine the choice of raw materials (in terms of type, purity, grain size and specific surface area), as do the supplementary ingredients.

With their distribution and purity, additives such as

- (inorganic) sintering aids

and the (usually organic) forming aids, such as

- liquefaction agents,
- plasticisers or
- binders

are as significant as the raw materials themselves.

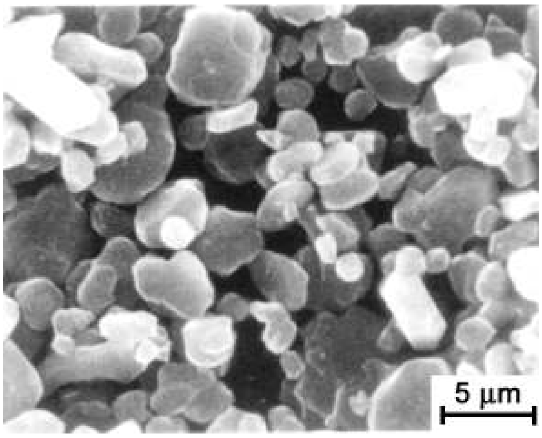


Figure 50: Coarse Al_2O_3 powder

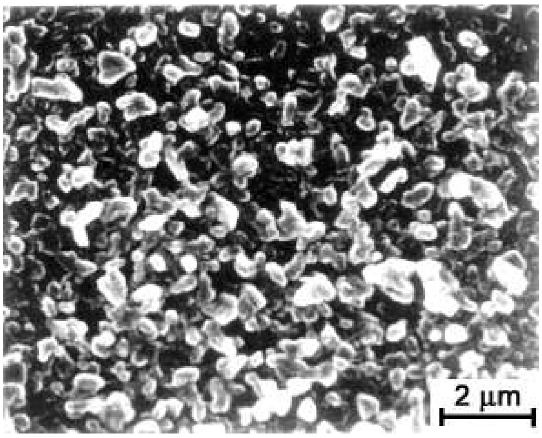


Figure 51: Fine Al_2O_3 powder

4.1.2 Body preperation

There are two possibilities:

a) The ceramic manufacturer acquires the necessary raw materials and carries out all further processing tasks.

Specific preparations of unfired material are required for the different forming processes:

slips ⇒ for casting,
granulates ⇒ for pressing and
plastic material ⇒ for extrusion.

b) The ceramics manufacturer acquires ready-prepared unfired material, and begins at the forming stage of the ceramics process.

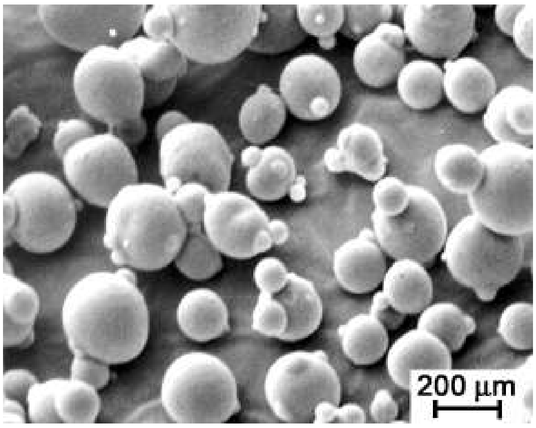


Figure 52: Sprayed aluminium oxide granulate

4.1.3 Forming

The powder particles are compacted to form a coherent shape with sufficient strength for subsequent handling. If necessary, this shaped, unsintered mass of powder (known as a green body) can be machined economically before firing, since corresponding steps are much more expensive after sintering. When applying the various forming processes, care must be taken to avoid significant density gradients and textures in the green body, since these can be amplified during sintering, leading to distortions and internal mechanical stresses. The choice of a suitable forming process is usually determined by economic factors (efficient manufacturing).

Methods of shaping ceramic parts can be divided into the following basic types:

- pressing (0 – 15 % moisture)
- plastic forming (15 -25 % moisture)
- casting (> 25 % moisture)

Dry pressing

is used to manufacture mass-produced precision products. Non-clumping granulates are compressed in steel dies designed appropriately for the part to be manufactured. The high cost for the dies (sometimes made of carbide) can only usually be justified for large runs.

Figure 53: Dry pressing

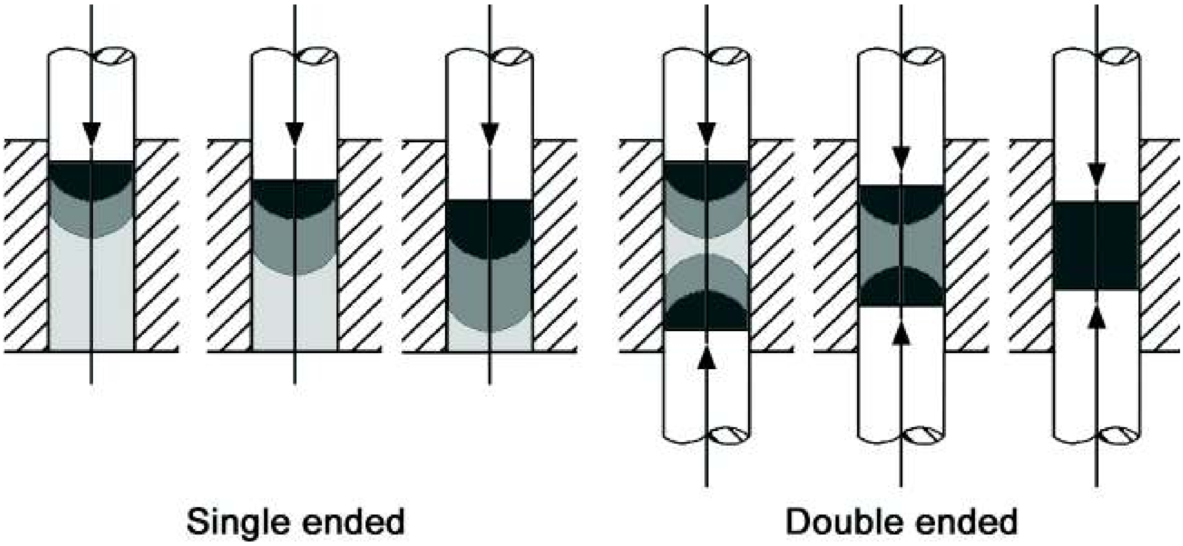


Figure 54: Single axis dry pressing, single and double ended, with regions of different compression (grey levels)

Dry pressing is the most economic process for large production runs, and is suitable for both simple and complex geometries. Depressions and holes are normally only designed in the pressing direction.

Depending on the design of the dry pressing machine, components ranging in size from tiles down to match heads can be manufactured. Small discs or plates can be pressed with thicknesses of around 0.8 or 1.0 mm. The tape casting process is more suitable for even thinner, flatter components. It is still possible to manufacture fine ridges or similar structures on the component if the granulate being pressed can effectively fill hollows in the pressing tool, and provided it is possible to create the necessary tool.

Isostatic pressing

is suitable for the manufacture of uniformly compressed blanks and large parts that are appropriate for machining in the green state. Simple rubber moulds determine the initial form.

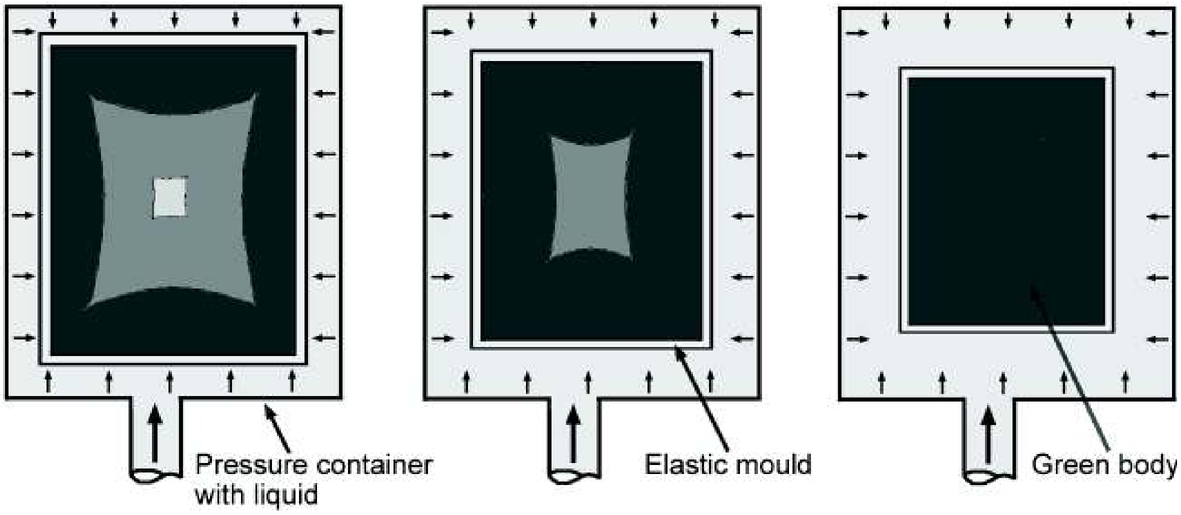


Figure 55: Isostatic pressing with regions of different compression (grey levels)

This type of forming is well-suited to the manufacture of exacting prototypes and small series, but for some products can also be fully automated (spark plugs, grinding balls, small pistons, welding nozzles).

Wet pressing / moist pressing

allows the manufacture of parts with complex geometries such as screw threads, side holes, recesses and undercuts.
The unfired material used for this purpose usually has moisture levels in the range of 10 to 15%. Compressing with a single axis makes these materials able to flow freely, so that relatively even compression can be achieved.
The disadvantage of this, however, is that wet pressing materials can accept only low compressive strains. This also means that the degree of compression is limited. It depends heavily on the moisture content of the unfired material, and is lower than in the case of dry pressed parts.

In some circumstances, moreover, it is necessary to dry the pressed parts before sintering. Mean tolerances in accordance with DIN 40 680-1 are based on this.

Extrusion

is carried out using piston extruders or vacuum screw presses. The homogenised mass of material is pressed through a nozzle, so forming endless billets. Optimum compression of the material is important.
Extrusion is particularly suitable for manufacturing rotationally symmetric parts such as axles or pipes. Complex profiles can also be made with the aid of appropriate nozzle design. The lengths of the billets to be manufactured depend to a large extent on the tendency of the material being processed to warp.

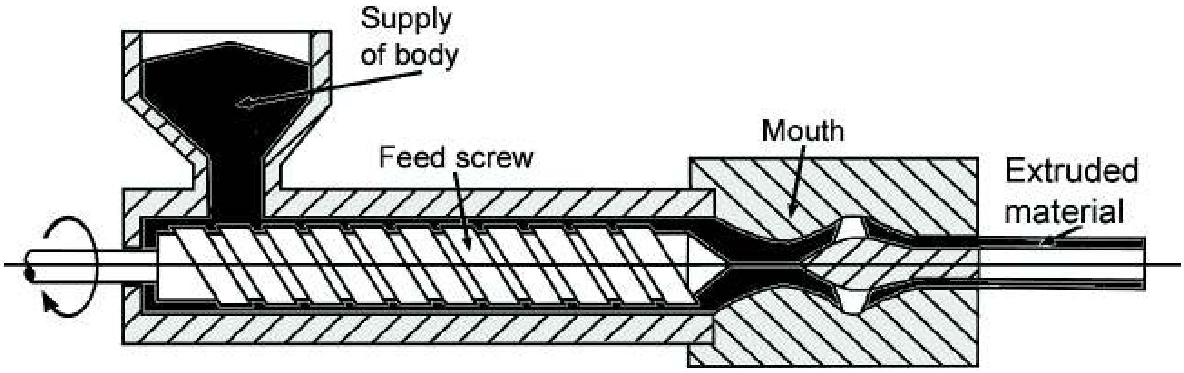


Figure 56: Extrusion

Injection moulding

is principally suited to the mass production of complex products. It is limited by relatively high die costs and the complex burnout of organic additives. The conveying capacity ("shot weight") of large injection moulding machines is typically up to about 70 g. Generally, the part should be designed so that thicknesses are as consistent as possible, having an upper limit of approx. 12 mm.

Slip casting

is a simple method for the manufacture of prototypes, parts with complex geometries and relatively large items. It can be used to manufacture both thin-walled and solid objects. Ceramic slip casting involves a stable suspension, referred to as the slip, being poured into a porous, absorbent plaster mould. Extraction of the suspending liquid causes a layer of particles to develop on the mould wall. This layer develops, in solid casting, to create the fully moulded body. In the case of hollow casting, the superfluous slip is poured out once the desired wall thickness has been achieved.

Tape casting

Here, a ceramic slip containing various organic additives is poured onto an endless steel strip carried by rollers. The slip flows continuously from a reservoir through an adjustable slot onto the strip. Hot air is blown over the strip in the opposite direction to dry it, so that at the end of the strip, thanks to the organic additives, a flexible tape of green ceramic is obtained. This can either be wound up and stored for further processing at a later time, or maybe processed immediately through cutting, punching, stamping or other similar methods.

Tape casting is typically used to manufacture ceramic parts with thickness ranging from 0.25 to 1.0 mm. The formed products are suited for the manufacture of substrates, housings, capacitors and multi-layer transducers.

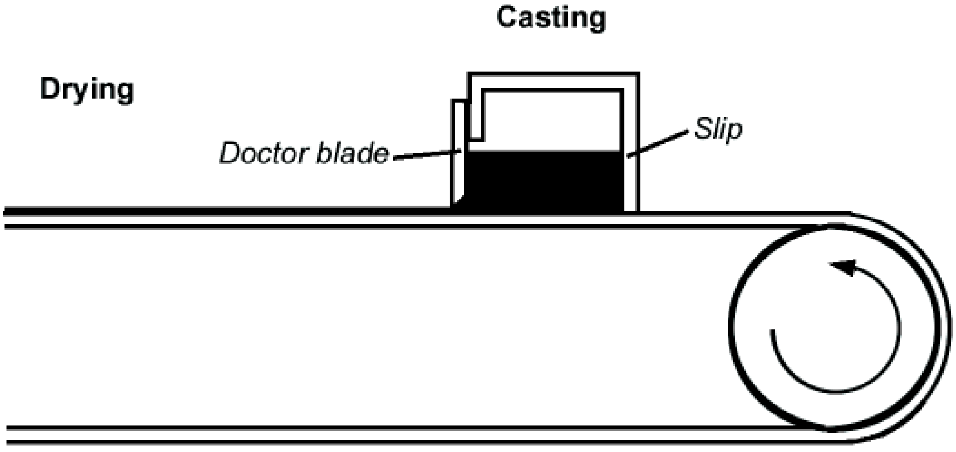


Figure 57: Tape casting

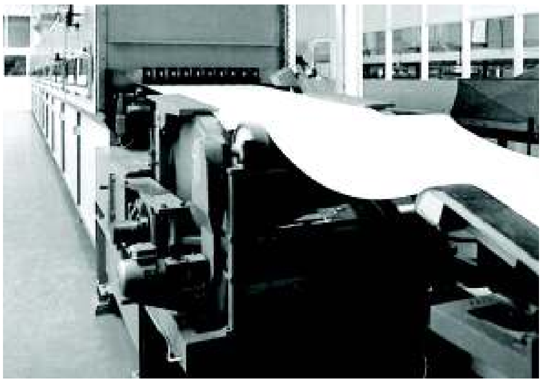


Figure 58: Tape casting machine

The choice

of the forming process to be used in any particular case depends, from a technical point of view, on the geometry and size of the part and the needs of the application. The piece count, raw material consumption and process costs determine the most economic choice.
Further extensions to the forming processes initially introduced here are possible.

Forming process
F1 Casting
• Slip casting including hollow, solid and vacuum casting. • Pressure casting • Tape casting
F2 Plastic forming
• Spraying, injection moulding • Extrusion • Copy turning
F3 Pressing
• Dry pressing • Isostatic pressing • Wet pressing/ moist pressing
F4 Special processes
• Slip jointing • Laminating

Table 3: Summary of ceramic forming processes

Forming process	***Advantageously*** permits	***Disadvantageously*** associated with
Slip casting	• Complex geometries (thin walls, asymmetric) • Low material consumption	• Complex rheology • Rough surfaces • Difficult mould manufacture • Limited form tolerance • High dimensional tolerance
Pressure casting (in comparison to slip casting)	• Fast build up of the body • Very low drying shrinkage • Good dimensional accuracy • No necessity to dry forms • Low space requirement	• Expensive tools • Large lot sizes are necessary • Problematic organic solvents
Tape casting	• Continuous production • Thin layers • Good dimensional accuracy • High manufacturing capacity	• Limited part geometries • Drying is necessary
Injection moulding	• Complex geometries • Close tolerances • Good reproducibility • High surface quality • Accurate contours • High lot sizes	• Expensive tools • High die wear • Limited part size • Expensive debindering • Noticeable density gradients
Extrusion	• Continuous production • High manufacturing capacity • High part lengths • Economical manufacture	• Distinct textures • Drying is necessary
Dry pressing	• Process can be automated • Good reproducibility • Good dimensional accuracy • Limited drying • Economically large lot sizes	• Limitations in the part geometries • Density gradients possible • Expensive moulding tools • Expensive powder preparation
Wet pressing/ moist pressing (in comparison to dry pressing)	• Complex part geometries • Uniform density distribution	• Drying is necessary • Lower compaction • Higher tolerances
Isostatic pressing	• High density without textures • No density gradients	• Low cycle times

Table 4: Advantages and disadvantages of common forming processes

4.1.4 From Forming to Firing

As a rule, green bodies made by a forming process like casting, plastic forming and pressing, contain, in addition to the ceramic powder mixture (including the permanent additives), moisture and often organic deflocculants, plasticisers, binders and other additives.
All components that are volatile at higher temperatures, i.e. which vaporise or decompose, must be removed from the green body with particular care before sintering in order to avoid damage.
Depending on the powder, the shape of the part and its size, and on the initial forming process, the green body incorporates greater or lesser density gradients. After sintering it is possible that these will make themselves noticeable in the tolerances of the part.

Drying

All particles in a formed moist body are surrounded by a film of water. The particles move closer together as the water is removed and a volume reduction takes place; this is referred to as drying shrinkage. The drying shrinkage increases with increasing moisture content. Shrinkage is also dependent on the grain size, the type of raw materials and the forming process.
For example, the plate-like form of clay mineral particles in extruded porcelain results in less shrinkage in the length than in the cross-section. Such orientations, called textures, must be taken into careful consideration when drying, according to size and geometry of the ceramic product.
Different drying methods are applied depending on the particular ceramic products.

Burning out

Green bodies formed from unfired material that is naturally plastic are often sufficiently resistant to breakage in this state. The resistance can, however, be improved with the aid of organic additives. Such additives are, however, indispensable when the unfired material is not plastic.

Burning out the remaining plasticisers and binders along with other organic additives requires a carefully adapted temperature-pressure-atmosphere-time profile in order to achieve a non-destructive and

reproducible removal of these additives from the finely porous green body.
One variation of burning-out is referred to as **carbonising or coking**, for example with SiC. Here, organic components are converted to carbon, which remains in the structure and is converted, with the help of added reagents, to a ceramic matrix during the sintering reaction.
After the drying and burning out (or carbonising/coking), the structure of the green body (pressed powder with the shape of component) is held together only by weak cohesive forces, and requires particularly careful handling during the subsequent process steps. For this reason, drying and burning out are integrated with the sintering wherever possible.

Prefiring

In order to reduce the level of risk during handling, and to allow the alternative *white machining*, the moulded green body can be strengthened by firing with relatively low shrinkage in **preliminary firing**. This requires strength and shrinkage to be made reproducible through control of the process parameters.

Firing

The goal of ceramic technology is the manufacture of a mechanically strong body able to withstand the widely differing requirements and conditions of the application. There is only a small degree of bonding between the particles of the green body. The ceramic bonding, and the very high strength associated with it, is obtained only by sintering at high temperatures. Firing allows sintering (with or without a liquid phase) to take place, and this is what actually creates the ceramic material.
The processes that occur during the sintering of the ceramic body are very complex. The sintering rate is dependent on purity, grain size, compaction and the sintering atmosphere. Products made of oxide ceramics with very high purity sinter via solid state reactions; they thus require much higher sintering temperatures than bodies containing feldspar, such as porcelain, that include a high proportion of glass phase material.

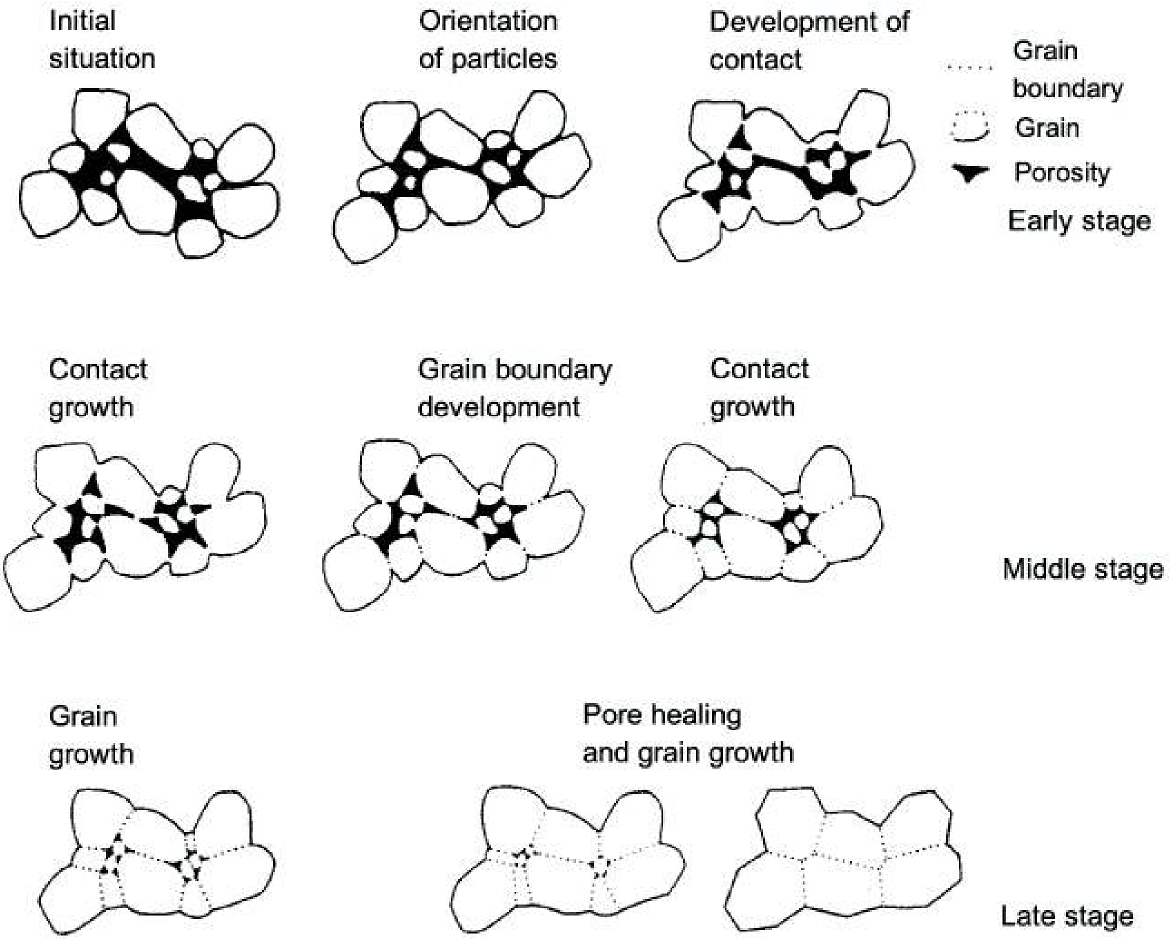


Figure 59: Grain growth during the sintering process

Through reactions that occur during sintering, a strengthening and densification of the ceramic takes place, resulting in a reduction in porosity. This process results in a volume reduction; this is called sintering shrinkage. The amount of shrinkage for the various ceramic materials is widely different.

Similar to drying, well-defined times and suitable atmospheres are required when firing ceramic products. Disregarding these can lead to increased internal stresses, to defects in the part, and to unsatisfactory characteristics. Thinner shapes and densely formed products behave better and can be sintered faster than large ones with greater wall thickness.

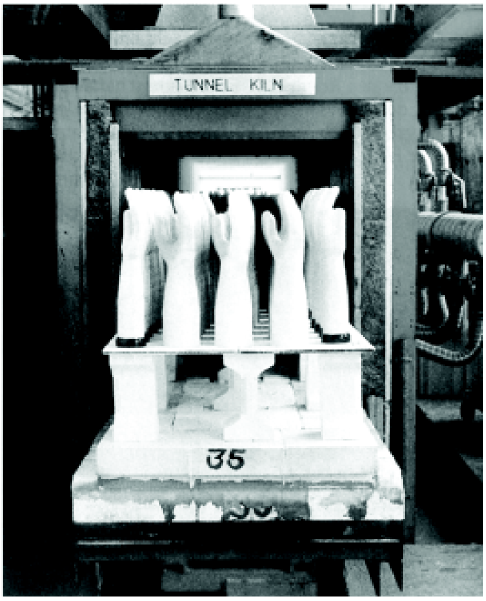


Figure 60: Tunnel kiln

Typical sintering temperatures:

Ceramic	Sintering temperature
Alumina porcelain	approx. 1,250 °C
Quartz porcelain	approx. 1,300 °C
Steatite	approx. 1,300 °C
Cordierite	1,250-1,350 °C
Aluminium oxide	1,600-1,800 °C
Recrystallised silicon carbide	2,300 - 2,500 °C
Sintered silicon carbide	approx. 1,900 °C
Silicon nitride	approx. 1,700 °C

Table 5: Sintering temperatures of various ceramic materials

The energy required for the sintering process increases disproportionately as the firing temperature rises. In addition to the energy input, the kiln furniture used to stack the green bodies in the kiln is made of highly refractory material, and is a significant cost factor.

Special varieties of material can be created from some ceramic materials with the aid of particular types of sintering process:

Hot pressing (HP)

is used to manufacture components with a density close to the theoretical maximum. It is a sintering process supported by uniaxial pressing.

Hot isostatic pressing (HIP)

allows small parts particular to achieve the maximum density through the application of isostatic gas pressure of up to 3,000 bar at temperatures up to approximately 2,000°C (usually within a collapsible silicate glass envelope).

4.1.5 Dimensions and Shrinkage

The primary goal when forming the green body from unfired ceramic material is to come as close as possible to the final dimensions and shape of the product to be manufactured, since machining after sintering is costly due to the very high hardness of the material.
In contrast to metals, the forming of ceramic parts is not the last step in the process chain, but rather almost at the beginning.

The green body for the ceramic product must be formed larger than the final dimensions, since one of the particular properties of ceramic technologies is that almost all materials experience a reduction in volume during the manufacturing process. This is due to volume loss during process steps such as moisture removal, drying and firing.
The actual ceramic material and its characteristic microstructure are not created until firing, making the desired material from the mixture of raw materials.
The high temperatures lead to a reduction of the specific surface area of the particles (diffusion processes, the creation of liquid phases, phase changes) and thus to compaction of the microstructure. This is associated with a reduction in volume, and is called **shrinkage**. For this reason, moulds or dies must be **"over-dimensioned"** with respect to the desired geometries, in order to compensate for the shrinkage that takes place during processing.

Material	Shrinkage S
Silicon infiltrated/ recrystallised silicon carbide	approx. 0 %
Sintered silicon carbide	18 - 20 %
Cordierite	3 - 8 %
Alumina porcelain	13 - 16 %
Aluminium oxide	17 - 20 %
Zirconium oxide	25 - 32 %

Table 6: Longitudinal shrinkage of some materials

After the mould has been filled with a measured quantity of material, even very slight variations in the density of the loose granulate being pressed have the effect that, in pressing, the unfired parts compact to a variable degrees, with the result that the degree of shrinkage occurring during sintering varies.

Tolerances in the linear dimensions of sintered parts using standard processes are therefore approximately ± 2 %, despite density variations and high shrinkage. These standard tolerances are specified in DIN 40 680[8]. The use of optimised, synthetic powders or working materials along with highly developed process control nowadays permit tolerances of < ± 0.5 % to be guaranteed.

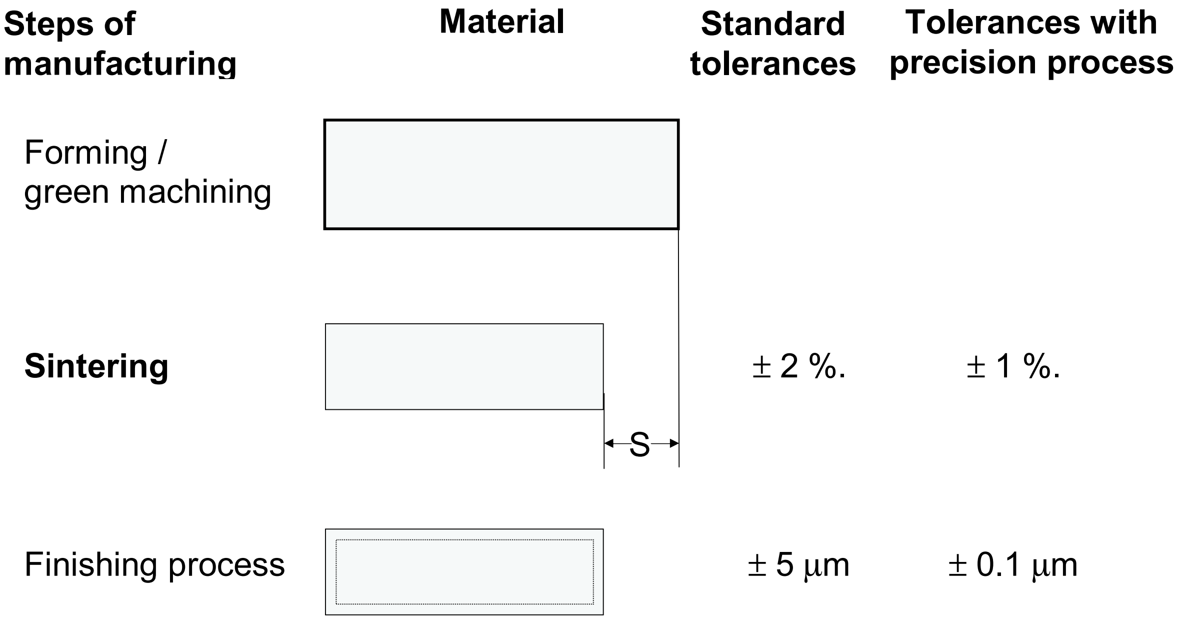


Figure 61: Dimensional tolerances after sintering and after hard machining

---

[8] See also pp. 212–221.

In contrast to the usual procedure with metallic materials, all dimensions should be given the widest possible tolerance ranges in order to avoid increased manufacturing costs. Above all, particular stress must be placed on the need for the user to limit close tolerances to whatever is absolutely necessary for the function of the ceramic part.

4.1.6 Machining

As shown in figure 62, **green machining** (after drying), **white machining** (after burning out and prefiring) and **hard machining** (after sintering) are to be distinguished.

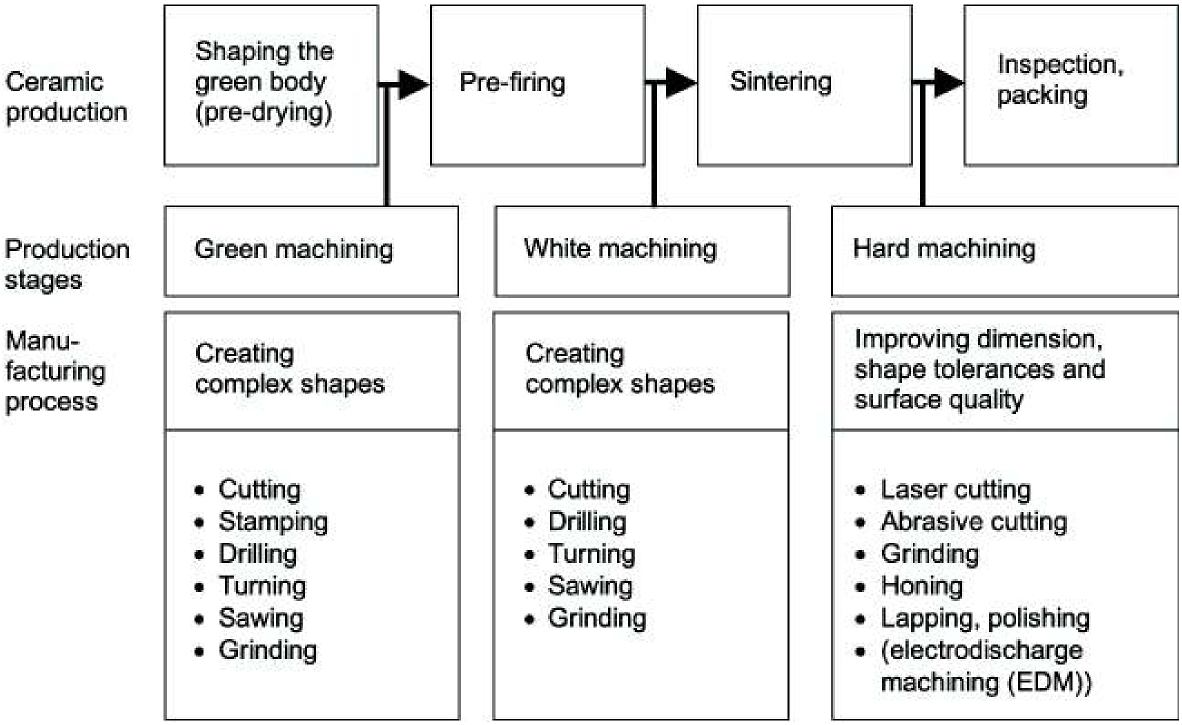
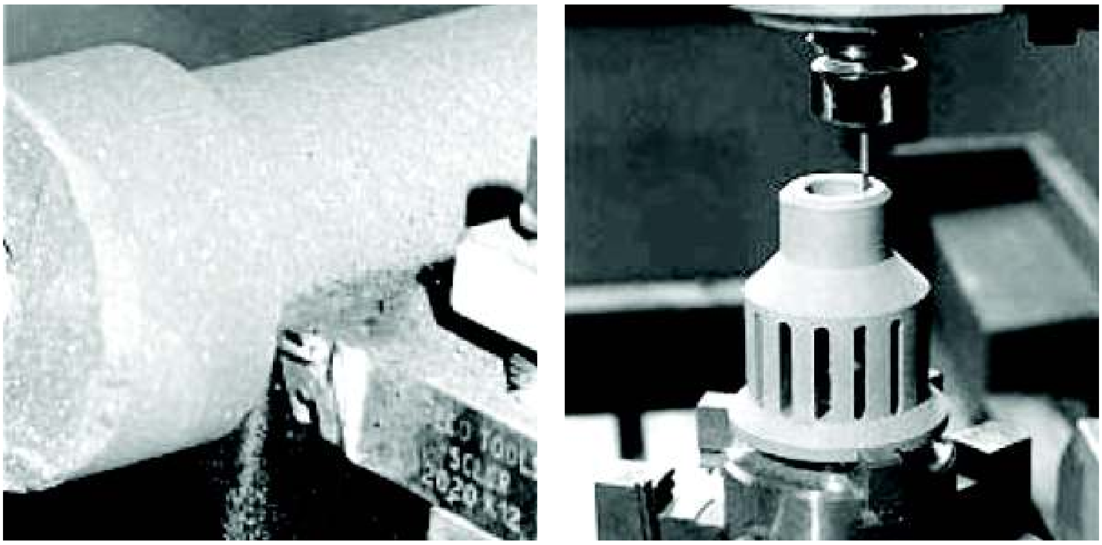


Figure 62: Classification of green, white and hard machining in the production process

Green machining

is performed on the dry parts while they still contain organic additives. It is well suited to the manufacture of individual parts and small series. It is also used with large series to manufacture shapes that cannot be realised directly by initial forming procedure, such as holes transverse to the direction of dry pressing.



Figures 63 and 64: Components being machined green

White machining

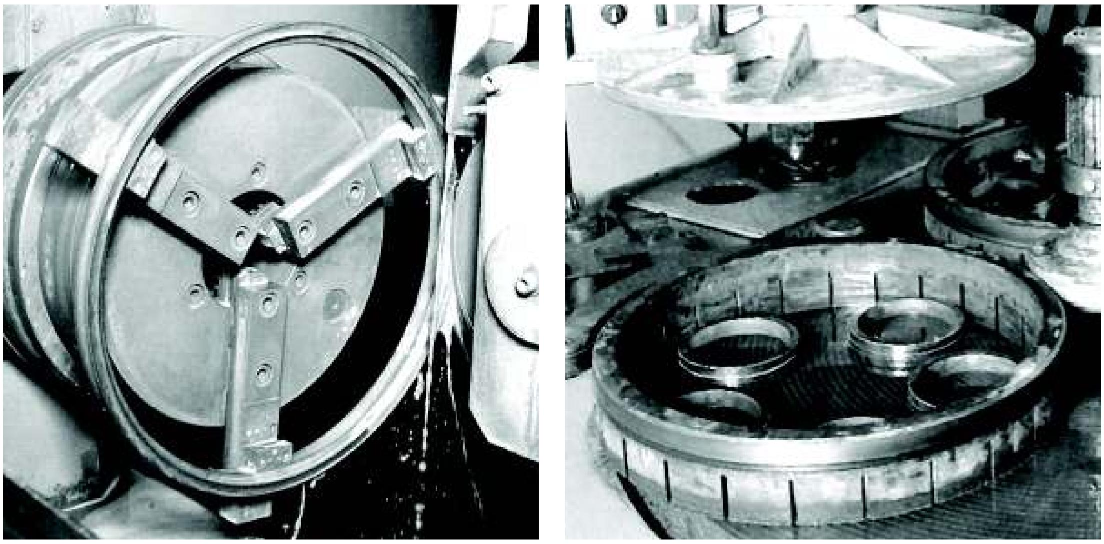
is performed on the prefired parts, now free from organic additives. The strength depends on the prefiring.
In this way, extremely high removal rates be achieved with relatively low tool wear using conventional, ceramic or diamond coated tools. This process is used by manufacturers both for making prototypes and for mass production.

4.2 Finishing

4.2.1 Hard machining

Final machining (hard machining)

is carried out on fully sintered items that have been brought as close as possible to the final dimensions through forming, or through green or white machining. The closest possible tolerances can be achieved through a final machining procedure involving material removal.
Tight requirements for dimensional precision and the wide variety of geometries and surface qualities require the use of modern machine tools for processing ceramic components. Due to the high hardness of ceramic materials, diamond tools (bonded or pastes) are used here almost exclusively.



Figures 65 and 66: Hard machining components: grinding and lapping

Methods	Tool material	Goal
Grinding	Mechanically bonded grit, wet; diamond grinding wheel	Coarse or fine machining (e.g., profiles and bearing surfaces), Manufacture of functional surfaces while complying with the required tolerances and surface qualities.
Cutting	Mechanically bonded grit, wet; diamond cutting wheel Diamond grinding wheel	Separation of blanks
Honing	Mechanically loose grit, wet Diamond honing bar	Improving the dimensional precision and surface quality (e.g., sliding surfaces)
Lapping, polishing	Mechanically loose grit, wet Diamond lapping mixture	Improving the dimensional precision and surface quality (e.g., section preparation, sealing surfaces)
Ultrasonic lapping	Mechanically loose grit, wet; diamond lapping mixture.	Drilling, engraving
Water jet cutting	Mechanically loose grit, wet	Cutting
Sandblasting	Mechanically loose grit, dry	Removal of softer areas on the surface; surface roughing
EDM	Electric; copper, tungsten or graphite electrode	Complex shapes, almost only with SISIC
Laser processing	Thermal; CO_2 laser	Drilling, separating, cutting

Table 7: Possible finishing processes.

Grinding is of central importance. A large number of factors affect the grinding process and the result of the grinding. For this reason, the appropriate grinding wheel for any particular workpiece is selected with great care for its grain type and size, the bonding, and the hardness of the wheel. Extremely flat surfaces such as for slip rings and sealing surfaces must be **lapped** and then **polished** after grinding.

4.2.2 Surface Characteristics

Surface characteristics, and the way in which they depend on the most important hard machining processes, are described below.
Definitions used in measuring surfaces and examples are illustrated on page 231.

4.2.2.1 Ground Surfaces

The characteristic of grinding is the overlapping of a large number of scraping movements on fixed paths taken by grinding grains in one particular direction parallel to the surface of the workpiece. The scraping movement of the cutting grains directly induces micro-cracks, brittle breakage and/or plastic flow, and hence the ductile separation of ceramic particles.

Figure 67 shows machining tracks which illustrate the mechanisms by which material becomes separated, with areas of primarily plastic deformation, of primarily brittle fracture and of a crack may clearly be distinguished. The crack area is characterised by microscopic axial, radial and lateral cracks.

Surfaces whose creation has primarily been influenced by plastic deformation procedures typically display scoring, rounding, stratification, flaking and a relatively small number of break-outs. The process is called *"ductile cutting"*.
In contrast to this, break-outs, pile-ups, facetting and spalling are typical of "brittle cutting".
Grinding a surface usually results both in ductile and in brittle cutting. The dominant mechanism of material separation depends on the local stress conditions on the individual grains of the ceramic microstructure during the scraping process. The changeover from brittle to ductile

cutting depends in particular on exceeding a critical cutting thickness at the individual grain, but also on the micro-geometries of the cutting grains.

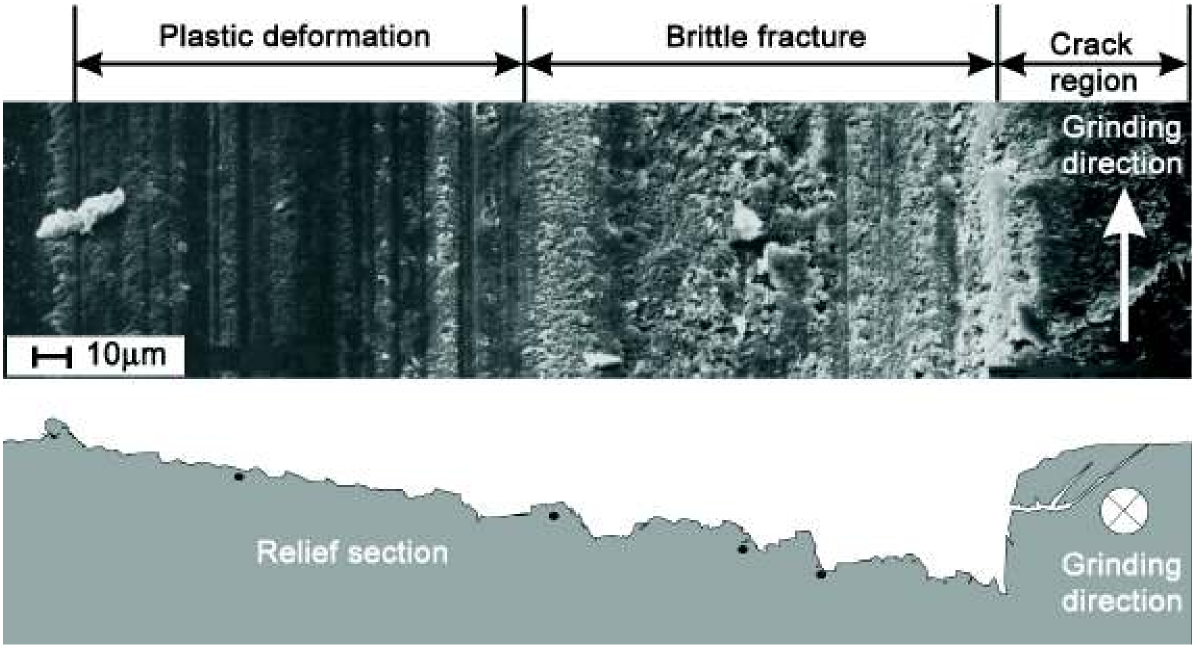


Figure 67: Different material separation mechanisms in ground silicon nitride

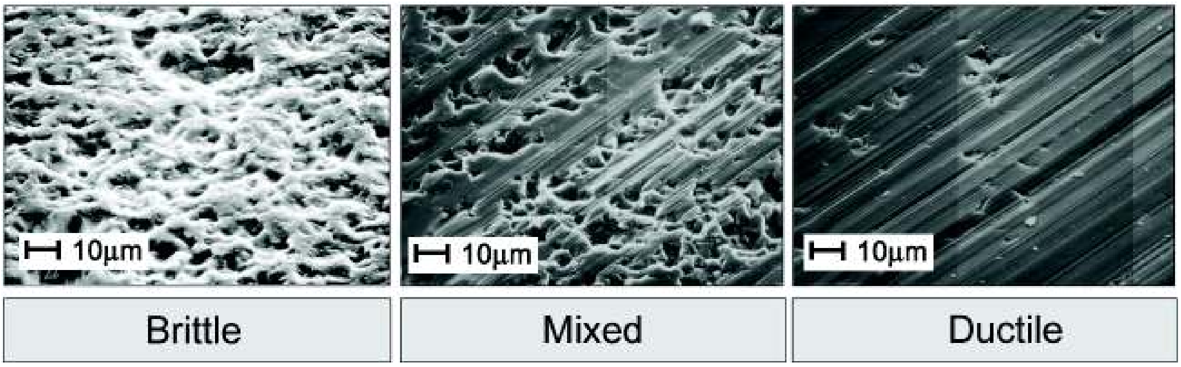
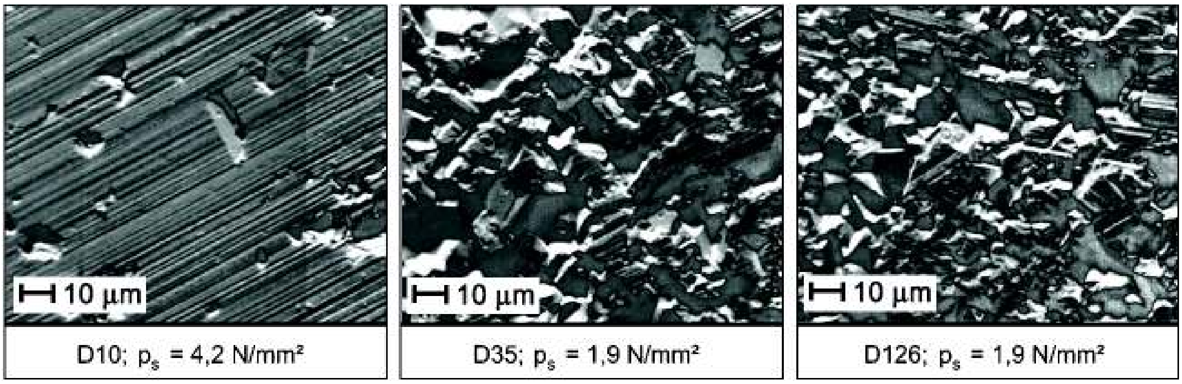


Figure 68: Ceramic surfaces subjected to brittle, mixed and ductile grinding

4.2.2.2 Honed surfaces

The overlaying of a large number of fixed-force scraping movements of cutting grains over the material, involving wide-area tool contact and a primary active direction parallel to the surface of the workpiece are characteristic of honing. The cutting speed involved in honing is perhaps an order of magnitude lower than that used for grinding, which means that thermal effects are comparatively small. As a result of this, honed ceramics surfaces generally do not display any signs of fusion or thermally induced cracks. As with grinding, both ductile and brittle material separation mechanisms occur next to one another. The penetration depth of the cutting grains and the cutting speed are the primary factors influencing which of these mechanisms will be dominant.



D10; p_s = 4,2 N/mm²

D35; p_s = 1,9 N/mm²

D126; p_s = 1,9 N/mm²

Figure 69: Surface generation depending on the cutting grain size, D, and the contact pressure, p_S, when honing aluminium oxide

Higher cutting speeds have a positive effect on the rate at which material is removed when honing with brittle cutting. Higher cutting speeds are, however, are a disadvantage for the surface quality due to the increased tendency to induce cracks that lead to break-outs and spalling.

4.2.2.3 Lapped surfaces

DIN 8589 defines lapping as a cutting process using loose grains distributed in a paste or liquid (the lapping mixture) that is applied to a lapping tool, most often one that provides shaping, where the cutting tracks of the individual grains are largely unordered.

Because of the low rate at which material is removed, lapping processes are used to improve forming accuracy and surface quality. The almost isotropic surface topography of the microgeometry, in which the scratches are unordered, a large number of very homogeneously distributed hollows and isolated inter-crystalline surface break-outs are characteristic of this process. These structures are often found to be beneficial when the tribological or optical functional demands are high
In lapping, the surface material is carried away by the rolling motion of the cutting body and by scratches made by cutting grains that have temporarily anchored themselves in the lapping wheel.

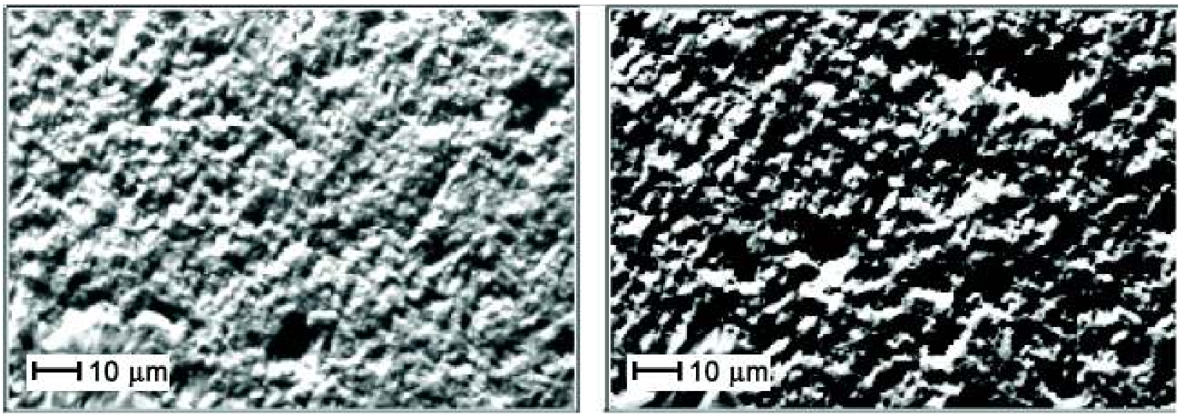


Figure 70: Silicon carbide surfaces lapped using F180 and F800 lapping grains

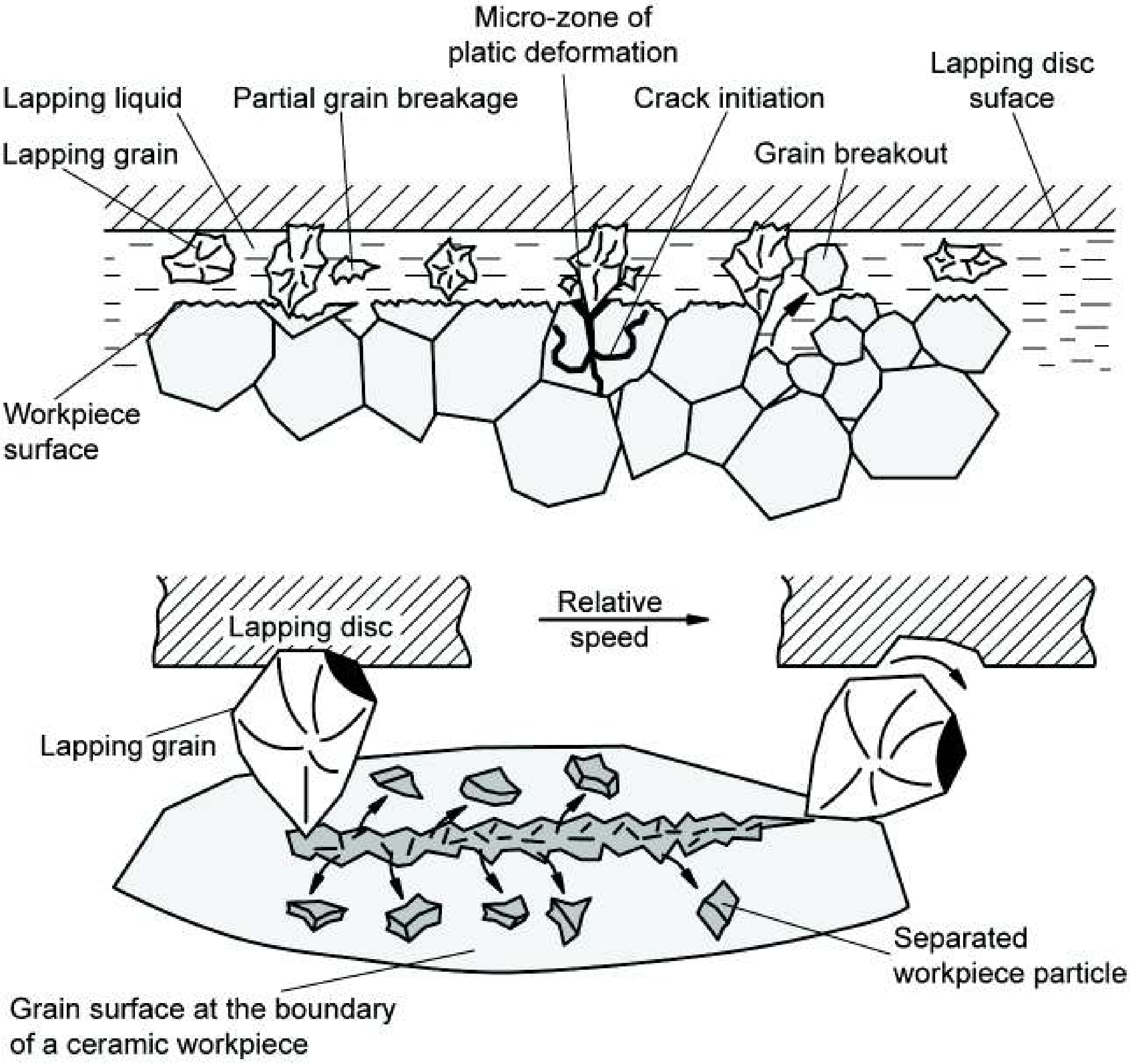


Figure 71: Model of material removal by lapping

The surface quality that can be achieved with lapping depends on the microstructure of the ceramic material being machined. The more fine-grained and the denser the material is, the higher the achievable surface quality. Depending on the grain size, process conditions and microstructure of the ceramic being lapped, dimensional precision of 1 µm/m, plane parallelism of up to 0.2 µm, and mean roughness figures $R_a < 0.3$ µm, can be achieved.

4.2.2.4 Polished surfaces

According to DIN 8589, polishing is not an independent production process, and is only used in association with other manufacturing processes. Processes such as polish grinding, polish honing, polish lapping, electrolytic polishing and polishing through coating (the application of polish with mechanical treatment) are distinguished. Polishing is primarily intended to create a high quality of surface. In contrast to lapping, the polishing grains are embedded in a cloth or polishing wheel so that directed tool movement, which is necessary to create optically reflective surfaces, is achieved. Because of the low rate of material removal, polishing is time-consuming.

Slight plastic deformation is only normally achieved in ceramic machining through extremely high localised pressure. For this reason, the removal of material when polishing ceramic is explained through scratches involving cutting depths in the range of nanometres. Polished surfaces are characterised by smooth areas and hollows, depending on the polishing time and the polishing grains used. Other surface characteristics are only occasionally met, and are not typical.

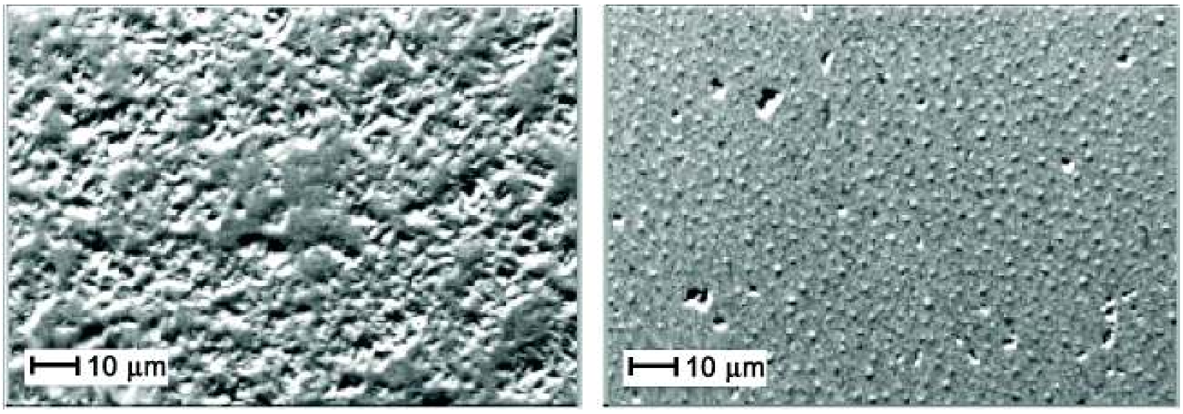


Figure 72: Silicon carbide surfaces polished with 9 µm and 0.25 µm polishing grains

4.2.3 Metallisation

Some manufacturers of technical ceramics offer metallised ceramics. Aluminium oxide and aluminium nitride are available as substrate materials. The metallisation offered is suitable for brazing, and, of course, also for soft soldering, and consists of a base metallisation of tungsten having a layer thickness of at least 6 µm, applied by a screen printing process and fired on. A layer of nickel, applied non-electrolytically, with a minimum thickness of 2 µm, is applied on top to assist the flow of solder. Other layer thicknesses are possible.
A gold layer with a thickness of approx. 1 µm can be deposited to protect against corrosion. Alternatively, the electroless applied nickel layer can be reinforced with a bondable gold layer. An additional layer of tin can also be applied if soft soldering is planned.

4.2.4 Glazing and Enamelling (“engobe”)

Depending on the grain size of the starting materials and the crystalline phases created during the firing, the ceramic product possesses a certain surface roughness, as a result of which the surface can more easily become soiled.
By applying a **glaze**, the surfaces are made smooth and visually more attractive. Above all, however, the glaze may noticeably improve many technically important properties of the ceramic product (for example, electrical behaviour, mechanical strength, resistance to chemicals, etc.).
The glaze contains a higher amount of flux than the fired ceramic body. Thus at high temperatures it has a corrosive effect on the body. The result is the creation of an intermediate layer, leading to a strong bond between the glaze and the ceramic material underneath. A wide variety of glaze colours can be created by mixing in colorants (metal oxides).
In order to achieve the increase in strength that is possible, the thermal expansion coefficient of the glaze must be matched to that of the body very precisely. A slight compressive stress in the glaze increases the strength of the finished product. Tensile stress reduces this effect, and is thus undesirable.

A thin mineral “**engobe” or non-vitreous enamel** layer is applied to ceramic surfaces by dipping, rolling, spraying or brushing.

In contrast to glazing, an engobe is porous and largely free from glass phase material. They usually consist of fire-resistant oxides (Al_2O_3, SiO_2, MgO, ZrO_2), mixtures of these, or of fire-resistant minerals such as mullite, spinel, zircon silicate, or even kaolin or clay.
Engobes are used in furnace engineering to protect ceramic surfaces from mechanical or corrosive attack. Applied to fire-resistant kiln furniture such as plates, beams or cases, engobes prevent both contact reactions with the supported firing materials and adhesion from any glaze running off the fired items that are standing on the coated kiln furniture.

4.2.5 Ceramic Coatings

Ceramic coatings, which offer the excellent properties of ceramics such as high hardness and wear resistance, electrical insulation, low thermal conductivity and reproducible surface structures, are used for surface protection.

Thick film and thin film techniques are differentiated in the manufacture of ceramic coatings.

Thick films (> 20 µm) are applied, for example, by thermal spraying. Plasma spraying has shown excellent results in this application. During plasma spraying, oxide ceramic powder or powder mixtures such as aluminium oxide, aluminium oxide / titanium dioxide, zirconium oxide and chromium oxide are melted in a plasma flame at approx. 10,000 °C and sprayed on a previously sandblasted metal surface.

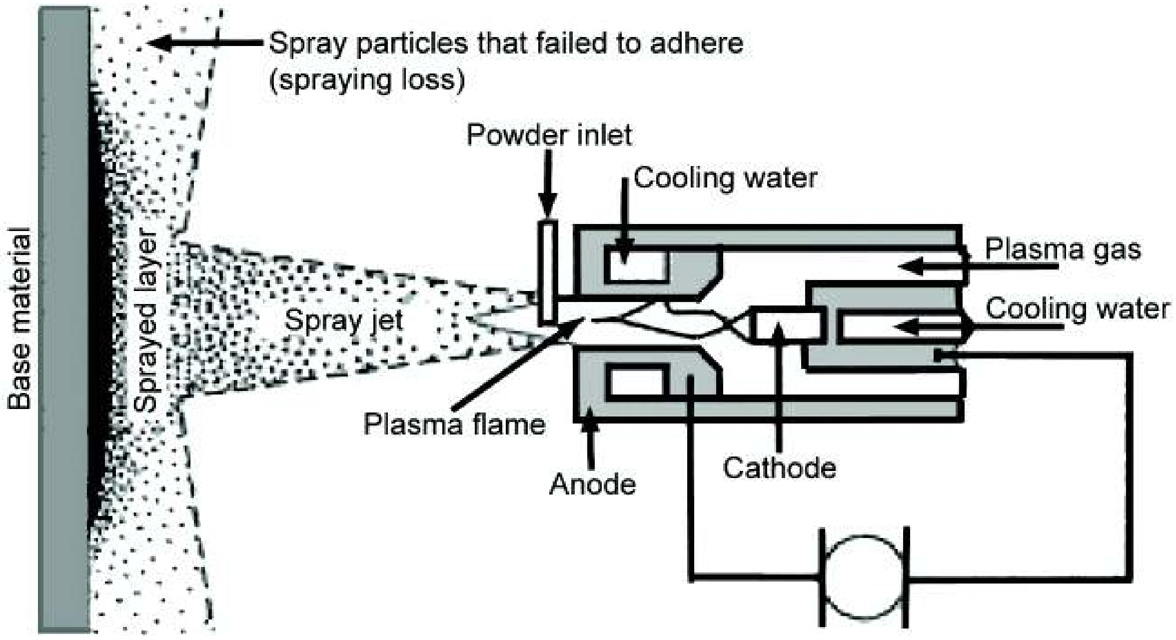


Figure 73: The principle of plasma spraying

However, it is necessaryto ensure that before plasma spraying a fissured surface is created through sandblasting to which the ceramic particles can cling as they arrive.
Several layers are applied, so that a lamellar layer structure with good adhesion results.

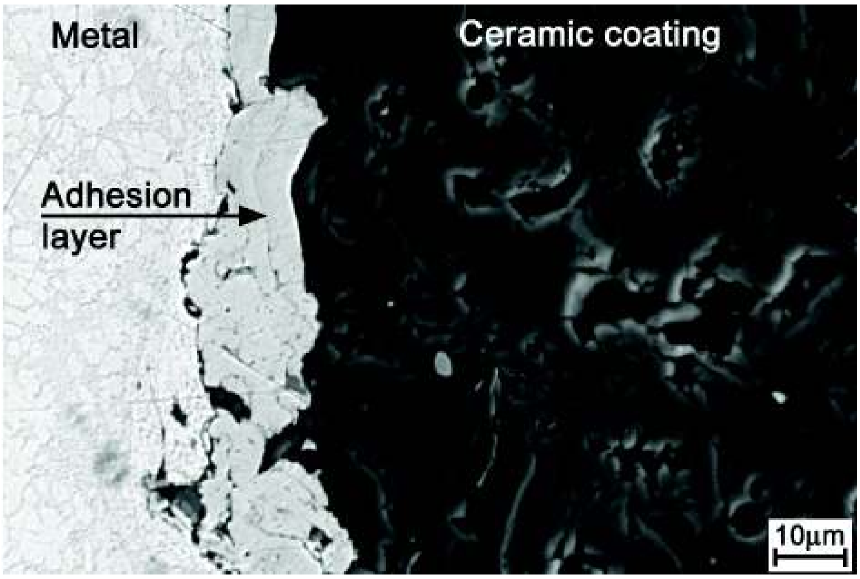


Figure 74: Section through a coating showing the intermediate layer

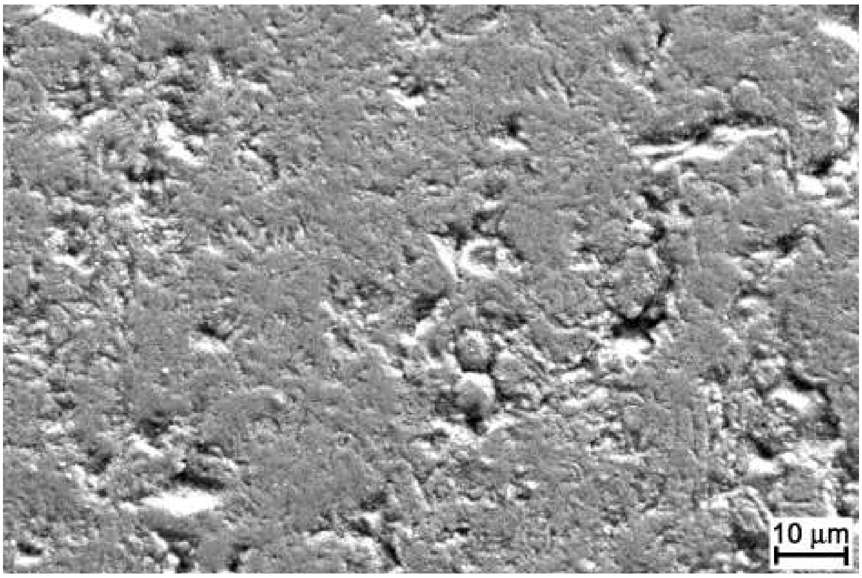


Figure 75: Ground surface of a chromium oxide coating

An advantage of this process is that any metallic material (with the exception of magnesium) can be coated with ceramics. Oxide ceramic powders such as pure white aluminium oxide may be applied for electrical insulation and as a protection against wear, or zirconium oxide for thermal insulation. For increased wear resistance, mixtures of aluminium oxide and titanium dioxide in various proportions are used. Titanium dioxide stabilises the alpha phase of aluminium oxide and makes this ceramic coating tough, and resistant to impact and fracture. Its colour varies between grey, blue grey and black, depending on the mixture. Chromium oxide is preferred over metallic materials for bearings and pumps because of its very good tribological properties. An intermediate layer of nickel-chromium (the ‘bond coat’) improves adhesion.

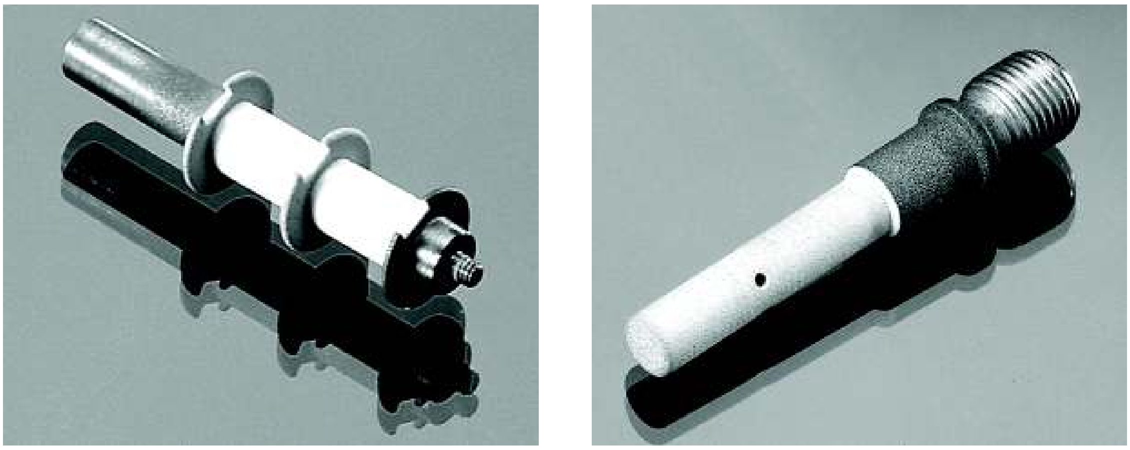
The ceramic surface is brought to a reproducible roughness through subsequent machining. In most applications, a standard surface with an Ra = 1.5 to 2 µm has been found to be reliable. A shiny surface with a $R_a \approx 0.5$ µm is achieved through hard machining.

For aluminium oxide, the hardness of the ceramic layers is around HV ≈ 1,800. In comparison, the hardness of hardened steel is around HV ≈ 700, and that of hard-chromed surfaces around HV ≈ 1,200.

Figure 76: Components coated for wear resistance

The advantage of an insulation layer 0.1 to 0.5 mm thick is the saving of space. It is, moreover, insensitive to heat, shock, and, to a certain degree, to aggressive media and wear. Due to the porous lamellar structure, stainless steel is recommended as the substrate in corrosive environments. An important application of ceramic coatings is their electrical insulation (up to approximately 500 V) at operating temperatures over 200° C, for example of heating elements. The ceramic layer adheres reliably up to 600 °C.

The metal parts should be free from visible blow-holes, scratches and pores, since the growth of the ceramic layer reproduces any surface irregularities. A finely turned or polished metal surface with R_z = 8 to 16 µm is recommended. The thickness of the metal parts should be a minimum of 1 mm in order to avoid heat build-up, which can deform the parts. Thin sheets or wires cannot therefore be plasma sprayed. The maximum length of the metal parts to be coated is dependent on the size of the chamber and extract ducting available, and is typically limited to 2 m.



Figures 77 and 78: Components with coatings for electrical and thermal insulation

Adhesion to edges is limited. For this reason, edges should be rounded to have a radius > 0.7 mm. Consideration of the clamping region (thread or pin) is necessary if a design appropriate for coating is to be achieved. Products can also be partially coated. In this case, the metallic surfaces are covered where necessary.

These coating procedures using ceramics are suitable for experimental batches of 1 to 10 as well as for production series of 10,000 or more. The procedure offers a facility for rapid production at short notice. It allows metal parts to be created on CNC machines, coated and further processed within a few days. Repair coatings are also of interest. Used ceramic coatings that have been damaged by shocks and impacts during heavy use can simply be sandblasted away. Expensive metal parts can be re-ground and coated with ceramic again.

Plasma sprayed coatings have proved themselves, for example, in textile and wire drawing machines.

Thin films (< 20 µm) are applied by PVD (physical vapour deposition) or CVD (chemical vapour deposition), by galvanic processes or by sol-gel processes. Here, for example, tools with the familiar gold coloured TiN coatings have found wide acceptance.

5 Properties of Technical Ceramics

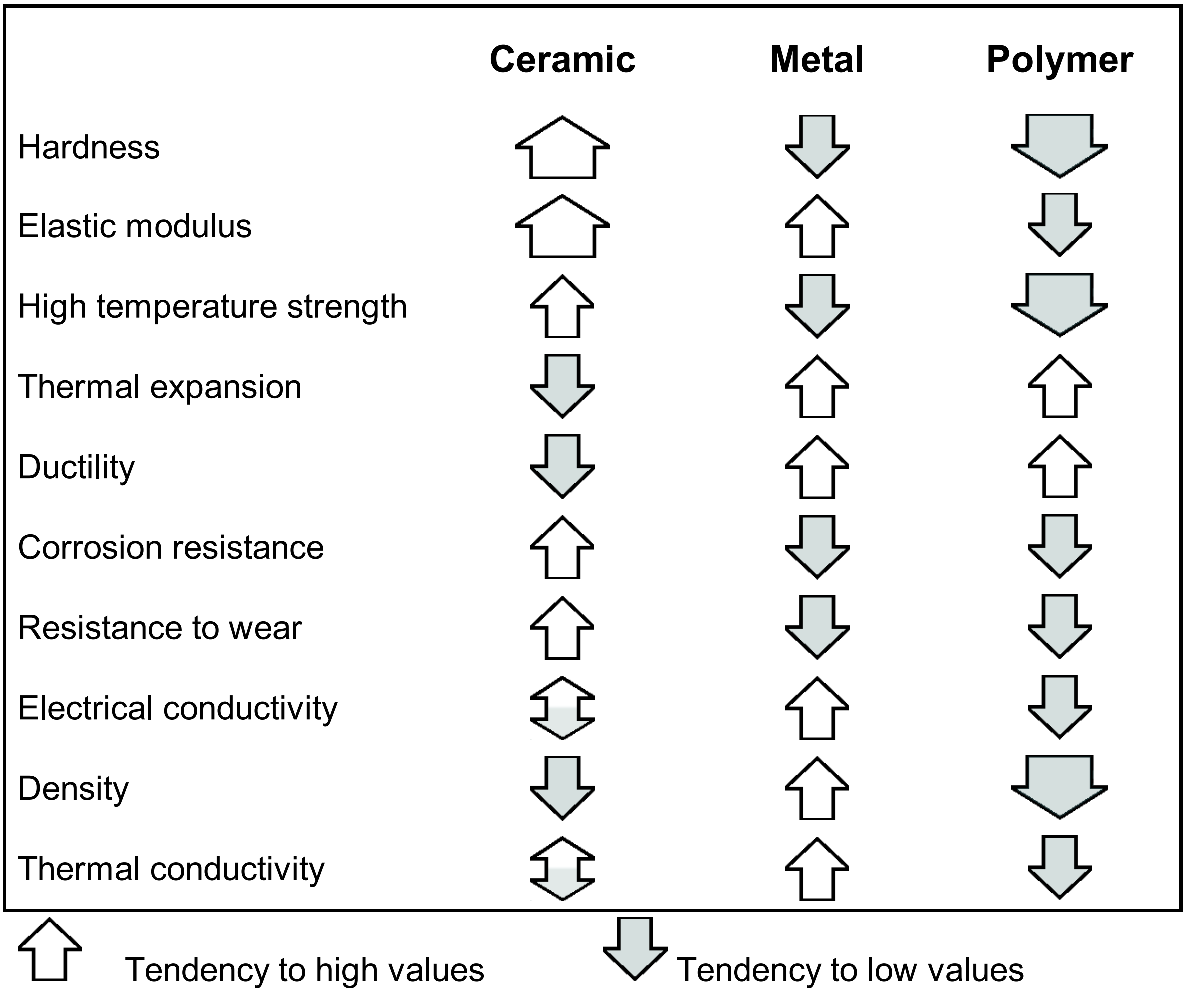
5.1 General Comparison

The wide variety of application possibilities for ceramic materials arise from their specific properties which in many respects cannot be achieved by other materials. To highlight some positive properties:

- low density,
- high hardness,
- high mechanical strength,
- dimensional stability (specific stiffness),
- resistance to wear,
- resistance to corrosion (resistance to chemical attack),
- weathering resistance,
- high working temperature,
- low or high thermal conductivity,
- good electrical insulation and
- dielectric and ferroelectric properties.

Depending on the composition and the processing of the raw materials as well as on forming and the type of sintering, the properties of the material can be closely tailored to the desired application.

Figure 79, which compares the most important properties, simplifies an assessment of the property profile of **technical ceramics** as against metals and polymers.



	Ceramic	Metal	Polymer
Hardness	⬆	⇩	⬇
Elastic modulus	⬆	⇧	⇩
High temperature strength	⇧	⇩	⬇
Thermal expansion	⇩	⇧	⇧
Ductility	⇩	⇧	⇧
Corrosion resistance	⇧	⇩	⇩
Resistance to wear	⇧	⇩	⇩
Electrical conductivity	⇳	⇧	⇩
Density	⇩	⇧	⬇
Thermal conductivity	⇳	⇧	⇩

⇧ Tendency to high values ⇩ Tendency to low values

Figure 79: A comparison of the properties of ceramics, metals and polymers

The direction of the arrow indicates the tendency in comparison with typical values. Any assessment must depend on the particular application.
A broad arrow indicates a particularly strong manifestation of the feature.

The characteristic properties[9] of metals, ceramics and plastics can be explained by the different nature of their atomic bonds.[10]

---

[9] Further material comparisons are shown later in this chapter.

[10] See Section 10, p. 209, Bonding types and strength

5.2 Classification of Useful Properties

The stress-strain relationship, which is often crucial for mechanical applications, is illustrated in Figure 80 using the example of a steel, an Al_2O_3 ceramic and a thermoplastic. The limited breaking elongation of the ceramic[11] compared to that of metals, combined with an often significantly lower fracture toughness K_{IC}, is generally to be considered a disadvantage, although it simultaneously entails the advantage of dimensional stability, in particular at high temperatures.

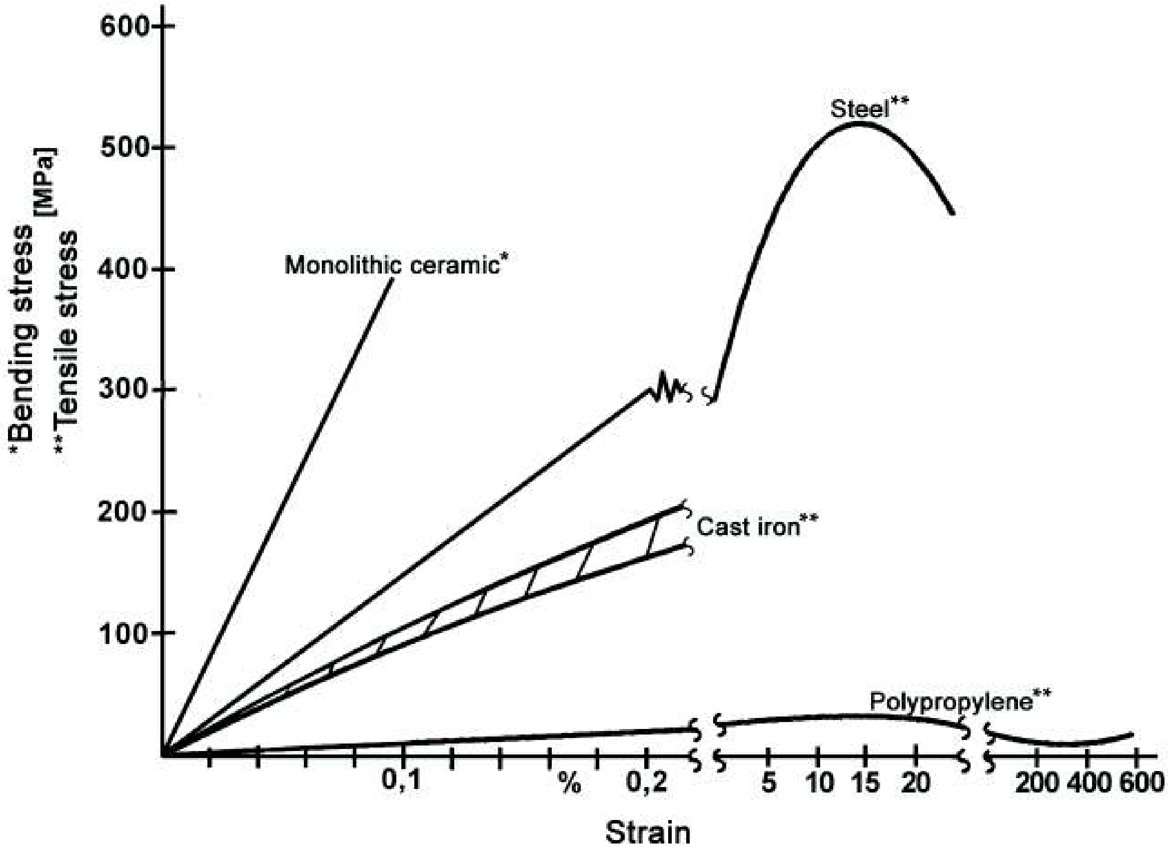


Figure 80: Stress-strain behaviour of selected materials

---

[11] Other characteristic values for ceramic materials may be found on pp. 263-273.

Material properties		Porcelain	Steatite	Aluminium oxide	Zirconium oxide	Silicon nitride			SIALON	Silicon carbide			Mild steel	Cast iron
				(> 99 %)	PSZ	SSN	HPSN	RBSN		SSIC	RSIC	SISIC		
Density	g/cm^3	2.3	2.7	3.94	6	3.3	3.4	2.5	3	3.15	2.8	3.12	7.85	7.3
Bending strength (25 °C)	MPa	110	140	520	1000	1000	900	330	355	600	120	450	300 - 450	95 - 170
Bending strength (1000 °C)	MPa	-	-	-	-	-	-	300	355	650	130	450	-	-
Elastic Modulus	GPa	70	110	360	210	330	800	180	231	450	280	350	200 - 210	70 - 130
Fracture toughness	MNm$^{-3/2}$	-	-	5.5	> 8	8.5	8.5	4	2.2	5	3	5	140	-
Linear coefficient of thermal expansion (20-1000 °C)	10^{-6}K^{-1}	8	8.5	8	5	3.5	3.28	3	3	4.8	4.8	4.8	10	12
Weibull modulus	m	-	-	> 10	> 15	> 10	> 10	> 10	15	> 10	-	> 10	-	-

(*) Data not usually provided

Table 8: A comparison of typical mechanical characteristics of some ceramics with grey cast-iron and construction steel

Technical aspect	Characteristics relevant to application
Mechanical	Density, strength, hardness, stiffness, resistance to abrasion
Thermal	High/low thermal conductivity, thermal expansion, resistance to high temperature, resistance to aging, resistance to temperature cycling, resistance to thermal shock
Chemical/ biological	Resistance to corrosion, adsorptive capacity, biocompatibility, inertness
Electrical	Dielectric strength, electrical insulation, withstand voltage, loss factor, permittivity, specific semiconducting properties
Electro-mechanical	Piezo-electric effect
Electrochemical	Ionic conduction
Nuclear	High-temperature strength, corrosion resistance, resistance to radiation

Table 9: Technical aspects and relevant properties of ceramics

5.3 Mechanical properties

5.3.1 Density

The **density** ρ [g/cm³] of technical ceramics lies between 20 and 70% of the density of steel. This presents the possibility of weight reductions, which is an advantage for moving parts in machine construction. The relative density, d [%], has a significant effect on the properties of the ceramic. For this reason it can be important, for instance, for mechanical applications to achieve a density close to the theoretical figure without generating density gradients, in order to obtain the best possible mechanical properties.
On the other hand, relatively low densities resulting from uniform porosity can, for instance, have a positive effect on the ability to withstand thermal shock.

Test procedures for determining density and porosity are specified in DIN EN 1 389, DIN EN 623-2 and DIN EN 60 672-2.

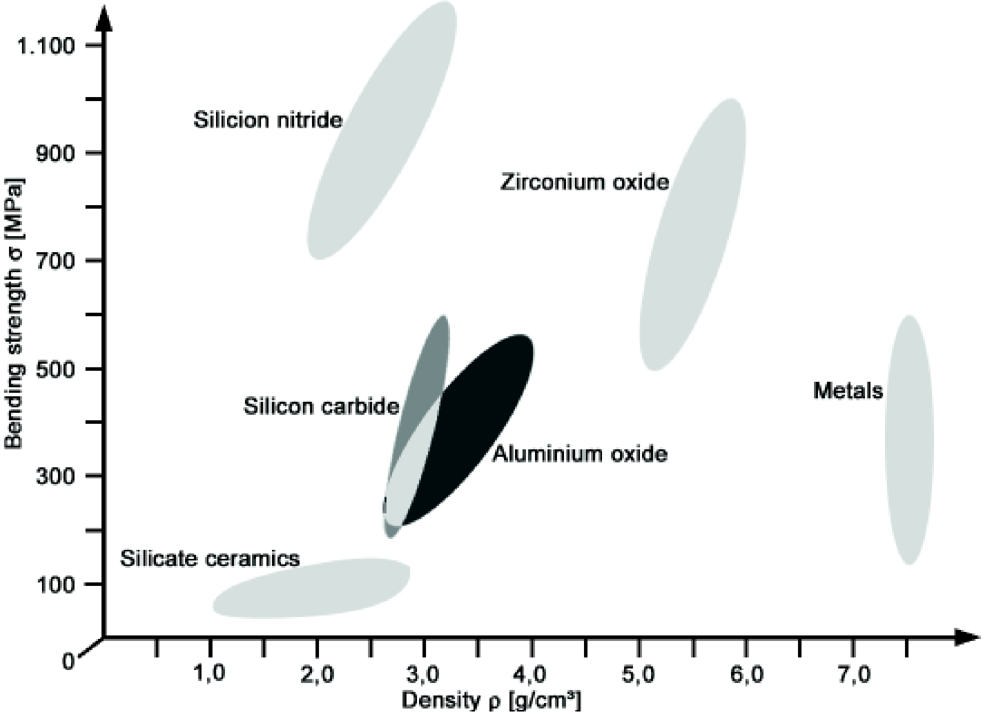


Figure 81: A guide to the bending strength and density of selected materials

5.3.2 Porosity

As a rule, technical ceramic materials have no open **porosity**, and are thus gas tight. For some materials, however, porosity is desirable. This may be because thermal stresses are more easily managed by porous materials, or because larger surface areas are required. Porosity can be deliberately generated through the appropriate selection of raw materials, the manufacturing process, and in some cases through the use of additives. This allows closed and open pores to be created with sizes from a few nm up to a few µm.

Test procedures for determining open porosity are specified in DIN EN 623-2.

5.3.3 Strength

The figure for the **strength of ceramic materials,** σ [MPa][12] is **statistically** distributed depending on the material composition, the grain size of the initial material and the additives, the production conditions and on the manufacturing process. According to the **weakest link model**, the defect distribution and what is termed the critical defect decide the reliability of the part. For this reason the scatter between batches can be greater than within one batch.

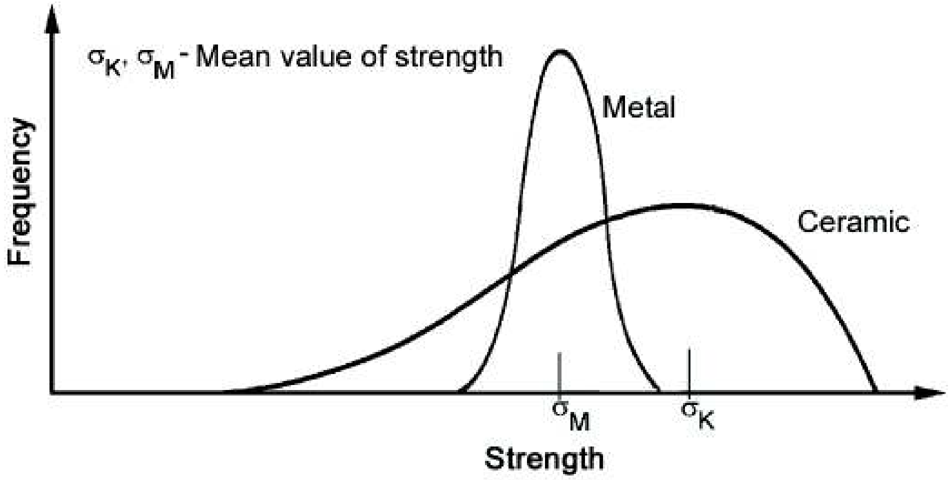


Figure 82: Strength distribution within batches

5.3.3.1 Bending Strength

The bending strength, σ_B [MPa], is the most important parameter for estimating the strength of components and for dimensioning them. Tables of materials properties contain values obtained from either 3-point or 4-point tests[13] on special bending test bars. The value obtained from the 3-point bending test is around 30% higher than that from the 4-point test. In **Germany** it is usual to quote figures based on the **4-point** procedure. Comparing the data is often made more difficult by the absence of information about the method used for the measurement.

The values for a component's bending strength are affected by the size, shape, surface ("as fired", ground etc.), and, in some cases, by

---

[12] See also pp. 226ff. and 239ff.
[13] The test procedure is described on pp. 226ff.

inhomogeneities in the microstructure resulting from the manufacturing process.

Test procedures for determining the bending strength are defined in DIN EN 843-1, DIN EN 820-1 and DIN EN 60 672-2.

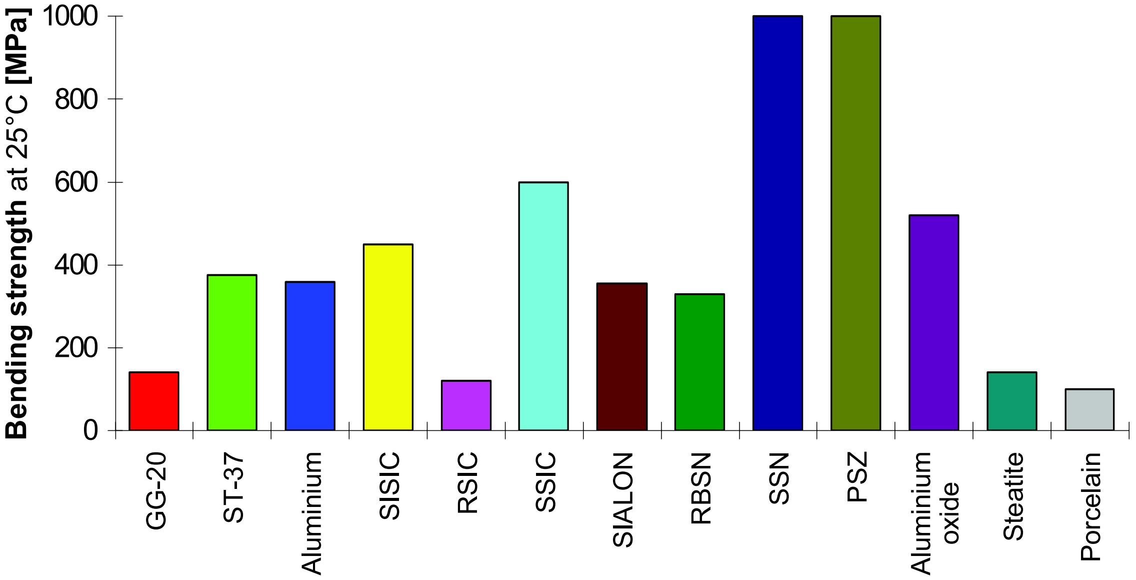


Figure 83: Bending strength of selected materials

Technical ceramics are distinguished by their very good high-temperature strength, with maximum **working temperatures** that even exceed those of metallic *superalloys*. Ceramic materials are thus ideal for applications in high-temperature processes (see Figure 84).

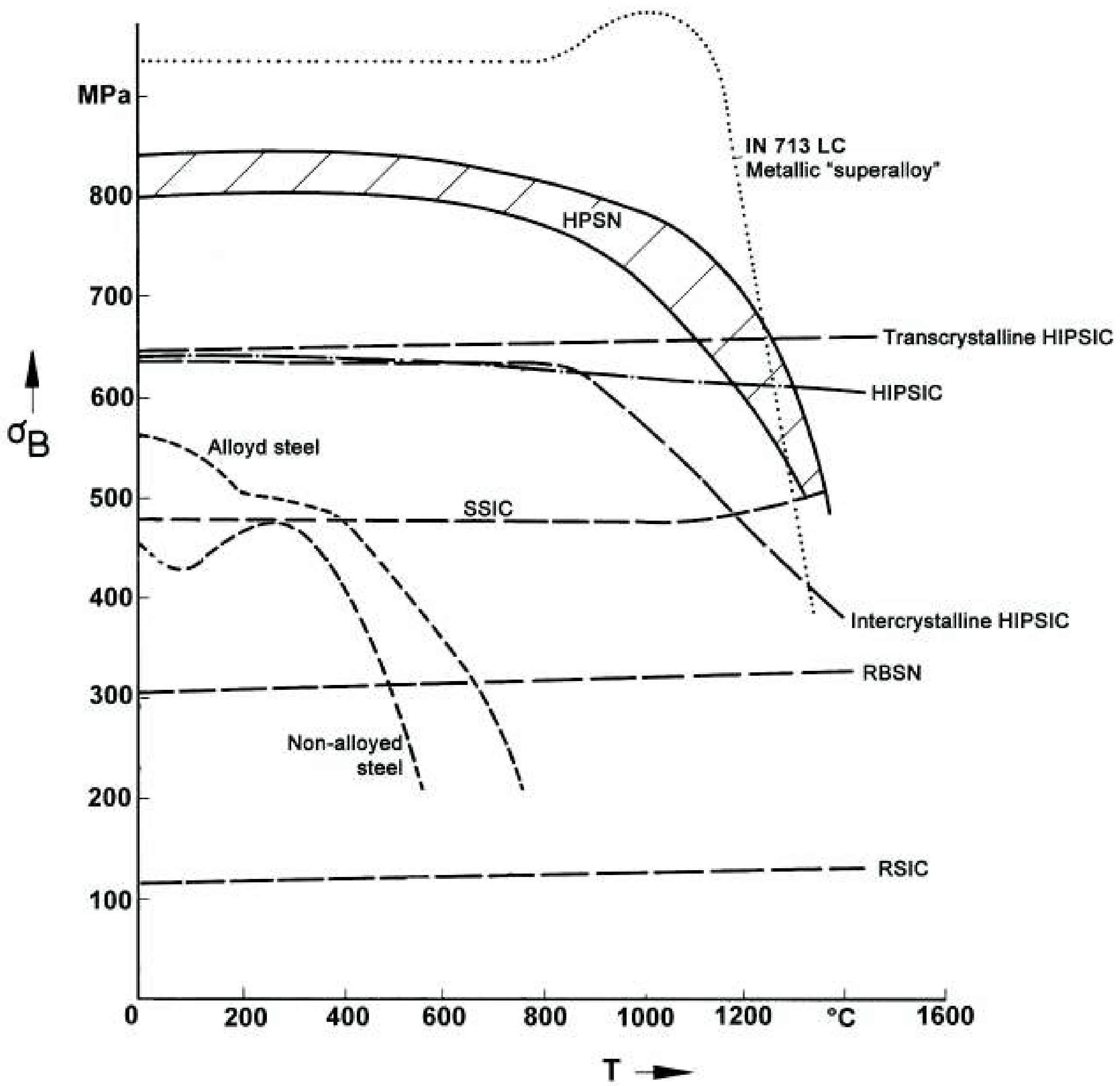


Figure 84: Effect of temperature on bending strength

5.3.3.2 Compression strength

The compression strength of ceramics is between **5 and 10 times** greater than the bending strength. Inhomogeneities in the microstructure play a less important role here. Where possible, therefore, ceramics should be subject to compressive stress.

5.3.3.3 Tensile strength

The low tensile strength, which can often be **20** % less than the bending strength, and the tendency to brittle breakage (see Figure 80) of ceramics require that tensile stress should be avoided or minimised, or at least that the stress distribution should be calculated as accurately as possible. This does not entirely exclude the possibility that, for instance, components such as open-air insulators used for high voltage power transmission can be successfully, if inappropriately for ceramics, used under conditions of tensile stress.

5.3.3.4 Weibull modulus

Using a theory developed by Weibull, based on the concept of the failure of the weakest link, the strength distribution of ceramic materials can be described effectively in mathematical terms. An important assumption is that the failure is caused by a single "failure type" (structural inhomogeneity). Weibull chose to describe the strength behaviour using a special form of extreme value distribution; this was later named the Weibull distribution in his honour.

This results in a definite relationship between mechanical load and the failure probability of a part if the distribution parameters are known. Using a level of strength at which the failure probability becomes 63.2 % (σ_0), the **Weibull modulus** (m) becomes a measure of the distribution of strengths. The higher the Weibull modulus is, the more consistent the material (which means that uniform "defects" are evenly distributed throughout the entire volume) and also the narrower the probability curve of the strength distribution. Today, values between $10 < m < 20$ are typically achieved. These values are determined for ceramic materials usually using the four-point bending method, since measuring the tensile strength of these materials is extremely difficult.

$$F = 1 - \exp\left[-\left(\frac{\sigma - \sigma_u}{\sigma_0}\right)^m\right]$$

$$F = 1 - \exp\left[-\left(\frac{\sigma - \sigma_u}{\sigma_0}\right)^m\right]$$

F	=	failure probability	σ	=	stress
σ_u	=	minimum strength	m	=	Weibull modulus

σ_o = Location parameter of the Weibull distribution, strength at 63.2% failure probability; in the Weibull distribution this plays the role of the mean value in a normal distribution.
Typically, $\sigma_u = 0$ is used.

Since the number of possible defects in this ceramic is dependent on the volume of the part, the volume under load must be taken into account. The strength of larger parts is thus less than what is measured on test samples. However, with large volumes under load, a larger Weibull modulus results in higher load capacity. Using Weibull statistics, the following component strength results from the volume relationship:

$$\sigma_{\text{Part}} = \sigma_{\text{Test piece}} * (V_{\text{Test piece}} / V_{\text{Part}})^{1/m}$$

The volume under stress is to be inserted here for the component volume, and the stress distribution must be identical (e.g. σ_{tensile} or $\sigma_{4\text{pb}}$). This relationship does not apply to compressive stress!

Test procedures for determining the Weibull modulus are specified in DIN EN 843-5 and DIN 51 110-3.

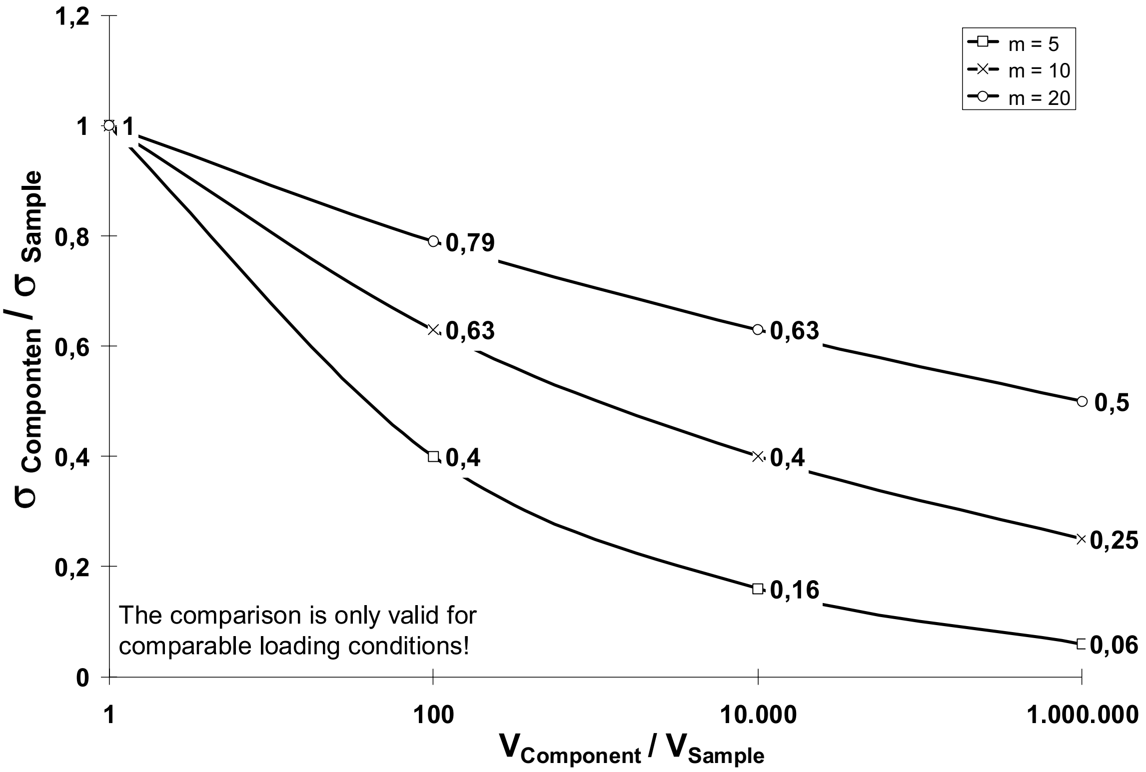


Figure 85: Relationship between component size and strength for different values of Weibull modulus, m

Effective volume	**Permitted bending stress [MPa]**			
$V_{part}/V_{test\ sample}$	*Ceramic 1*	*Ceramic 2*	*Ceramic 3*	*Ceramic 4*
1 : 1	400 (m = 10)	300 (m = 10)	250 (m = 20)	200 (m = 30)
10 : 1	252 (63 %)	237 (79 %)	210 (84 %)	186 (94 %)
100 : 1	160 (40 %)	189 (63 %)	197 (79 %)	172 (86 %)
Material	New high-performance material	Aluminium oxide, Silicon infiltrated silicon carbide	-	-
Comment	Process not mature	**State-of-the-art**	Leading current technology	Construction engineer's wish

Table 10: Comparison of the strengths of components and test pieces for different strength scatters (Weibull modulus, m)

5.3.3.5 Stress Intensity Factor

Ceramic materials are subject to brittle fracture. Ductile deformation, as observed in metals, is possible only at temperatures close to the softening temperature. The **stress intensity factor K_I** has been adopted from fracture mechanics in order to determine the behaviour of brittle materials with respect to crack growth.

The **critical stress intensity factor, K_{IC}** [MPa*√m] is a measure of the susceptibility to cracking or the brittleness of the material (crack resistance). Crack growth behaviour is not dependent on loading alone, but on a combination of loading and crack size. Failure occurs when the critical value K_{IC} is reached.

K_{IC} is essentially the product of stress perpendicular to the plane of a crack caused by outside forces, σ, and the square root of the length of the most dangerous crack, a. Furthermore, there is also a dependency on the geometry of the part and that of the crack and therefore on a correction factor, Y.

[illegible]

Simply put, materials with a high K_{IC} value (for example, SN or zirconium oxide PZT → K_{IC} = up to 10.5) have a high resistance to crack propagation.

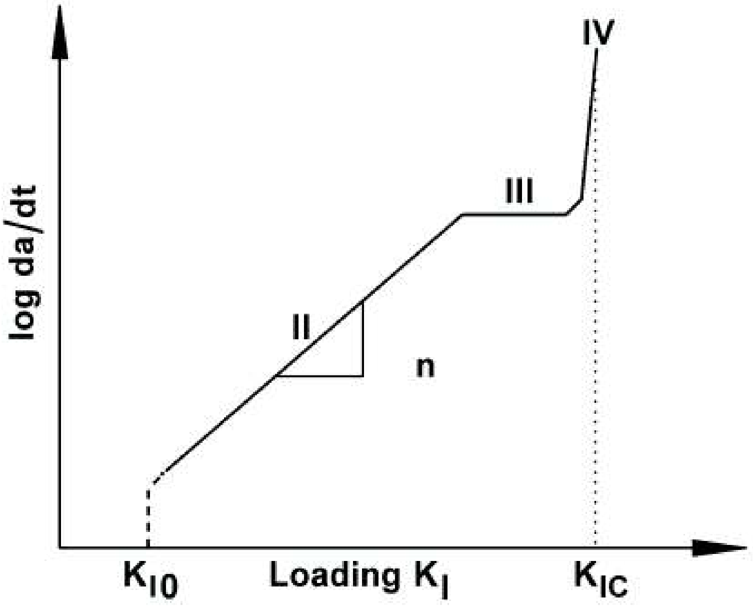


Figure 86: Scematic crack growth diagram for technical ceramics

5.3.4 Elastic Properties

5.3.4.1 Elastic modulus

The **elastic modulus E** [GPa] of almost all oxide and non-oxide ceramics is consistently higher than that of steel. This results in an elastic deformation of only about 50 to 70 % of what is found in steel components. The high stiffness implies, however, that forces experienced by bonded ceramic/metal constructions must primarily be taken up by the ceramic material.

Test procedures[14] for determining the modulus of elasticity are defined in DIN EN 843-2 and DIN EN 60 672-2.

---

[14] See also the appendix, p. 230 (Hardness Testing and Ultrasonic Testing).

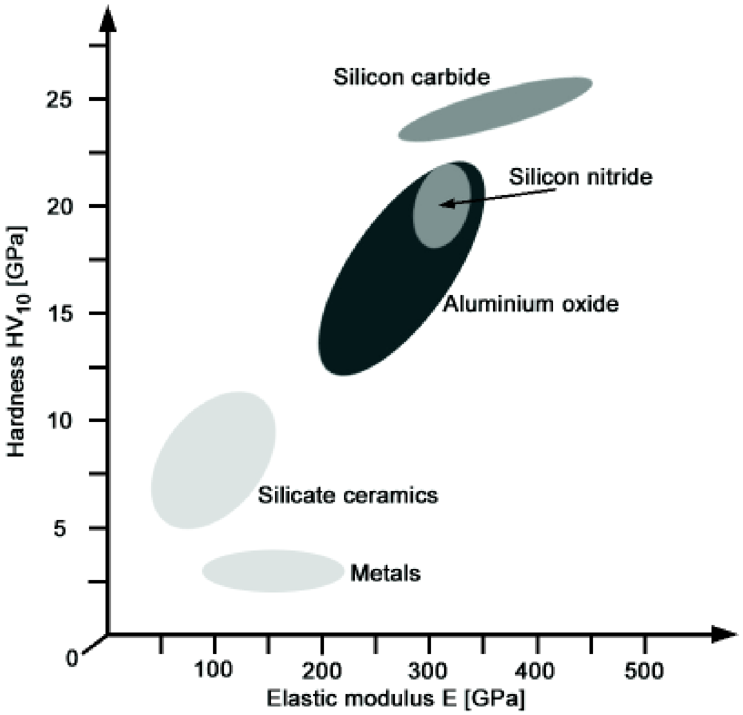


Figure 87: A guide to the hardness and elastic modulus of selected materials

5.3.4.2 Transverse contraction

The transverse contraction ν, often known as the Poisson ratio, expresses the relationship of the (negative) transverse contraction, ε_2, to the longitudinal extension, ε_1. Expressed as a formula, $\nu = -\varepsilon_2 / \varepsilon_1$ or, rearranged as $\varepsilon_2 = -\nu * \varepsilon_1 = -\nu * \sigma /$, we obtain $\nu = - E * \varepsilon_2 / \sigma$.
Values for ceramics lie typically in the range $\nu \approx 0.18 - 0.30$.

5.3.4.3 Shear modulus

The shear modulus G is the specific change in shape for pure shear stress with pressure from all sides. Expressed as a formula, $G = \tau / \gamma$ (τ = shear stress, γ = shear angle).
A figure of about 1/3 of the modulus of elasticity can be expected for ceramics.

5.3.4.4 Crack Growth

A ceramic component must be designed not only with respect to its maximum load, but also for a certain lifetime. For this reason, knowledge of the relationship between strength and time is necessary. Failure results as a rule from single defects which (often) lie on or close to the surface, since the greatest stresses usually occur there. Assuming that the component is subjected to loads below its design strength, and particularly if water or moist air are present in its environment, a crack can start from a critical defect, growing very slowly at first, then accelerating under further load until the part finally fails. This behaviour is known as **subcritical crack propagation** (stress crack corrosion). It most often occurs in oxide ceramics, but also in non-oxide ceramics that possess an amorphous oxide grain boundary phase. This type of crack propagation behaviour is well described using a method known as "linear-elastic fracture mechanics".

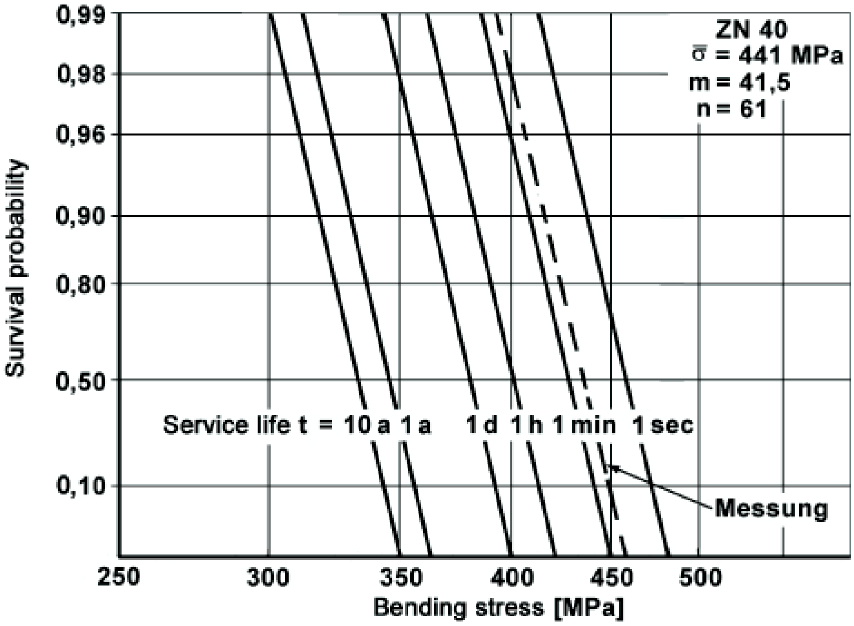


Figure 88: SPT-diagram for zirconium oxide

Taking subcritical crack propagation into account, the relationship between **s**trength, **p**robability and **t**ime can be illustrated for a ceramic material on what is known as an **SPT**-diagram.

Test procedures for determining the parameters of subcritical crack propagation are specified in DIN EN 843-3.

5.3.4.5 Creep properties

Plastic deformation of metallic materials under static loads is observed in long term experiments. Creep phenomena are amplified at higher temperatures and limit the application possibilities of metallic materials. Generally speaking, the tendency of ceramic materials to creep at temperatures below 1,000°C is very low. However, in contrast to metallic materials, creep extensions of only a few per cent can lead to failure of the material. As opposed to slow crack growth, in which a single crack propagates, creep damage is understood as the development of creep porosity and microcracks. This causes a relatively homogeneous distribution of damage through the entire volume of the material under stress. As a result, the physical properties of the material are changed.

The creep behaviour in ceramic materials is influenced not only by the stress but also the chemical bonding and microstructure characteristics (grain size, grain shape, porosity, grain boundary phases).

Test procedures for determining the parameters of creep deformation in flexure at high temperatures are specified in DIN ENV 820-4 and EN 820-2.

5.3.5 Hardness

Hardness implies a high resistance to deformation and is associated with a large modulus of elasticity. Technical ceramic components are therefore characterised by their stiffness and dimensional stability.
The high **hardness** of technical ceramics results in favourable wear resistance. Ceramics are thus good for tribological applications. Material type and microstructure strongly influence the wear resistance.

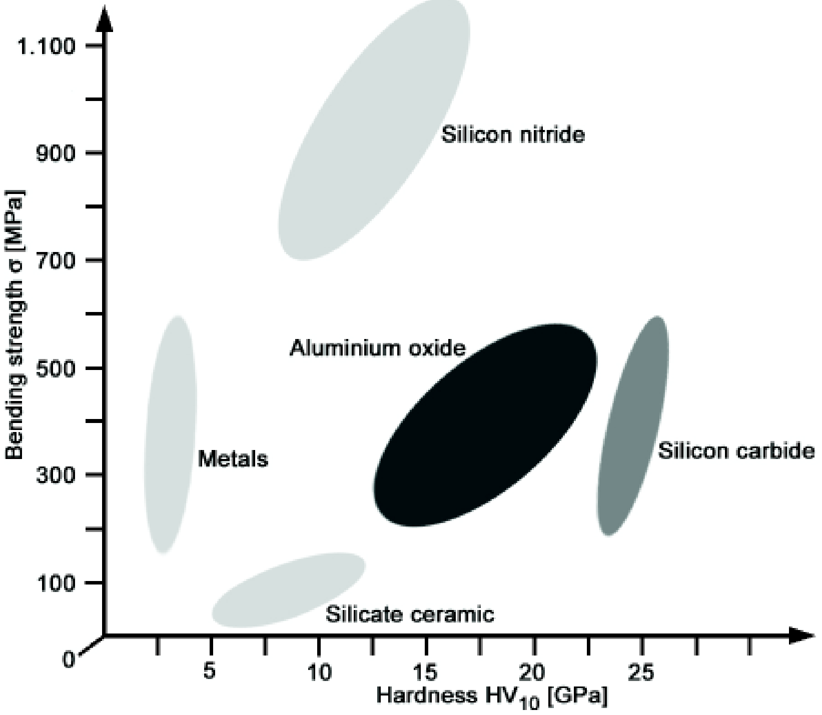


Figure 89: A guide to the flexural strength and hardness of selected materials

The high hardness of ceramic materials is at the expense of a lack of plastic deformation (ductility) that could absorb stress concentrations. The part could break without warning (see figure 80).

Test procedures[15] for determining the hardness according to Vickers, Knoop and Rockwell are specified in DIN EN 843-4. It is usual to quote the **Vickers hardness HV** [MPa], although it is important to quote the test force (in kg) as the result is very dependent on that. The values of $HV_{0,1}$ and HV_{50}, for instance, may differ by about 30 %.
In practice, it has been found that quoting HV_{10} values is useful for ceramics.

---

[15] See also Appendix, p. 209.

5.4 Thermal Properties

5.4.1 Thermal conductivity

The **thermal conductivity** λ [$Wm^{-1}K^{-1}$] of ceramics is generally less than that of metals such as steel or copper. Materials such as silicon carbide or aluminium nitride however, find applications as heat conductors, due to their relatively high thermal conductivity compared with other electrically insulating materials.
Other ceramic materials, in contrast, are used for thermal insulation due to their low thermal conductivity. These insulating properties can be enhanced by inducing porosity in the ceramic. Ceramic fibre matting has a similar effect.
When comparing the thermal conductivity of different materials, it is important to note the temperature range, e.g. $\lambda_{30\text{-}100}$ for figures relevant to the range from 30 to 100 °C.

Test procedures for determining thermal diffusivity (a), which is related to thermal conductivity as $\lambda = a \cdot \rho \cdot c_p$, are specified in DIN EN 821-2.

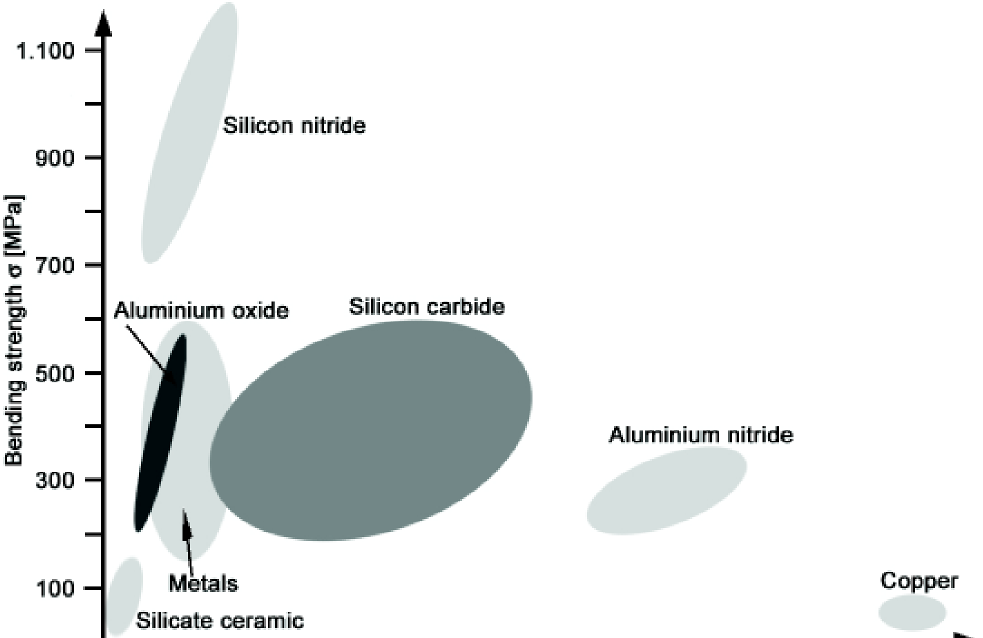


Figure 90: A guide to the flexural strength and thermal conductivity of selected materials

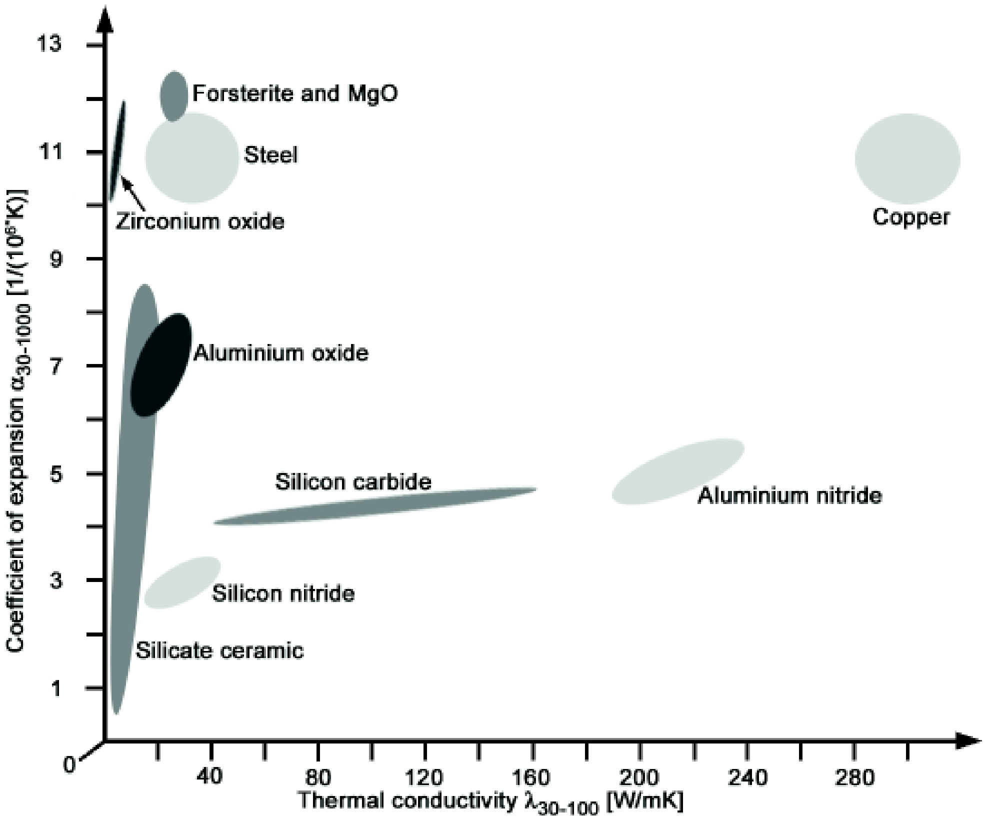


Figure 91: A guide to the coefficient of thermal expansion and thermal conductivity of selected materials

5.4.2 Coefficient of linear expansion

The thermal **coefficient of linear expansion** α [$10^{-6}K^{-1}$] of technical ceramics is usually less than that of steel or grey cast-iron, with the exception of zirconium oxide, forsterite and MgO. This must be taken into account in composite construction.

When comparing the linear expansion of different materials, it is important to note the temperature range, e.g. α_{30-100} for figures relevant to the range from 30 to 100 °C.

Test our procedures for determining coefficients of thermal expansion are specified in DIN EN 821-1 and DIN EN 60 672-2.

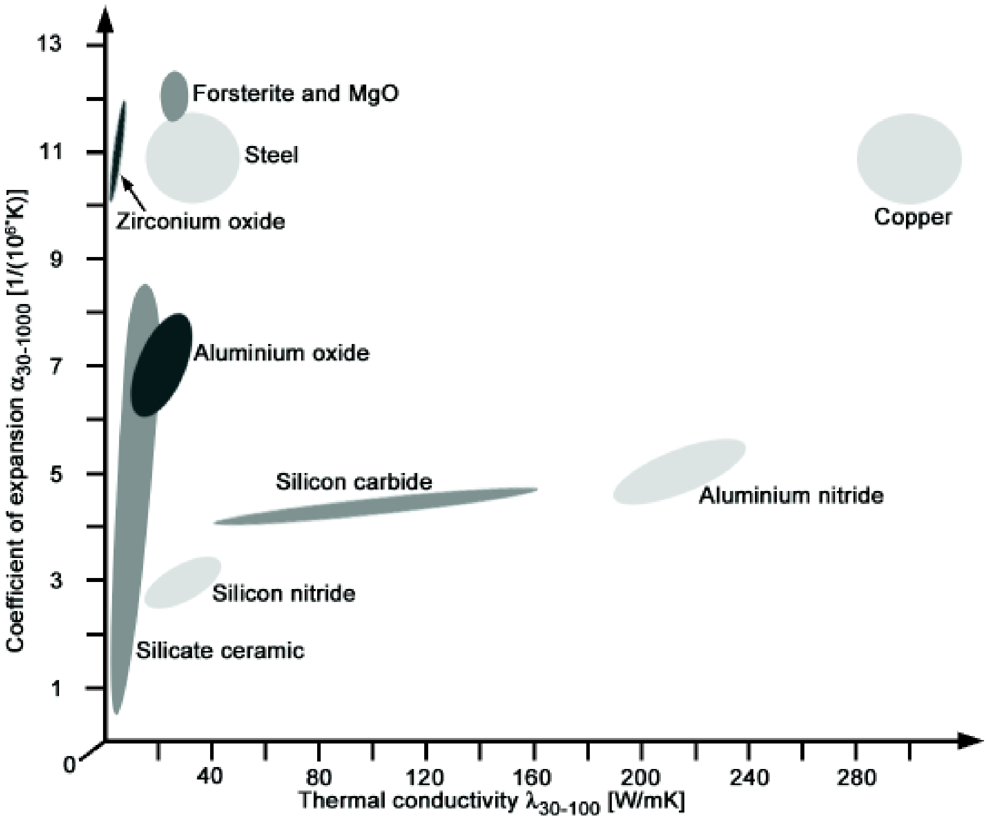


Figure 92: A guide to the flexural strength and coefficient of expansion of selected materials

5.4.3 Thermal Shock Resistance

A large number of ceramic materials are sensitive to thermal shock, which means that sudden changes of temperature can lead to failure. Aluminium titanate, sintered fused silica and materials based on cordierite are notable exceptions.

The causes of this sensitivity to thermal shock are the internal mechanical stresses induced by temperature gradients, and the highly brittle nature of the ceramic material. Whereas high local thermal stresses in metals merely lead to a slight local plastic deformation, they can lead to the propagation of cracks in ceramic materials. For this reason sudden, large changes of temperature should be avoided whenever possible.

The thermal stresses responsible for the response to temperature stress depend on:

- **geometrical boundary conditions**
- **thermal boundary conditions**
- **physical parameters, such as**

coefficient of thermal expansion	α
modulus of elasticity	E
thermal conductivity	λ
strength	σ
and others.	

Determination of the sensitivity to thermal shock can be carried out using a method suggested by Hasselmann. Test pieces – in the simplest case these are bending bars – are quenched to drop them from a temperature T_0 to a temperature T_u. The strength of the samples is measured after the quenching. The curve of strength against the temperature difference, $\Delta T = T_0 - T_u$, has the shape shown on Figure 93. Up to a temperature difference of ΔT_c the strength does not alter. The strength then drops sharply within a narrow range, ΔT. Up to ΔT_c' this reduced length then remains constant, falling away again at higher temperature differences.

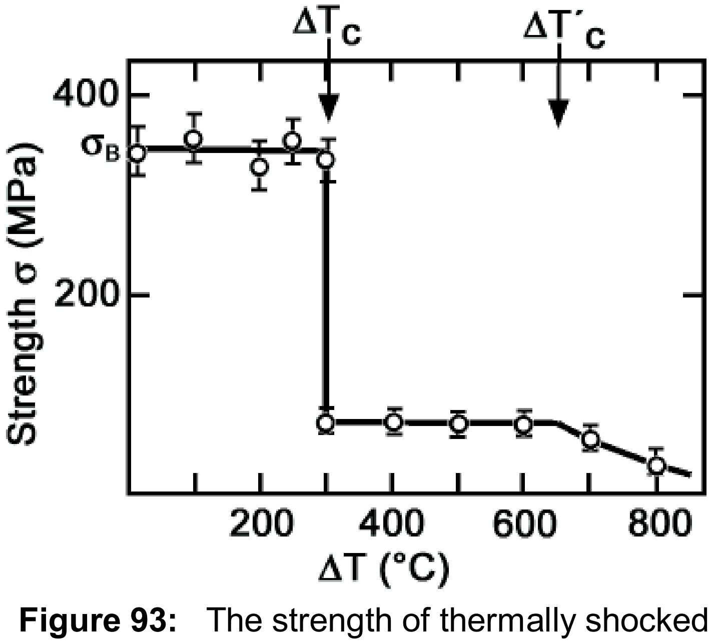


Figure 93: The strength of thermally shocked bending samples according to Hasselman

Resistance to thermal shock or stress is characterised in the literature by what are known as R parameters (R_S = resistance to thermal shock).

$$\mathbf{R_S = (\lambda * \overline{\sigma_B}) / (\alpha * E)}$$

where: $\overline{\sigma_B}$ = mean bending strength
α = coefficient of thermal expansion
E = modulus of elasticity
λ = thermal conductivity

The values listed there for thermal shock behaviour must only be looked on as general guidelines for the various materials, because the individual physical and mechanical data can vary widely. Other factors such as the fracture toughness, K_{IC}, and the specific thermal capacity, C_p, also play a part.
Values obtained from homogenous ceramic material have only limited relevance to the associated porous ceramics.
In practice, the geometry also plays an important part. For this reason we have included a qualitative assessment in our tables of materials.

Test procedures for determining the resistance to temperature change are specified in DIN V ENV 820-3.

5.5 Electrical Properties

Test procedures for determining electrical properties are specified in DIN EN 60 672-2.

5.5.1 Electrical Resistance

Most technical ceramics possess a **high electrical resistivity** of typically $\rho = 10^{11}\ \Omega\mathrm{m}$ combined with a high dielectric **breakdown voltage gradient** (typically E_d >10 kV/mm) sometimes even at high temperatures (see pp. 262 to 273); exceptions include SiC, B_4C and speciality materials).

Test procedures for determining the electrical resistance are specified in DIN prEN 50359-1-2.

5.5.2 Permittivity

The **permittivity** of technical ceramics is generally small ($6 < \varepsilon_R < 12$), which means that very little electrical polarisation takes place. Materials in group C 300 can exhibit $350 > \varepsilon_R > 3{,}000$ (cf. Table 38, p. 265), and are used to manufacture capacitors. The capacitance of a capacitor is calculated according to the formula

$$\mathbf{C = \varepsilon_0 * \varepsilon_r * F / d}$$

where C = capacitance
ε_0 = permittivity of free space
ε_r = relative permittivity
F = capacitor area
d = distance between the plates

5.5.3 Dielectric Loss Factor

The **dielectric losses** are very low. The ionic polarisation, which decreases with increasing frequency, is responsible for this. At higher temperatures, the **dielectric loss factor, tan** δ increases, especially at low frequencies. Ceramic materials with deliberately high loss factors can also be manufactured.

$$\mathbf{\tan \delta = P_W / P = P_W / (U * I)}$$

where P_W = power loss.

5.6 Corrosion

Corrosion refers to the reaction of a material with its environment, resulting in a measurable change in the material and capable of leading to corrosion damage (DIN 50 900). Originally, the term "corrosion" was only applied to metals, but nowadays it is generally used for any materials, including polymers, glass and ceramic.

Corrosion refers to the chemical attack of a medium on a material. In contrast, abrasion is defined as the mechanical interference of a solid body (the opposing body) with the main body of a tribological system. In most cases, corrosion increases the level of any abrasive wear.

In comparison to metals, ceramic materials may be considered resistant to corrosion, because their corrosion rates are a great deal lower than those of metals. There are significant differences in the types of corrosion and corrosion resistance between the different groups of ceramic material (silicate, oxide and non-oxide ceramic). Whereas corrosion in metals is an electrochemical process, the solubility of the material is the determining factor in the level of ceramic corrosion. The chemical composition and the microstructure are the key factors for low corrosion rates.

5.6.1 Corrosion mechanisms

The following mechanisms of corrosion must be considered in order to characterise the corrosion processes of inorganic materials:

Surface corrosion:	Corrosive material loss is even.
Selective corrosion:	Easily soluble components are dissolved out of the composite material.
Defect site corrosion:	Defects on the surface (impurities, cracks, pause...) provide the attack sites.
Inter-granular corrosion:	The corrosive attack proceeds along the grain boundaries.

5.6.1.1 Surface corrosion and selective corrosion

The removal of material from the surface by aggressive media implies that the material has an isotropic structure (as glasses do). The speed of the corrosion process depends here on the solubility product[16]. Ceramic materials, however, generally have a heterogeneous microstructure, that prevents uniform chemical attack over the surface. This does not apply to ceramics containing a high proportion of glass phase material. For this reason, corrosion-resistant porcelains, such as laboratory porcelain, include an acid-resistant glass phase. Application in alkaline media, however, is critical for these materials.

---

[16] $L = [K^+][A^-]$, where $[K^+]$ = the concentration of cations $[A^-]$ = the concentration of anions

5.6.1.2 Defect Site Corrosion

Defect site corrosion can occur in practically any ceramic. If the defects are small, they are not relevant to deterioration.

Example:
Aluminium oxides (99.5 %) typically contain small proportions of Na_2O_3CaO, Fe_2O_3 and often of MgO as additives. Na_2O and MgO combine with Al_2O_3 to form a small number of isolated crystallites distributed through the material, with the chemical composition of $MgO \cdot Al_2O_3$ (spinel) or $Na_2O \cdot 11Al_2O_3$ (β-Al_2O_3). Corrosive attack is not critical, because the reactions only take place on the surface itself.
If larger inhomogeneities are dissolved away, significant damage to the surface occurs. In the final stage this can lead to deeper damage (in particular if intergranular corrosion is also taking place), which can in the end result in component failure.

5.6.1.3 Intergranular Corrosion

The important corrosion mechanism here is the dissolution of the glassy/crystalline material which is present between the grains, particularly in liquid phase sintered materials (LPS) such as LPSSIC, LPSN, LPBN or Al_2O_3 with < 99.5 % Al_2O_3 content.
The rate of corrosion depends on the solubility product, L, of those ions in the intermediate phase that are relevant to corrosion.
Intergranular corrosion can be significantly reduced through the use of suitable intermediate phases with low solubility products, or by enlarging the grains in the microstructure, which is associated with a reduction in the grain boundary area.
Solid-phase sintered materials (S-Al_2O_3, SSIC and SSN) and hot pressed materials (HP-Al_2O_3, HPSIC etc.) show almost no susceptibility to corrosion.

5.6.2 Corrosion Types

In practice, three types of corrosion are distinguished:

- liquid phase corrosion,
- corrosion in the melt and
- corrosion due to (hot) gases.

5.6.2.1 Liquid phase corrosion

This is of the greatest importance for applications in machine and plant construction.

5.6.2.1.1 Acids

Laboratory porcelain, similar to silicate and borosilicate glasses (laboratory glass), is highly resistant to corrosion at moderate temperatures (up to approx. 100 °C).
Aluminium oxides (where the Al_2O_3 content is between 92 % and 99.5 %) are very resistant to mineral acids if the **secondary phase** (the phase between the grain boundaries) is **acid resistant**.
After extremely pure aluminium oxides, extremely pure non-oxide materials have the lowest corrosion rates. This applies above all to the S and HP materials which, in contrast to the LPS materials, **do not contain an inter-granular phase**.
SISIC has a special position, due to the infiltrated, **acid resistant**, silicon phase.

Hydrofluoric acid (HF) and its mixtures with concentrated H_2SO_4 and HNO_3 attack all materials that contain SiO_2. Only extremely pure aluminium oxide (purity > 99.9 %) and SSIC or HPSIC are resistant.
Generally speaking, dilute acids are more corrosive than concentrated acids (due to the effect of the pH value).

5.6.2.1.2 Alkaline Solutions and Molten Alkalis

Like laboratory porcelain, aluminium oxides containing low proportions of Al_2O_3 only react slightly with alkaline solutions, but are heavily corroded by molten alkalis. Highly pure oxides are more resistant, but do react significantly with melts. The aluminium oxide is then dissolved forming, for example, sodium aluminate ($Na_2Al_2O_4$).
Non-oxide ceramics are less heavily attacked by alkaline solutions than Al_2O_3. The silicon phase in SISIC, however, is significantly attacked, and resistance to corrosion from molten alkalis is poor.

5.6.2.1.3 Water

Hydrothermal corrosion, i.e. corrosion in water or water vapour at temperatures > 100°C and increased pressure, is a special case. With the exception of SSIC, where weak corrosive attack can be detected in distilled water, all the other materials show a significant loss of mass that rises at higher temperatures and increasingly dissolves the inter-grain phase. In the case of Al_2O_3 at 220 °C and above the Al_2O_3 matrix also starts to dissolve. Drinking water and dilute solutions of salts attack ceramic materials significantly less than distilled water.

5.6.2.2 Corrosion From Melts

The corrosion mechanisms of ceramics exposed to inorganic, non-metallic melts (such as molten salts, oxides, slags or glasses) are different from those arising with molten metals.

5.6.2.2.1 Non-metallic melts

The extent of the reaction between inorganic melts and ceramics depends on a large number of factors. The most important of these are:

- the viscosity of the melt,
- the acidity or basicity of the melt,
- the chemical composition and solubility of the reaction products,
- the chemical composition of the principal and secondary phases in the ceramic, and

- how easily the ceramic is wetted by the melt.

If it is necessary for ceramic materials to withstand melts, in practice it is almost always necessary to rely on tests.

5.6.2.2.2 Molten metals

In contrast to the oxide ceramics, **non-oxide materials** are more resistant to corrosion by metallic melts. **Silicon nitride** is not wetted by most melts, but is not resistant to molten copper in oxidising atmospheres. Due to its low wettability, boron nitride is very resistant to most molten metals.

Aluminium titanate (ATI) displays high resistance, in particular to molten non-ferrous metals, again because it is not easily wetted.

5.6.2.3 Corrosion by (Hot) Gases

All **oxide materials** are resistant to corrosion in *air* and *oxidising atmospheres* up to temperatures close to their melting point.

At temperatures above 1,200°C, all **non-oxide** materials react with oxygen. Many non-oxide materials – SiCs in particular – develop thick protective layers of silicon dioxide when oxidation begins, and this protects them from further oxidation. Corrosion increases significantly at temperatures above 1,420°C.

The corrosive reaction of ceramics to other gases (Cl_2, SO_2, NO_x etc.) is not well known.
In hydrothermal atmospheres certain quality classes of Al_2O_3 are resistant to Cl_2, SO_2 and NO_x. Cordierite also meets the demand for resistance to corrosion by hot gases in hydrothermal atmospheres.

5.6.3 The Determination of Corrosion

5.6.3.1 Liquid phase corrosion

5.6.3.1.1 Test conditions

No standardised test procedures are known for the determination of liquid phase corrosion, although the experimental equipment required for the purpose is relatively simple. Methods employed include:

- the storage of test samples in the corrosive media at room temperature (over a test period of between 10 and 100 days),
- storage of the test samples in the reflux cooler at higher temperatures (over a test period of between 5 and 50 days) and
- storage in autoclaves at higher temperatures and pressure (test period 1 to 5 days).

In the first two methods, preliminary conclusions can be drawn after about a week by then subjecting the samples to penetration tests.

5.6.3.1.2 Determining the Level of Corrosion

Penetration test
After the exposure period, the washed, dried sample is dipped in a dye solution. The intensity of coloration is a measure of the degree of corrosion. The penetration depth can be determined on samples cut perpendicularly to the surface.
This method, however, fails if there are no wide intergranular regions between the grains.
A negative penetration test alone does not permit clear conclusions to be drawn over the corrosion resistance of a material. Further investigations are necessary.

Dimensional changes
The determination of dimensional changes, e.g. thicknesses, can be used to examine surface corrosion, but fails in respect of inter-granular corrosion.

Mass loss Δm

The determination of mass loss, Δm in g, in relation to the area of the component, is the procedure most often applied. Because of the corrosion mechanisms at work[17], Δm values do not permit quantitative conclusions to be drawn about the corrosion behaviour of ceramic components.

Corrosion at grain boundaries is usually present in ceramic materials. Deeper damage – as is visible, for instance, in the penetration test – cannot be detected in this way. The result of this is that in the case of, for instance, $Al_2O_3 > 99.5$ %, S and HP materials, hardly any measurable loss of mass is found. For this reason it is only extremely rarely that calculations of rates of material removal or component lifetimes for technical ceramics on this basis are satisfactory.

Loss of flexural strength $\Delta\sigma_B$

The determination of bending strength (in association with Weibull statistics) permits a reliable conclusion to be drawn about the effect of corrosion processes on the strength and therefore on the service life of ceramic components.

Loss of hardness ΔH_V

The hardness of corroded samples drops significantly. However, the measured values vary so widely that reliable conclusions cannot be drawn from this measurement.

Resistance to wear

Abrasion tests on corroded samples permit conclusions about the service life of components in corrosive media to be drawn. Appropriate abrasion tests are used[18].

Examination with microscopes and scanning microscopes

Conclusions can be drawn from corroded samples regarding the progress of corrosion processes over time and the corrosion mechanisms that occur.

---

[17] See Surface corrosion, p. 120 and Inter-granular corrosion, P. 121

[18] See Wear measurement in model systems, p. 135 ff.

5.6.3.2 Corrosion in the Melt

5.6.3.2.1 Test conditions

Corrosion tests must always be properly related to the real conditions of the application. The relevant stress criteria, and the way in which the material can be expected to behave as it interacts with the corroding medium, must be estimated beforehand.

Points that need consideration include:

- thermal stresses,
- chemical aspects,
- the type of material to be examined and
- mechanical stress.

5.6.3.2.2 Determining the level of corrosion

Test procedures for corrosion in the melt are, in contrast to liquid phase corrosion, covered by national and international standards. The most important of these standards are:

- measurements of the wetting angle using an HT reflected light microscope,
- the crucible slagging process (DIN 51069-2),
- the scattering and tapping process (ASTM C 768) and
- the dip process (finger test) (ASTM C 874).

In summary: The corrosion of refractory materials in liquid slags and metallic melts is a complex process whose details are difficult to understand. Standardised test procedures are therefore only relevant if they reflect the conditions that will apply in practice.

5.6.3.3 Hot Gas Corrosion

After exposing the materials for a period of time to defined gas concentrations and temperatures, it is generally possible to determine the level of the corrosion through microscopic investigations of the corroded samples.

Corrosive attack by gases, even at high temperatures, can be determined through thermo-analytical procedures (e.g. thermogravimetric balance).
A standard for oxidation resistance testing is ENV 12923-2.

5.6.4 Concluding Comments

If only one method of measurement is used the results of corrosion tests will often be inadequate (if not even false).
The measured corrosion figure (e.g. the loss of mass) cannot simply be converted to find the changed properties of the corroded component. Because of the different types of corrosion, this must normally be measured directly.
The most important corrosion mechanism in ceramic materials is inter-granular corrosion. The rate of corrosion is dependent on the rate at which the medium diffuses through the ceramic. As a consequence, the level of corrosion can be expected to follow a $\sqrt{t}$ law. The steepness of the corrosion parabola is determined by the solubility product.
If, under external corrosion conditions that remain constant, the curve of measured properties against time is not continuous but shows an inflection, then this is an indication either that secondary processes are playing a part or, in general, that the corrosion conditions in the component are changing (perhaps because of a layered structure). This may need additional investigation.

5.7 Wear

Wear is defined as progressive loss of material from the surface of a solid body as a result of mechanical causes, i.e. contact with and movement relative to a solid, liquid or gaseous opposing body. It manifests in the form of small separated particles (wear particles) and in changes to the material and shape of the tribologically stressed surface. Wear can be looked on as an element of tribology.

Wear is of great economic significance, since the service lives of machines and equipment are dependent on it. Ceramics allow significant improvement to be achieved here, as may be seen from the example of the fixed and control washers in a water tap, or linings of aluminium oxide. Other selected application fields include shaping technology, the ready-mixed concrete industry, the textile industry, the paper industry, metal cutting, pump construction, and large sectors of chemical and process technology where, for instance, ceramic fittings, slip ring seals and nozzles are used.

5.7.1 Tribology

Tribology is the science and technology of interacting surfaces in relative movement. It comprises the whole field of friction and wear, including lubrication, and incorporates associated boundary layer interactions both between solid bodies and between solid bodies and liquids or gases.

5.7.1.1 Friction

Dynamic friction refers to the force that opposes relative motion. The coefficient of fiction, μ or f, which describes the ratio of the frictional force, F_R, to the normal force between the surfaces, F_N, is used to characterise movement of translation.

5.7.1.2 Tribological systems

Generally speaking, friction and wear are thought of as reflecting the losses in tribological systems. They depend not only on the properties of the individual materials, but also on interactions that occur and on the magnitudes of all the stresses operating in the system. Under some circumstances, even small changes in the system can have significant effects on the coefficient of friction and on the degree of wear.

Friction and wear are therefore properties of a system, not simply characteristics of individual materials!

A tribological system consists of these four elements: the main body, the opposing body, the intermediate material and the surrounding medium. These, together with the total of all the stresses involved, which we may call the stress system, determine the coefficient of friction, the type of wear and the level of wear that occurs.

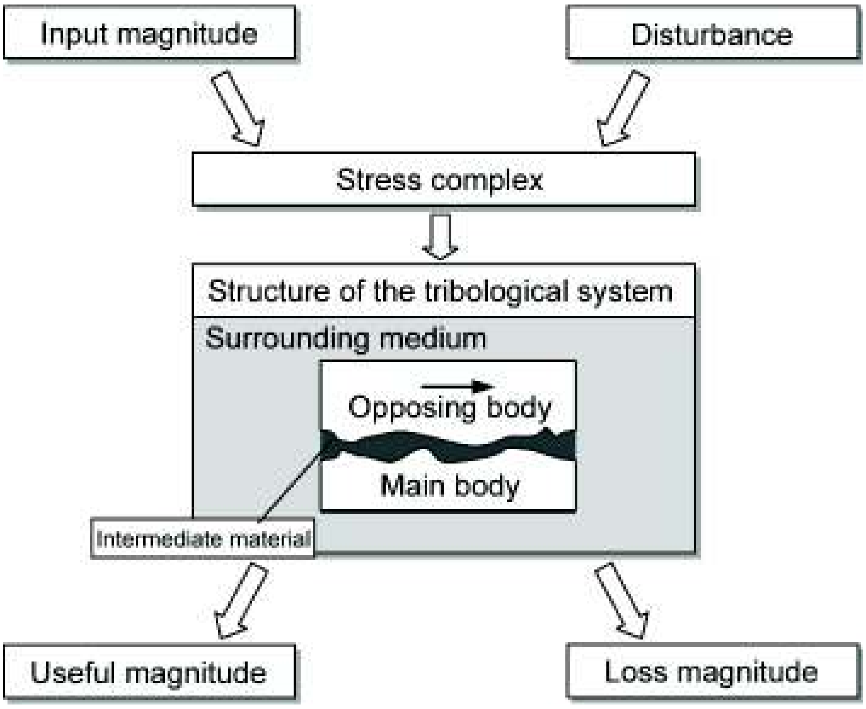


Figure 94: Representation of a tribological system

The stress system is composed of the technical and physical parameters of the normal force, F_N, the velocity, v, the temperature, T, the duration of the stress t_s, the types of movement and the changes of these factors over time.

In practice, tribological systems are divided into

- **closed tribological systems** such as bearings and seals, corresponding to Figure 94 and
- **open tribological systems** such as chutes, channels and pipe systems. In these cases, the function of the opposing body, which is not present, is performed by the intermediate material.

Systematic analysis of a tribological reaction is treated in DIN 50 320.

5.7.2 Types of wear

The types of wear can normally be divided in practice according to the stress. Sliding abrasion, grain sliding, rolling wear, impact and fretting wear are typical of closed tribological systems (see Table 11). Impact, cavitation, score grooving, scouring and jet wear occur in open

tribological systems (see Table 12). The last two are also referred to as erosive wear.
It should be remembered that more than one wear mechanism can be active in any one wear process.

5.7.3 Abrasion mechanisms

Abrasion mechanisms can be divided according to the fundamental processes that result from the action of the stress complex on the elements of the tribological system. According to our present understanding, four different principal abrasion mechanisms must be distinguished:

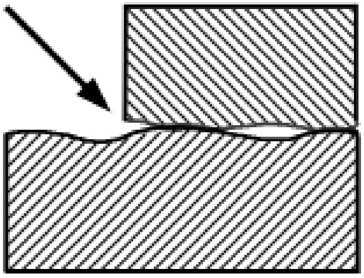


Figure 95:

Adhesion:
Boundary layers form and are separated (e.g. cold welding)

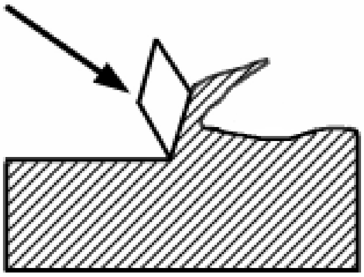


Figure 96:

Abrasion:
Material is removed as a result of scratching stress (microchips)

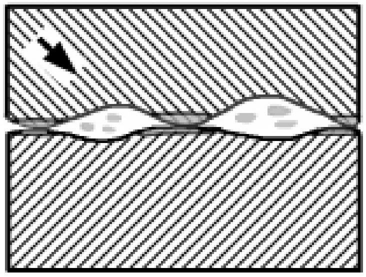


Figure 97:

Tribo-chemical reaction:
The formation of reaction products through tribological stress in chemical reactions (e.g. hot spots)

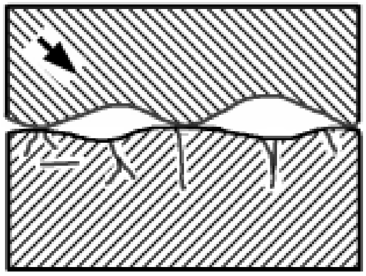


Figure 98:

Surface spalling:
Fatigue and crack growth in the surface region as result of cyclical tribological stress causing material to separate.

5.7.4 Stresses and their effects

In closed tribological systems, stresses occur in accordance with Table 11:

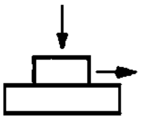
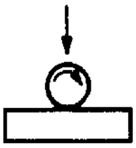
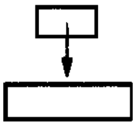
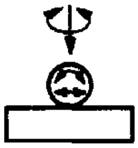
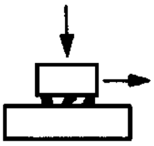
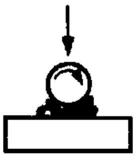
Stress	Type of abrasion	Active mechanism			
		Adhesion	Abrasion	Surface spalling	Tribo-chemical reactions
	-			X	X
	Sliding abrasion	X	X	X	X
	Rolling abrasion	X	X	X	X
	Impact abrasion	X	X	X	X
	Fretting abrasion	X	X	X	X
	Grain sliding			X	
	Grain rolling			X	

Table 11: Classification of closed tribological systems according to stress and abrasion type

Open tribological systems can be described in terms of the following stresses, abrasion types and active mechanisms:

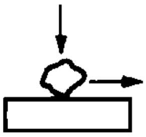
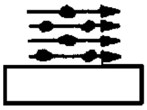
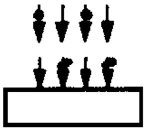
Stress	Type of abrasion	Active mechanism			
		Adhesion	Abrasion	Surface spalling	Tribo-chemical reactions
	Score grooving abrasion			X	
	Scouring abrasion (erosion abrasion)		X	X	X
	(Sliding) jet abrasion		X	X	X
	Jet impact abrasion		X	X	X
	Cavitation erosion			X	X
	Droplet impact			X	X

Table 12: Classification of open tribological systems according to stress and abrasion type

The following parameters affect the type and intensity of the corrosion:

Elements	Main body	Hardness, ductility, strength
	Opposing body	Hardness, ductility, strength
	Intermediate material	Hardness, strength, grain shape and grain size
	Surrounding medium	Neutral, corrosive
Stress complex	Type of movement	Sliding, rolling, impact
	Progress of movement	Continuous, oscillating, intermittent
	Relative speeds	
	Normal force, pressure	
	Kinetic energy, momentum	
	Temperature	
	Time	

Table 13: Effects on abrasion

Futher information may be found about this in the relevant Standards[19] or in the literature quoted in the appendix.

5.7.5 Measurements of Abrasion

Measurements of abrasion directly or indirectly characterise the change in shape or mass of a body as a result of abrasion. Because such measurements do not represent properties of the material but rather of the system, it is only worth quoting figures if the stress system and the structure of the tribological system is described at the same time. The following measurements of abrasion are in use:

Linear abrasion figure:	Change in thickness of the abraded surface. *Symbol:* W_L *Unit: m*

---

[19] The standards DIN 50 323-1 (1988), DIN 50 323-3 (1993), DIN 50 320 (1979) and DIN 50 321 (1979) are no longer available from Beuth-Verlag.

Planimetric abrasion figure:	The area of a section perpendicular to the abraded surface that is removed. *Symbol:* W_q *Unit:* m^2
Volumetric abrasion figure:	Change in volume of the abraded body (volume abrasion). Symbol: W_V Unit: m^3
Abrasion mass:	Change in volume of the abraded body (mass abrasion). *Symbol:* W_m *Unit: kg*
Relative abrasion figure:	The ratio between the abrasion figures of an abraded body and of a reference body abraded under identical conditions. *Symbol:* W_r *Unit: - or %*
Abrasion resistance:	The reciprocal value of the abrasion figure *Symbol:* $1/W$ *Unit:* m^{-1}, m^{-2}, m^{-3}, kg^{-1}

In practice it is common to link the abrasion figure with some reference magnitude. Parameters typically measured include the abrasion speed, abrasion intensity (ratio of abrasion to distance), abrasion/throughput ratio, abrasion-limited life, abrasion-limited throughput quantity.

5.7.6 Special examples

5.7.6.1 The measurement of abrasion in model systems

The sketch in Figure 99 illustrates some of the measurement set-ups used, consisting of a shaft and test body (a), a shaft and test body with grinding material (b), and a pin and disc arrangement (C).

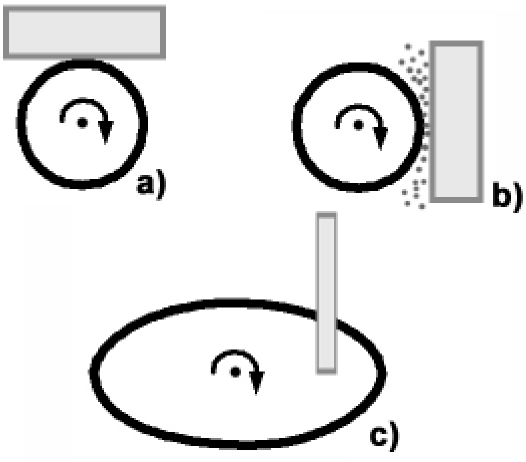


Figure 99: Set-ups used for measuring abrasion

Using the test bed for slip ring seals shown, it is possible to measure the speed of rotation, temperature and torque under operating conditions. The rotation speed, and the choice between dry and wet machining, can be varied.

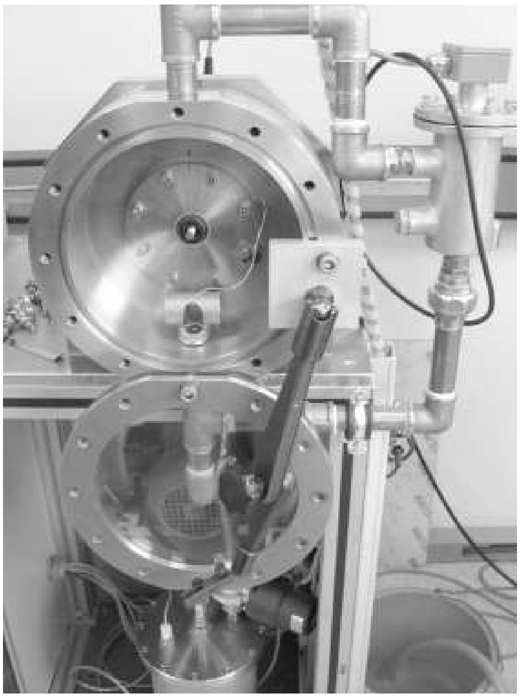


Figure 100: Measurement set-up for slip ring seals

Jet abrasion in open systems can relatively easily and quickly be measured in a blasting test. Materials can be compared, and ranked according to their abrasion resistance.

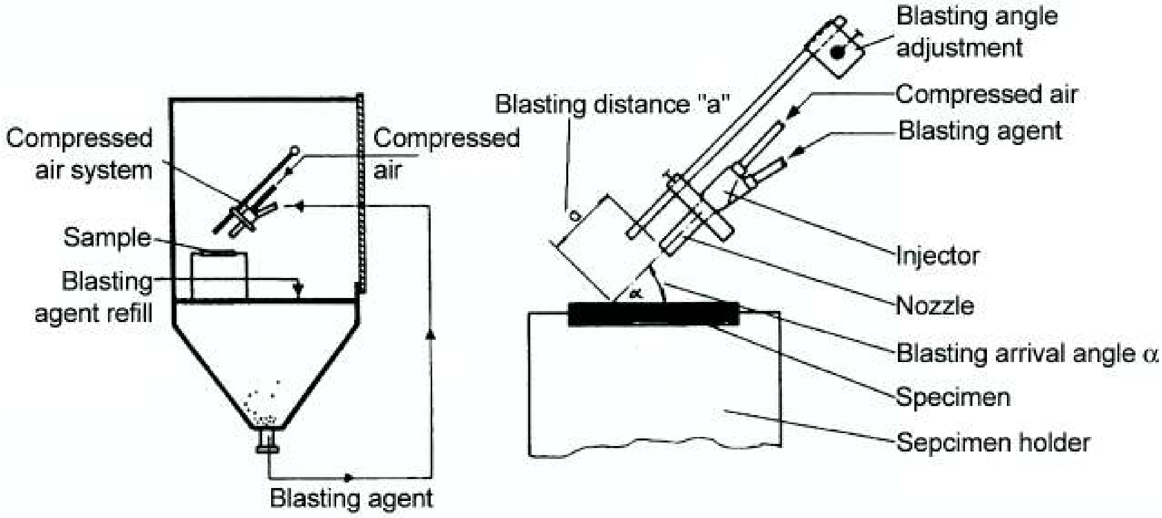


Figure 101: Experimental set up for jet abrasion[20]

The blasting medium, blasting speed and the size of the blasting particles have a critical effect on the results of such measurements.

5.7.6.2 Protection against abrasion

Ceramic materials are employed in highly stressed tribological systems because of their resistance to abrasion. As well as the property of great hardness, this calls for high stiffness (modulus of elasticity), high pressure resistance and high fracture resistance. In the case of ceramics, however, this is at the expense of fracture toughness. Other positive properties offered by ceramics for use in tribological systems are their low-density, low thermal expansion, and their resistance to temperature and to corrosion.

Whereas in the case of adhesion and tribo-chemical reactions, the wear behaviour is largely dependent on the chemical and thermo-chemical properties of the wear-protection material, in the case of abrasion taking place through the mechanisms of adhesion and surface spalling, the abrasion resistance is determined by the physical properties of hardness and fracture toughness. This is illustrated schematically in Figure 102.

---

[20] According to the DIN 50 332 (1979) standard, no longer available from Beuth-Verlag.

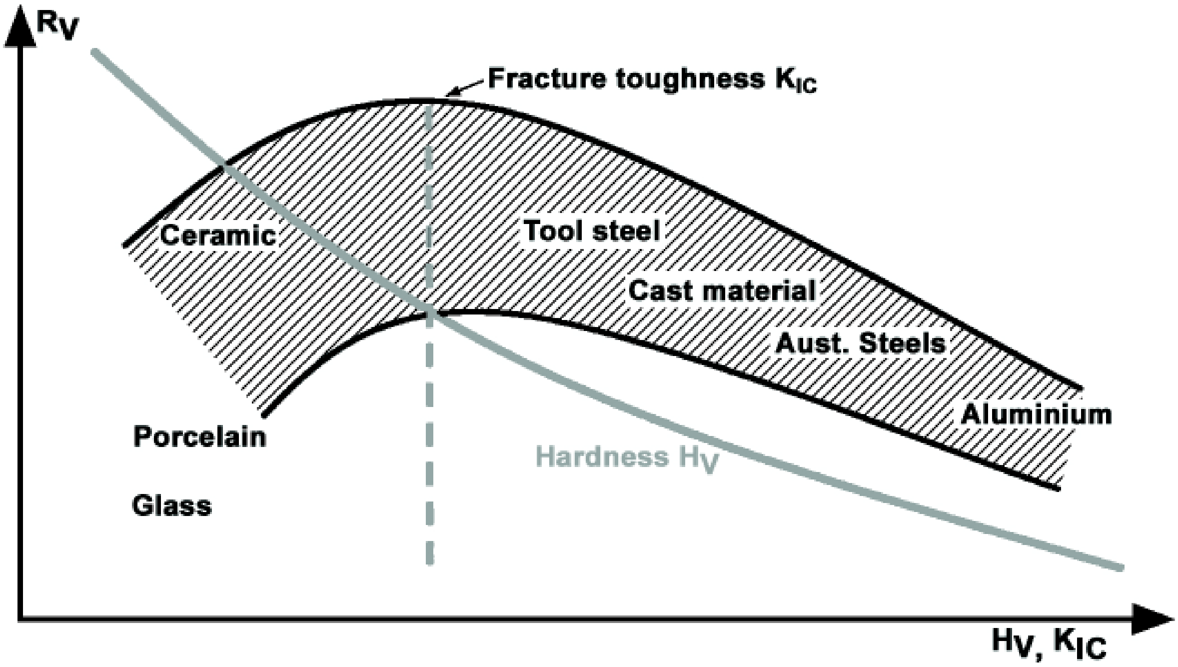


Figure 102: Dependency of the abrasion resistance, R_V, on hardness and fracture toughness determined in a defined model system

The maximum resistance to abrasion is therefore achieved when the wear protection material has an optimum combination of hardness and fracture toughness.

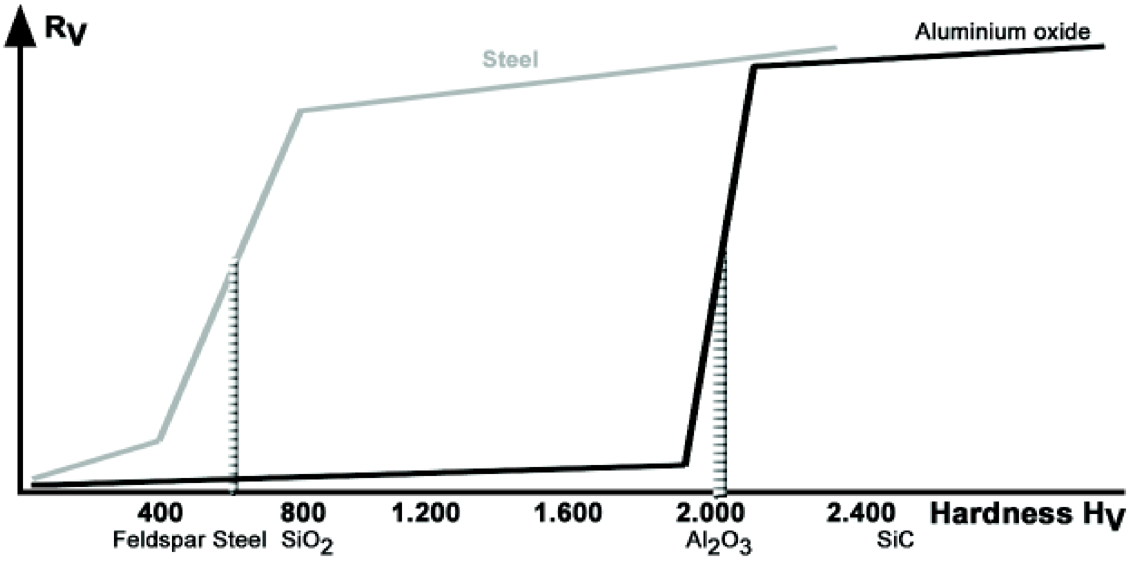


Figure 103: Curve showing abrasion minima and maxima

When abrasive wear is important, the relationship between the minimum and maxima of abrasion can be helpful when selecting the main body. It is based on the familiar Mohs' hardness scale: a harder material abrades a softer material.

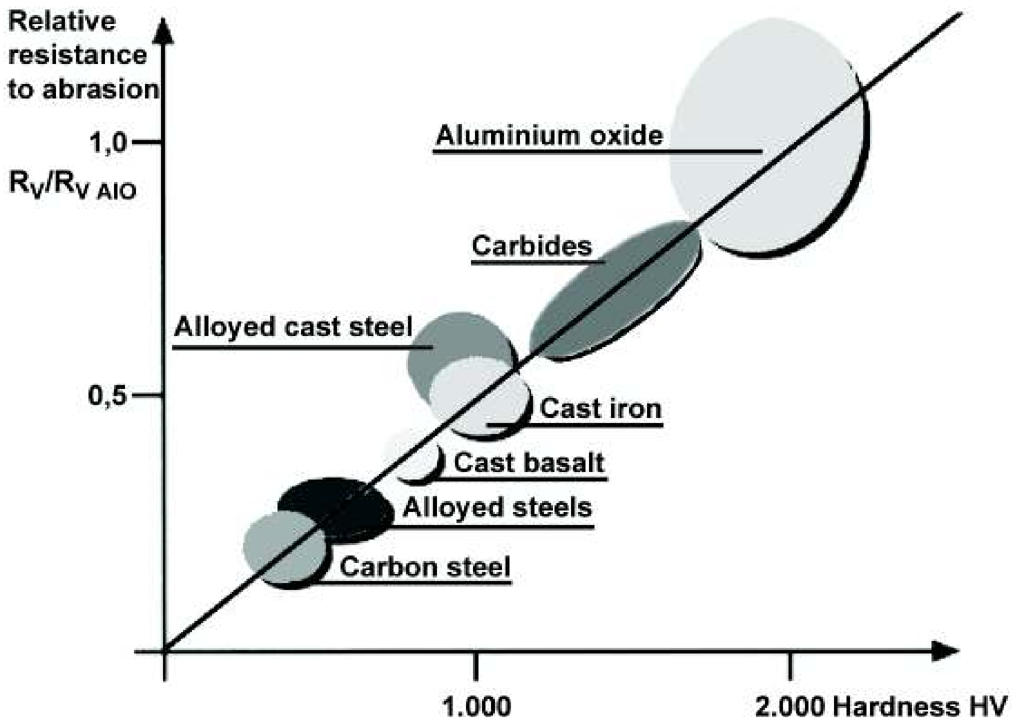


Figure 104: The effect of hardness on abrasion resistance, R_V, with reference to the abrasion resistance of aluminium oxide, $R_{V\,AlO}$

Because of their high hardness levels, abrasion is of subsidiary importance in the wear of ceramic materials.

Ceramic materials, furthermore, have little tendency to cold welding that occurs in metals, due to the high lattice bonding forces (ionic and covalent bonds). Adhesion as an abrasion mechanism can largely be neglected.

Equally, tribo-chemical reactions occur relatively rarely when ceramics are used (they always occur, but are relatively small). In closed tribological systems they cannot be ruled out, in particular in the presence of solid body and mixed friction.

In contrast, surface spalling is the main wear mechanism in brittle ceramic materials in both closed and open tribological systems. It is triggered by high stresses from normal forces, or by high kinetic energy. For example, inclined jet abrasion largely follows the function $W_V = \frac{1}{2} mv^2 \cdot \sin^{1/2}\alpha$, where α = angle of incidence. In conveyor systems such as pipe bends, pipe splits, pipe contractions and nozzles with angles of up to 30°, aluminium oxide has therefore been found to be very effective, whereas rubber is optimum at larger angles.

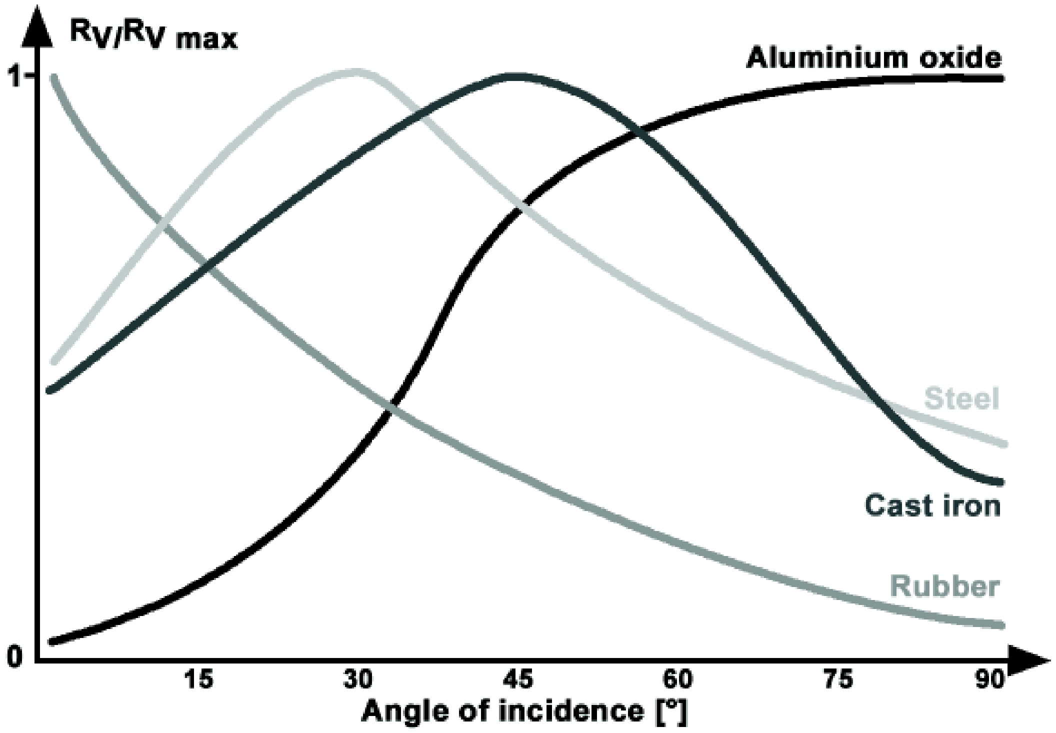


Figure 105: The effect of the angle of incidence on the abrasion resistance, R_V, in relation to the maximum abrasion resistance

5.7.6.3 Cutting

Carbide tools have traditionally been used for turning, cutting and drilling. These conventional cutting materials, based on metals, can only withstand a limited thermal stress, and do abrade. They are therefore, typically, supplied with cooling lubricant.

Ceramic-based materials retain their strength at significantly higher operating temperatures. These new materials therefore permit higher machining speeds with higher process reliability and with the omission of cooling lubricants. This is not just helpful from the production point of view, but is environmentally friendly due to the question of disposal.

A range of such cutting materials is now available on the market based on aluminium oxide, silicon nitride and mixed ceramics, supplemented by polycrystalline, cubic boron nitride (PCBN). These are also outstandingly suitable for cutting hard materials with high values of Vickers hardness. In addition to simple hard turning, the use of hard turning before grinding is increasingly found in practice. Mixed ceramics and PCBN cutting materials are suitable for precision hard turning of workpieces with hardnesses of up to 64 HR_C. Production times and production costs are significantly reduced through the high-speed machining of cast-iron materials and in hard cutting.

Silicon nitride ceramics have won a significant market share in high-speed turning, drilling and cutting of cast-iron in the manufacture of large series for the automobile industry and its suppliers. Mixed ceramics including polycrystalline cubic boron nitride are also being used more and more to replace grinding with turning.

Cutting ceramics must have significantly greater hardness than the material to be cut. This high hardness does, however, finally have an effect on the toughness of the cutting materials. Literature therefore often contains advice to the effect that cutting ceramics cannot be used for intermittent cutting. It must, however, be pointed out that it is perfectly possible to use PCBN materials to machine with intermittent cutting.

6 Areas of Application

Technical ceramics are used because of their special properties or combinations of properties. The following tables covering applications in mechanical and process engineering, high-temperature technologies, electrical engineering and electronics are an overview of the products made with technical ceramics, and show the reason for using ceramics along with some alternative choices of materials.[21]

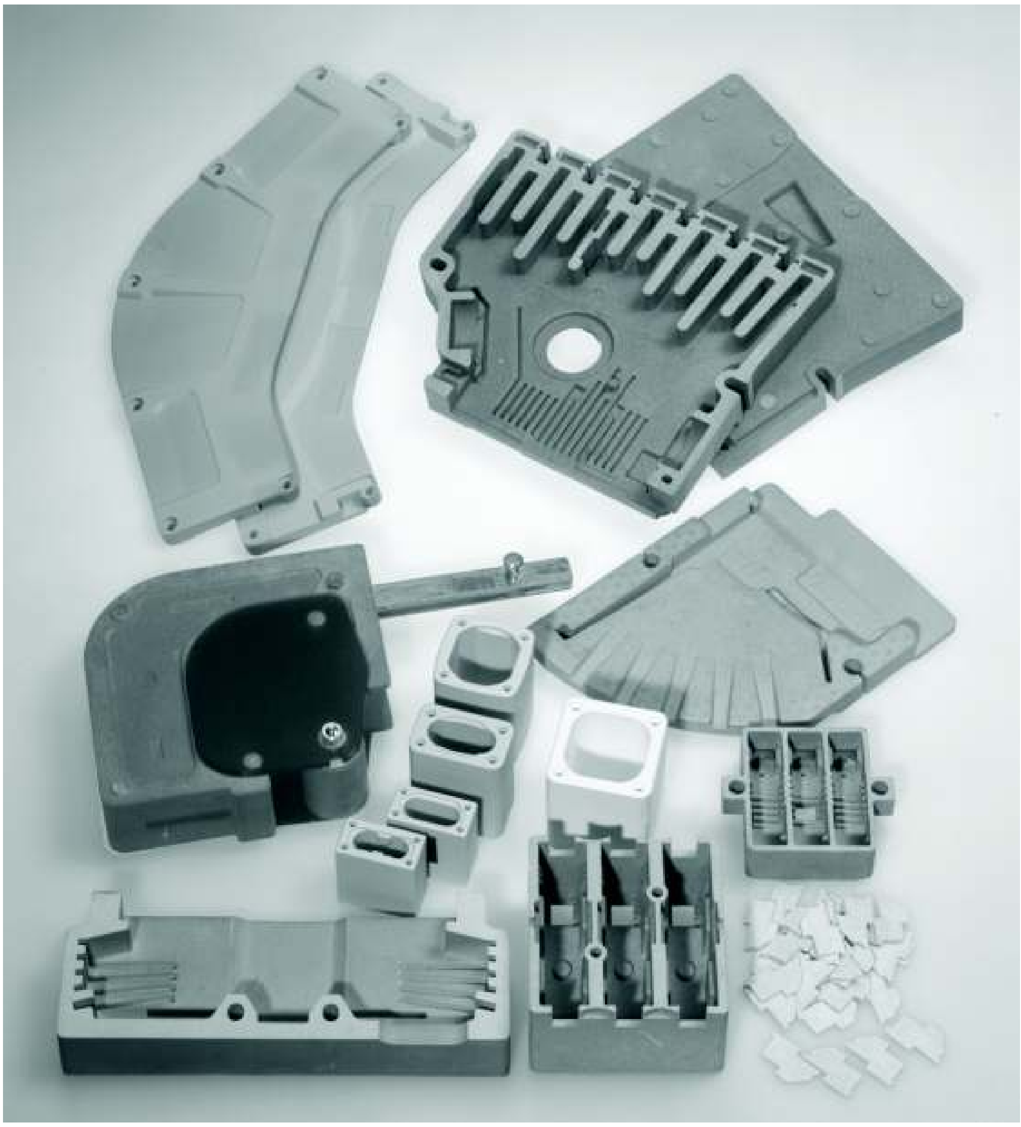


Figure 106: Low-voltage electrical engineering components

---

[21] See also Bibliography, p. 278.

6.1 Mechanical Engineering

Area of Application	Parts	Why use ceramic?	Materials
Mechanical engineering, general	Coatings, bushings, nozzles, extruder linings, guide rollers, guides, conveying elements in worm extruders, bearing bushes slip rings, mixing elements in screw extruders, shearing, cutting, protective sleeves, protective tubing, sifter wheels, seating rings slide rails, roller bearings, shaft protection tubes,	High wear resistance and / or corrosion resistance and mechanical strength	Aluminium oxide, silicon carbide, silicon nitride, zirconium oxide, quartz porcelain
	Grinding machine spindles, milling arbors	High stiffness	
	Guide wheels, high speed roller bearings	Low density	
	Roller bearings, thermal insulators	Good high temperature strength	

Table 14: Applications in general machine construction

Figure 107: Slip and sealing rings of SiC

Figure 108: Parts for linings from aluminium oxide

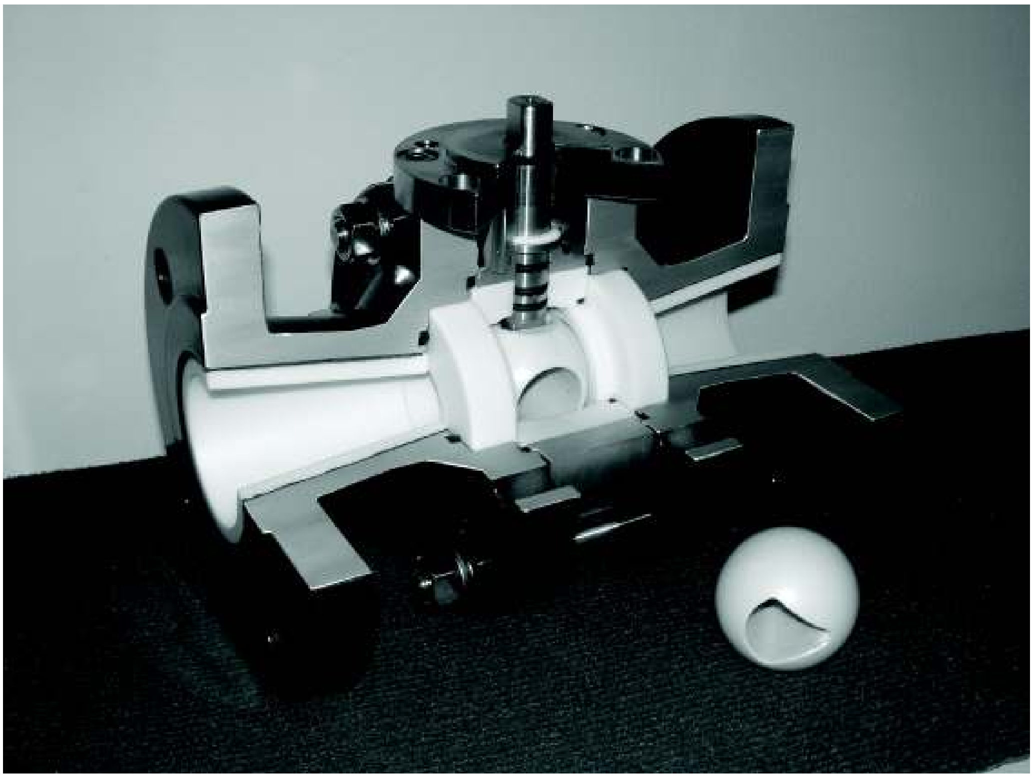


Figure 109: Ball valve type KSV DN 25 PN 40

Area of Application	Parts	Why use ceramic?	Materials
Pumps and fittings	Linings for sleeves and cylinders, sealing plates, housings, bearing bushes, slip ring seals, pistons, ball plugs, balls, bushings, plungers, pump impellers, guide wheels, rotors, valve plates, shafts, shaft protection sleeves, cylinders	High wear resistance and / or high corrosion resistance	Aluminium oxide, silicon carbide, silicon nitride, quartz porcelain
Plant engineering	Linings for mills, concrete mixers, containers, linings for screw conveyors and drive rollers for conveyor belts, filters, grinding bodies mixers, pipes, agitators, chutes, sifters	Good corrosion resistance and high resistance to wear	Aluminium oxide, silicon carbide, silicon nitride, zirconium oxide
Paper production machines	Stripping bars, linings, cutters, suction bars	High wear resistance	Aluminium oxide, zirconium oxide, Silicon carbide

Table 15: Applications in pumps and fittings, plant engineering and paper production machines.

Area of Application	Parts	Why use ceramic?	Materials
Textile machines	Exhaust nozzles, exhaust tubes, friction disks, thread brakes, thread guides, hooks, eyes, tubes, rollers, cutting elements, spinning rings, bars, vortex nozzles	High wear resistance and high surface quality	Aluminium oxide, zirconium oxide, quartz porcelain
Metalworking	Splaying mandrels, bending tools, drills, wire drawing rollers, wire drawing cones, cutter spindles, rollers, sandblasting nozzles, indexable inserts, drawing dies	High hardness and high wear resistance	Aluminium oxide, zirconium oxide
	Casting moulds, casting cores, casting funnels, soldering substrates, filter cores, melt filters, smelting crucibles, protective tubes, welding bars, welding nozzles, welding electrode insulators, welding pins, welding rings	High temperature resistance and/or good corrosion resistance, resistance to thermal shock	Dense cordierite, porous cordierite, mullite, aluminium oxide, silicon nitride
	Spacers, rules	Low thermal expansion and high stiffness	Cordierite
	Oxygen sensors	Oxygen ion conductivity	Zirconium oxide

Table 16: Applications for textile machines and in metalworking.

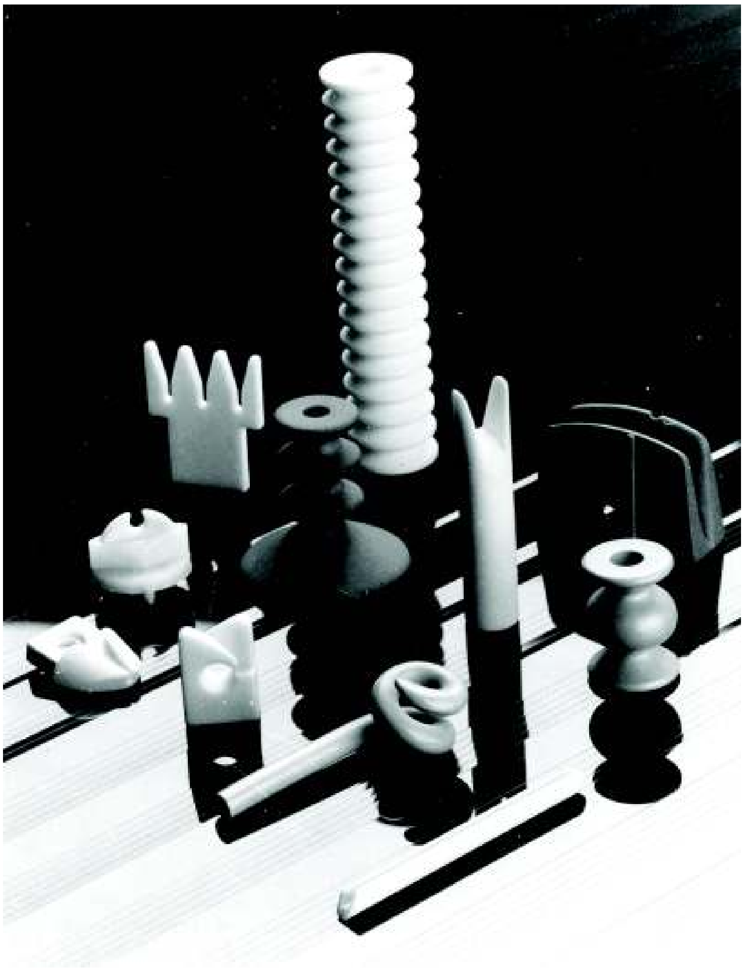


Figure 110: Thread guides

Figure 111: Cutting tool ceramics

Area of Application	Parts	Why use ceramic?	Materials
Motors, turbines	Combustion chamber linings, piston heads, sleeves, port liners,	Thermal insulation	Aluminium titanate
	Rocker arm inserts, valves, valve guides, valve seats	High wear resistance, low density, hardness	Silicon nitride, silicon carbide
	Piston pins, turbo rotors, roller bearings,	Low density high strength	Silicon nitride, silicon carbide
	Diesel catalysts, catalyst carriers	Good corrosions and heat resistance	
	Spark plugs, glow plugs	Electrical insulation and heat resistance	Technical porcelain
	Gas turbine wheels, turbine blades and guide vanes, turbocharger impellers and housings	High-temperature resistance	Silicon nitride, silicon carbide
	Oxygen sensors	Oxygen ion conductivity	Zirconium oxide
Chemical and process Engineering	Linings, laboratory porcelain, pyrometer tubes	Good corrosion and heat resistance, high wear resistance	Aluminium oxide, quartz porcelain, mullite
	Tower packing media, catalyst carriers	Good corrosion and heat resistance	Aluminium oxide
	Filters	Good corrosion resistance	Aluminium oxide

Table 17: Applications in motor and turbine construction and in chemical and process engineering.

Figure 112: Tower packing

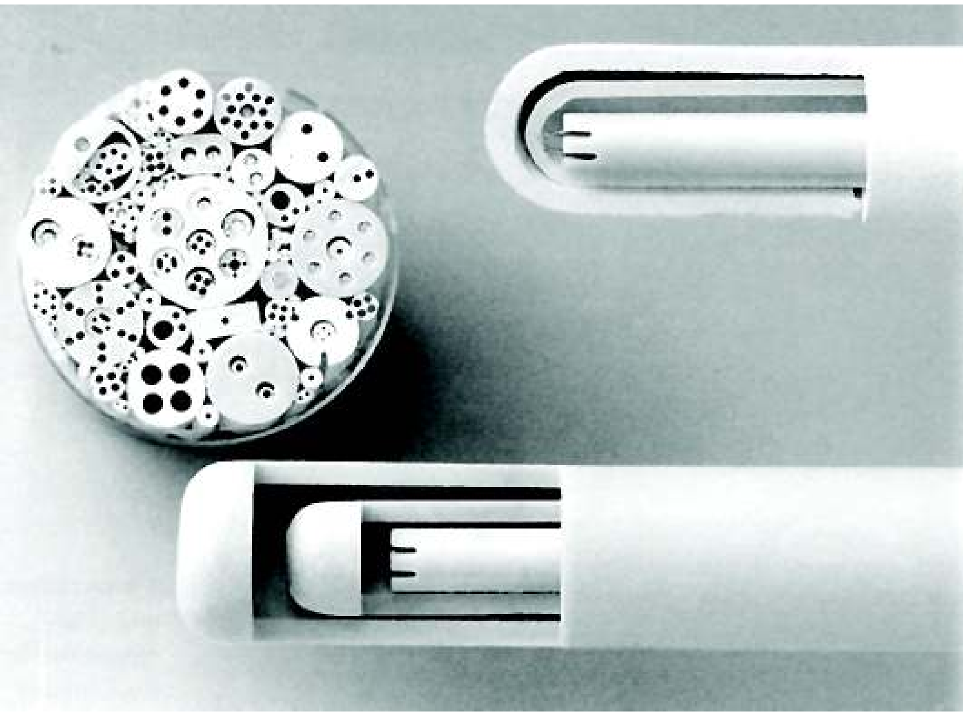


Figure 113: Pyrometer tubes

6.2 High-temperature Technologies

Area of Application	Parts	Why use ceramic?	Materials
Furnace construction and combustion engineering	Beams, burner nozzles, Denox rods, flame tubes, heating elements, boiler inserts, kiln linings, plates, recuperators, jet pipes, supports, dish enclosures, support rollers, heat exchangers	Thermal conductivity, high temperature resistance, corrosion resistance	Silicon carbide, silicon nitride
	Catalytic converters	Good heat resistance	
Miscellaneous applications	Incandescent gas mantle holders, infrared radiators, hole jets, welding nozzles, crucibles	Thermal shock resistance, good heat resistance and corrosion resistance	Cordierite, aluminium oxide

Table 18: Applications in high-temperature technologies

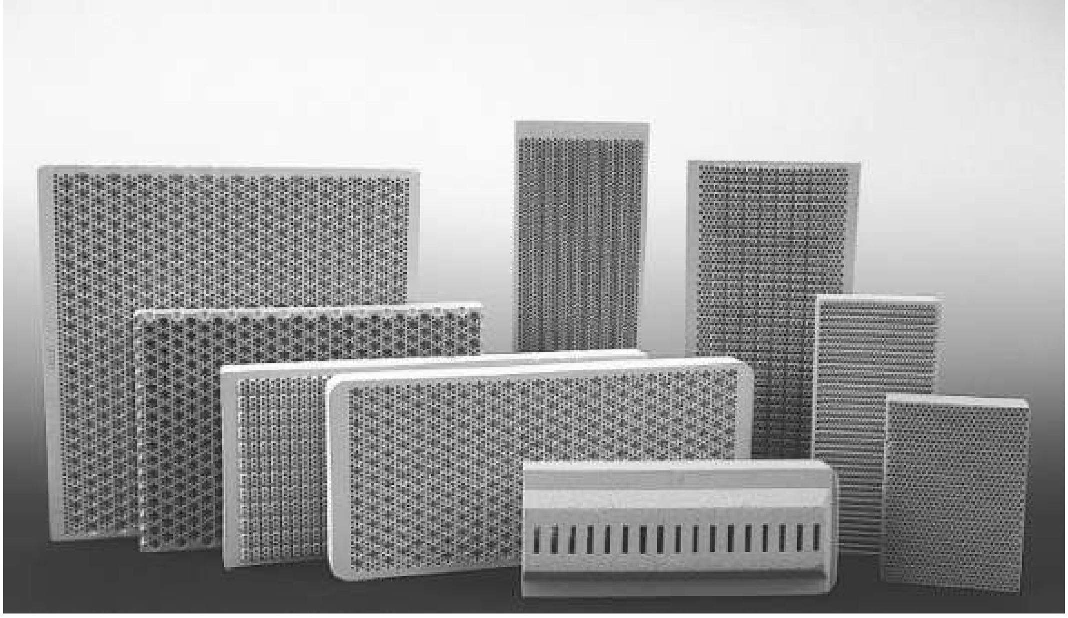


Figure 114: Gas-fired radiant elements

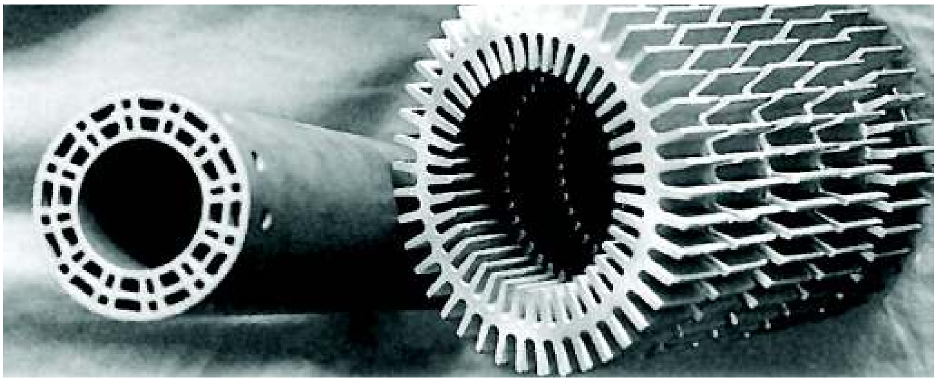


Figure 115: Heat exchangers

Figure 116: Kiln furniture (posts and beams)

Figure 117: Kiln furniture

6.3 Electrical Engineering

Area of Application	*Parts*	*Why use ceramic?*	*Materials*
Insulators	Antenna rods, spacers, feed-throughs, terminating sockets, threaded pipes, retaining pins, sleeves, adjusting pins, contact spring holders, potentiometer rings, regulator brings, regulator sockets, tubes, switch pins, slotted tube plates, protective tubes, external fuse tubes, fuse housings, fuse bodies, fuse tubes, fuse sockets, fuse bases, resistor bodies	Electrical insulation, low loss factor, mechanical strength	Steatite, cordierite, mullite, aluminium oxide, magnesium oxide alumina porcelain

Table 19: Applications in electrical engineering and insulators

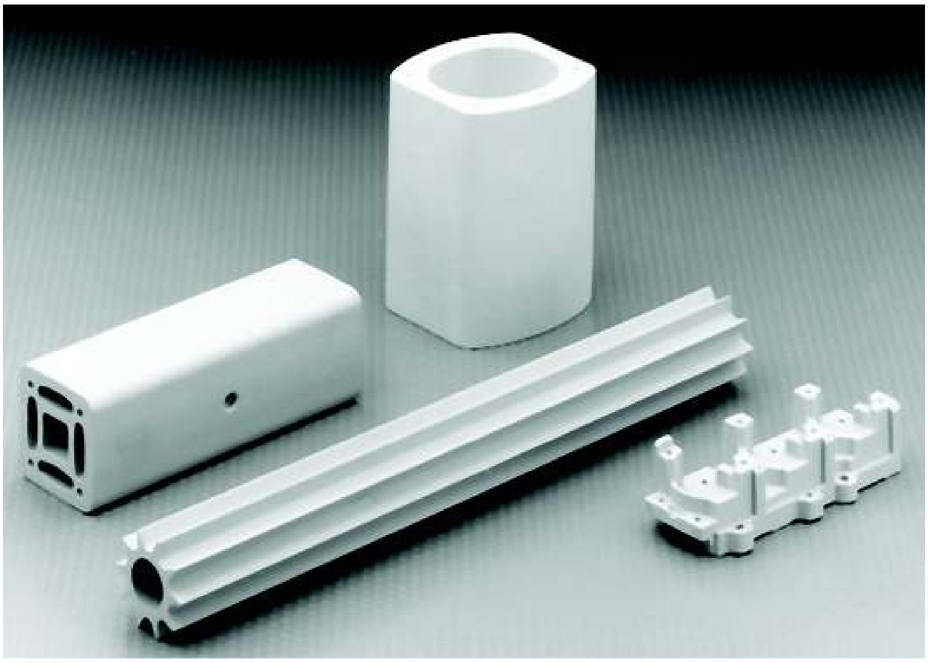


Figure 118: Electrical fuse bodies, sockets, etc.

Figure 119: Resistor bodies

Figure 120: Sockets

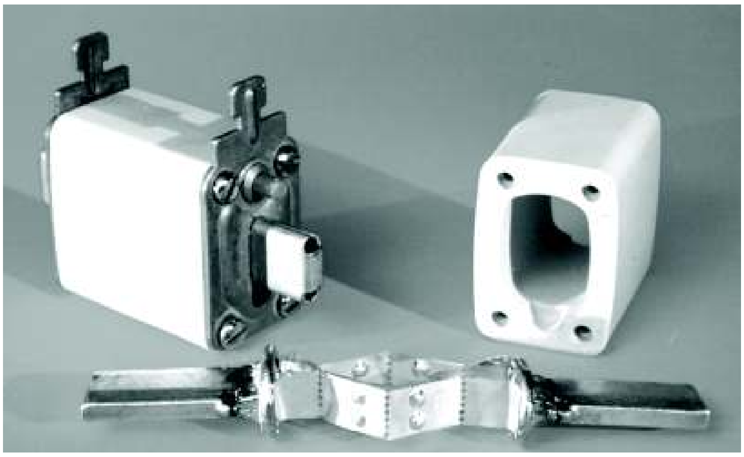


Figure 121: Low-voltage power fuses

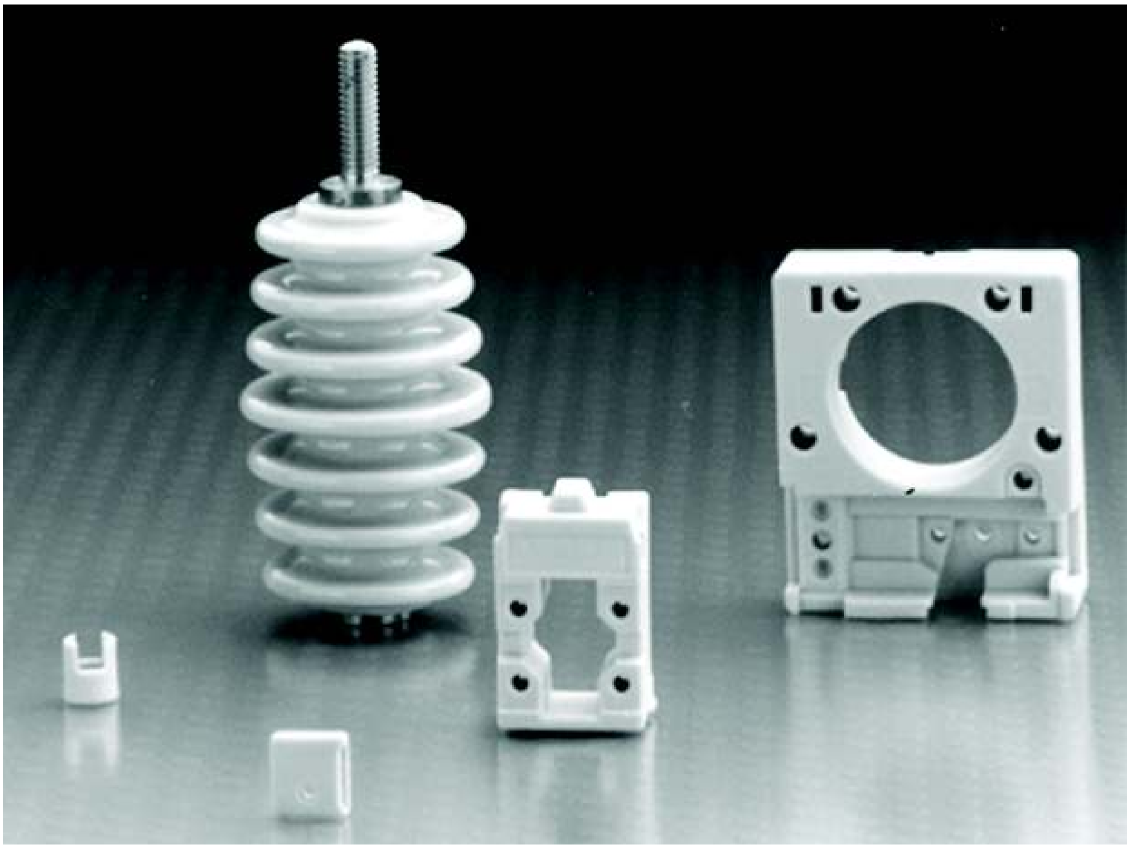


Figure 122: Feed-throughs, sockets and insulators for halogen lamps

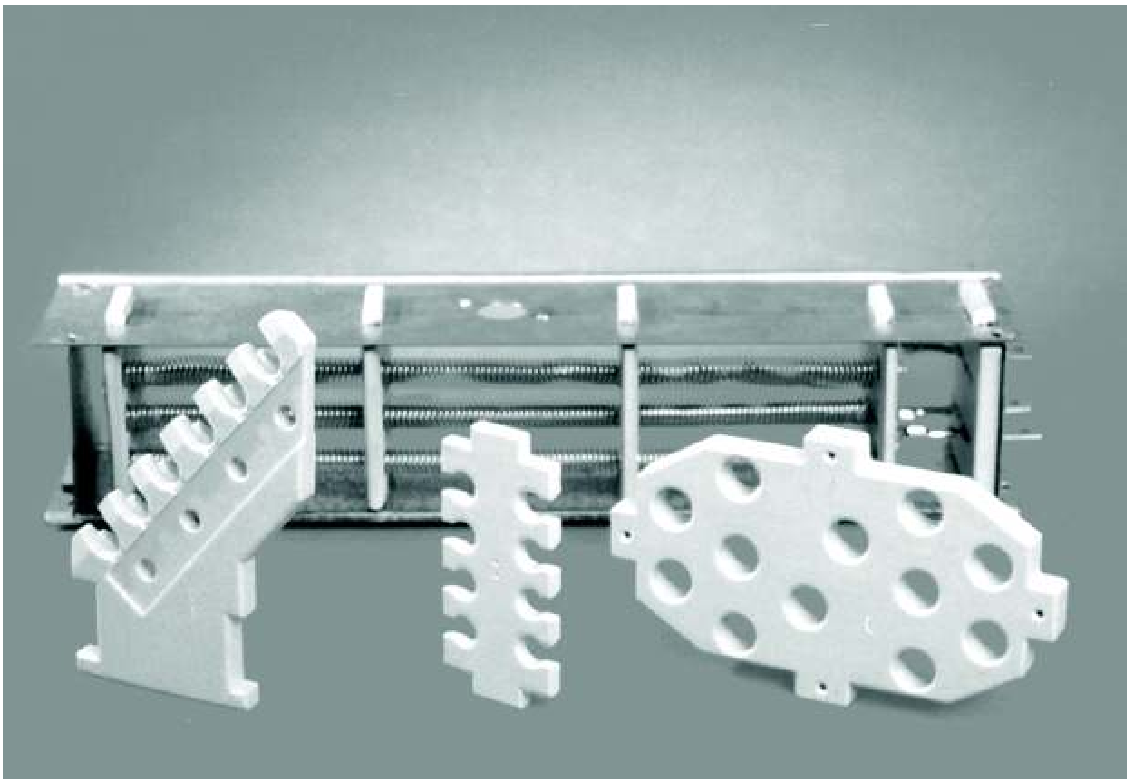


Figure 123: Heating element supports

Area of Application	Parts	Why use ceramic?	Materials
High-temperature insulators	Terminating clamps, sockets, spark protection chambers, spark protection plates, housings, segment radiators glow plugs, base plates, heat conductor pipes, heat conductor supports, oven connection terminals, insulating beads, chamber plates, terminals, lamp sockets, perforated strip, perforated plate, multi-hole tubes, protective tubes, external fuse tubes, support strips, corbels, indexable inserts, resistor bodies, spark electrode holders, spark plugs, strain relief pieces	Electrical insulation, low loss factor, mechanical strength, temperature resistance, resistance to thermal shock	Steatite, cordierite, mullite, aluminium oxide, magnesium oxide
	Fuel cells, sensors	Ionic conduction	Zirconium oxide
	Transformers	Good heat-resistance	Aluminium oxide, aluminium nitride
	Heat sinks	Very high thermal conductivity and electrical insulation	Aluminium oxide, aluminium nitride

Table 20: Thermally stressed insulators for electrical engineering

Figure 124: Various insulators

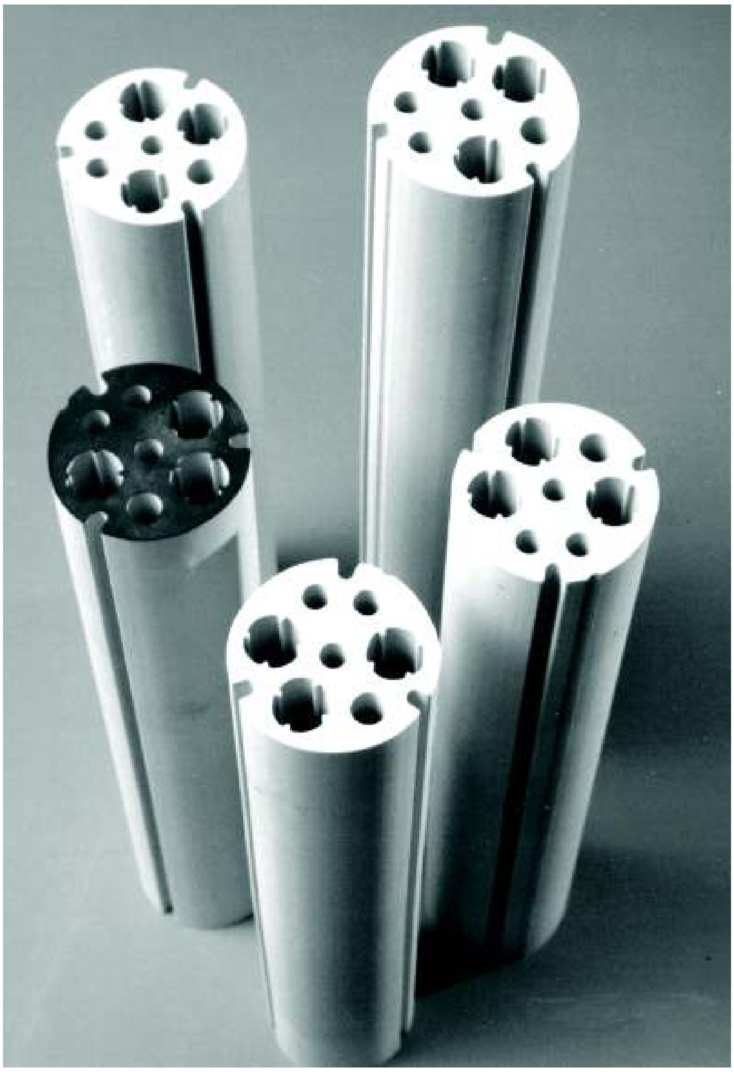


Figure 125: Insulating tubes (multi-hole tubes)

Area of Application	Parts	Why use ceramic?	Materials
High-voltage engineering	Feed-throughs, open-air insulators, housing insulators, high frequency insulators, hollow insulators, long rod insulators, high-strength supports, overhead line insulators, supports	Mechanical strength, resistance to ageing, electrical insulation	Alumina porcelain quartz porcelain, steatite

Table 21: Applications in high-voltage engineering

6.4 Electronics

Area of Application	Parts	Why use ceramic?	Materials
Electronics, general	Feed-throughs, housings, ferrules, insulators, heatsinks, sleeves, substrates, over-voltage protection	Electrical insulation, temperature and particular electrical properties	Alumina porcelain quartz porcelain, aluminium oxide, aluminium nitride
Piezotechnology	Signal transducers: acoustic-electrical, electrical -acoustic, electro-mechanical, mechanical-electrical	Piezo-electric effect	Lead zirconate titanate, (piezo-ceramics; PZT)

Table 22: Applications in electronics

Figure 126: Power semiconductor housings of ceramic and metal

Figure 127: Various piezo-ceramic parts.

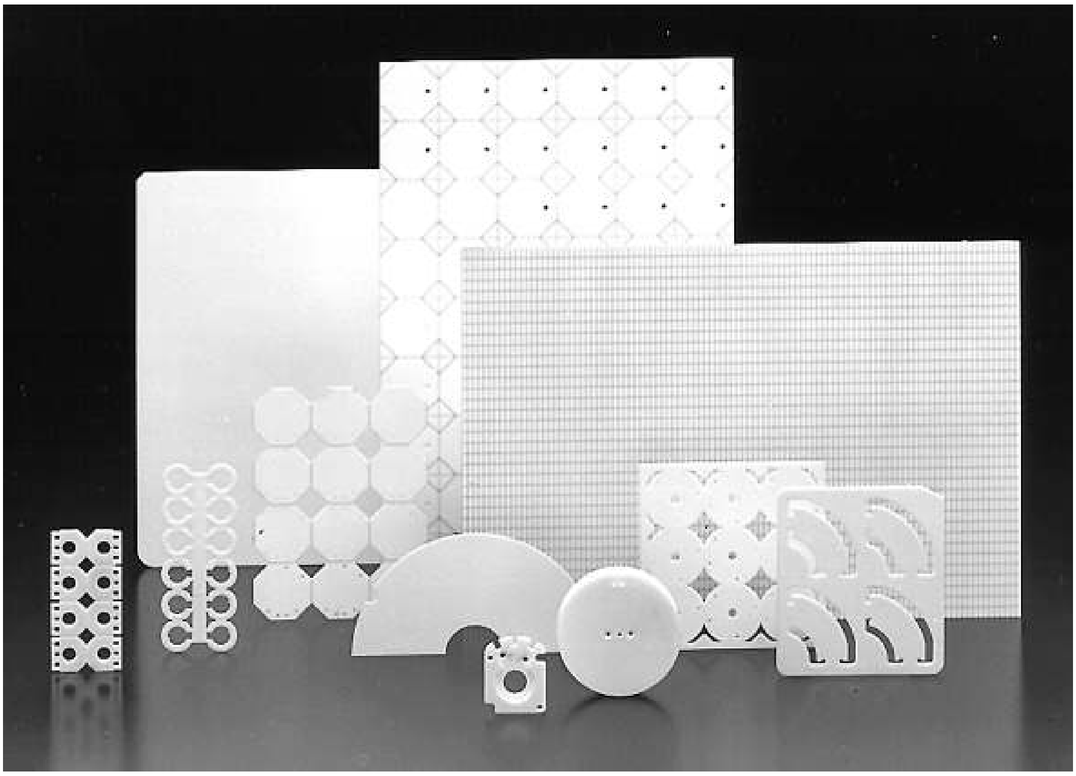


Figure 128: Substrates of aluminium oxide

6.5 Medical Technology

Area of Application	*Parts*	*Why use ceramic?*	*Materials*
Medical technology	Inner ear implants, granules/granulates (for bone repair), prosthetic hip and shoulder joints, bone replacement, dental crowns.	Mechanical strength, surface quality, bio-compatibility	Aluminium oxide, calcium phosphate, zirconium oxide, hydroxylapatite

Table 23: Applications in medicine

7 Ceramics-appropriate design

In contrast to most other materials, forming in ceramic technology takes place before the thermal processing that leads to the formation of the desired material and during which the formed component is liable to shrink.

The true ceramic material is only present after the firing process has been completed. This strongly influences the design of ceramic parts.

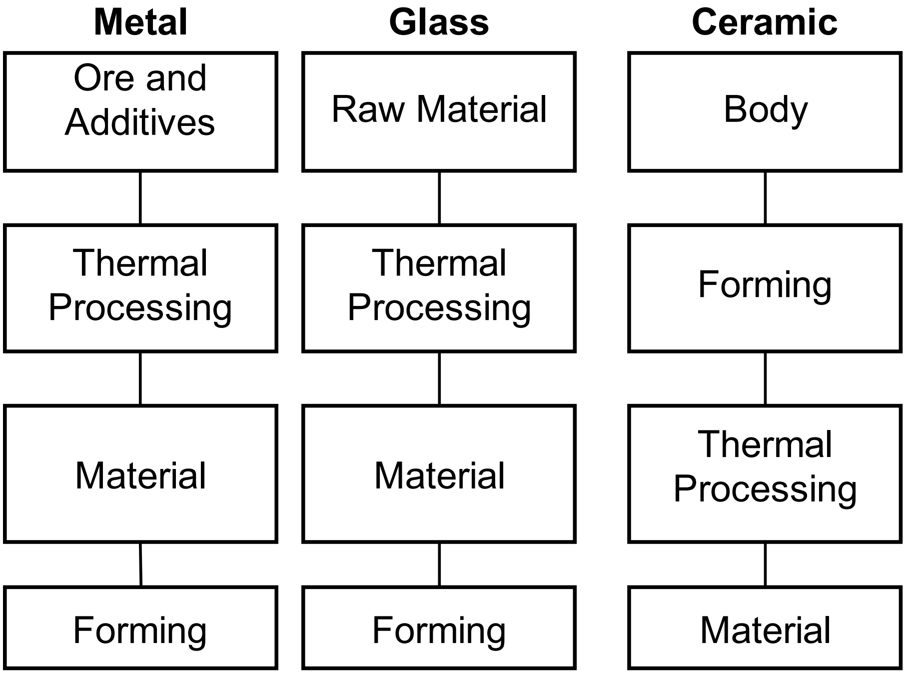


Figure 129: The creation of materials

The use of typical metallic and polymeric materials (steel, cast-iron, aluminium alloys, nickel-based alloys, etc.) for machine and tool construction, automotive construction and process engineering is deeply ingrained in most design engineers. Many generations of engineers have accumulated experience with these materials, and have passed this on in the education of new engineers.
The situation his very different when it comes to the application of newly developed materials, or to new uses for materials that may have been familiar for a long time but which to date have only been used for a restricted range of applications. This is the case for **technical ceramic** materials.

When a technical problem has to be solved, the designer must create a number of technical elements; if ceramic materials are to be used, he must pay particular attention to the need for the **design to be appropriate for the material**.

Ductile materials react to small area/local overloads, compensating for them through elastic extension in accordance with Hooke's law, with some plastic deformation in reserve.
This does not apply to materials that are hard and therefore brittle - and also not flaw-tolerant. There are therefore considerable differences between the local loading capacity of parts made of ductile (metallic) materials and of brittle/hard (ceramic) materials. This therefore also calls for different design rules.

The designer will find some analogies in the basic rules for designing parts of cast materials and in the manufacturing possibilities relevant to powder metallurgy.
The combination of ceramic with metallic components presents a series of problems in addition to the design of the parts themselves. In most applications, a single component in the product (for example, replaceable wearing parts) is manufactured using ceramic materials, and is combined with the neighbouring metallic parts and assemblies.

It is the job of the design engineer to make use of the outstanding properties of technical ceramics and to apply them effectively and economically, while reducing the effect of their limiting properties. This is what is understood under the concept of design for ceramics.

7.1 The Design Sequence

The task of an engineer is the solution of a technical problem. This solution must both fulfil the technical specifications and must be economically feasible. It is absolutely necessary that both these conditions are met. This means that a compromise must be found between improved performance and the required expense. Solutions that either do not guarantee the technical function or that are too expensive are unsatisfactory.

In a good design that is appropriate for ceramics, the advantageous properties of the ceramic materials are maximised and the disadvantages (such as brittleness) are minimised or even nullified through the use of good design principles (for example, separation of functions, modular techniques, compressive loading, etc.).

During the planning phase, information concerning the exact function of the part to be designed and the properties of the ceramic materials under consideration must first be obtained. It is thus helpful if the design engineer and the manufacturer work together at the earliest possible stage of the planning phase, in order to decide on the fundamental feasibility of the construction. Not only must the technical specifications be taken into consideration, but also manufacturing costs, including planning and development, so that the possibility of wasted investment is detected as early as possible in the design process. It is particularly advantageous when, on one hand, the design engineer already possesses knowledge of designing with ceramics, and on the other hand if the component maker has an understanding of the sequence of the customer's operations.

A valuable prerequisite for reaching a decision regarding the technical feasibility and for the purposes of cost calculations is a complete and correct drawing. With reference to the first design with which the design engineer approaches the ceramic manufacturer, it is desirable for all the variable parameters (shape, dimensions, tolerances, surface quality, etc.) be clearly emphasised. The same is true for any dimensions whose maintenance is crucial to the design.

The way in which the component will function, and the stresses to which it will be subject, should be explained in the initial discussions with the ceramic manufacturer, so that the optimum ceramic material for the particular case can be chosen. As a second step, the variable parameters mentioned above should be discussed with reference to the ultimate function, so that both sides become clearly aware of any difficulties that might arise.

During the first meeting between the user and the component manufacturer, figures concerning the expected lot sizes should be available, since these are decisive for the choice of manufacturing process to be used, and therefore for the expected manufacturing costs. Small lot sizes, single parts and prototypes are often machined from a preform, while the construction of expensive tools, for example, for dry pressing, extrusion or injection moulding, are only cost-effective with large batch sizes. Parts manufactured using different processes do not necessarily possess identical properties, a fact which must also be taken into consideration when transferring experimental results to ordinary manufacturing conditions (density gradients, tolerances, wall thicknesses, taper, internal stress, taper etc. for example).

On the basis of the drawings with which he has been provided and of discussions held with the user, the component manufacturer is able to suggest changes that are necessary because of the production technology. These changes frequently do not have any effect at all on the function of the part, but are often necessary to make it at all possible to manufacture the part, or offer a reduction in costs without which economical manufacture would not be possible.

As a rule, a few sample parts are manufactured and tested after the modified design drawings have been discussed and approved. On the basis of experience that can be obtained from field tests using these parts a decision is reached as to whether the production order can begin or whether the part must be modified once again.

There can be differences between the properties of the prototype and the series part. Tests prior to final approval should therefore use samples produced in a way similar to full production.

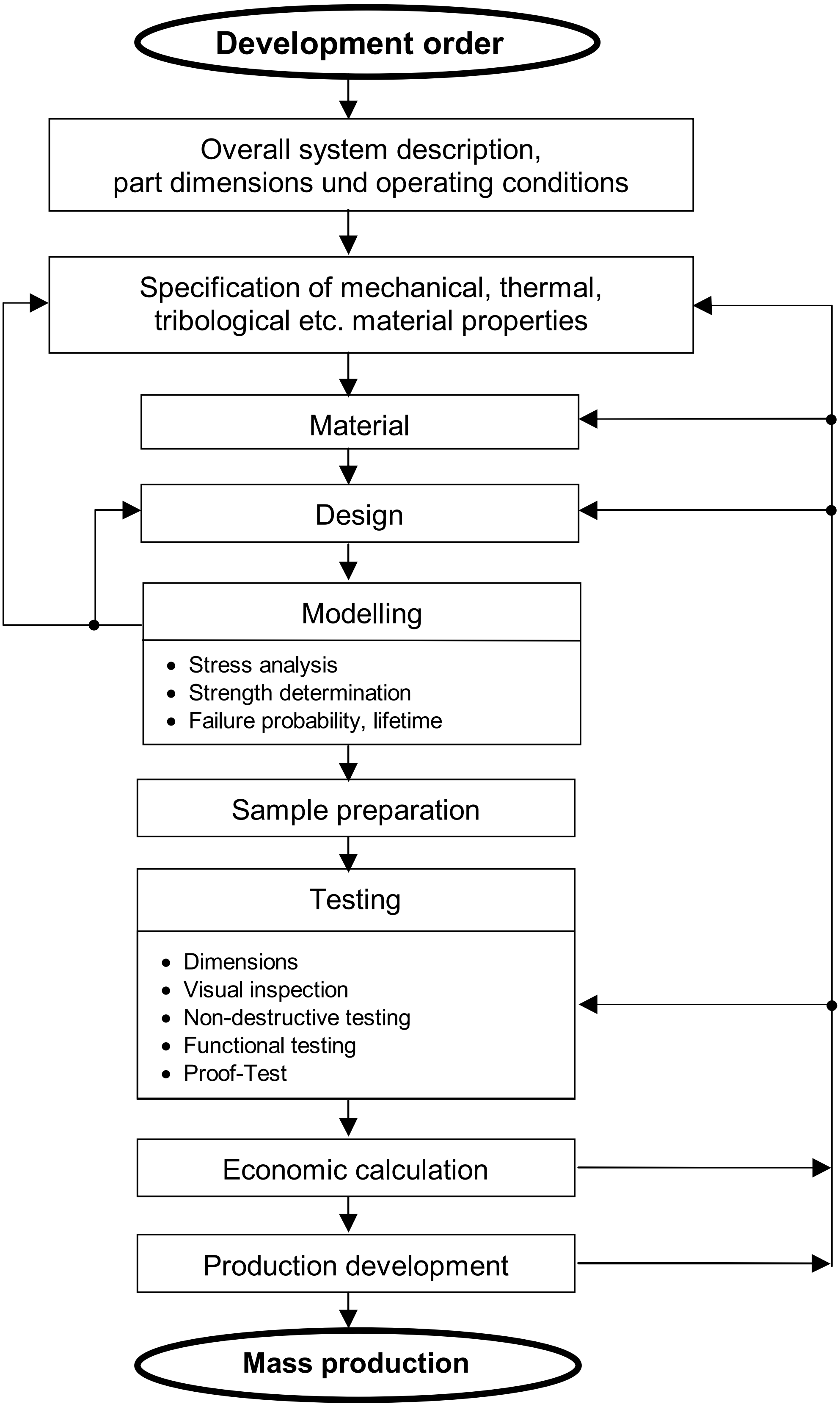


Figure 130: The development of ceramic components

7.2 Design Notes

Every possible type of forming and treatment process entails certain demands that must be considered in the design. The physical properties of the ceramic material and of composite parts having ceramic and metal components must also be considered. Some of these demands are explained below.

7.2.1 Influence of Material Properties

Due to the complete lack of plastic deformation, ceramics fail suddenly at low and medium temperatures on reaching the local material strength in the region of critical microstructural inhomogeneities. High stresses occur particularly in the region of small radii, sharp edges, steps, offsets and holes, as well as in areas where forces are applied at points or along lines. Under certain circumstances stresses will be generated that reach the limit of the material strength much earlier than would be expected on the basis of the part's external loading, due to notch effects associated with these geometrical features, effects that can be considerable.

For this reason, notch-like geometries (stress concentrations) should be avoided in the design of a ceramic part, or at least only implemented in a softened or optimised form. The particular advantage of ceramic materials is the ability to withstand high compressive loading. One of the primary goals of design for ceramics should therefore be to make use of this property as much as possible, and to keep the number of areas where the part will experience tensile or bending stress as low as possible. High stress concentrations should particularly be avoided in regions subjected tensile stress.

These basic principles are often not sufficiently considered by some users. Instead, the desire is often expressed to obtain a direct copy of a component that was originally designed "metallically", in ceramic material but having the same shape. This can, however, not only increase the manufacturing costs, but can even put the feasibility of the product in question.

7.2.2 Influence of the Forming Process

Similarly to the manufacture of metallic or polymeric materials, the manufacturing process for ceramic parts possesses not only certain advantages but also has its limitations.

Thus for example, using **slip casting**, parts with constant wall thickness can be manufactured, but only up to a maximum of a few millimetres (depending on the material). It is more difficult to manufacture parallel surfaces, since the removal of the cast part from the mould is more difficult. Undercuts are also difficult and only possible through the use of complex, multi-part casting moulds.

Tubular or bar-shaped parts are usually manufactured by **extrusion**. Here, the manufacturing skill lies in retaining the cross section of the body and in avoiding deformation (sagging, ovalising) both axially and radially.

Injection moulding permits the production of very complex forms very close to their final dimensions. The tooling costs and batch sizes represent a considerable factor in the cost calculations.

The **isostatic pressing** technique is used mainly for the production of blanks with a particularly uniform density. These are subsequently processed further using chip-forming operations such as turning, milling, boring, grinding or cutting (using diamond tools).

Dry pressing is a process often used for the series production of smaller parts. This process allows the economical production of relatively flat parts with a height to wall thickness ratio < 4 (in special cases < 8) and with no excessive height differences (blind holes, steps, etc.). The pressing tools are subject to high wear due to the high hardness of the ceramic powders. The lifetime of the tools is therefore limited if sufficiently accurate dimensions are to be maintained in the parts.

7.2.3 Modular Design

Ceramic bodies that are either large or that have complex shapes often cannot be formed, or can only be formed with great difficulty, using the forming processes described above. A method that is often practised, and is worth considering, is that of splitting a complex part into two or more smaller and simpler units that can therefore be manufactured much more easily using the usual techniques. It is only necessary to ensure at the design stage that these smaller units can later be joined to form a whole. (Example on page 173)

The *design of ceramic parts using modular techniques* in many cases offers advantages with respect to the economic manufacturing processes, simplifying quality control, increasing load capability, reducing thermal stresses, and so on. For example, insulators that are 4 to 5 m tall, rated for 550 kV, are assembled from prefabricated parts that are either glued together or joined by glazing.

A number of different techniques have already been successfully applied to joining identical materials (ceramic-ceramic):

- slip joining
  (assembly of parts in the green state)
- lamination
  (layered structure)
- co-sintering
  (axle and rotors in some brands of turbochargers, etc.)
- gluing
- soldering.

7.3 Cost-Effectiveness

7.3.1 Component Costs in Principle

Manufacturing costs for a part made of technical ceramic are comprised of the following:

- material costs,
- forming costs,
- finishing costs,
- firing costs,
- test costs and
- other miscellaneous costs.

The material costs are dependent on the material used, and in most cases are comparatively low. Increased demands on the properties of the ceramic can cause the raw material price to have a significant influence on the total costs due to the high purity required and to the well-defined, reproducible powder properties. This is particularly the case when manufacturing large parts.

Forming costs are also not insignificant for single parts or small batch sizes. This is due to the large number of single steps that must either be carried out manually or that can only be partially automated.
If hard finishing is necessary, the final finishing costs are often the dominating factor.
Testing can, under certain circumstances, become a noticeable fraction of the total cost for parts that are geometrically complex and highly stressed. These may require many tests and property certificates.

7.3.2 Component Costs in Mass Production

The costs involved in mass production depend heavily on the manufacturing steps that are technically necessary and on the degree of automation, which in turn depends on the batch size. Recent developments, for instance, are demonstrating significant progress in hard machining, achieving a similar cost basis as that of metal machining. High performance ceramics also offer significant cost optimisation to the advantage of the user.

7.3.3 Cost-Effectiveness in the System

It is generally also appropriate to consider the additional benefits that ceramic components bring to the total cost structure.

- Some technical demands can only be met at all through the use of ceramics, permitting innovation and generating a competitive advantage.

The longer service life and improved reliability bring

- significant savings in production machines:
    - fewer spare parts need to be procured,
    - repair expenses are reduced and
    - there is less downtime.

- consumer goods:
    - fewer returns and
    - reduced liability risk.

7.4 Design for Strength

Manufacturers and users currently assess the mechanical loading capacity of ceramic products in four ways:

1. by experience (intuition),
2. through the analytical calculation of stress distribution or
3. the numerical calculation of stress distribution, or
4. again through the calculation of stress distribution and, based on this, the local distribution of failure probability obtained through statistical methods.

The effort required for the strength-oriented design of a part increases from 1 to 4. The degree of utilisation of the material properties also increases however, through which some engineering solutions may become possible for the first time.

The design of ceramic parts for long-term use or subject to fatigue stress can be carried out using the same process. However, since the failure of these materials is generally the result of crack initiation and crack growth phenomena, the application of fracture mechanics in combination with numerical calculation methods and statistical failure models is recommended.

For many less critical applications, intuitive knowledge and approximate calculation are used in practice for the design of the part as well as the choice of material. The conditions of use are also taken into account, and the part designed accordingly. Intuitive knowledge develops out of years of experience of both the design of ceramic parts and of their behaviour in operation. Many basic rules for the design of ceramic materials (for example, compressive stress is OK, tensile stresses are critical, notches are critical, etc.) are a result of this experience. However, a mathematical description is not given here.

7.5 The Design of Parts

7.5.1 Basic Rules

- **Aim for simple forms and dimensioning that is suitable for manufacturing**
  - adapt the design to suit the forming process of the green body,
  - make the forming process and sintering processes easier,
  - split complex forms into several simpler pieces,
  - avoid over-specifying surface properties and unnecessarily close tolerances.

- **Avoiding stress concentrations**
  - minimise notch stresses,
  - apply forces over large areas,
  - avoid sudden changes in cross-sectional area,

  - avoid corners and sharp edges.

- **Minimise tensile stresses**
  - specify cross-sections appropriate to the expected loading,
  - convert tensile stress into compressive stress through appropriate construction,
  - include compressive pre-stressing,
  - arrange for forces to be applied in a manner suitable for ceramics

- **Avoid material accumulations**
  - pay attention to keeping wall thickness as uniform as possible,
  - separate the nodes in the design,
  - avoid sudden changes in cross-section,
  - design for good densification.

- **Minimise final finishing**
  - specify the shape of the green body and the green body machining, leaving only very little working allowance for final finishing,
  - prefer green machining to final finishing,
  - allow only small and limited machined surfaces,
  - only specify requirements that are absolutely necessary,
  - define non-machined roundings and chamfers.

- **Pay attention to manufacturing-specific details**
  - ease removal from the mould,
  - avoid undercuts,
  - choose the most favourable forming process for the green body,
  - avoid thin walls and bridges,
  - aim to keep the component proportions suitable for manufacturing,
  - create clear seating and fastening facilities for subsequent machining

- pay attention to special requirements of the individual manufacturing steps such as:
    - wet and dry pressing,
    - extrusion
    - sintering and
    - glazing.

7.5.2 Ways to Improve Loading Capacity

- **Constructive design**
    - compressive stress is preferable in ceramic parts and can be achieved through appropriate
        - specification of how the load is applied,
        - part design,
        - the positioning of joints and contact points
    - creating compressive pre-stress to compensate for tensile stresses during use, for example by
        - casting metal around the ceramic,
        - shrink-on bushings/sleeves on rotationally symmetrical ceramic parts,
        - pre-stressing when assembled,
        - technological measures (e.g. glazing high tension insulators).
    - increasing the loading area, avoiding stress concentrations,
    - dividing large-volume parts into several pieces (modular construction). consideration of the effect of volume on the strength, in particular if the Weibull modulus $m < 20$.

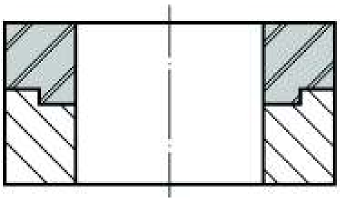
- **Choosing a different material**
    - using a material with higher strength,
    - using a material with greater K_{IC}-value (greater crack resistance),
    - using dispersion-strengthened material (e.g. aluminium oxide reinforced with zirconium oxide),
    - using fibre-reinforced materials.

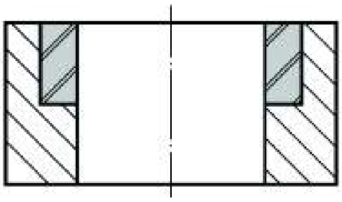
- **Technological measures**
  - machining only in a direction parallel to the direction of maximum stress,
  - creating compressive stress in the surface region,
  - controlling and exploiting transformation processes in the crystal structure, especially when using zirconium oxide.

7.5.3 Examples

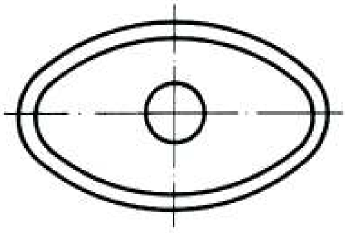
In order to exploit fully the properties of technical ceramics and to design economical parts with them, a few material-specific design recommendations should be observed in addition to the common construction rules. Some basic rules will be illustrated through examples in the following sections.
For the sake of clarity, cross-sections of ceramic parts are shaded grey.

7.5.3.1 Keep Shapes Simple

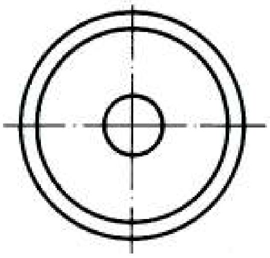




- Avoid steps and offsets if possible

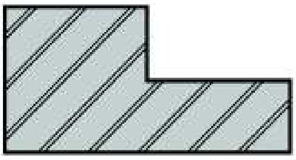


unfavourable

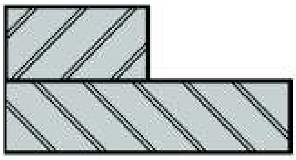


favourable

- avoid oval parts

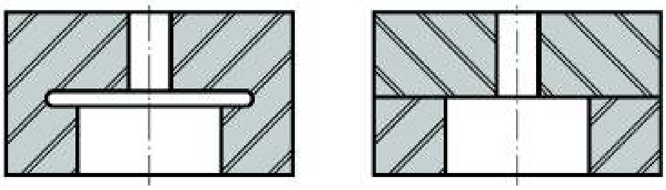


unfavourable



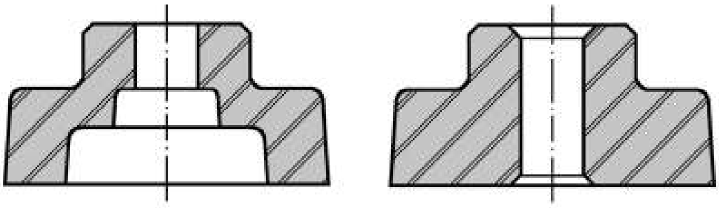
favourable

- give preference to modular construction



unfavourable **favourable**

- avoid undercuts and prefer modular construction

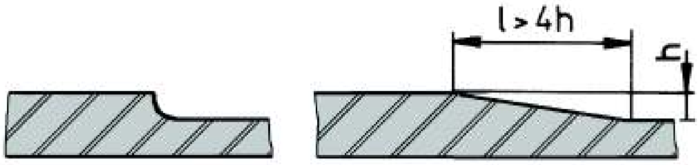


unfavourable **favourable**

- avoid complex wall forms and shapes

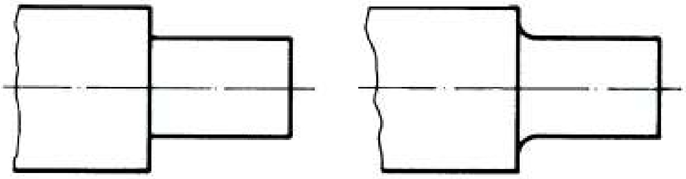
Figures 131–135: Keep forms simple

7.5.3.2 Avoid Stress Concentrations



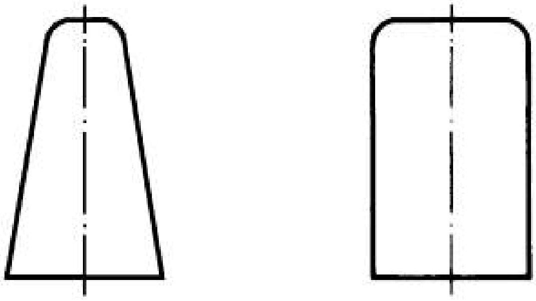
unfavourable **favourable**

- avoid sudden changes in cross-sectional area



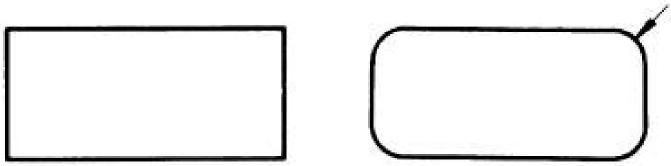
unfavourable **favourable**

- minimise notch-like structures



unfavourable **favourable**

- provide large contact areas

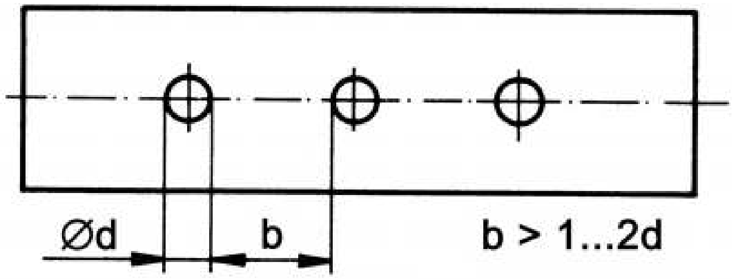


unfavourable **favourable**

- Avoid corners and sharp edges, round inner edges and cutouts

unfavourable **favourable**

- avoid long, sharp edges (risk of breakage)

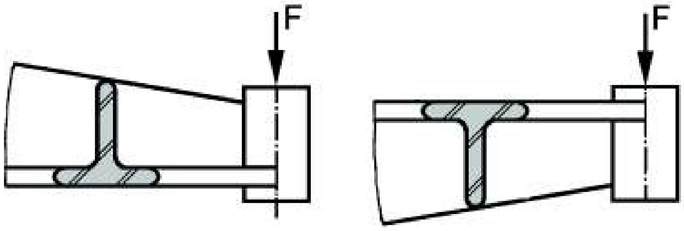


favourable

- do not locate holes too close together

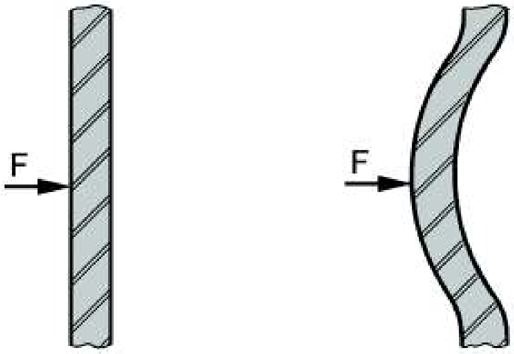
Figures 136-141: Avoid stress concentrations

7.5.3.3 Minimise Tensile Stresses



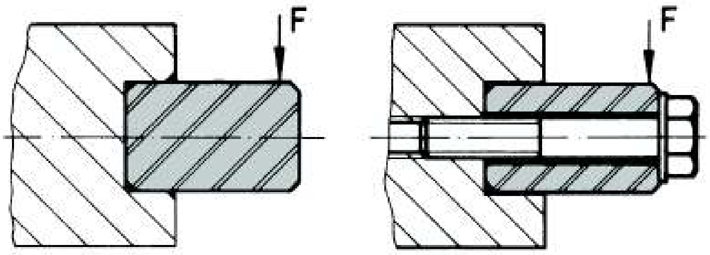
unfavourable **favourable**

- choose profiles so that tensile stresses are minimised (ribs under compression)



unfavourable **favourable**

- convert tensile to compressive stress (arches instead of beams)

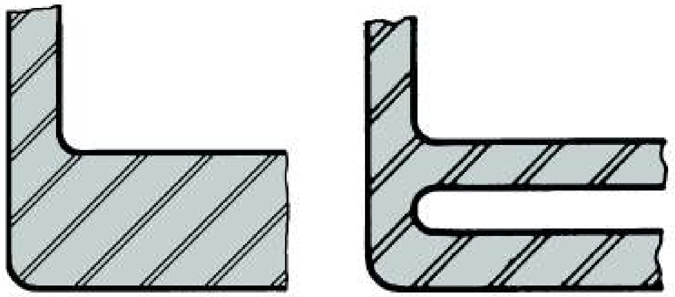


unfavourable **favourable**

- pre-stress with compression

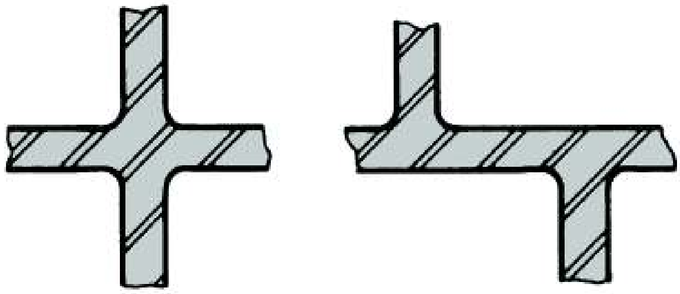
Figures 142-144: Minimise tensile stresses

7.5.3.4 Avoid Material Accumulations



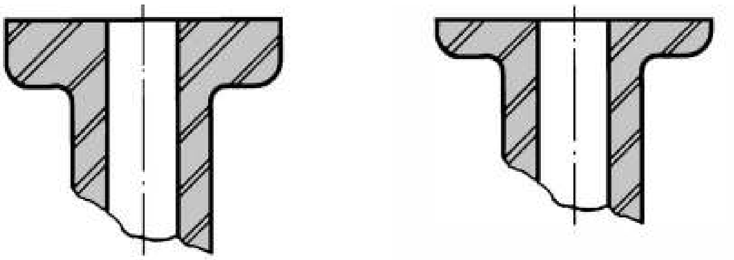
unfavourable favourable

- aim for even wall thickness in extrusions



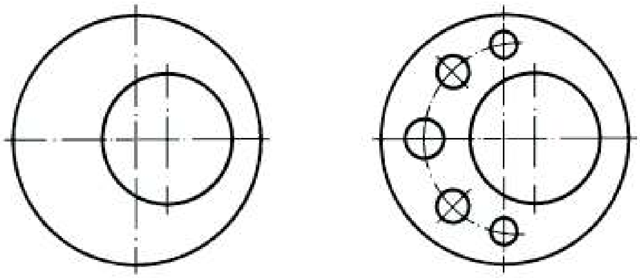
unfavourable favourable

- separate the nodes



unfavourable favourable

- avoid thick ends on mouldings

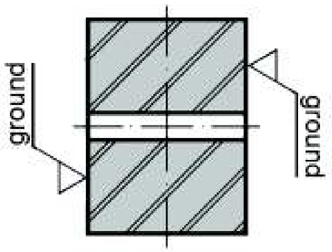


unfavourable favourable

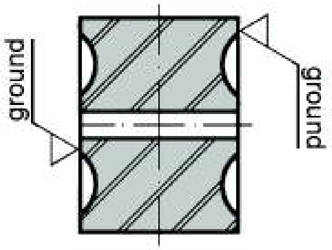
- avoid large differences in wall thickness in extruded parts (risk of distortion)

Figures 145-148: Avoid material accumulations

7.5.3.5 Minimise Final Finishing

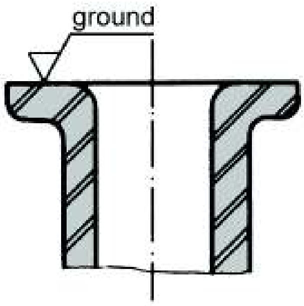


unfavourable

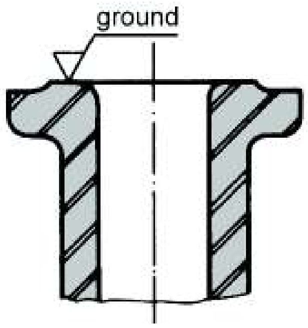


favourable

- keep surfaces that are to be machined small

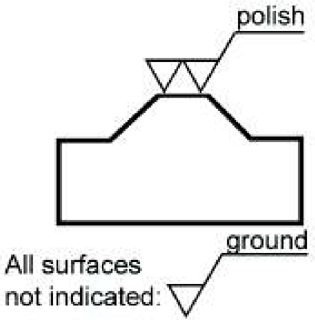


unfavourable

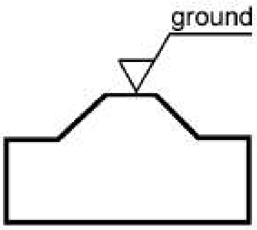


favourable

- raise surfaces to be machined

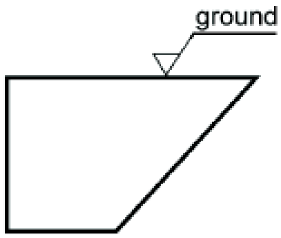


unfavourable

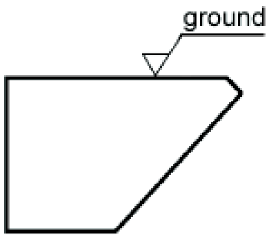


favourable

- only specify requirements that are absolutely necessary

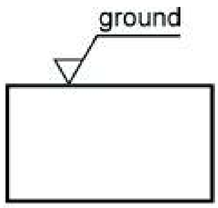


unfavourable

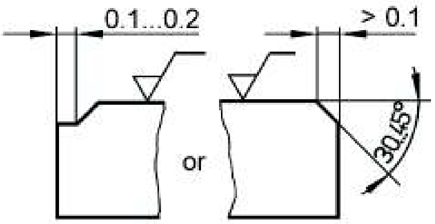


favourable

- Avoid edge angles < 90°

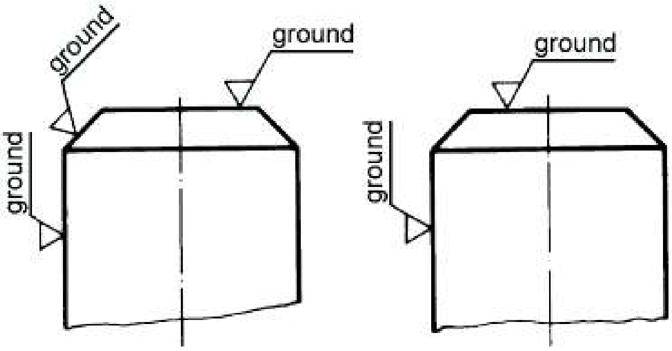


unfavourable



favourable

- bevel surfaces to be finished

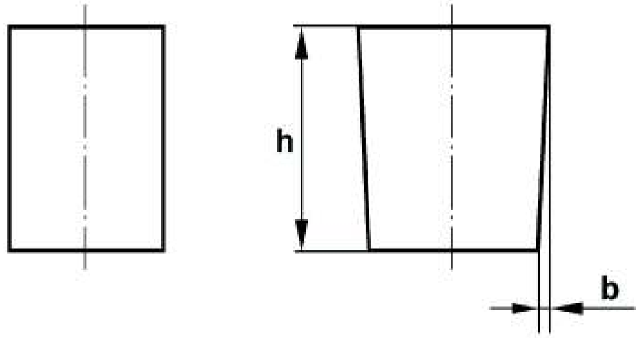


unfavourable **favourable**

- dimension bevelling so that facets do not need to be finished

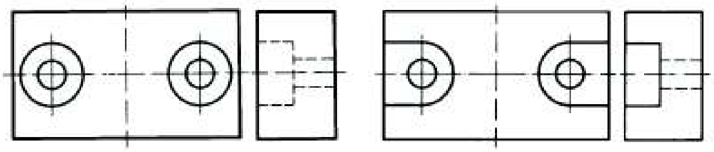
Figures 149-154: Minimise final finishing

7.5.3.6 Manufacturing-Specific Details



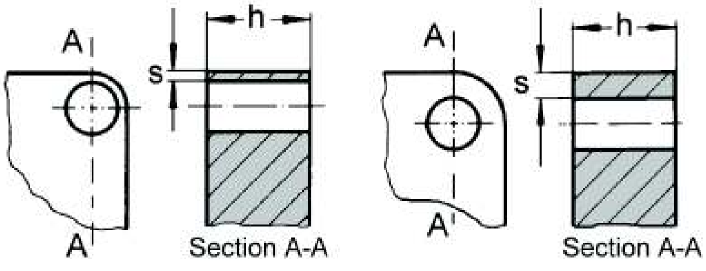
unfavourable **favourable**

- Provide taper with b ≈ 0.005 h to ease removal from the mould (not necessary for isostatic pressing and extrusion)



unfavourable **favourable**

- leave countersinks open to the edge (crack prevention)



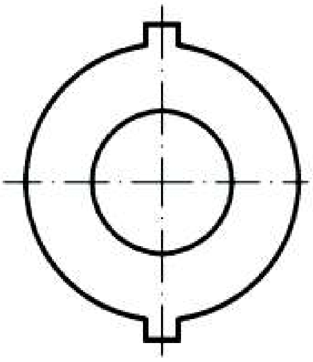
unfavourable **favourable**

- select a sufficiently large edge clearance for holes

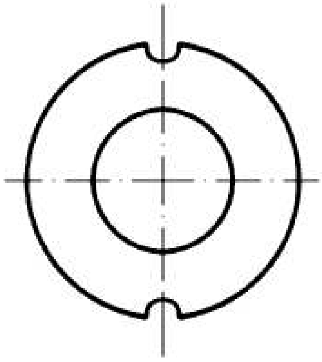
- Ratio s/h

Examples:

h [mm]	s [mm]
< 10	¼ h (s ≥ 1mm)
10 - 20	1/5 h - 1/6 h
> 20	< 1/6 h

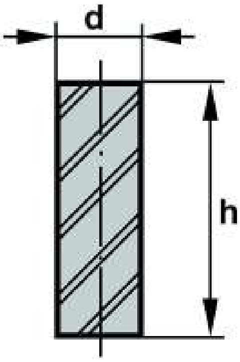


unfavourable

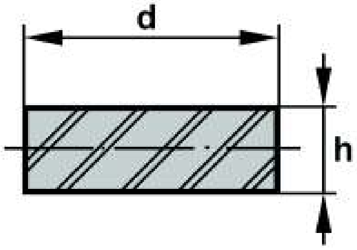


favourable

- avoid protruding details with a small cross-sections



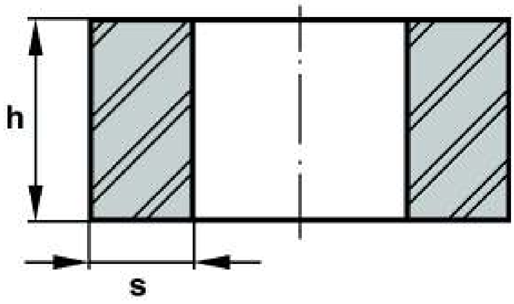
unfavourable



favourable

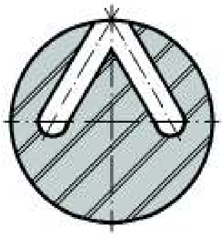
- limit the height of parts that are uniaxially pressed

h/d < 6	possible
h/d < 3	favourable

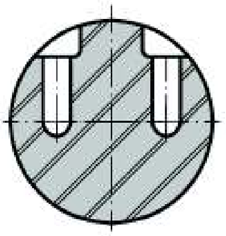


- ensuring minimum wall thickness

h/s > 8	Extrusion or isostatic pressing



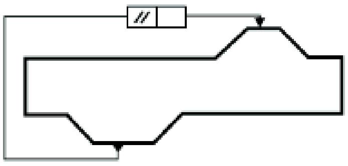
unfavourable



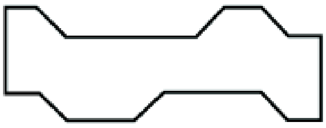
favourable

- lateral holes should not intersect

- avoid lateral holes

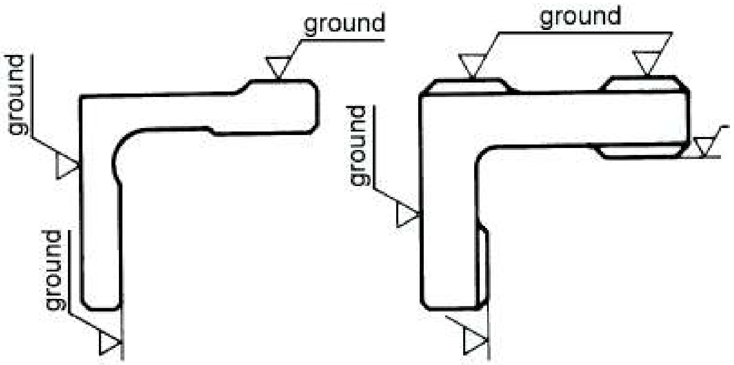


unfavourable



favourable

- ensure technically practicable parallelism

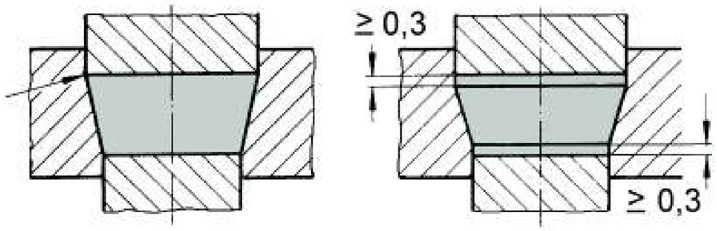


unfavourable **favourable**

- Angled parts should have thick arms, minimised finishing surfaces and well-defined mounting areas

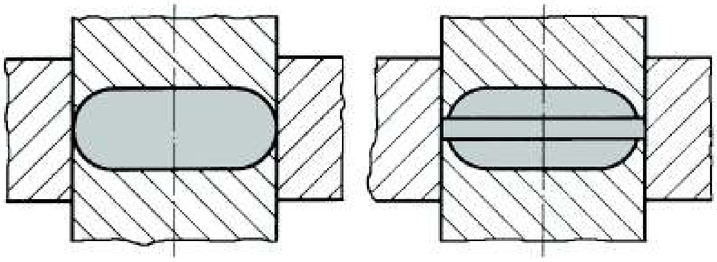
Figures 155-163: Pay attention to manufacturing-specific details

- *Special features of wet and dry pressing*



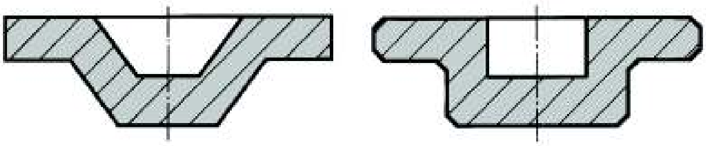
unfavourable **favourable**

- Avoid tapered shapes (cylindrical ends result in good edges and reduced tool wear)



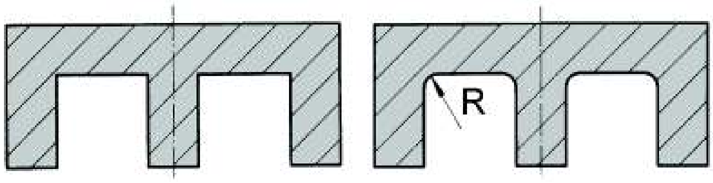
unfavourable **favourable**

- Sharp (or feather-) edged dies that may meet during pressing are unusable, add a small cylindrical section with a small end region



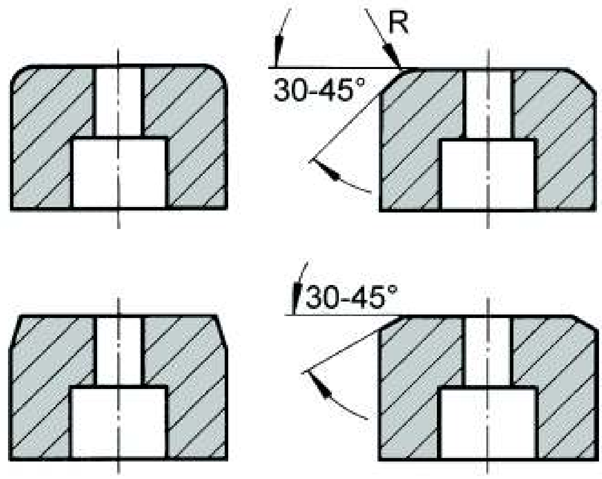
unfavourable **favourable**

- shallow inclines, or none at all, yield denser microstructures



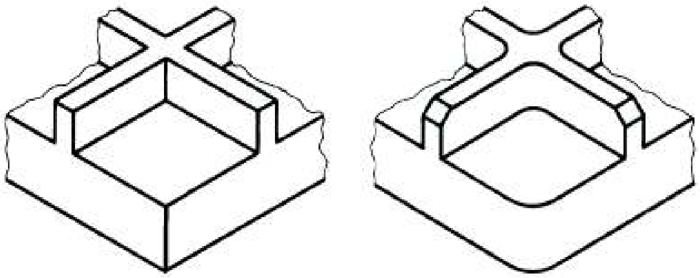
unfavourable **favourable**

- avoid sharp internal corners



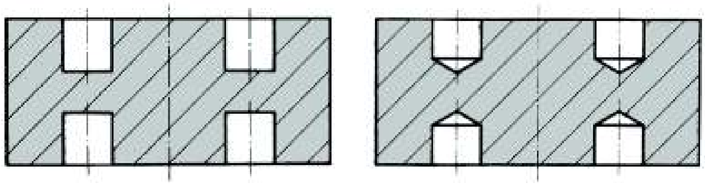
unfavourable **favourable**

- avoid rounded edges or edges with acute angles



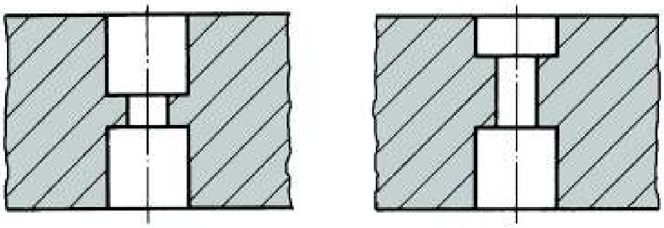
unfavourable **favourable**

- avoid sharp corners and edges at the intersection of lands and ribs (risk of cracking and liability to fracture)



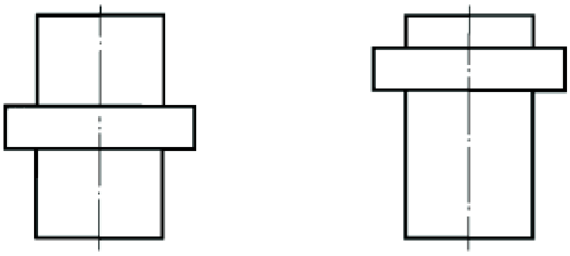
unfavourable **favourable**

- avoid flat bottoms in blind holes (overpressing)



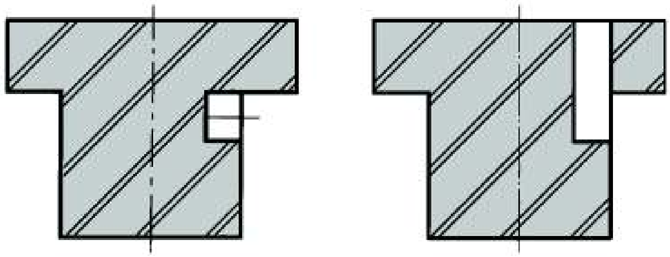
unfavourable **favourable**

- reduce upper countersink depth and allow sufficient wall thicknesses to result in lands without cracks and a more uniform density



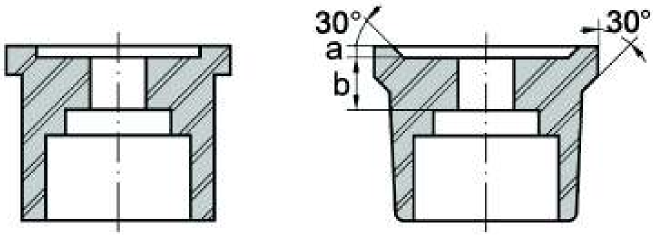
unfavourable **favourable**

- avoid overpressing flanges, keep press depth from the top small in order to achieve a uniform density



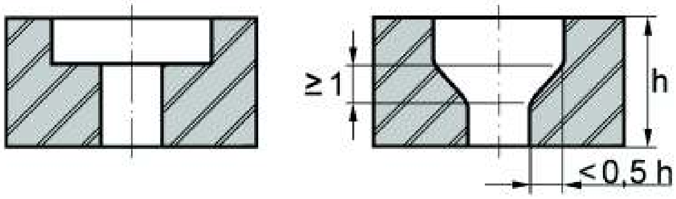
unfavourable **favourable**

- run lateral undercuts (internal and external) to the top



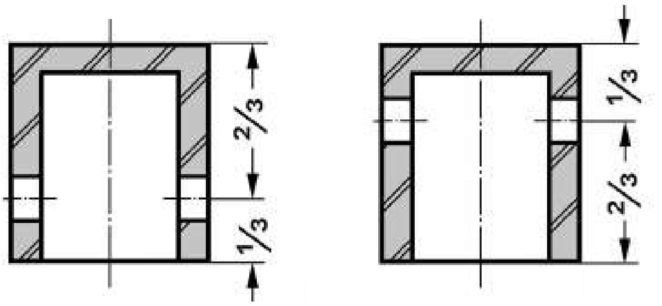
unfavourable **favourable**

- rounded or bevelled edges are easier to demould; keep bottom thicknesses large; keep depression ‘a’ on the top face if possible to only 0.5 to 1 mm deep



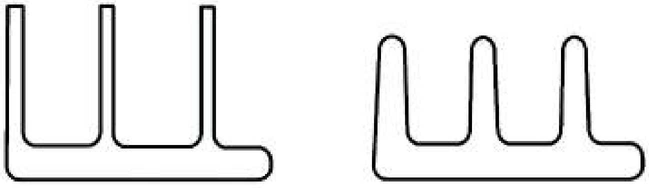
unfavourable **favourable**

- incline transitions wherever possible



unfavourable **favourable**

- move lateral holes into the upper region of the part
  (easier manufacture using a bar)

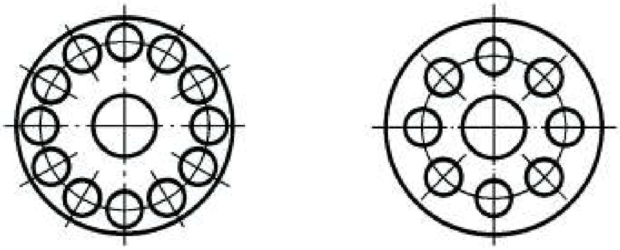


unfavourable **favourable**

- Avoid thin free-standing walls (danger of distortion)

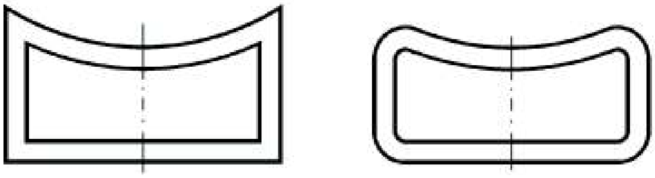
Figures 164-177: Consideration of process-specific features for *wet and dry pressing*

- *Special features of extrusion*



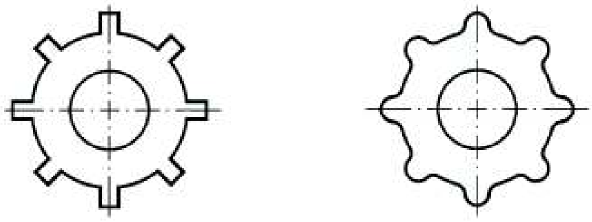
unfavourable favourable

- non-uniform material distribution and excessively thin walls lead to cracks



unfavourable favourable

- avoid sharp outer edges

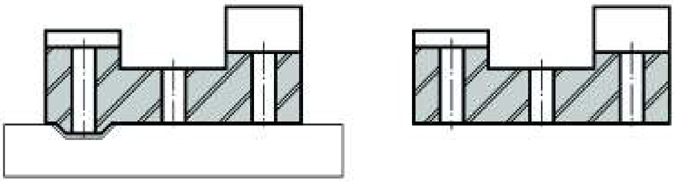


unfavourable favourable

- rounding prevents cracks and spalling

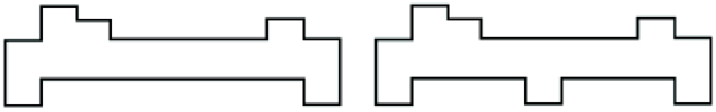
Figures 178-180: Consideration of process-specific features for *extrusion*

- *Special features of sintering*



unfavourable favourable

- provide flat surfaces to avoid the need for custom-made kiln furniture
- avoid offset and relatively small mounting surfaces

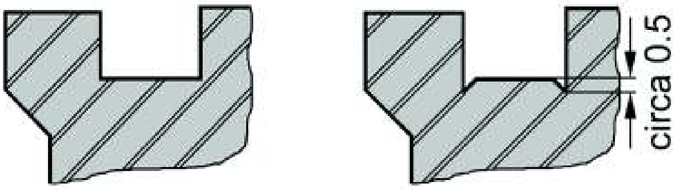


unfavourable favourable

- keep support points close together (risk of warping)

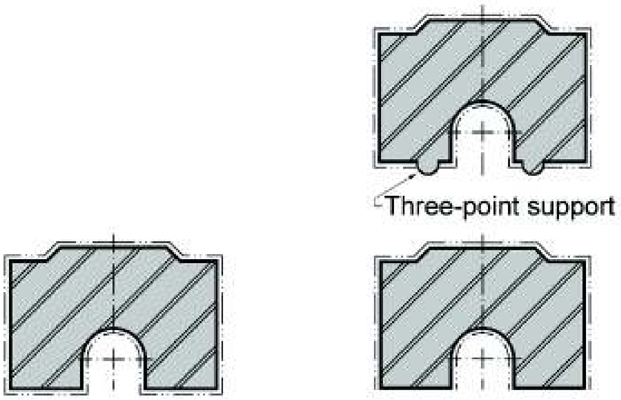
Figures 181-182: Consideration of process-specific features for *sintering*

- *Special features of glazing*



unfavourable **favourable**

- provide channels to accept the glaze



unfavourable **favourable**

- attempt to keep support or mounting points free from glaze

Figures 183-184: Consideration of process-specific features for glazing

7.6 Summary of Important Guiding Principles

- Design with ceramic materials requires an approach fundamentally different from design with metals. Different principles of construction, calculation procedures and joining processes must be applied.
- The integration of ceramic parts with a metallic system results in different requirements from the ceramic part, the assembly environment and the bond between the two. Compromises are often necessary, and these may also lead to changes in the metallic system.
- As a rule, copying a metal part or its exact conversion to ceramic leads to failure.
- The advantages of using ceramic for the system should be utilized as far as possible, while the weaknesses should be avoided and unfavourable loading minimized.

- The properties resulting from the nature of the chemical bonding in ceramics, which is the reason for their high hardness, must be taken into account differently compared with metals:
  - brittleness,
  - cracks and crack growth in the material,
  - high scatter of strength data,
  - low tensile strength,
  - limited variety of forms and
  - larger tolerances for non-machined parts.
- Finishing is typically time and cost intensive and should thus be avoided, or at least reduced to a minimum.
- Very close cooperation with the ceramic manufacturer is necessary, since the technical and economic implementation using ceramics is even more demanding than with metals or plastics.

An indicator for the cost of a part is the degree of difficulty represented by the demands on a ceramic part. This can be divided into five levels. A low level of difficulty should therefore be aimed at if a cost-effective product is to be obtained.

Degree of difficulty	Demands on the ceramic part	Design is crucially influenced by
1	• low mechanical stress • application temperature ≈ room temperature	forming process (tooling costs, etc)
2	• as in 1 + • specified dimensional and mould tolerances	forming process, finishing (possibilities and costs)
3	• as in 2 + • specified surface quality	finishing (possibilities and costs)
4	• greater mechanical stress • and / or thermally induced stress	stress distribution in the part under load
5	• as in 4 + • Joining with other parts	forming and finishing (dimensional and mould tolerances, costs) stress distribution in the composite under load

Table 24: Levels of difficulty

8 Joining and Bonding Techniques

Bonding and joining techniques play a decisive role in the integration of ceramic components into a technical system. It is necessary to integrate a ceramic part into a complete system reliably and in such a way that those special properties, the reasons for which the component was manufactured out of ceramic, are exploited under all operating conditions.

The system as a whole must be tested again under working conditions, paying special attention to the compatibility of the ceramic part to its environment. Usually the difficulties in assimilation result from differences between the thermal expansion coefficients or elastic behaviour (modulus of elasticity) of the ceramic and the surrounding components, most of which are metal. Generally speaking, a large number of joining techniques are available.

Basically, a ceramic can be temporarily or permanently bonded with another ceramic or with any other material. To achieve a reliable connection between ceramic components or with other materials, techniques using material bonding, interlocking and friction may be considered.

8.1 Principles

The materials to be bonded and the demands to be placed on the bond are crucial for the choice of bonding technique.

Design appropriate for ceramics means, for example, that when bonded with metals, the ceramic should be placed under compressive stress whenever possible, and that tensile or bending loads be transferred to the metal

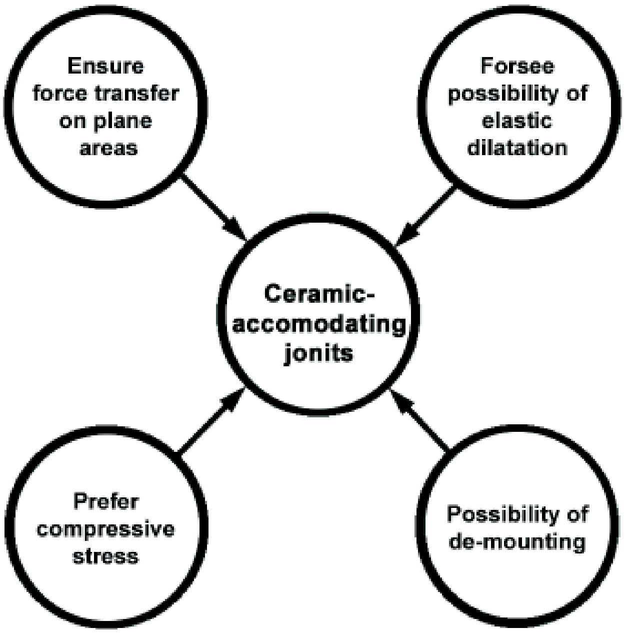


Figure 185: Factors affecting joints

The behaviour of the functional unit takes the primary focus in every case. The reliability of the bond must be guaranteed against overloading and loosening during manufacture and use. The main task of the designer is to match the plastic, elastic, thermal and geometric expansion differences between this ceramic component and its surroundings. The suitability of the joining technique or combination of techniques is decided on a case-by-case basis. Joining is more than just a matter of adapting the expansion coefficient and elastic modulus. The interaction of material data, part design and contact surfaces demands close, multi-disciplinary cooperation between technologists, manufacturing technicians and constructors, particularly in order to overcome the internal stresses of the combined materials.

The designer should proceed in a manner suitable for the materials, and should pay attention to the following basic rules:

- avoid stress concentrations and point-loads by
    - using large areas to apply forces,
    - parallel contact surfaces,
    - using elastic intermediate layers where appropriate and
    - force transfer without acute changes of direction.
- avoiding tensile stress in the ceramic part and preferring compressive stress by:
    - press-fit joints (ceramic part on the inside),
    - compressive pre-stressing
    - properly arranged load application points.
- avoiding impact or shock stress by:
    - applying loads over larger areas,
    - reducing applied load
    - supplying additional resilient, elastic and / or damping elements.

- avoiding additional stress[22] resulting from constrained thermal expansion by using
    - materials with similar thermal expansion coefficients,
    - resilient or elastic elements and
    - air gaps.
- compensation of differences in deformation resulting from differing elastic moduli (if they increase the stress on the ceramic part) by:
    - resilient or elastic intermediate elements and
    - matching the stiffnesses.
- Interlock/frictional jointing
    - geometrical interlocks avoid the need for further fasteners.
    - Frictional bonding compensates problems due to differences in thermal expansion coefficient and stiffness

8.2 Methods

Joining subcomponents by geometrical interlock *prior to sintering* in the green or white-ware assumes that the they are made of similar ceramics, and that joining proceeds via material bonding processes (slip jointing and laminating) during manufacture. (Cf. Modular construction, p. 192)

---

[22] In ceramic/metal joints, the thermal expansion coefficient of metals are in general, substantially larger than that of the ceramic (see materials tables on pages 263-273). Increasing the difference between the joining temperature and the application temperature results in increasing stress in the area of the joint due to constrained dimensional change. This applies to all joining techniques. If the stresses cannot be reduced by plastic deformation processes or the inclusion flexible elements, premature failure can occur.

This must be done at other locations, since ceramic materials are not able to deform plastically to reduce load peaks. Through carefully choosing the material to which the bond is to be made (metal alloys with appropriately chosen coefficients of thermal expansion, ferritic instead of austenitic steels, etc.), by optimising the geometry of the joint (wall thickness, transitional regions between joint and air gaps) and suitable intermediate materials (solder, glue, elastic elements), a way must be found to disperse the tensile stress in the ceramic or keep it as small as possible. Extra care must be taken to take the conditions of use into account.

Material bonding techniques belong to technically established processes such as:

- gluing with thermoplastics, elastoplastics and thermosetting plastics (*fixing wear-protection plates*)
- soldering with metallic solders (*soldering in ceramic substrate and packaging technologies, soldering pins on substrates, solder joints on rectifiers and thyristor packages and surge arresters, wear-plates on rocker arms in automobile motors, etc.*) and glass soldering or
- glued joints using ceramic adhesives.

This means that the most important goals and areas of work are:

- adapting the glues and solders,
- matching the joining and application temperatures and
- reducing internal stresses in the composite.

After firing the ceramic, bonding techniques based on its interlock or friction include:

- shrink-fitting (*slip-ring seals, pressing tools, etc.*),
- press-fitting,
- casting-in and filling (*port liners, ceramic piston lids, fasteners for insulators, etc*),
- crimping / rolling,
- clamping (*fastening burner tubes, fixing and sealing heat exchangers, fastening cutting plates on lathe or machining tools, etc.*),
- push-fitting *(e.g. bayonet joints)*,
- riveting / swaging and
- bolting (*attachment of burner tubes, fastening and sealing of heat exchangers, fastening cutting plates on lathe or machining tools, etc*)

and may require the development of specially adapted joining elements.

Joining method	**Material combinations Ceramic with**			**Demountable**	**Ceramic materials**
	Ceramic	Metal	Plastic		
Cementing	+	+		no	all
Gluing	+	+	+	no	all
Soldering / brazing after metallisation		+		partial	all
Active solder bonding		+		no	all
Soldering / brazing with sealing glass	+			no	all
Screwing / bolting	+	+	+	yes	all
Plug-in jointing		+	+	yes	all
Clamping		+		yes	all
Snap connections		+	+	yes	all
Slip jointing / laminating	+			no	all
Fill casting / casting in		+	+	no	limited
Crimping / rolling		+		no	all
Pressing / shrink fitting		+		partial	all
Vulcanising		+		no	all

Table 25: Joining techniques for ceramic components: ‘+‘ = feasible

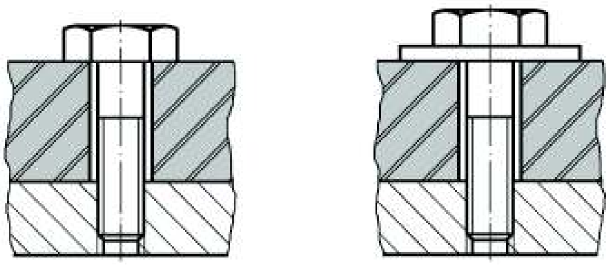
Jointing method	Active ceramic surfaces		Joining method	
	Preferred geometry	Hard machining	Additions	Conditions
Cementing	-	-	Sulphate cement, lead alloys, putty / cements	-
Gluing	-	Contact areas	Glues (organic and/or inorganic)	Hardening temperature; pressure
Soldering / brazing after metallisation	-	Contact areas	a) Soft solders b) Hard solders	a) 200–300 °C b) 500–1,000 °C
Active solder bonding	-	Contact areas	Active brazes e.g. Ti, Cu sometimes as multi-layer	Special atmosphere 600–1,130 °C
Soldering / brazing with sealing glass	-	Contact areas	Sealing glasses	450–1,600 °C, sometimes with ad. pressure and sp. atmosphere
Screwing / bolting	Fill-cast or glued-in thread or through-thickness joint	Contact areas	Screw, washer, nut	Intermediate layer
Plug-in jointing	Rotational symmetry	Contact areas	-	-
Clamping	Planar or rotational symmetry	Contact areas	Fasteners	Elastic and/or plastic intermediate layer
Snap connections	Planar or rotational symmetry	-	-	-
Slip jointing / laminating	-	-	Identical ceramic slip	Sintering, pressure
Fill casting / casting-in	Hollow bodies, rounds or oval	-	-	Preheating, very few materials suitable
Crimping / rolling	Planar or rotational symmetry	Contact areas	-	-
Pressing / shrink fitting	Rotational symmetry, external metal part	Joint surfaces	-	Pressing force / heating
Vulcanising	-	-	Rubber	-

Table 26: Brief summary of the characteristics of joining methods

8.2.1 Friction and Interlock-Based Joints

A few basic principles for the design of joints and some typical problems are now presented. The ceramic can be identified from the grey colouring.

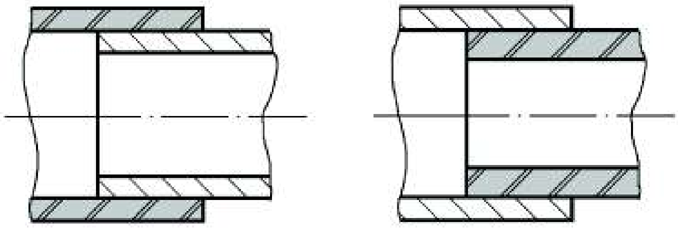
8.2.1.1 Avoid Stress Concentrations


unfavourable **favourable**

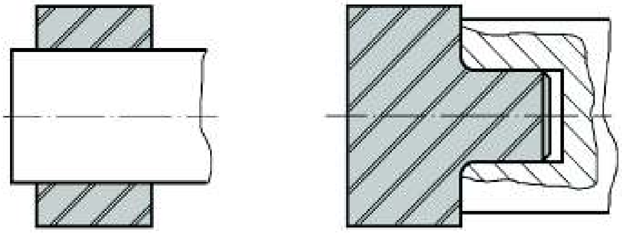
- apply forces over large areas

Figure 186: Avoid load peaks and point-loads

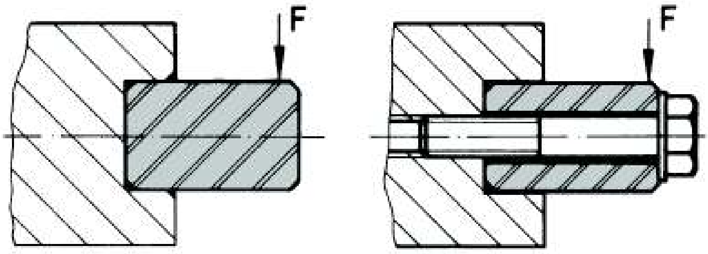
8.2.1.2 Prioritise Compressive Stress


unfavourable **favourable**

- in tube joints, keep the ceramic tube under compression from the metal tube

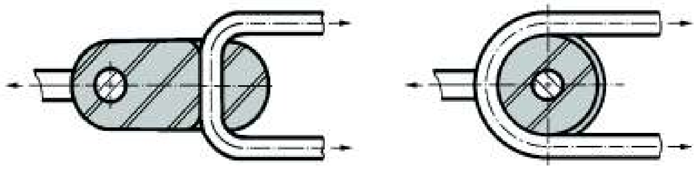

unfavourable **favourable**

- press-fit joints should have the ceramic on the inside and the metal on the outside



unfavourable **favourable**

- pre-stress with compression

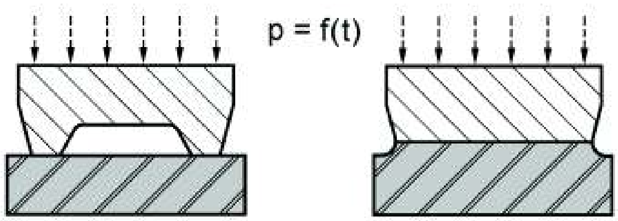


unfavourable **favourable**

- introduce force into ceramic components in such a way that they are only subjected to pressure

Figures 187-190: Prefer stressing ceramic parts with compression only

8.2.1.3 Avoid Impact Stress



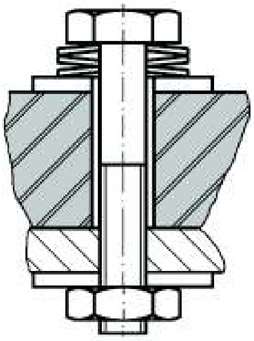
unfavourable **favourable**

- make force introduction regions as large as possible

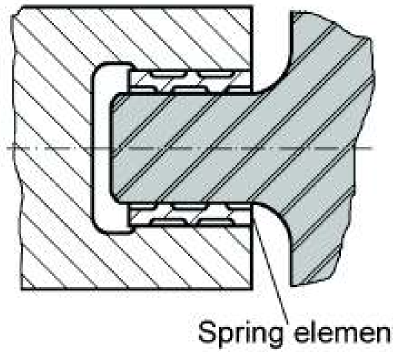
Figure 191: Avoid impact or shock stress

Section 7.5.3.2. contains further examples

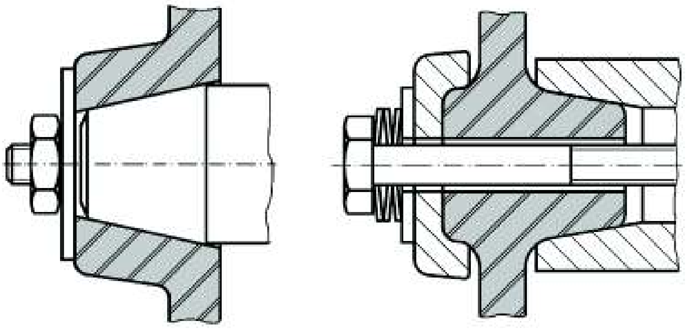
8.2.1.4 Bear Thermal Expansion in Mind



- compensate for expansion with elastic clamping
  - provide spring washers

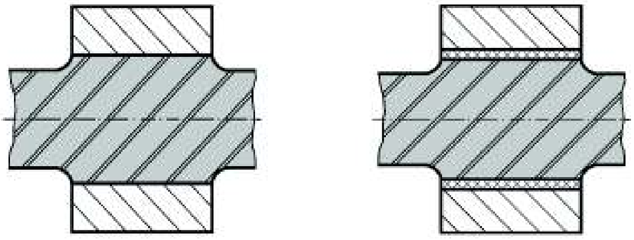


  - provide spring jointing elements



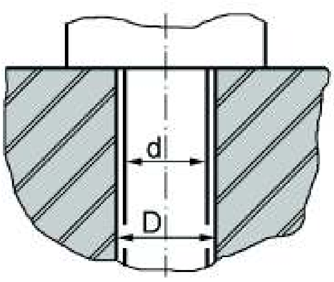
unfavourable **favourable**

  - in tapered seats, always keep the ceramic under compression



unfavourable **favourable**

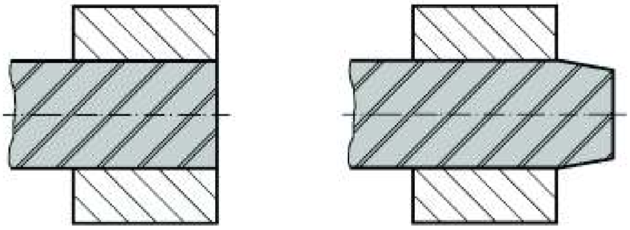
- introduce intermediate compliant layers



- design clearance between parts such that differences in thermal expansion coefficient do not lead to mismatches
  - $D > d(\alpha_{ST}\Delta T+1)$ at assembly

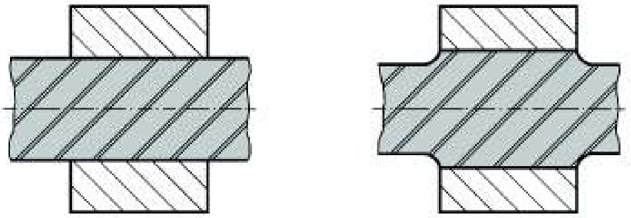
Figures 192–196: Additional stress through obstructed thermal expansion

8.2.1.5 Careful Introduction of Force



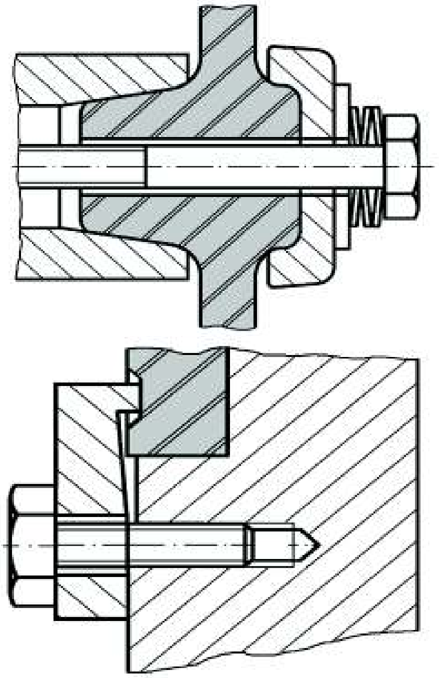
unfavourable **favourable**

- avoid corner breakage resulting from stress concentrations close to edges in shaft-hub joints



unfavourable **favourable**

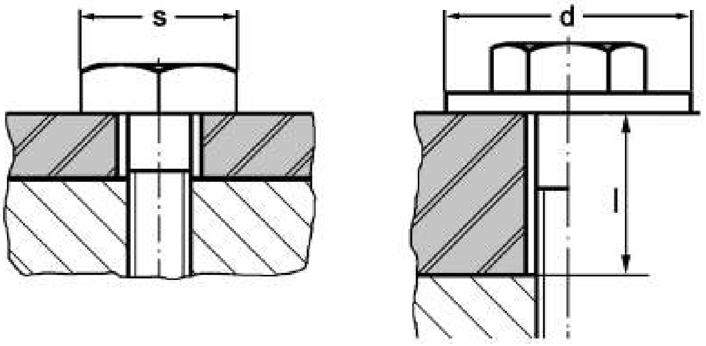
- avoid notch effects and abrupt changes in the direction of forces



- floating fastening with small axial bores by means of
  tension rods or bolts
  - introduction of force over large area
  - limiting to compressive stress
  - remember to compensate for thermal expansion using spring methods of clamping

Figures 197-200: Careful introduction of force

8.2.1.6 Adapt Force Transfer



unfavourable **favourable**

- bolted connections should not clamp thin ceramic plates

  - Hexagonal bolts with washers: $l \geq d > s$

Figure 201: Careful introduction of force

8.2.2 Potting with Plastic

The use of plastics is limited if

- there is friction resulting in wear,
- higher temperatures bring a deterioration in insulation capacity or
- the mechanical strength falls with rising temperature.

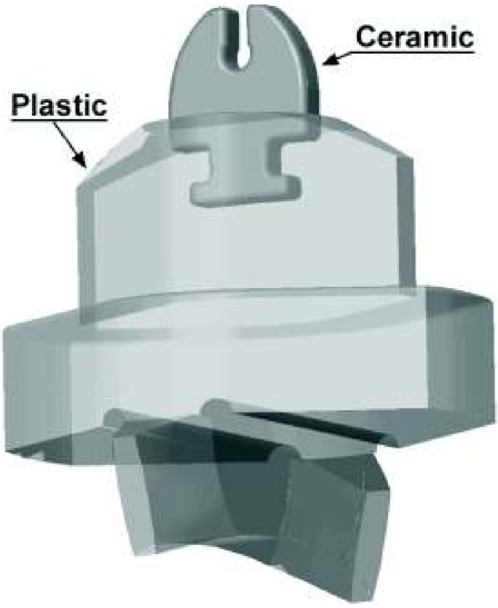


Figure 202: Ceramic component potted in plastic

Armouring the area at risk with ceramic may be a solution in these cases. The ceramic insert is placed inside the injection mould, and is encased and fixed when the plastic is injected for the component. To achieve the necessary tolerances of 0.01 mm the insert must usually be hard machined so that the molten plastic cannot leak out at the injection stage. The insert will be more effectively anchored if there are openings in the material and if the insert has a shape that engages the plastic from behind.

This type of insertion creates a joint with relatively high mechanical strength, and avoids additional stresses on the other material. The materials combination of polyamide with ceramic has been particularly well tried in this context.

Figure 203: Traversing thread guides

Figure 204: Other ceramic components encased by injection moulding

8.2.3 Gluing

Gluing is a conventional jointing method. This technique can generally be used to join materials of the same or different types. Gluing creates a joint based on material bonding and in which force is transferred over the entire area. This is particularly advantageous for ceramic parts, since gluing does not generate particularly high stress concentrations as may occur, for instance, with bolted connections.

Gluing, furthermore, generates very little thermal stress, if any, and for that reason has no effect on the properties of the materials involved in the joint. Glued joints are also usually gas-tight and liquid-tight, and have good mechanical damping properties.

A limited capacity to accept thermal stress is a significant disadvantage of glued joints.

8.2.3.1 Types of Glue

The following glues are the most suitable for demanding applications (high-tech or structural glues):

- acrylate glues,
- cyanoacrylate glues,
- epoxy resin glues,
- polyurethane glues,
- phenolic resin glues and
- polyester resin glues.

In order to select the appropriate glue it is important that requirements of the joint are accurately profiled. It is therefore necessary that stresses on the components, such as mechanical or thermal stress, and any effects from the surrounding media that may be relevant, are known.

Characteristic material values of the jointed parts, the surface finish, the dimensions of the glued areas and the temperature are also relevant to the properties of the resulting joint and to the selection of the appropriate glue.

8.2.3.2 Example: Torque Transmission

If the medium being pumped is particularly aggressive, the metallic rotors of eccentric screw pumps are subject to high levels of mechanical wear. SiC rotors are significantly harder than metal rotors, and offer a service life up to 20 times longer.

Force is introduced to the rotor through a pin joint. Because the ceramic reacts sensitively to impact and tensile stress it is not helpful to make the rotor entirely out of ceramic. An appropriate jointing method is therefore required in order to use ceramic rotors and to exploit the benefits of ceramic material.

Gluing may be an appropriate jointing technique for such a case. When designing the joint for an eccentric screw it is necessary to bear the following points in mind:

- the material of the (metal) head,
- the size and type of the forces that occur,
- the maximum temperature in application and
- the surrounding medium.

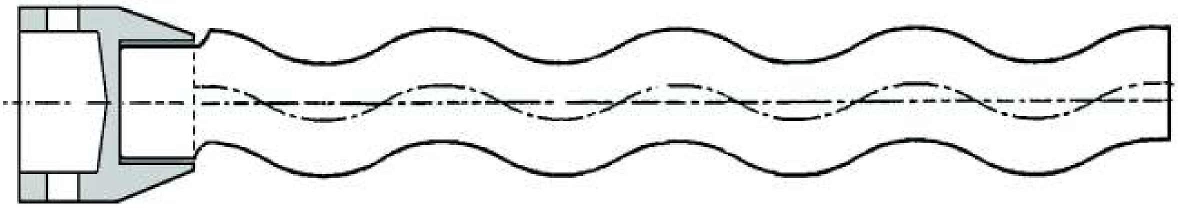


Figure 205: A silicon carbide eccentric screw

The necessary surface preparation (e.g. degreasing and sand blasting), and treatment of the surfaces where relevant, depend on the silicon carbide used for the eccentric screw and the stainless-steel or hardened tool steel of the head. Some materials have passive surfaces that must be treated with bonding agents in order to ensure adequate adhesion between the glue and the jointed part.

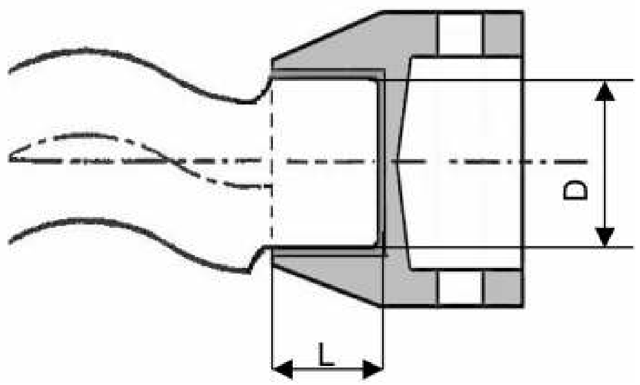


Figure 206: Gluing location of the eccentric screw

The type and magnitude of the stresses that occur in operation will determine the design and dimensioning of the glued areas and the selection of the glue. Eccentric screws are primarily subjected to torsional stress, which means that gluing to the face is not effective. The force is therefore introduced around the circumference of a centralised head.

The sizes of the glued areas depend on the maximum forces. The moment (Nm) that can theoretically be transmitted can be calculated from the following formula:

$$M_t = \tau_t \frac{\pi D^2 L}{2}$$

where τ_t is the adhesion strength of the glue, D is the diameter of the joint, and L the length of the glued region.

The stress on the joint, however, should not exceed 10 % - 30 % of the theoretical strength, depending on the glue in use.
The operating temperature is very important for the choice of glue. The maximum application temperatures of glues based on organic materials reach up to 400°C. If the temperature is too high the layer of glue will soften or decompose, and the joint will rapidly fail.
The effect of the surrounding medium is relevant to the long-term stability of the glued joint. The strength of some glues drops sharply if, for instance, moisture diffuses into the material.

8.2.3.3 Further Applications

- **High-voltage insulator**
  Fixing the mounting of an insulator subject to tensile or compressive stress.

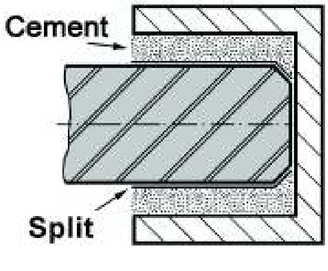


Figure 207: Cemented joint

- **Coupling ring wheel**
  Reinforcing a plastic
  - epoxy resin, ceramic filled
  - hardening conditions: 180 °C, 30 min
  - working temperature 220 °C

Figure 208: Coupling ring wheel

- **Slotted thread guide**
  Precisely reinforcing the wear location on a component
  - 2-component glue
  - hardening conditions: 80 °C, 1 h
  - working temperature 100 °C

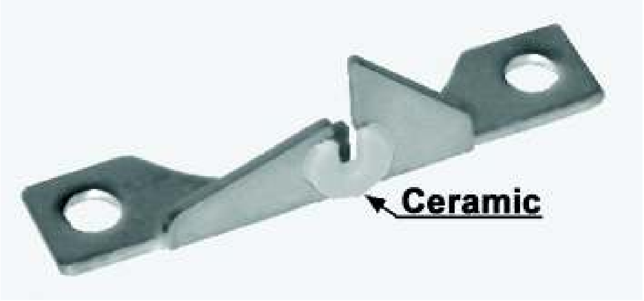


Figure 209: Slotted thread guide

8.2.4 Soldering

Joints between ceramic and metal, and between one ceramic and another, based on material bonding can be created through soldering.
The ceramic is usually metallised prior to this process[23]. The type of metallisation will vary according to whether hard or soft soldering is expected to follow, and must be appropriate for the particular ceramic material. Aluminium oxide and aluminium nitride are preferred ceramic materials for hard and soft soldering.
In addition to this, there are active soldering processes that dispense with metallisation of the ceramic and which require special active solders. Further soldering procedures are described in the literature[24].

8.2.4.1 Soft Soldering

According to DIN 8505 soft solders melt below 450 °C; typical soft solders melt between 150 and 250 °C. They are used at between 190 and 250 °C. Typical solders include the eutectic systems of tin/lead (melting point 183 °C) and tin/silver (melting point 221 °C).
The metallisation is usually based on a noble metals (silver, silver/palladium, silver/platinum, gold, palladium/gold, platinum/gold).

Soft soldering is widely used in electrical engineering and in electronics, particularly for hybrid circuits. As a rule, passive and active components can withstand the temperature stress involved in the soft soldering process.

The soldering temperature does, however, represent a temperature shock to the metallised ceramic, although this is usually not critical even for sensitive ceramic materials.

---

[23] See p. 91.
[24] See Tietz, Chap. 5.2.3, p. 212ff.

8.2.4.2 Hard Soldering

According to DIN 8505 hard solders melt at temperatures above 450 °C; typical hard solders melt at between 600 and 800 °C, and are processed typically at temperatures of between 600 and 900 °C. Typical representatives of this class include hard silver solders based on silver, copper and zinc. Flux-free vacuum soldering and soldering under a protective atmosphere in soldering ovens is used for high temperature soldering at temperatures > 900 °C.
The metallisation requires metals with high melting points (refractory metallisation) such as molybdenum or tungsten. Metallised ceramic suitable for hard soldering can be supplied in this form by ceramic manufacturers.
The most frequent applications are found in machine construction.

The soldering temperatures involved are not usually critical for the ceramic material. It must, however, be borne in mind that the materials that are to be soldered have different coefficients of thermal expansion. Mechanical stresses will develop in the solder and in the materials that have been soldered together as the item cools. The stresses must be held down to acceptable levels through matching temperature coefficients and through appropriate construction.

8.2.4.3 Active Soldering

Active soldiers typically melt at between 600 and 1,000°C, and are processed at between 800 and 1,050 °C.
Active soldering makes it possible to solder directly to ceramic without an additional metallisation process. These solders are metallic, the compositions of which alloys permit them to wet non-metallic inorganic materials. They contain components such as titanium, zirconium or hafnium that react with ceramics.

Special attention is called for by the active soldering process, since the solders do not flow like conventional solders, and the capillary effect cannot be used. Active soldering in a furnace must, however, be carried out in a carefully monitored furnace atmosphere.
The process of active soldering is achieved through the high reactivity of titanium. During the soldering process, a thin yet continuous reaction

layer forms on the surface of the ceramic, providing the necessary adhesion.

Active soldering systems typically consist of silver/titanium, silver/copper/titanium, or silver/copper/indium/titanium. The soldering is usually carried out under argon or in a vacuum.

In addition to aluminium oxide and aluminium nitride, almost any other ceramic and metals that are not easily wetted may be soldered. Actively soldered joints are therefore appropriate in the machine construction sector.

Solders for various ceramics are available on the market.[25]

8.2.4.4 Measures to be Taken

Soldering joins different materials together through a material bond. The coefficients of thermal expansion, which depend on the materials, can sometimes be very different. Unrestrained materials shrink differently as they cool, so that stresses still develop in the joint after different materials have been soldered.

There are a number of ways of keeping such thermally induced stresses under control:

- The design of the construction is such that the ceramic is subject to acceptable compressive stress.
- The two materials being combined only have small differences in their thermal expansion coefficients.
- An additional buffer material can be used that compensates through elastic or plastic deformation. The solder itself can represent such a buffer material. The physical properties of soft solders, and the thicknesses used in that process, are particularly suitable for this purpose.

---

[25] E.g. Degussa-Hüls CB1 to CB6.

9 Quality

Quality requires strong customer-manufacturer relationships.

9.1 Planning Quality

Quality must be planned.
Planned quality begins at the customer through contact with sales and applications departments.

Request and offer phase:

- specify quality features,
- specify the production process,
- create a drawing of a design suitable for ceramics,
- agree tolerances,
- calculate manufacturing costs,
- specify product and process tests and
- estimate deadlines.

Order:

- Create production sequence plans,
- timetable plans,
- a material plan,
- and a test plan.
- Inform the tool-making department and
- ensure that detailed planning is carried out, operating materials obtained
- preventative maintenance is performed, etc.

9.2 Producing Quality

Quality must be produced through

- optimisation of the procedures that will generate predictable, well-managed processes through quality techniques such as:[26]

– QFD	Quality Function Development
– DOE	Design of Experiments
– FMEA	Failure Mode and Effects Analysis
– SPC	Statistical Process Control, C_{pk}-values, etc.
– Poka Yoke	The generation of error-tolerant processes,

- identification of the workers with the product (each individual is responsible for quality)
- setting a production goal of zero failure-rate (+ 6 s, C_{pk} >2) and Comment: should this be ‘6 sigma’, not ‘6 s’?
- independent quality certification demonstrating that the product and services correspond to the agreement with the customer.

9.3 Managing Quality

Quality must be managed through

- an appropriate quality management system
  (for example, DIN ISO 9000ff / EN 29000)
- as a consistent company philosophy.
  (TQM = total quality management)

9.4 Tests (Q-Certificates)

The wide variety of factors affecting ceramic technologies require continuous monitoring in all areas of production.
A consistent quality standard is guaranteed by an extensive quality management system. The quality steering measures that accompany the manufacturing process are documented in test schedules which form part of the manufacturing schedules.

---

[26] See p. 207.

Routing slips, quality-control cards and test protocols provide the ability to check all the documented process steps and guarantee traceability back to the raw materials.

The tests mainly emphasise[27]

- monitoring incoming raw materials and semifabricated products,
- monitoring material data as per test specification,
- process monitoring in order to obtain a consistent, predictable and regulated process[28], and
- final testing.

Tests range from the 100 % testing of certain parameters, integrated with automatic manufacturing, all the way to extensive long-term tests on random samples. Statistical testing plays an important role in the final check by the manufacturer and the incoming tests carried out by the customer. Although the delivery of products that are free from defects is the basis of every delivery agreement, the ability to certify the quality level is indispensable for legal and commercial reasons. The need to access the **A**cceptance **Q**uality **L**evel (AQL)[29] therefore makes it essential to obtain a statistically formed judgement on the basis of random samples.

9.5 Quality Control Techniques

QFD (Quality Function Deployment)

- focusing and thorough planning of quality expectations (using the "House of Quality" model),
- planning schemes to translate market / customer expectations into action for production that is as free from failure as possible, in four phases:
  - product strategy,

---

[27] See Section 4, p. 67, Manufacturing Processing Procedures.

[28] See p. 239ff.

[29] AQL Tables containing sampling plans for a normal, reduced and strict testing can be obtained from the Verband der Keramischen Industrie e.V. (Ceramic Industry Association).

  - product specification,
  - process specification and
  - process protection.

DOE (Design of Experiments)

- statistical experiment planning for the systematic and efficient accumulation of information for continuous quality improvement. For this purpose, methods such as
  - Taguchi,
  - Shainin and
  - factor experiment plans are applied.

FMEA (Failure Mode and Effects Analysis)

- the analysis of failure modes and effects, or, more precisely: detection and neutralisation of sources of error.
- The most well-known/most widely used applications are
  - development FMEA and
  - process FMEA.

SPC (Statistical Process Control)[30]

- Statistical process regulation using quality rule cards and
- systematic improvement of processes through intervention when process parameter limits are exceeded. This includes the capability testing of:
  - measuring instruments and
  - equipment.

Poka Yoke

- Avoiding errors in processes through the provision of specified routines. This means creating an attitude and preventing errors in the process or on the product that occur as a result of human error.

---

[30] See p. 239ff.

10 Appendix

10.1 Bonding Types and Strength

Metallic bonding is explained through the existence of free, mobile electrons between the atoms. This model accounts for their properties such as electrical conductivity and *ductility*. Due to the non-directional nature of the metallic bond, metals typically develop dense packing and high co-ordination figures. The ductility of metallic materials can be modelled by slipping between the most densely packed planes without any change in the state of the bond. As a rule, the metallic bond is weaker than ionic or covalent bonds.

In **ceramic materials** the bonding is generally a hybrid of **ionic and covalent bonds**. Whereas the ionic bond is distinguished by the transfer of an electron between a metal and non-metallic atom, the electron pair of a purely covalent bond is shared between non-metallic atoms. The strong bonding forces of ceramic materials result in properties such as *high elastic modulus* and *hardness*, *high melting points*, low thermal expansion, and *good chemical resistance*. The covalent bond is a highly directional; the orientation and distance of neighbouring atoms are precisely determined. The stability of ionic and covalent bonded solids is highly dependent on the maintenance of the atomic geometries and explains the *lack of plastic deformation* under load (low fracture toughness). Ceramic materials are hard and therefore *brittle*. Their brittle fracture behaviour must be kept in mind by the designer when calculating stresses.

Organic polymers consist of long chains of molecules which are either tangled or ordered at room temperature. Intermolecular forces known as **van der Waals forces** are found almost exclusively between non-crosslinked polymers. These are up to two orders of magnitude smaller than covalent forces, and can be easily overcome by thermal motion. This underlies their *low heat resistance*, *low elastic modulus*, and *high thermal expansion coefficient*, and is also responsible for the outstanding elastic and plastic strain values of these materials. Like ceramics, polymers have good chemical resistance, electrical and thermal isolation properties. They display a noticeable brittleness at low temperatures.

10.2 Materials Comparison

	Electrical		Thermal		
Material	Permittivity	Volume resistvity	Thermal conductivity	Coefficient of expansion	Maximum temperature of use
Symbol Unit	ε_r -	ρv Ω cm	λ $Wm^{-1}K^{-1}$	$\alpha_{RT\text{-}1000°C}$ $10^{-6}K^{-1}$	T_{max} °C
Steel	Not normally quoted	$> 10^{-5}$	> 30	> 10	400
High-temper-ature steel	Not normally quoted	$> 10^{-5}$	> 0	> 6	800
Cast-iron	Not normally quoted	$(0.5 - 1.7)10^{-4}$	15 - 60	5 - 18	400
Aluminium alloy	Not normally quoted	$(0.03 - 1.1)10^{-4}$	70 - 130	20 - 26	250
Wood	3.5 - 5	$10^{11} - 10^{14}$	0.1 - 0.2	4	180
Plastic	2.2 - 4.6	$10^{15} - 10^{18}$	0.14 - 0.25	20 - 180	200
Technical ceramic	5 - 10	$10^{-2} - 10^{14}$	1 - 200	0 - 11	1000 - 2000
Glass	3 - 19	$>10^{13}$	1 - 3	3 - 10	200 - 1.200

Table 27: Comparison of electrical and thermal data for various materials

Table 28: Comparison of mechanical data for various materials

	Mechanical							
Material	Density	Bending strength	Tensile strength	Critical stress intensity factor	Notch impact figure	Elongation at rupture	Elastic modulus	Hardness
Symbol Unit	ρ g cm^{-3}	σ_b MPa	σ_z MPa	K_{IC} MPa $\sqrt{m}$	Jm^{-2}	ε %	E GPa	HV
Steel	7.8	$-\sigma_z$	360 - 700	140	10^5 - 10^6	10 - 20	200	200 - 400
High-temperature steel	7.8	$-\sigma_z$	500 - 1000	50 - 154	-	-	200	< 900
Cast-iron	7.3	300 - 600	150 - 400	15 - 25	10^4	< 2	70 - 130	150 - 250
Aluminium alloy	2.8	150 - 300	350	45	10^5	5 - 20	70	30 - 140
Wood	0.2 - 1.2	50 - 150	70 - 130	0.5 - 1	10^4	- 1	10	35 - 150
Plastic	0.9 - 222	10 - 150	10 - 705	0.3 - 4	10^6 - 10^8	2 - 1200	1 - 4	-
Technical ceramic	2.25 - 5.98	30 - 1400	(*)	1 - 10.5	(*)	< 0.1	40 - 450	1200 - 3200
Glass	2.2 - 2.5	70	70 - 100	< 1	10^1	-	2.5	200 - 800

(*) Not normally quoted

10.3 General Tolerances for Dimensions and Shapes

Technical ceramics make use of different standards. **DIN 40 680** specifies dimensional and shape tolerances for components that are to be used "**as fired**", i.e. **without any additional processing** after firing. The precision required depends on the manufacturing technique and the material.

DIN ISO 2768 and DIN ISO 1101 specify tolerances for components that will require additional **hard machining**, such as grinding, after firing in order to achieve the precision necessary for machine construction.

10.3.1 Tolerances and Function

Tolerances meeting the DIN 40 680 standard are based on application-dependent requirements and the conditions relative to different ceramic manufacturing procedures and materials when hard machining is not used.

To achieve higher dimensional, shape or position tolerances it is necessary to carry out some type of machining (e.g. grinding, lapping, polishing etc.) of the "as fired" component after firing. The tolerances that can be achieved in this way are specified in DIN ISO 2768 (general tolerances for workpieces produced with machining) and in DIN ISO 1101 (shape and position tolerances).
These are the standards usually applied in machine construction and related branches of industry.

> **For economic reasons it is always necessary to ensure that only those surfaces of ceramic components, typically functioning surfaces, are specified with close tolerances, and that general tolerances in accordance with DIN 40 680 apply to all other surfaces.**

The dimensional tolerances described in DIN ISO 2768 are classified into **f**ine, **m**edium and coarse (**g**) categories, depending on the dimensions of the component. Tolerance classes for selected shape and position tolerances are also quoted ("H" for fine, "K" for medium and "L" for coarse). Requirements that exceeded these specifications, or different requirements for shape and position tolerances, are dealt with by DIN ISO 1101.

A corresponding specification of dimensional, shape or positional tolerances would, for instance, be

DIN ISO 2768-m-K or, for example, DIN ISO 2768-g-L

For further details see DIN ISO 2768 and DIN ISO 1101.

The manufacturers of technical ceramic components have specialised in particular materials and manufacturing processes. This permits them to manufacture economically, since the different material groups require entirely separate production lines and, in some cases, special equipment. Manufacturers who concentrate on components for machine construction are regularly confronted with close tolerances, for which reason they are usually equipped with machines suitable for hard machining.

10.3.2 General Dimensional Tolerances

10.3.2.1 "As Fired" Ceramic

The general dimensional tolerances in DIN 40 680-1 cover products made of ceramic materials as defined by DIN EN 60 672-1. This is also applied in an analogous manner to fine ceramic products for general technical purposes
Dimensional deviations arise due to the peculiarities of ceramic technologies (see p. 81). Reducing dimensional tolerances is only possible with increased technical effort, and must be agreed upon by the manufacturer and customer in the light of the particular application. In addition to dimensional tolerances, shape tolerances may have to be taken into account for some applications (see p. 218).

If ceramic parts are to be glazed or given an electrically conductive coating, then the dimensions and tolerances apply to the finished part. The choice of tolerances depends on:

- the necessary precision and
- the feasibility from the point of view of ceramic fabrication technology, which in turn depends on the material.

Precision grades are divided into

- **coarse (g)** (which derives from the German "**g**rob", meaning coarse) for tolerances that can be maintained by ceramic manufacturing techniques such as extrusion or casting,
- **medium (m)** for tolerances that can be maintained on small parts, especially those used for low voltage equipment, through, for instance, extruding, unmetered pressing, metered moist pressing, metered dry pressing and white wear finishing.
- **fine (f)** for products where the accuracy grades coarse and medium are not sufficient. "Fine" cannot be achieved through ceramic production methods, and makes special, additional procedures such as grinding or drilling etc. necessary after firing. If the required accuracy is fine, then the degree of manufacturing precision in accordance with ISO tolerances must be agreed between the manufacturer and user.

The label for a general dimensional tolerance (A) with a medium (m) precision grade is:

General tolerance DIN 40 680-A-m

Avoid specifying a higher accuracy for all dimensions, as this increases costs considerably.

10.3.2.2 Hard Machined Ceramic

For parts made of technical ceramics for machine construction applications, the tolerances mentioned above for functional surfaces[31] are often inadequate for the user's needs. For this reason, tolerances for ceramic parts in accordance with

DIN ISO 2768-m-K

are quoted. These can be achieved through hard machining.

---

[31] See p. 218.

Drawing specifications

Dimensional tolerances that do not correspond to the general tolerances according to this standard are to be listed according to DIN 40 680-1 and -2 as tolerances or as ISO tolerance zones, directly stating the appropriate nominal dimension.

General tolerances with symmetrical dimensions with accuracy grades "medium" and "coarse" according to tables 29 and 30 are not added directly to the nominal dimensions. Instead, the following entries are made in the title block:

DIN 40 680-A-m or

DIN 40 680-A-g.

If several ceramic parts are shown on a single drawing, and if those parts are produced using different processes and therefore possess general tolerances with different grades of precision as specified by DIN 40 680-1, then the coarsest precision grade is entered into the title block. The tolerances with the finer precision grade are then added to the corresponding nominal dimension.

It can happen that for reasons of function, or for reasons concerned with production techniques, either only positive or only negative tolerance dimensions can be shown, but that the tolerance range is nevertheless intended to correspond to one of the particular precision grades in the general tolerances according to tables 29/30. In such cases, the figure for the associated general tolerance is doubled where the relevant nominal dimension is stated, and simply given an arithmetic sign. These tolerances, however, are not considered general tolerances, and are thus added to the corresponding nominal dimension rather than being entered into the title block.

Since the general tolerances for the "fine" accuracy grade are not fixed, either the tolerance agreed between the user and the manufacturer or the ISO tolerances are always added after the nominal dimension.

For further details, see DIN 40 680-1.

Manufacturing process	**Precision grade**						
	Finished parts of ceramic insulation material according to DIN EN 60 672-1						
	C 100	C 200	C 300	C 400	C 500	C 600	C 700
cast	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**
turned	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**	
extruded parts with an envelope size of 30 mm or more	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**	**coarse (g)**
extruded parts with an envelope size of up to 30 mm	**fine (f)**	**fine (f)**	**fine (f)**	**fine (f)**	**fine (f)**	**fine (f)**	**fine (f)**
pressed unmetered	**fine (f)**	**fine (f)**		**fine (f)**	**fine (f)**	**fine (f)**	
metered moist pressed	**fine (f)**	**fine (f)**		**fine (f)**	**fine (f)**		
metered dry pressed		**fine (f)**	**fine (f)**	**fine (f)**	**fine (f)**		**fine (f)**
white finished	**fine (f)**	**fine (f)**	**fine (f)**	**fine (f)**	**fine (f)**	**fine (f)**	**fine (f)**

Table 29: Manufacturing procedures for dimensional tolerances in accordance with DIN 40 680-1 for the "coarse" and " fine" precision grades

Nominal dimension range for diameter or length in mm *d*	Tolerance according to DIN 57 446-1 / DIN 0466-1	Precision grade coarse (g) according to DIN 40 680-1	Precision grade medium (m) according to DIN 40 680-1
up to 4	± 1.6	± 0.4	± 0.15
from 4 to 6	± 1.7	± 0.6	± 0.20
from 6 to 8	± 1.8	± 0.7	± 0.25
from 8 to 10	± 1.9	± 0.8	± 0.30
from 10 to 13	± 2.0	± 0.9	± 0.35
from 13 to 16	± 2.1	± 1.0	± 0.40
from 16 to 20	± 2.3	± 1.2	± 0.45
from 20 to 25	± 2.5	± 1.2	± 0.50
from 25 to 30	± 2.7	± 1.5	± 0.55
from 30 to 35	± 2.9	± 2.0	± 0.60
from 35 to 40	± 3.1	± 2.0	± 0.65
from 40 to 45	± 3.3	± 2.0	± 0.70
from 45 to 50	± 3.5	± 2.5	± 0.80
from 50 to 55	± 3.7	± 2.5	± 0.90
from 55 to 60	± 3.9	± 2.5	± 1.00
from 60 to 70	± 4.3	± 3.0	± 1.20
from 70 to 80	± 4.7	± 3.5	± 1.40
from 80 to 90	± 5.1	± 4.0	± 1.60
from 90 to 100	± 5.5	± 4.5	± 1.80
from 100 to 110	± 5.9	± 5.0	± 2.00
from 110 to 125	± 6.5	± 5.5	± 2.20
from 125 to 140	± 7.1	± 6.0	± 2.50
from 140 to 155	± 7.7	± 6.5	± 2.80
from 155 to 170	± 8.3	± 7.0	± 3.00
from 170 to 185	± 8.9	± 7.5	± 3.40
from 185 to 200	± 9.5	± 8.0	± 3.80
from 200 to 250	± 11.0	± 9.0	± 4.20
from 250 to 300	± 13.5	± 10.0	± 4.60
from 300 to 350	± 14.8	± 11.0	± 5.00
from 350 to 400	± 16.0	± 12.0	± 5.50
from 400 to 450	± 17.3	± 13.0	± 6.10
from 450 to 500	± 18.5	± 14.0	± 6.80
from 500 to 600	± 21.0	± 15.0	± 7.60
from 600 to 700	± 23.5	± 16.0	± 8.30
from 700 to 800	± 26.0	± 17.5	± 9.00
from 800 to 900	± 28.5	± 19.0	± 9.50
from 900 to 1,000	± 31.0	± 20.0	±10.00
from1,000	± (0.025*d+6)	± 0.02*d	±0.01*d

Table 30: General tolerances for products without finishing after firing

10.3.3 General Shape Tolerances

10.3.3.1 "As Fired" Ceramic

The general shape tolerances according to **DIN 40 680-2** are valid for parts made of ceramic materials according to DIN EN 60 672-1. This is also applied in an analogous manner to fine ceramic products for general technical purposes.
Deviations in shape arise due to the peculiarities of ceramic technologies (see p. 81). Reducing shape tolerances is only possible with increased technical effort, and must be agreed between the manufacturer and customer in the light of the particular application.
In addition to shape tolerances, dimensional tolerances may have to be taken into account for some applications (see p. 218).

A **shape tolerance** relates only to the corresponding form element of a ceramic part. It defines a range within which the actual shape of a form element can deviate from the geometrical form. Types of shape tolerance include

- straightness tolerance,
- flatness tolerance and
- cylindrical tolerance.

Additionally, positional tolerances such as:

- parallelism,
- perpendicularity,
- run out and
- wobble

must be borne in mind and may have to be specified.

The shape tolerance for a geometric form element of the ceramic part is defined by **tolerance zones**.

If the ceramic parts are to be glazed or given an electrically conductive coating, the combined accuracies are valid for the finished product.

Straightness (B)

Definition:
The **straightness tolerance** of a line is the distance between two parallel planes between which all points on the line must lie if the tolerance is specified in only one direction.

Table 31 lists straightness tolerances in mm for workpieces up to 1000 mm long. They are to be calculated according to the quoted formula for workpieces more than 1000 mm long. Depending on the manufacturing process, three accuracy grades are differentiated.

- **Coarse (g)** for tolerances that can be maintained by ceramic manufacturing techniques, for example, by extruding, casting or turning, which find use in high voltage electrical and chemical apparatus technologies.
- **Medium(m)** applies primarily to ceramic products of medium size produced by extruding, unmetered pressing, metered moist pressing, metered dry pressing or white finishing.
- **Fine (f)** applies to products for which the accuracy grades coarse and medium are inadequate. The fine grade can only be achieved using additional measures such as grinding after sintering. If the required accuracy is "fine", then the degree of accuracy must be agreed between the manufacturer and user.

The specification for general tolerances for straightness (B) of "medium" accuracy grade is:

General tolerance DIN 40 680-B-m.

Straightness measurement:

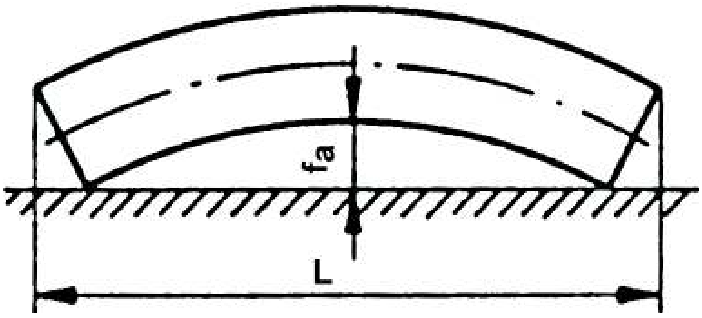


Figure 210: Deviation of straightness of a cylindrically shaped part in accordance with DIN 40 680-2 (cf. Table 31)

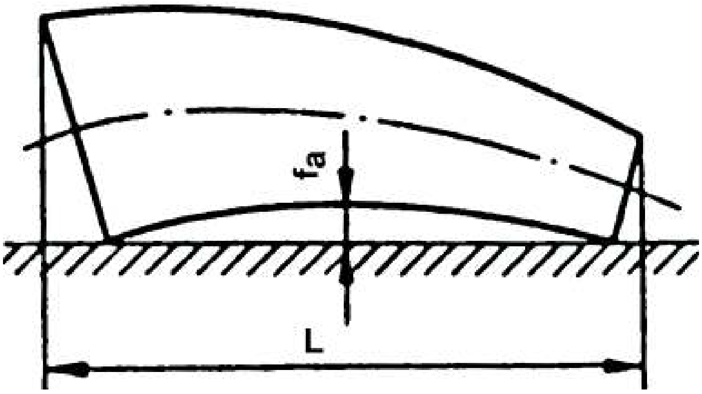


Figure 211: Deviation of straightness of a non-cylindrical shaped part (cone) in accordance with DIN 40 680-2 (cf. Table 31)

Flatness (C)

Definition:
The **flatness tolerance** is the distance between two parallel planes between which all points of the specified surface must lie.

The specification for flatness tolerance depends on the type of ceramic material, the shape of the part and the manufacturing process. Similarly to straightness, and depending on the manufacturing process, the three precision grades of "coarse", "medium", and "fine", are distinguished. They correspond approximately to a percentage of the longest linear dimension to be found within the surface, and are listed in Table 31.

- **coarse (g)**
  tolerance = 0.8 % * length
- **medium (m)**
  tolerance = 0.5 % * length
- **fine (f)**
  is to be agreed between the manufacturer and user.

Cylindrical shape (D)

Definition:
The **cylindrical shape tolerance** is the distance between two coaxial cylinders between which all the points on the surface of the cylinder must lie.
The cylinder shape tolerance to be specified depends on the type of ceramic material, the shape of the part and the manufacturing process. The values for the cylindrical shape tolerance are subject to agreement between the manufacturer and the user.

10.3.3.2 Hard Machined Ceramic

For parts made of technical ceramics for machine construction applications, the tolerances mentioned above for functional surfaces[32] are often inadequate for the user's needs. For this reason, tolerances for ceramic parts in accordance with

DIN ISO 2768-m-K

are quoted. These can be achieved through hard machining.

Drawing specifications

Should it be necessary to specify a different level of precision for the straightness to that specified for the shape, this must be noted additionally in this block.

E.g.: general tolerance DIN 40 680-A-m
general tolerance DIN 40 680-B-g

The rules for identification and quotation on drawings apply correspondingly to flatness and cylindrical form.

---

[32] See p. 213.

See DIN 40680 for further details and examples.

Manufacturing process	Precision grade	
	coarse (g)	medium (m)
cast, turned, extruded parts 30 mm long and more	+	
extruded parts up to 30 mm in length, pressed unmetered, metered moist pressed, metered dry pressed, white machined		+
Nominal tolerance range for lengths *L* in mm	straightness tolerance f_a in mm	
	coarse (g)	medium (m)
up to 30	1.7	0.15
from 30 to 40	1.8	0.20
from 40 to 50	1.9	0.25
from 50 to 60	2.0	0.30
from 60 to 70	2.1	0.35
from 70 to 80	2.1	0.40
from 80 to 90	2.2	0.45
from 90 to 100	2.3	0.50
from 100 to 110	2.4	0.55
from 110 to 125	2.5	0.60
from 125 to 140	2.6	0.70
from 140 to 155	2.7	0.80
from 155 to 170	2.9	0.85
from 170 to 185	3.0	0.90
from 185 to 200	3.1	1.00
from 200 to 250	3.5	1.25
from 250 to 300	3.9	1.50
from 300 to 350	4.3	1.75
from 350 to 400	4.7	2.00
from 400 to 450	5.1	2.25
from 450 to 500	5.5	2.50
from 500 to 600	6.3	3.00
from 600 to 700	7.1	3.50
from 700 to 800	7.9	4.00
from 800 to 900	8.7	4.50
from 900 to 1,000	9.5	5.00
over 1,000	1.5 + 0.8% * L	0.5% * L

Table 31: General tolerances for straightness

10.3.4 Practical Examples of Current Technology

Many manufacturers of ceramics have developed special expertise in the market segments in which they operate, enabling them to produce components with tolerances closer than those quoted in DIN 40 680 **without** additional hard machining. As a result, the hard machining costs are no longer required, and the component can be manufactured more economically.
The following examples will illustrate how present technology now compares with the tolerances according to DIN 40 680 mentioned above.

10.3.4.1 Abrasion Protection Plates

Large numbers of such plates are placed in the way of impacts, glued to a substrate, to protect surfaces against abrasion.
Close tolerances are required here for the individual plates, so that the total tolerance of adjacent plates is kept within reasonable limits.

A typical dimension for such plates is 100 x 100 mm. The plates are manufactured by dry pressing, and are not machined after firing.
According to DIN 40 680-A-m a tolerance of ± 1.8 mm or ± 1.8 % per plate would be permissible.
Using present techniques, the total of length tolerances arising from 10 adjacent plates does not exceed + 2 mm / - 0 mm or + 0.2 % / - 0 %.

10.3.4.2 Plates as Kiln Furniture

A cast plate has dimensions of 500 x 350 x 6 mm, the diagonal therefore having a length of approx. 610 mm. According to DIN 40 680-C-g a flatness tolerance along the diagonal of 7.1 mm or 1.16 % would be permissible.
Current technology achieves a flatness tolerance for such plates of at most 1.3 mm or 0.2 %.

10.3.4.3 Transport Rollers for Roller Kilns

The transport of goods through a roller kiln is facilitated by a roller track. The goods to be fired stand on plates, and these are transported through the kiln by the slowly rotating rollers.

The evenness and straightness of these rollers must be tightly-controlled, since "crooked" rollers would result in uneven transport velocities, disturbing the relative arrangement of plates and eventually resulting in malfunctions.
It is clear that for rollers with a diameter of 40 mm and a length of 2500 mm, the manufacturing tolerances achieved nowadays are closer than the values quoted by DIN 40 680.

This is shown in Table 32, where present technical standards are contrasted with DIN 40 680. According to DIN 40 680, it is necessary to use the "coarse" precision level according to Table 29 in order to determine the tolerances, since the component has a diameter > 30 mm. The standard tolerances quoted below are taken from Table 30 for dimensional tolerances and Table 31 for shape tolerances.

	Tolerance for	Tolerances according to DIN 40 680	State of the art
silicon carbide	∅D	± 2 mm	± 0.5 mm
	Length	± 50 mm	± 1.5 mm
	maximum sag	21.5 mm	2.0 mm
oxide ceramics	∅D	± 2 mm	± 0.4 mm
	Length	± 50 mm	± 1.0 mm
	maximum sag	21.5 mm	1.5 mm

Table 32: A comparison of the tolerance values according to DIN 40 680 ("coarse") with the usual manufacturing tolerances (unmachined) for a transport roller with Ø = 40 mm and l = 2,500 mm

10.4 Agreeing Test Procedures

It is essential that in every case the user and the manufacturer agree on the necessary and economically achievable tolerances at an early stage. It is equally important that consistent measurement procedures (standardised measurement procedures, wherever possible) are agreed for assessing the components.

Example 1:

The straightness of large-volume components (slabs, beams etc.) is usually measured statically in accordance with DIN 40 680 (see Figures 209 and 210). It can be appropriate to use dynamic measurements to achieve a more meaningful assessment of the quality of rotationally symmetrical parts such as, for instance, transport rollers. This is done by turning the roller once around its own axis of rotation and measuring the total excursion. In this way it is possible to determine errors in straightness as well as in ovality. Both are relevant to the later use of the component.

If the method of measurement is not specified in advance, customers and manufacturers are presented with wide scope for interpretation, with corresponding points of friction.

Example 2:

Ceramic sealing discs or rings are checked for flatness using what is known as the interference method. This is an optical measurement process by means of which variations in a surface's flatness of < 1µm can be made visible.
A beam of light of a defined wavelength (monochromatic light) is directed on to the component through a plane faced glass. The light is reflected from the component's surface. Extremely small variations in flatness have the effect of yielding different refractive deviations on the return journey through the plane glass, making errors visible and measurable.
The slabs of plane glass are strictly standardised into different precision classes.

Until about 15 years ago, helium vapour lamps were used to create the monochromatic light. For a number of reasons, sodium vapour lamps have since then become increasingly established. Two types of light source are thus represented on the market. Because of the different wavelengths of helium and sodium (although only specialists can distinguish the colours with the naked eye) the two light sources will provide different results from the same component.
This example illustrates how, as tolerances become tighter, it is not only necessary to use the same measurement procedures but even the same types of measuring instrument!

10.5 Measurement Procedures

10.5.1 Bending Strength

The fracture strength measured during a bending test depends on many factors such as the dimensions, cross sectional geometry, surface quality, loading velocity, environmental humidity, the geometry of the test device and the procedure. The result of such a test gives an indication of the **general magnitude of the strength properties** of the material, but **cannot** be directly used as **design data**. It is suitable for quality-control and for the general comparison with various materials, provided all of the parameters mentioned above remain constant. In practice, both 3-point and 4-point bending tests are used.

The necessary test equipment consists of:

- a mechanical test machine, with which a test piece is loaded with constant rate of force increase and which is capable of measuring the peak stress with an accuracy of ± 1 %,
- a test piece loading jig whose geometry and dimensions are suitable for the test,
- a micrometer meeting the specifications of ISO 3 611 and capable of measuring test piece dimensions to an accuracy of ± 0.01 mm,
- a travelling microscope with a slide rule or similar measuring device meeting the specifications of ISO 6 906 in order to measure the distance between the centre axes of the sample supports and the loading pins.

10.5.1.1 3-point Bending Test

The test jig consists of two parallel supports for the sample and a single loading pin in the middle, between the supports, where the force is introduced. The support pins must be mounted in such a way that they can rotate freely on their axes in order to minimise the influence of friction on the measurement. One of the supports must also be able to rotate about an axis perpendicular to this and parallel to the axes of the sample so that the test piece can align itself when under stress. The loading pin must also possess similar rotational axes in order to ensure the uniform application of force on the test piece. The diameter of the support and loading pins and the distance between the centres of the supports (the loading span) can be taken from Table 33. The surface must be polished and free from burrs. The force is introduced perpendicularly to the test piece plane and/or the support plane. A typical set-up for such an instrument is shown in figure 212.

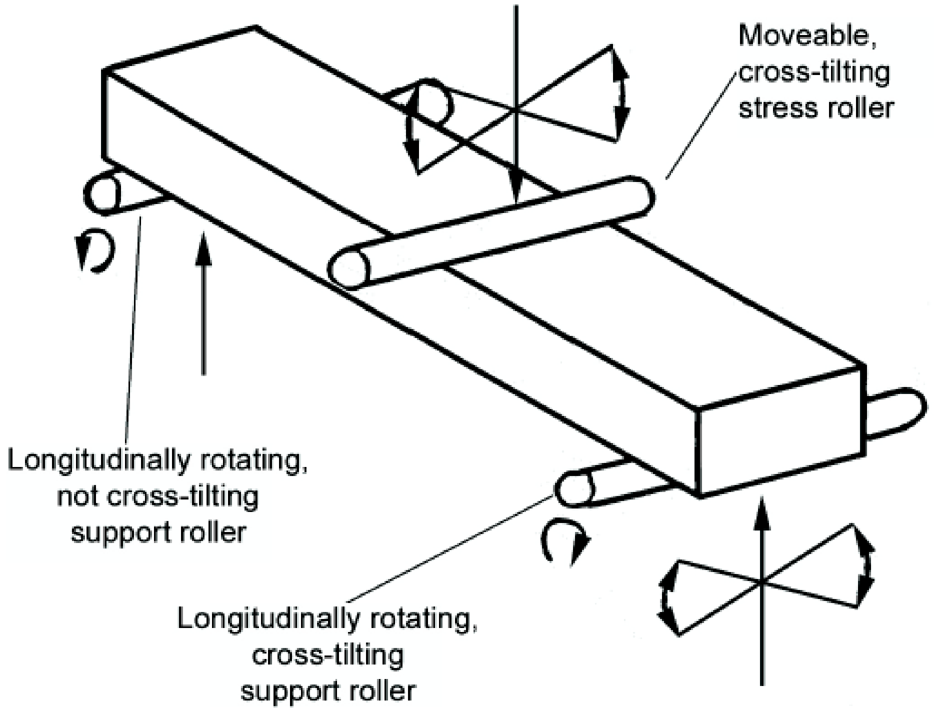


Figure 212: Schematic illustration of the 3-point bending test

10.5.1.2 4-Point Bending Test

The test jig consists of two supports, as in the 3-point bending test, with identical specifications. Two loading pins, whose centres are separated by half of the distance between the supports (see table 33), are positioned symmetrically to an accuracy of ± 0.2 mm between the sample supports, and the force is introduced perpendicularly to the test piece. Both loading pins must be able to rotate freely and independently around their axes and in a direction parallel to the long axes of the test piece. In this manner, the optimal alignment between the loading pins and the support pins can be achieved.

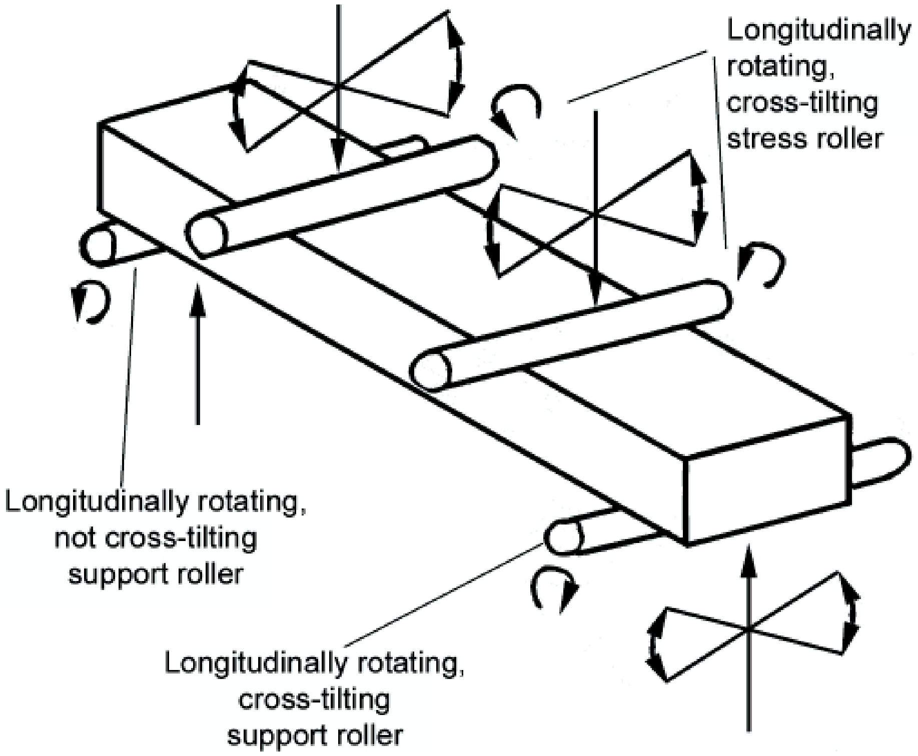


Figure 213: Schematic illustration of the 4-point bending test

The test piece must prepared to the dimensions given in Table 33 and shown in Figure 213, according to their group classification (DIN EN 60 672-2 and DIN EN 843-1). The test piece must be made using the process from which the product is expected to be manufactured (see pp. 70-76). Any surface treatment such as grinding, polishing, etc. should be noted and be representative of the surface of the product, since the fracture strength of ceramic can be affected by the surface quality. The minimum number of test pieces for each test is 10.

Material group	Material sub-group	Specimen dimensions in mm				Method	Dimensions of jig in mm	
		Length	Rod diameter d	Flattened hxb	Rectangular hxb		Support width	Roller diameter
C 100	All except C 111	120	10	-	-		100	10
	C 111	120	-	10 x 8	10 x 10	3-point	100	10
C 200	All	120	10	10 x 8	10 x 10	3-point	100	10
C 300	All	50	5	-	3 x 4	3-point	40	5
C 400	All	120	10	10 x 8	10 x 10	3-point	100	10
C 500	All	120	10	10 x 8	10 x 10	3-point	100	10
C 600	All	120	10	10 x 8	10 x 10	3-point	100	10
C700	All	50	5	-	3 x 4	Both	40	5
C 800	C 810	20	5	-	3 x 4	Both	40	5
	C 820	120	10	-	10 x 10	3-point	100	10
C 900	All	50	5	-	3 x 4	Both	40	5

Table 33: Sample and test instrument dimensions

10.5.2 Hardness

Only the Vickers and Knoop procedures are suitable for measuring the hardness of ceramics. The other hardness measurement procedures are either unsuitable for hard and brittle materials because, for instance, they use a very hard indenter and a small test force, or their testing technology has not yet been sufficiently developed. Assessing the impression made by the indenter in the usual way that this is done for metallic materials to determine the Vickers or Knoop hardness reaches the limits of its applicability with ceramic materials; a range of problems related to the procedure and to the materials arise.

For this reason, procedures with modified methods such as the

- UCI procedure (Ultrasonic Contact Impedance) or the
- universal hardness measurement technique are used.

The **UCI procedure** is based in the change of the resonant frequency of a test probe, with the Vickers indenter mounted on its tip, during the penetration process. The changing frequency is a measure of the surface area of the impression, and therefore an indicator of the hardness of the material.
The change in the resonant frequency of the oscillating bar is, however, also a function of the modulus of elasticity of the indenter and of the sample, and these must be determined through other procedures. This gives rise to material-specific calibration functions.
Conversely, the modulus of elasticity of the material can be found using the UCI procedure if its hardness is known.

The **universal hardness measurement** is based on a determination of the functional relationship between the indenter force and the penetration depth. In this way a hardness that depends on the test force is determined, taking the elastic and plastic deformation into account, and a hardness figure that is independent of the test force, satisfying the conditions for crack-free impressions.

It is important that the same method of measurement is used for materials that are to be compared.

10.5.3 Elastic Modulus

Because there is a material-specific relationship between the speed of sound, porosity and modulus of elasticity, ultrasonic testing can be used to determine the elastic modulus non-destructively. This method is suitable for finding small faults in the ceramic material. This does, however, require the ultrasonic instrumentation to be of high quality. To provide an indication of a 100 µm fault, a frequency of 100 MHz, tightly focusing test heads and instrumentation amplifiers are all required.

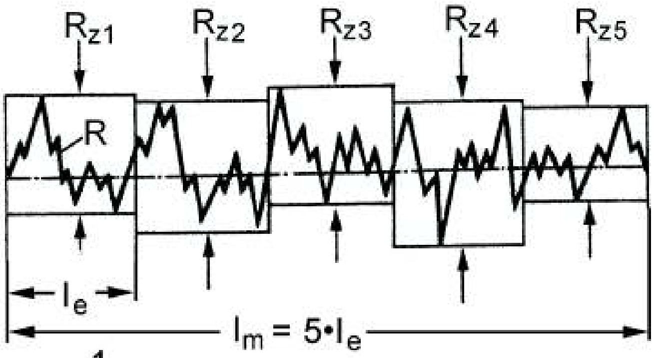
10.5.4 Surfaces

10.5.4.1 Definitions

The surfaces of ceramic materials in most cases do not display regular structures, but contain profile deviations which can be classified into roughness, waviness and shape. Important data for ceramic parts are:

R_a = mean roughness figure,
R_z = roughness depth,
M_r = material ratio, formerly : t_p = bearing area.

The average **roughness depth R_z** is the mean value of 5 individual roughness depths obtained from consecutive separate samples of the roughness profile. The extrema within each of the sampling lengths are summed and the total range divided by the number of the profile's sampling lengths.



$$R_z = \frac{1}{5}(R_{z1} + R_{z2} + R_{z3} + R_{z4} + R_{z5})$$

Figure 214: Calculation of the roughness depth R_z

The **average roughness R_a** is the computed average of all deviations of the roughness profile from the median line over the defined length. R_a theoretically corresponds to the distance between several lines when the peaks above the median and valleys below the median are converted into rectangles of equal size.

$$R_a = \frac{1}{l_m} \int_0^{l_m} |y| \, dx \qquad R_q = \sqrt{\frac{1}{l_m} \int_0^{l_m} y^2 \, dx}$$

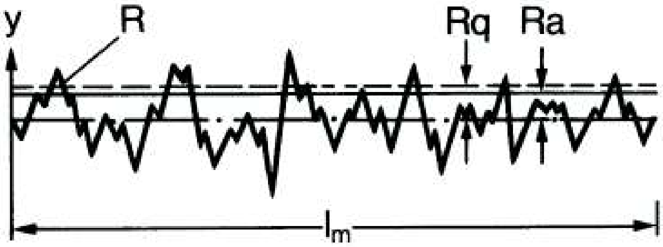
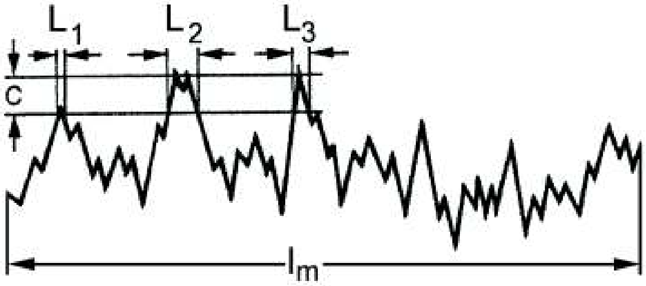


Figure 215: Calculation of the average roughness value R_a

The **material ratio M_r** (formerly: the bearing area t_p) is the ratio of the load bearing surface area (at a given intersection line) to the entire area under consideration (over the reference path) in %.



$$M_r = \frac{1}{l_m}(L_1 + L_2 \ldots L_n) \cdot 100[\%]$$

Figure 216: Calculating the material ratio M_r

When using optical methods, M_r is defined as a ratio of areas.

M_r = (area down to a defined depth) / (total area)

Although the optical method is not standardised, it is often used since it is possible to measure very quickly and with high precision.

The above mentioned parameters are defined in DIN EN ISO 1302.

In order for the manufacturer and the customer to be able to compare surface measurement data, it is important that measurements are made under identical conditions. The specifications affect the tracing stylus instrument, the stylus, the stylus geometry, the measuring length, filters, instrument and instrument settings as well as the surface parameters used. Examples with fundamental conditions are listed in Table 34.

Measuring instrument/type	Mahr, Perthometer S4P
Stylus type	RHT 6-50 Used for planar surfaces, outside surfaces and lengths (pipes, bars) FRW 750 Used on curved surfaces, radii as well as small holes, offsets, grooves and channels FRW 750/S Used on curved surfaces, radii as well as small holes, offsets, grooves and channels
Stylus geometry	RHT 6-50; tip angle 90°, radius 5 µm FRW 750; tip angle 90°, radius 10 µm FRW 750/S; tip angle 90°, radius 3-5 µm
Measuring path	Lt: 5.5 mm Lm: 4 mm
Filter	LC Gaus Lambda 0.8 mm
Data for sealing surfaces	R_a, R_z, (R_p, R_{max}, M_r)
Scale	Horizontal scale: 500 µm Vertical scale: 10 µm
Measuring location	According to drawings or the test schedules (corresponding to XXX markings in the drawing)

Table 34: Example of the specification of measurement conditions

The following examples of surfaces (see p. 234 f.), material ratios (see p. 236) and surface profiles (see p. 237 f.) will provide an impression of the characteristics of ceramics surfaces.

10.5.4.2 Hard Machined Surfaces

Material: ***Aluminium oxide 96 %***

- **Surface after sintering**

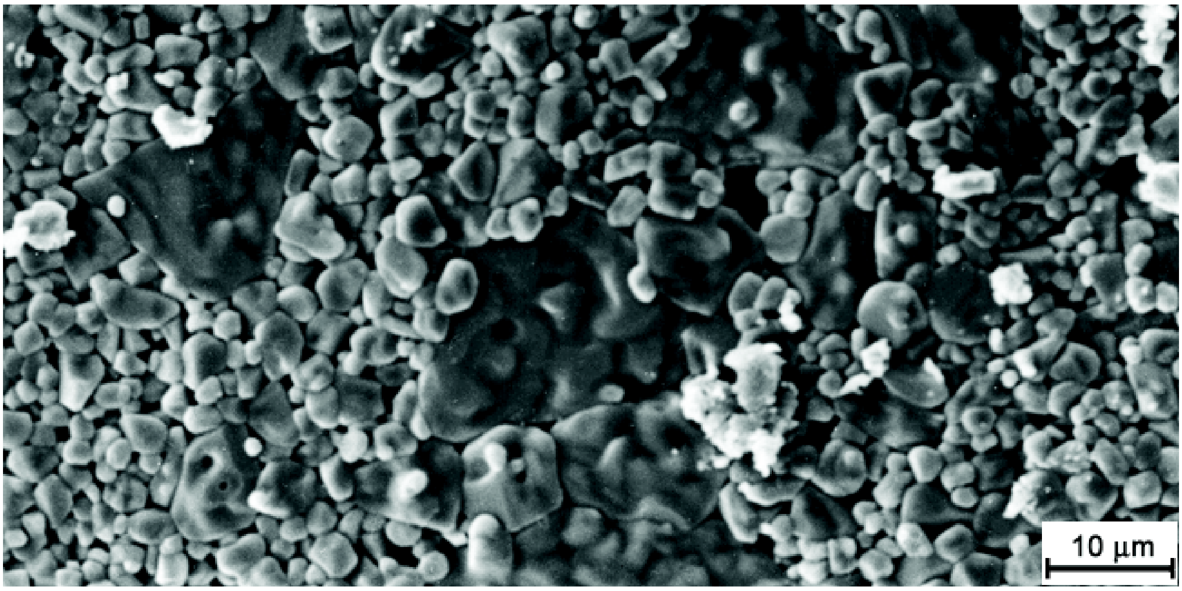


Figure 217: "as fired"

- **Tumbled or vibromilled surface**

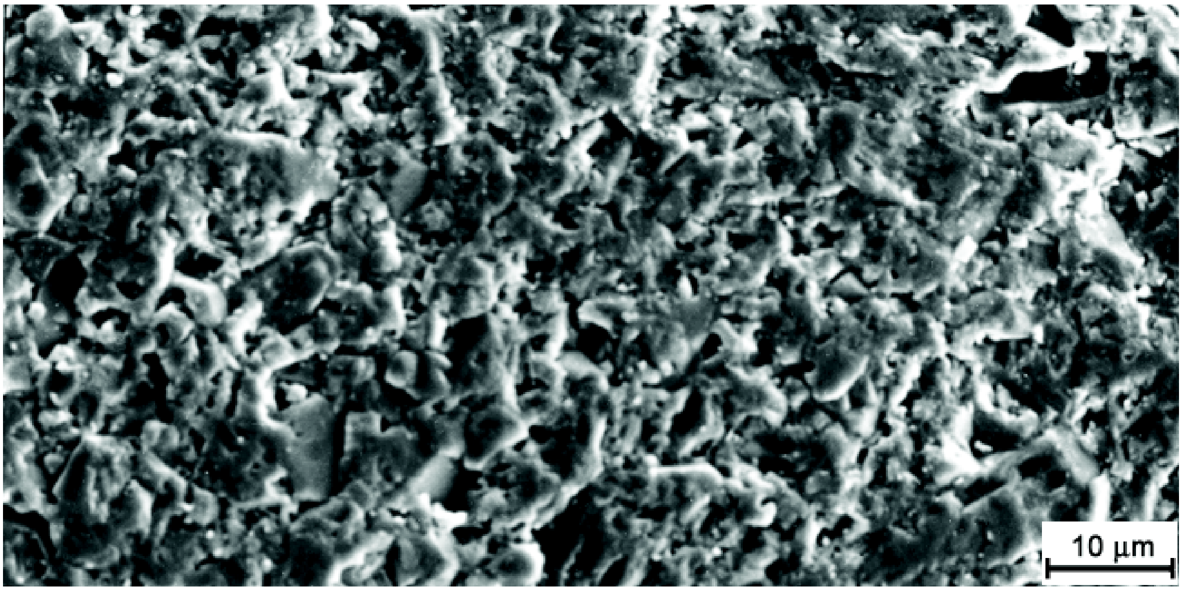


Figure 218: Tumbled or vibromilled

- **Ground surface**

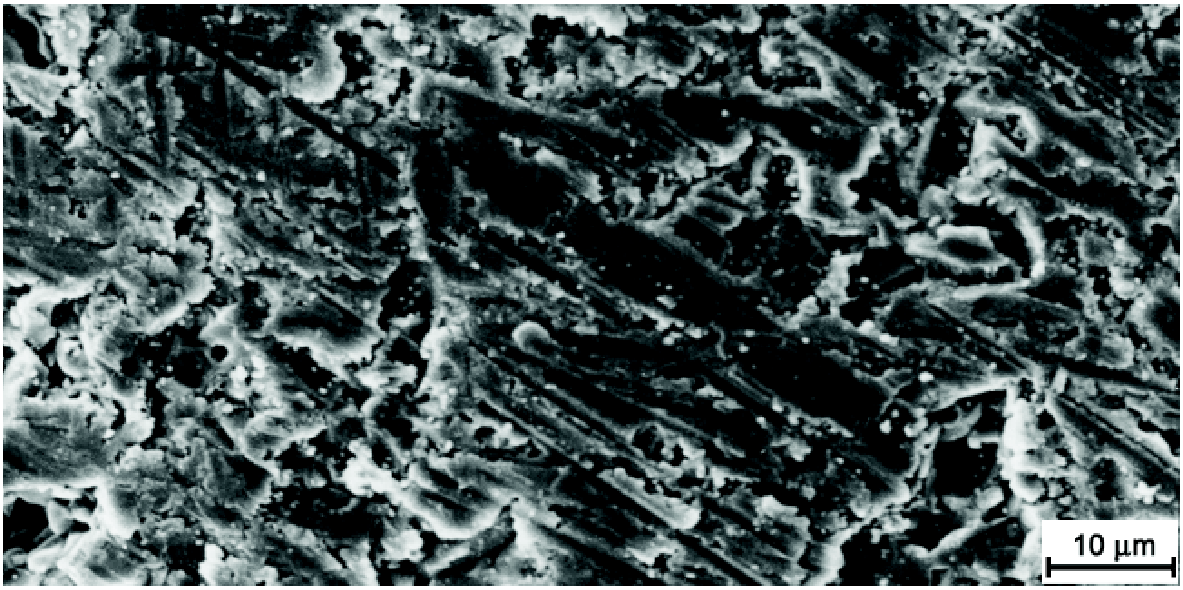


Figure 219: Ground

- **Polished surface**

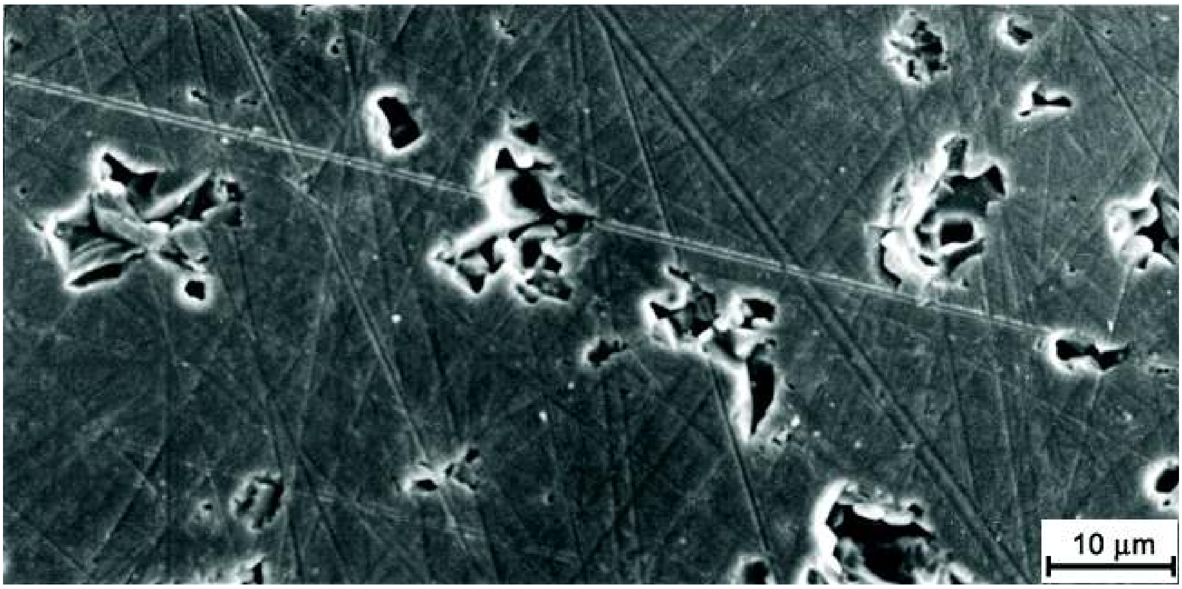


Figure 220: Polished

10.5.4.3 Material ratios M_r

Material: ***Aluminium oxide 96 %***

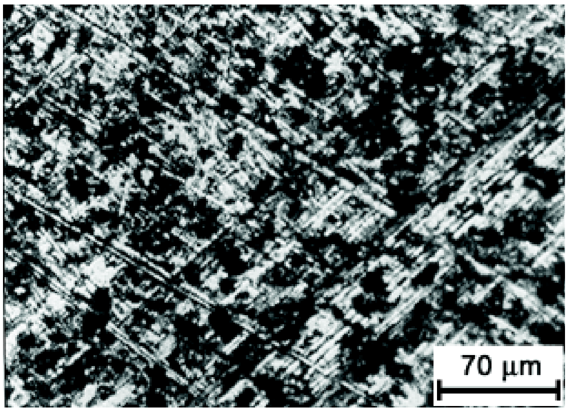


Figure 221: Ground

35 % M_r

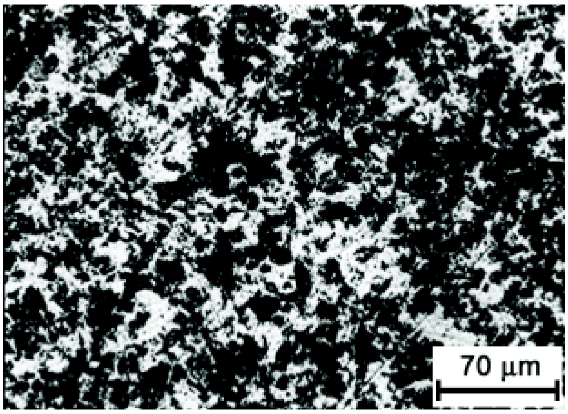


Figure 222: Lightly polished

60 % M_r

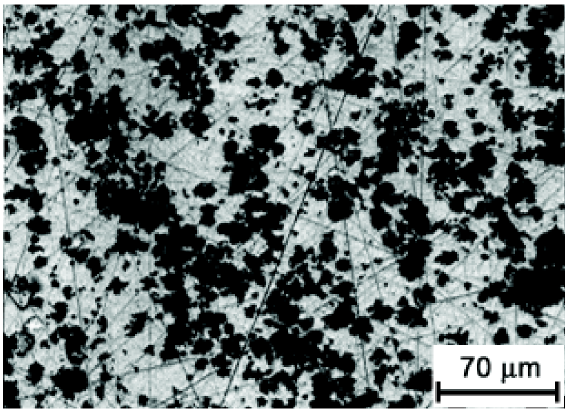


Figure 223: Polished (medium)

70 % M_r

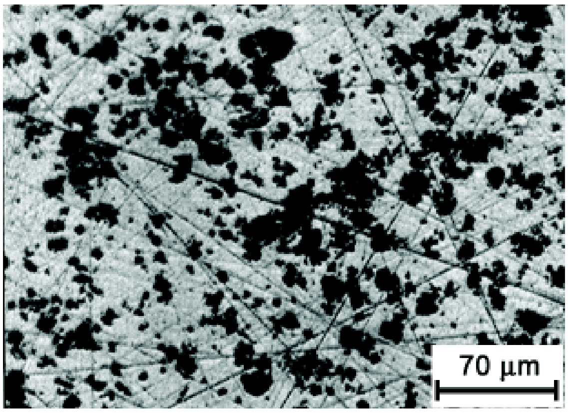


Figure 224: Polished (long)

75 % M_r

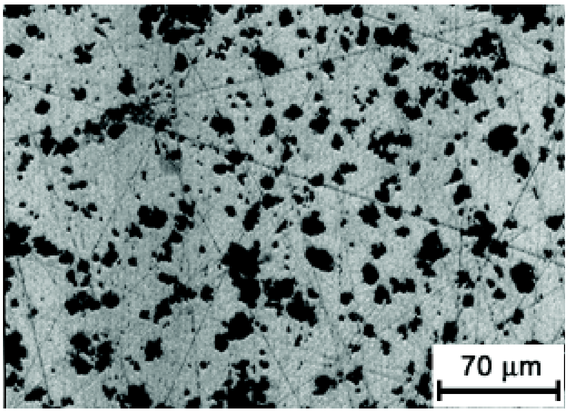


Figure 225: Polishing finished

80 % M_r

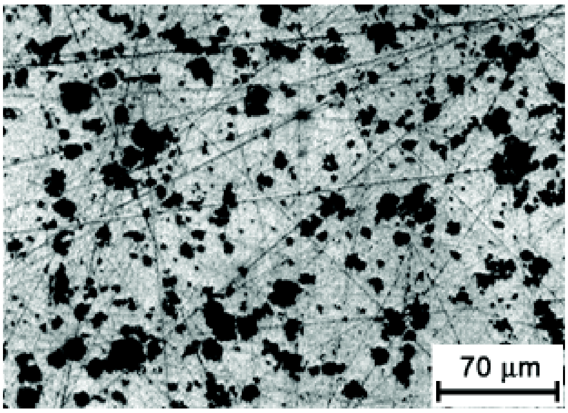


Figure 226: Highly polished

10.5.4.4 Roughness profiles

Material: ***Aluminium oxide 96 %***

- **Surface after sintering**

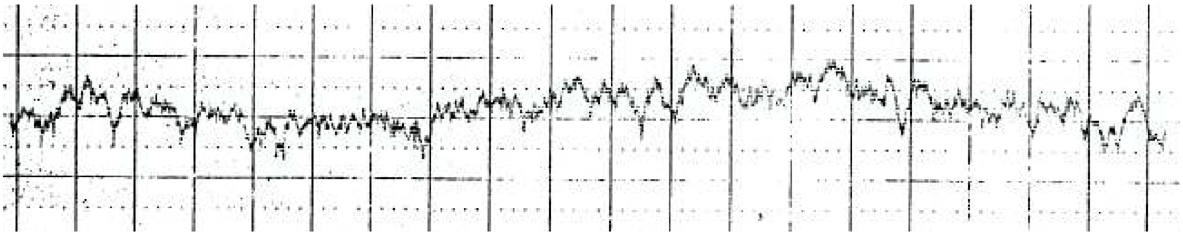


Figure 227: Roughness profile measurement after sintering with
R_a = 0.7 µm R_z = 4.8 µm

- **Tumbled or vibromilled surface**

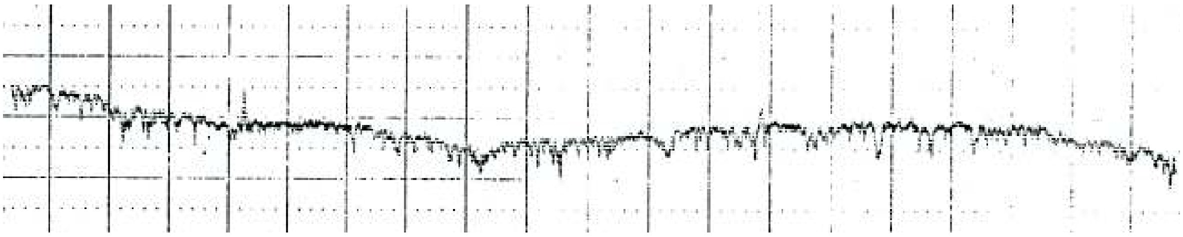


Figure 228: Roughness profile measurement after tumbling with
R_a = 0.35 µm R_z = 3.6 µm

- **Ground surface**

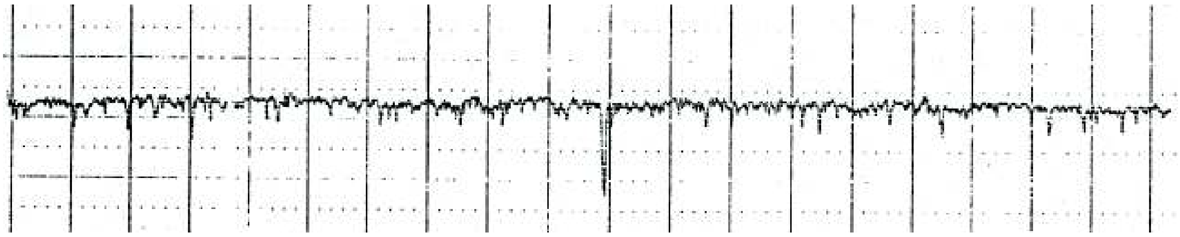


Figure 229: Roughness profile measurement after grinding with
R_a = 0.3 µm R_z = 3.7 µm

- **Lightly polished surface**

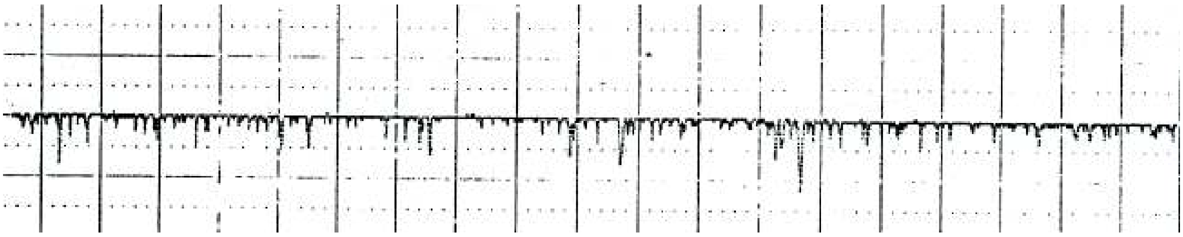


Figure 230: Roughness profile measurement after polishing with
$R_a = 0.23\ \mu m$ $R_z = 3.6\ \mu m$

- **Surface after long polishing**

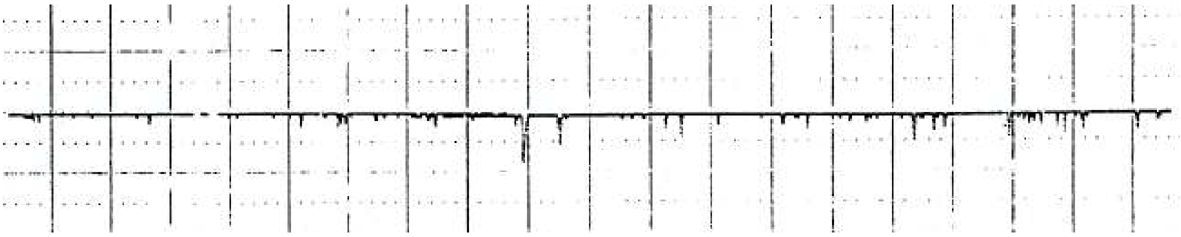


Figure 231: Roughness profile measurement after a long period of polishing with
$R_a = 0.1\ \mu m$ $R_z = 2.1\ \mu m$

10.6 Quality

10.6.1 Statistical Assessment – Summary

The following methods of representation provide support for the adequate analysis of data from production and for problem-solving:

Classifications
To distinguish partial problems according to their importance, errors logged by priority can be displayed using tally charts or histograms (Pareto diagrams/ABC analysis).

Relationships
Listing possible causes of errors and organising them with respect to the influence of man, method, machine and material in order to determine their reasons and effects is generally represented on a herring-bone diagram (Ishikawa).

Distributions
The conversion of series of measurements into distribution functions and their characteristic values (median x, variance σ) describe an operation and allow subsequent measurements to be predicted (histogram).

Control cards
The graphical representation of measurement data with respect to time along with the corresponding boundary values provides assistance to the decisions required for process control.

Scatter plots
The representation of individual values related by two influencing factors leads to a description of their relationships.

Diagram types
When analysing data, a clear graphical representation is helpful. In general, line plots, histograms and pie charts are used.

Test forms

These serve to represent the results of routine tests in tabular form.

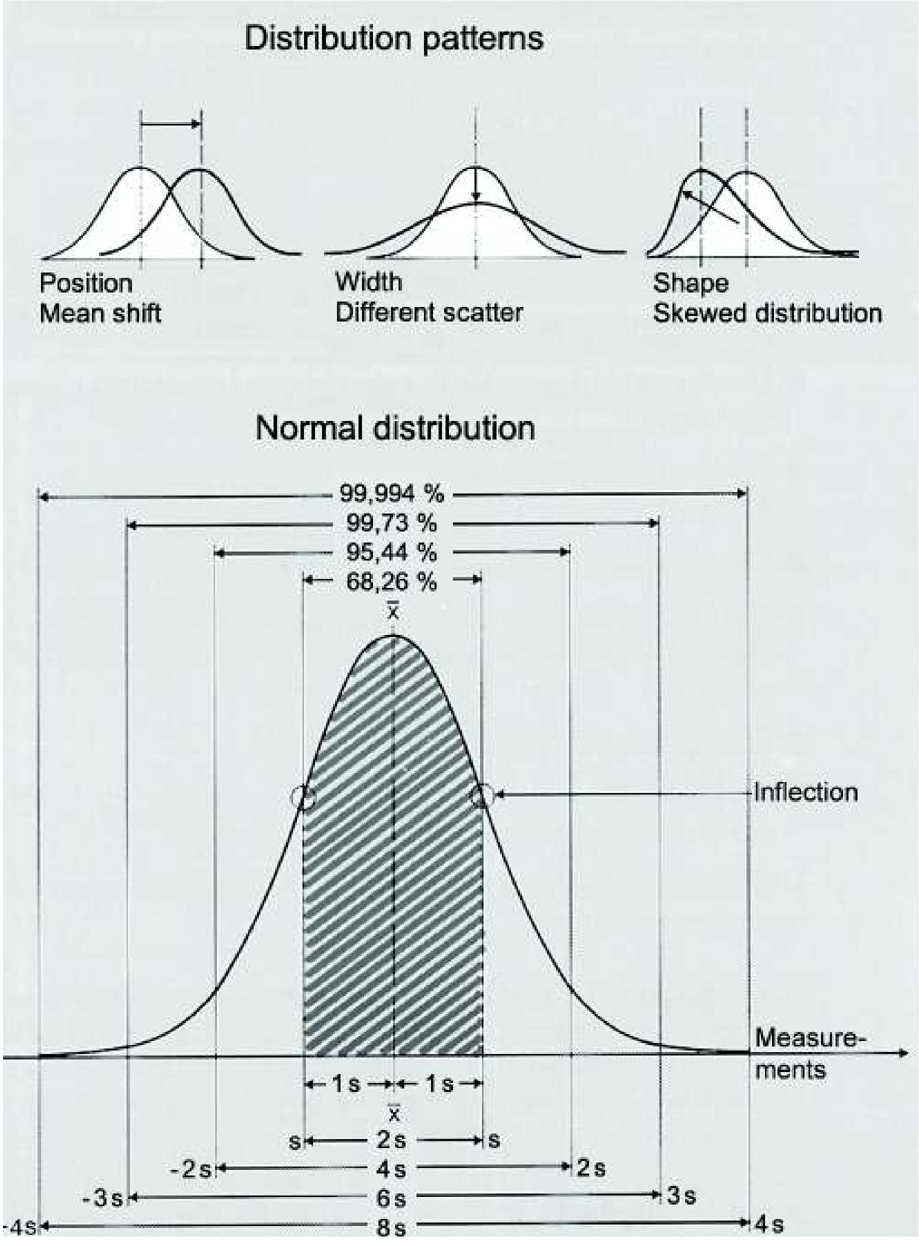


Figure 232: Shapes of distributions and normal distribution.

10.6.2 Statistical Methods

10.6.2.1 Computation Magnitudes

If a random sample is taken in order to inspect a large number of parts, a finite number of measured values are obtained. If a sufficiently large number of measurements is taken, a continuous curve can be drawn representing the entirety of all parts, even those that were not measured.

The curves associated with distributions are distinguished by their position, width and shape; they can occur next to each other and can be superimposed. Data very often display a **normal distribution**, also called a **Gaussian distribution** or **bell curve**, due to its form.

The normal distribution is mathematically described by the two following variables.

Arithmetic mean:

$$\overline{x} = \frac{x_1+x_2+x_3+...x_n}{n}$$

where n = number of values with individual values X_i from X_1 to X_n

Standard deviation:

$$s = \sqrt{\frac{(\overline{x}-x_1)^2+(\overline{x}-x_2)^2+(\overline{x}-x_3)^2+...+(\overline{x}-x_n)^2}{n-1}}$$

The mean value, $\overline{x}$, is the centre of the normal distribution curve and indicates the position of the distribution.
The standard deviation, s, describes the scattering of the process. It is a measure of the width of the normal distribution curve, and is the distance between the mean value, $\overline{x}$, and the inflection point of the normal distribution.

The area under the normal distribution curves is proportional to the frequency with which the values occur. In the region within ± 1 s around the mean value $\overline{x}$, i.e. 2 s, the hatched area underneath the normal distribution curve contains 68.26 % of all the values. The region ± 3 s around the average value, that is 6s wide, covers 99.73 % of all values. The points 3s from the mean value are defined as the **natural process boundaries**.

10.6.2.2 Control Cards

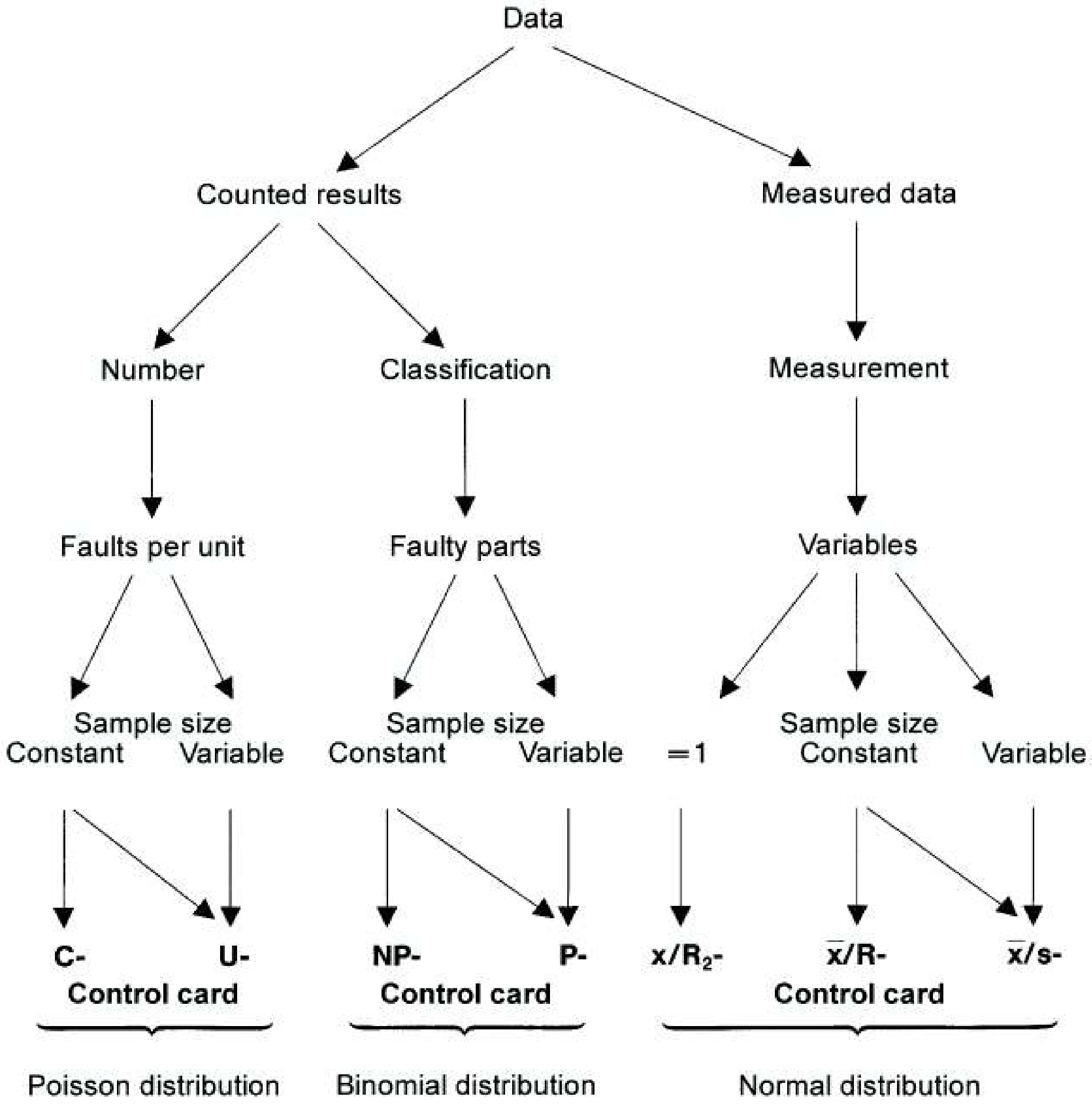


Figure 233: Distinctions between control cards

Control cards are graphical representations of measured values with respect to time, whereby the intervention boundaries are calculated from the sequence of measurements and are displayed as a line. They function as an aid to decision for operators for further process control. New measurement values are entered, interpreted immediately and corresponding comments, for example, relating to changes or interventions, are noted.

Combined control cards for measurement values are of particular importance in the industrial context, above all the **mean $\overline{x}$ card** combined with the **variation range R** or the **standard deviation s cards**. R is an abbreviation for "range ".

10.6.2.3 Process Flow Analysis

Control cards are interpreted with the help of statistical rules. The definitive statement is: this process is or is not statistically under control. A process which is under statistical control is stable and predictable. It is then possible to examine its capabilities, fulfil prescribed specifications and determine corresponding data. Such a parameter is called the **capability index**.

A statement about the spread of a process relative to the specified spread, independently of the position of the mean value of the corresponding product characteristics, is given by the **c_p value**. In contrast, the **c_{pk} value** permits the spread width and the position of the mean value of a process relative to the closest "critical" specification limit to be described.

$$\mathbf{c_p} = \frac{\text{OSG} - \text{USG}}{6\,s}$$

OSG = Upper specification limit
USG = Lower specification limit

$$c_{po} = \frac{\text{OSG} - \overline{x}}{3\,s}$$

$$c_{pu} = \frac{\overline{x} - \text{USG}}{3\,s}$$

$\mathbf{c_{pk}}$: lowest value of c_{po} or c_{pu}

The minimum requirement is that the value of c_p or c_{pk} should be greater than one. This means that the range $\overline{\mathbf{x}}$ = ±3s must lie within the specification limits.

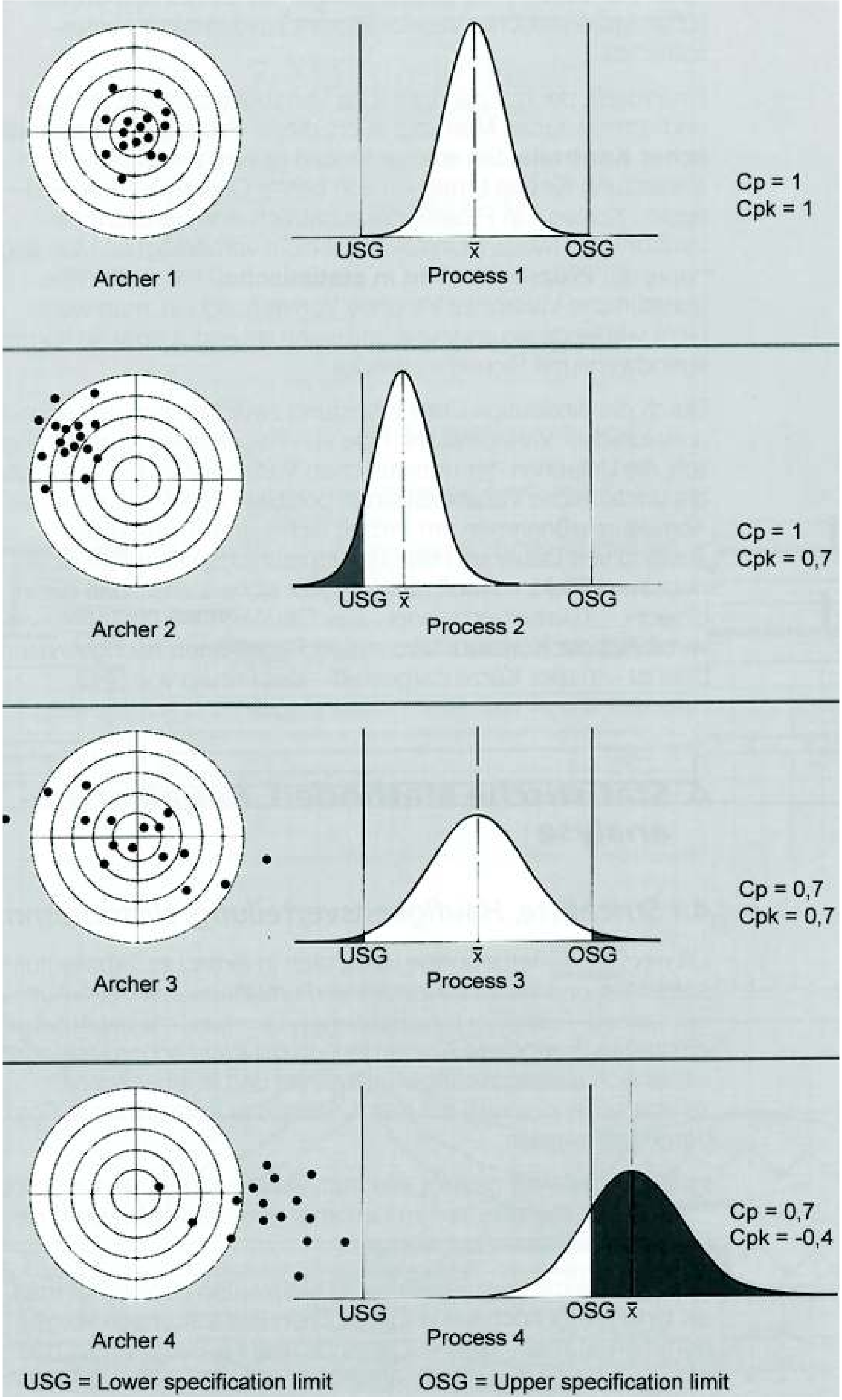


Figure 234: Process capability

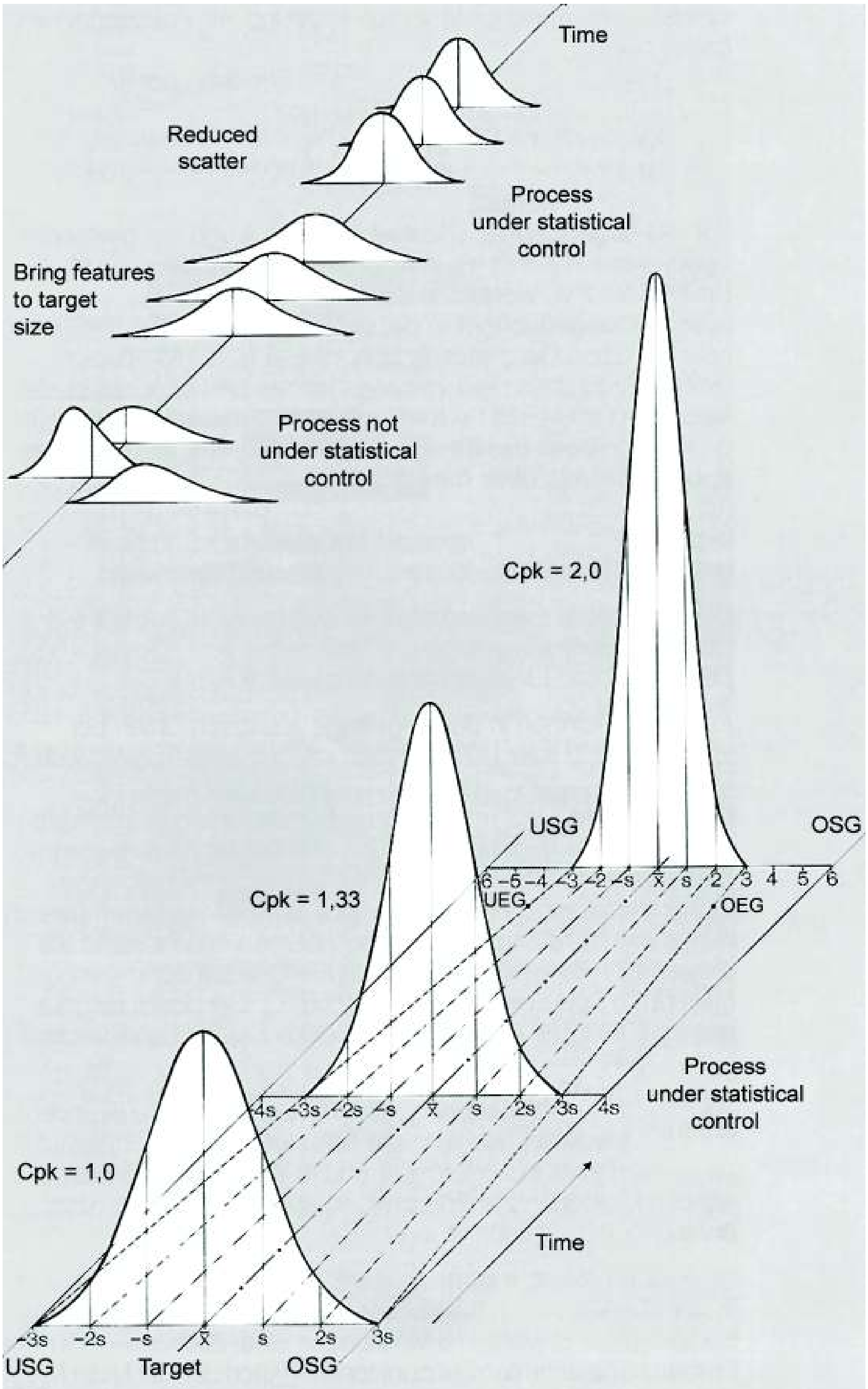


Figure 235: Reducing the spread of the process.

10.6.3 Statistical Process Control

SPC is a method for continuously improving processes and products. SPC is an abbreviation of ***S****tatistical* ***P****rocess* ***C****ontrol*.
Process is understood to refer to any repetitive operation. The SPC method is thus also applicable, for instance, to procurement, sales, engineering, research and development, production and management.

SPC serves

- as proof of quality production,
- process control and
- systematic diagnosis for the analysis and solution of problems with the purpose of continuous quality improvement.

The control card technique is an important tool for SPC.

A process that displays only natural variability is stable and predictable. Such a process is, in other words, under *statistical control*. A process of this type is an important precondition for achieving the highest quality. A process that also contains unnatural variability is unstable and unpredictable. Such a process is not under statistical control. The unnatural variability occurs without warning, with unknown duration but will inevitably reoccur sometime. With the help of control cards it becomes possible to track down the cause of the unnatural variability. The effectiveness and permanence of the correction can be proven using control cards.

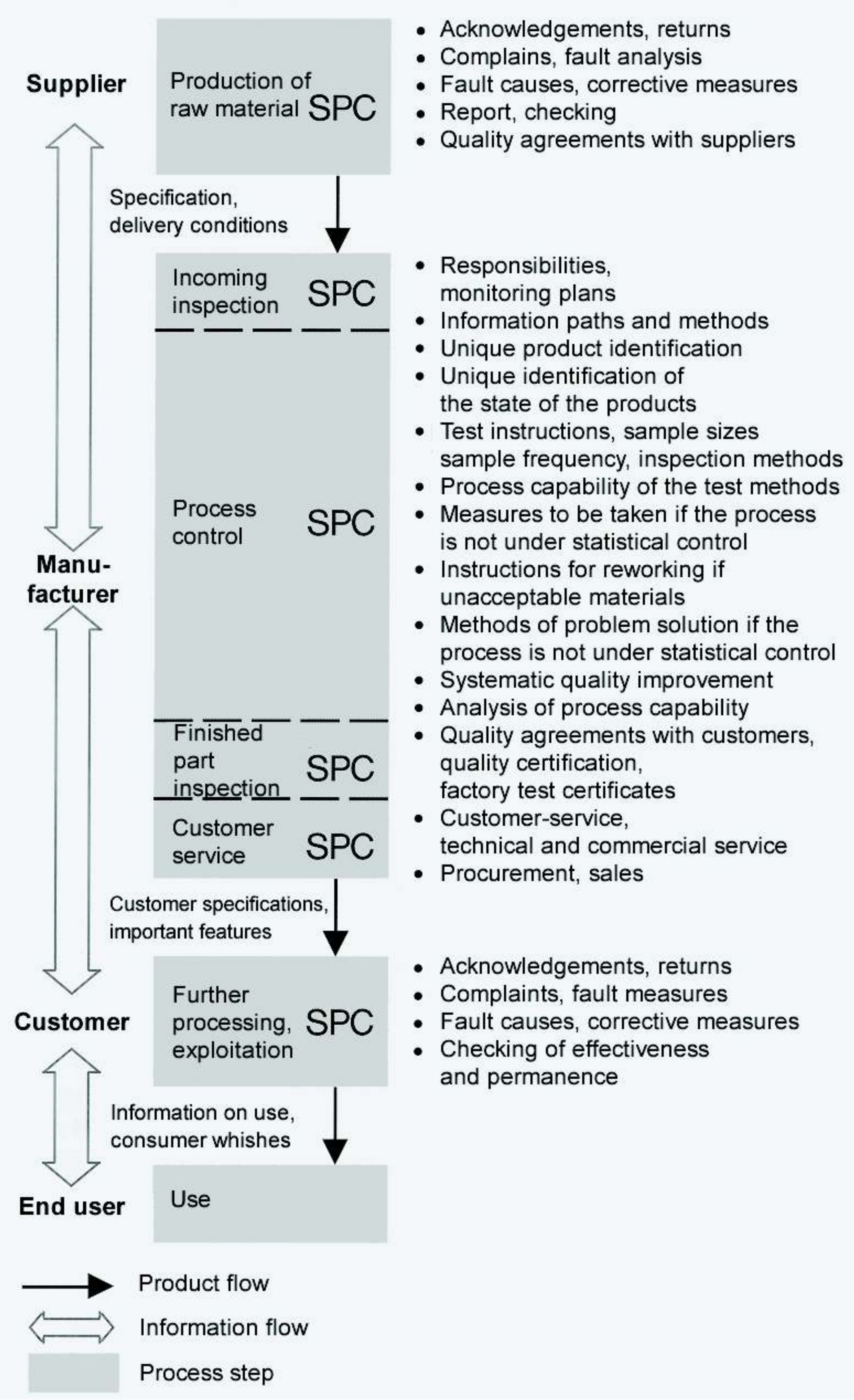


Figure 236: SPC and quality assurance systems

10.7 Standards Relevant to Technical Ceramics

10.7.1 General

DIN 40680-1	(08.83)	Ceramic parts for electrical engineering; General tolerances for dimensions
DIN 40680-2	(08.83)	Ceramic parts for electrical engineering; General tolerances for form
DIN 40686-1	(08.83)	Surfaces of dense ceramic parts for electrical engineering; general
DIN 40686 insert 1	(08.83)	Surfaces of dense ceramic parts for electrical engineering; specifications on drawings
DIN 40686 insert 2	(08.83)	Surfaces of dense ceramic parts for electrical engineering; measuring roughness
DIN 40686-4	(08.83)	Surfaces of ceramic parts for electrical engineering; the inspection of metallisation for soft soldering
DIN 40686-5	(08.83)	Surfaces of ceramic parts for electrical engineering; the inspection of metallisation for hard soldering
DIN 40686-6	(08.83)	Surfaces of dense ceramic parts for electrical engineering; high and low voltage insulators
DIN 40686-7	(08.83)	Surfaces of dense ceramic parts for electrical engineering; insulators
DIN EN 12212	(12.02)	High-performance ceramics – a unified method for classification
DIN V ENV 14232	(05.02)	High performance ceramics – terminology, definitions and abbreviations

DIN EN ISO 13565-1	(04.98)	Geometrical product specifications (GPS) – surface quality: Contact stylus procedure – surfaces with plateau-like, functionally relevant properties – Part 1: Filtering and general measurement conditions
DIN EN ISO 13565-2	(04.98)	Geometrical product specifications (GPS) – surface quality: Contact stylus procedure – surfaces with plateau-like, functionally relevant properties – Part 2: Description of the height using a linear representation of the material ratio curve
DIN EN ISO 13565-3	(08.00)	Geometrical product specifications (GPS) – surface quality: Contact stylus procedure – surfaces with plateau-like, functionally relevant properties – Part 3: Description of the height of surfaces using the probability density curve
DIN EN 60672-1 identical to IEC 60672-1	(05.96)	Ceramic and glass insulating materials – Part 1:Definitions and group classification
DIN EN 60672-2 identical to IEC 60672-2	(10.00)	Ceramic and glass insulating materials – Part 2:Test procedures
DIN EN 60672-3 identical to IEC 60672-3	(02.99)	Ceramic and glass insulating materials – Part:Specifications for individual materials
DIN ISO 1101	(08.95)	Technical drawings; shape and positioning tolerance; shape, direction, location and run-out tolerances; general, definitions, symbols, entries on drawings
DIN ISO 2768-1	(06.91)	General tolerances; tolerances for lengths and angular dimensions without individual tolerance entries
DIN ISO 2768-2	(04.91)	General tolerances; tolerances for shape and position without individual tolerance entries
DIN ISO 286-1	(11.90)	ISO system for limiting dimensions and fits; principles of tolerances, dimensions and fits

DIN ISO 286-2	(11.90)	ISO system for limiting dimensions and fits; tables of basic tolerance levels and limiting dimensions for holes and shafts
DIN EN ISO 1302	(06.02)	Geometrical product specification (GPS) – specifications of surface quality in technical product documentation
ISO 9000	(05.90)	Quality management and quality assurance standards; Guide for selection and application
ISO 15165	(10.01)	High-performance ceramics; classification system
DVS 3102	(02.93)	The fabrication of ceramic-ceramic and ceramic-metal bonds through active soldering
VDI/VDE 2603	(09.90)	Surface measurement procedures; measuring the bearing area ratio
VDI/VDE 2604	(06.71)	Surface measurement procedures; examining roughness through interference microscopy

10.7.2 Test Procedures for Powders

DIN EN 725-1	(06.97)	The determination of impurities in aluminium oxide powder
DIN EN 725-2	(03.94)	Determining the impurity content in barium titanate
DIN EN 725-3	(06.97)	Determining the oxygen content in non-oxide powders using hot carrier gas extraction
DIN EN 725-5	(03.96)	Determination of the distribution of particle sizes
DIN EN 725-6	(06.97)	Determination of the specific surface
DIN EN 725-7	(01.96)	Determination of the absolute density
DIN EN 725-8	(05.97)	Determination of the tap density

DIN EN 725-9	(05.97)	Determination of the fill density
DIN EN 725-10	(04.97)	Determination of the compaction properties
DIN V ENV 725-11	(11.93)	Determination of the compaction behaviour during natural sintering
DIN EN 725-12	(06.01)	Chemical analysis of zirconium oxide
DIN V ENV 14226	(07.02)	Determination of calcium, magnesium, iron and aluminium in silicon nitride using flame atomic absorption spectroscopy (FAAS) or atomic emission spectroscopy with inductively coupled plasma (ICP-AES)
DIN V ENV 14273	(09.02)	Determination of the crystalline phase in zirconium oxide
DIN 51079-1	(04.91)	Chemical analysis of silicon carbide as a raw material and as a component in other materials; soda-boracic acid treatment
DIN 51079-2	(03.98)	Chemical analysis of silicon carbide as a raw material and as a component in other materials; acid-pressure treatment
DIN V 51079-3	(03.98)	Chemical analysis of silicon carbide as a raw material and as a component in other materials; treatment of the free carbon through wet chemical oxidation
Pr DIN 51082	(06.01)	Determination of the pH value of suspensions of non-water-soluble powders
ISO 14703	(03.00)	Sample preparation for determining the distribution of particles in ceramic powders

10.7.3 Test Procedures for Monolithic Ceramics

DIN EN 623-1	(04.95)	General and structural properties; Testing for the presence of surface faults through colour penetration tests
DIN EN 623-2	(11.93)	General and structural characteristics; Determining density and porosity
DIN EN 623-3	(04.93)	General and structural characteristics; Determining grain size
DIN EN 623-4	(11.93)	General and structural characteristics; Determining surface roughness
DIN EN 623-5	(10.02)	General and structural characteristics; Determining the proportions by volume of different phases through analysis of microstructure photographs
DIN V ENV 820-1	(02.94)	Thermomechanical properties; Determining bending strength at elevated temperatures
DIN EN 820-2	(11.92)	Thermomechanical properties; Determining deformation from unloaded weight
DIN V ENV 820-3	(02.94)	Thermomechanical properties; Determining thermal shock resistance using the water quenching test
DIN V ENV 820-4	(12.01)	Thermomechanical properties; Determining creep under bending stresses at elevated temperatures
DIN EN 821-1	(04.95)	Thermophysical characteristics; Determining thermal expansion
DIN EN 821-2	(08.97)	Thermophysical characteristics; Measuring thermal conductivity using the laser flash (or heat impulse) method
DIN V ENV 821-3	(11.93)	Thermophysical properties; Determination of specific heat

DIN EN 843-1	(04.95)	Mechanical properties at room temperature; Determination of flexural strength
DIN V ENV 843-2	(02.96)	Mechanical properties at room temperature; Determination of elastic modulus
DIN V ENV 843-3	(11.96)	Mechanical properties at room temperature; Determining the parameters for subcritical crack growth from bending strength tests with constant stressing rates
DIN V ENV 843-4	(10.94)	Mechanical properties at room temperature; Vickers, Knoop and Rockwell hardness testing
DIN V ENV 843-5	(01.97)	Mechanical testing at room temperature; Statistical analysis
DIN V ENV 1006	(04.93)	Guidelines for sampling and taking samples
DIN V ENV 12923-1	(02.98)	Monolithic ceramics; General considerations on the execution of corrosion tests
DIN V ENV 12923-2	(05.02)	Monolithic ceramics; Oxidation tests
DIN EN 50324-1	(12.02)	Piezo-electric properties of ceramic materials and components; Terminology
DIN EN 50324-2	(12.02)	Piezo-electric properties of ceramic materials and components; Measurement procedures – small signals
DIN EN 50324-3	(04.01)	Piezo-electric properties of ceramic materials and components; Measurement procedures – large signals
DIN prEN 50359-1-1	(07.01)	High-performance ceramics; electrical properties; Procedures for testing dielectric strength, short-term behaviour
DIN prEN 50359-2-1	(07.01)	High-performance ceramics; electrical properties; procedures for determining the specific surface and volume resistances over the temperature range 20°C to 800°C

DIN 51069-2	(11.72)	Testing ceramic raw materials and processed materials; comparative test of the behaviour of fireproof materials in response to attack by solid and liquid substances at high temperature, crucible method
DIN 51110-3	(09.93)	Testing high performance ceramic materials; 4-point bending test; static analysis; determination of the Weibull parameter
DIN IEC 60483	(04.88)	Guideline for determining the dynamic properties of piezo-electric ceramics with high electro-mechanical coupling factors
DIN IEC 60642	(04.88)	Piezo-electric vibrators and resonators for frequency stabilisation and selection; standard values and conditions; measurement and test procedures
DIN 51045-2	(10.76)	Determination of the change in length of solid bodies under the influence of heat; testing fired fine ceramic materials
DIN 51045-3	(10.76)	Determination of the change in length of solid bodies under the influence of heat; testing unfired fine ceramic materials
ISO 14704	(08.00)	Determination of the flexural strength of monolithic ceramics at room temperature
ISO 14705	(03.00)	Test method for hardness of monolithic ceramics at room temperature
ISO 15490	(07.00)	Test procedure for determining the tensile strength of monolithic ceramics at room temperature
prISO/DIS 15732	(06.99)	Test procedure for determining the fracture toughness of monolithic ceramics at room temperature on bending samples notched on one side (SEPB procedure)

ISO 17532	(10.01)	Test procedure for determining the linear thermal expansion of monolithic ceramics at room temperature using the push-rod method
prISO 17565	(10.01)	Test procedure for determining the bending strength of monolithic ceramics at elevated temperatures
prISO/DIS 18756	(05.02)	Determination of fracture toughness of monolithic ceramics at room temperature by the surface-crack-in-flexure-method (SCF)
prISO/DIS 20509	(05.02)	Determination of oxidation resistance of non-oxide monolithic ceramics
ASTM C 768	(1999)	Determining the resistance of refractory stones to molten slags
ASTM C 874	(1999)	Testing the slagging resistance of refractory materials

10.7.4 Test Procedures for Composite Materials

DIN EN 658-1	(01.99)	Properties of ceramic composite materials at room temperature – Part 1: Determination of properties under tension
DIN V ENV 658-2	(05.93)	Properties of ceramic composite materials at room temperature – Part 2: Determination of pressure resistance
DIN V ENV 658-3	(02.93)	Properties of ceramic composite materials at room temperature – Part 3: Determining the flexural strength
DIN V ENV 658-4	(02.93)	Properties of ceramic composite materials at room temperature – Part 4: Determining the shear strength of notched samples under compressive load
DIN V ENV 658-5	(02.93)	Properties of ceramic composite materials at room temperature – Part 5: Determining the shear strength in the 3-point bending test with a short separation of the supports

DIN V ENV 658-6	(02.93)	Properties of ceramic composite materials at room temperature – Part 6: Determining the shear strength using the double shear impact penetration test
DIN V ENV 1007-1	(04.93)	Ceramic fibres for ceramic composite materials – Part 1: Determining the lubricant content;
DIN V ENV 1007-2	(04.93)	Ceramic fibres for ceramic composite materials – Part 2: Determining the fineness
DIN V ENV 1007-3	(11.93)	Procedure for testing the fibre reinforcements – Part 3: Determining the fibre diameter
DIN V ENV 1007-4	(05.94)	Procedure for testing the fibre reinforcements – Part 4: Determination of tensile properties of fibres at room temperature
DIN EN 1007-5	(05.02)	Procedure for testing the fibre reinforcements – Part 5: Determining the distribution of tensile strength and tensile extension of fibres in fibre bundles at room temperature
DIN V ENV 1159-1	(11.93)	Thermophysical characteristics; Determining thermal expansion
DIN V ENV 1159-2	(11.93)	Thermophysical properties; Determining the thermal conductivity
DIN V ENV 1159-3	(11.93)	Thermophysical properties; Determination of specific heat capacity
DIN V ENV 1389	(06.94)	Physical properties; Determination of density and porosity
DIN V ENV 1892	(07.96)	Mechanical properties of ceramic composite materials at high temperatures in inert atmospheres; Determination of properties under tensile stress
DIN V ENV 1893	(07.96)	Mechanical properties of ceramic composite materials at high temperatures in the air at atmospheric pressure; Determination of properties under tensile stress

DIN V ENV 1894	(07.96)	Mechanical properties of ceramic composite materials at high-temperatures in inert atmospheres; Determination of shear strength through compressive stressing of notched samples
DIN V ENV 12289	(10.96)	O'Hara Mechanical properties of ceramic composite materials at room temperature; Determination of in-plane shear properties
DIN V ENV 12290	(10.96)	Mechanical properties of ceramic composite materials at high temperatures in inert atmosphere; Determination of properties under compression
DIN V ENV 12291	(10.96)	Mechanical properties of ceramic composite materials at high temperatures in air at atmospheric pressure; Determination of properties under compression

10.7.5 Test Procedures for Layers

DIN EN 1071-2	(12.02)	Methods for testing ceramic coatings; Determination of layer thickness using the dome grinding procedure
DIN V ENV 1071-3	(06.94)	Methods for testing ceramic coatings; Determination of adhesion using the scratch test
DIN V ENV 1071-4	(06.95)	Procedure for testing ceramic layers; Determination of the chemical composition
DIN V ENV 1071-5	(04.95)	Procedure for testing ceramic layers; Determination of the porosity
DIN V ENV 1071-6	(09.02)	Procedure for testing ceramic layers; Determination of the resistance of layers to abrasion through microscopic examination of abrasion
DIN EN 1071-12	(12.02)	Procedure for testing ceramic coatings; Determination of layer thickness using a contact profilometer

DVS 2301	(06.01)	Thermal spraying procedure for metallic and non-metallic materials
DVS 2307-4	(01.97)	Working protection during plasma spraying

10.7.6 Application Standards

DIN 43724	(02.79)	Measurement and control; electrical thermometers, ceramic protection tubes and retainer rings for thermocouples
DIN 48108-1	(08.83)	Ceramic parts for electrical engineering; mounting locations for insulators; corrugation
DIN 48108-2	(08.83)	Ceramic parts for electrical engineering; mounting locations for insulators; splintering
DIN 48108-3	(08.83)	Ceramic parts for electrical engineering; mounting locations for insulators; corrugated profile
DIN 58835-1	(07.79)	Surgical implants; ceramic materials, aluminium oxide
DIN VDE 0466-2	(03.71)	Specifications for insulators for overhead lines, aerial contact lines and telecommunications cables; Part 2: Specifications for insulators for high power overhead lines and aerial contact lines at 1,000 V and for overhead telecommunication lines
VDI/VDE 3717 Sheet	(07.93)	Technical supply specifications; aluminium oxide substrates for thick film circuits

10.7.7 Other Standards Quoted

DIN 8589	(09.03)	Machining production procedures (13 parts)
DIN 8505-1	(05.79)	Soldering; general, terminology

DIN 8505-2	(05.79)	Soldering; classification of procedures, terminology
DIN 8505-3	(01-83)	Soldering; classification of procedures according to energy introduction technique, process descriptions
DIN 50900-2	(06.02)	Corrosion of metals – Terminology – Part 2: Electrochemical terminology
DIN 50323-1	(1988)	Tribology; Terminology **No longer in the Beuth-Verlag catalogue!**
DIN 50323-3	(1993)	Tribology; friction; terminology, types, states, parameters **No longer in the Beuth-Verlag catalogue!**
DIN 50320	(1979)	Abrasion; terminology, systematic analysis of abrasion processes, division of the abrasion area **No longer in the Beuth-Verlag catalogue!**
DIN 50321	(1979)	Measurable abrasion characteristics **No longer in the Beuth-Verlag catalogue!**

10.8 Unit Conversion

Unit	**Conversion Factor**	
Length	1m	= 100 cm = 10^{10} Å =39.75 inch = 3.281 feet = 1.0936 yards = 0.6214*10^{-3} miles
Area	1m^2	= 1,550 sq. Inch = 10.764 sq. feet = 1.196 sq. yards
Volume	1m^3	= 1,000 l = 61,023 cu. inch = 35.314 cu. feet = 2,114 US pints = 1,760 UK pints = 264.2 US gallons = 8.386 US barrels = 6.11 UK barrels = 28.37 US bushels = 27.51 UK bushels = 4.13 US quarters = 3.44 UK quarters = 0.3532 reg. tons
Mass	1 kg	= 1,000 g = 15,432 grains (gr.) = 35.273 ounces = 2.2046 pounds (lbs) = 1.102*10^{-3} US short tons = 0.9842*10^{-3} UK tons (US long tons) = 0.0220 US cwt = 0.197 UK cwt
Density	1 kg/m^3	= 0.001 g/cm^3 = 0.10197 kp s^2/m^4 = 0.6242 lbs/cu ft. = 0.01002 lbs/UK gallon = 0.08344 lbs/US gallon = 436.994 gr/cu ft
Force	1N	= 1 kg m/s^2 = 10^5 g cm /s^2 (dyn) = 0.10197 kp = 7.233 poundal (pdl) = 0.2248 pound-weight (lb. wt, lbf)
Pressure	1 Pa (N/m^2)	= 1 kg/m s^2 = 10^{-5} bar = 0.10197 kp/m^2 (mm WS) = 10 g/cm s^2 (dyn/cm^2) = 0.10197*10^{-4} at (techn.) = 0.09694*10^{-4} atm (phys.) = 750.1*10^{-5} Torr (mm QS) = 1.4504*10^{-4} lbf/sq. inch (psi)
	1 at	= 10,000 kp/m^2 (mm WS) = 735.6 Torr = 14.22 lbf/sq. inch = 28.96 inch Hg

Unit	**Conversion Factor**	
Work, energy	1 J	= 1 Nm = 1 Ws = 1 kg m^2/s^2 = 10^{7} g cm^2/s^2 (erg) = 0.10197 kp m = 2.3844 10^{-4} kcal = 0.27778*10^{-6} kWh = 9.4782*10^{-4} BTU = 0.37767*10^{-6} PSh = 34.12*10^{-12} t SKE (hard coal units – SKE derives from the German Steinkohleneinheiten = hard coal units)
	1 kcal	= 4,186.8 J = 426.94 kpm = 3.968 BTU
	1 kWh	= 859.85 kcal = 1.3596 PSh = 3,411 BTU
	1 SKE	= 29.3 MJ = 7,000 kcal
Power	1 W	= 1 J/s = Nm/s = 1 kg m^2/s^3 = 10^{7} erg/s = 0.10197 kp m/s = 1.3596*10^{-3} PS = 1.3775*10^{-3} HP
	1 PS	= 735.5 W = 75 kp m/s = 632.3 kcal/h = 0.987 HP
Dynamic viscosity	1 Ns/m^2	= 1 Pa s = 1 kg/m s = 10 g/cm s (Poise) = 0.10197 kp s/m^2 = 0.6721 lbs/ft. s = 0.020885 lbf/sq. ft
	1 m Pa s	= 1 cP (Centipoise)
Kinematic viscosity	1 m^2/s	= 10^{4} cm^2/s (Stokes) = 10.764 sq. ft/s
Heating content, heat of transformation	1 J/kg	= 1 Ws/kg = 1m^2/s^2 = 2.3884*10^{-4} kcal/kg = 4.30*10^{-4} BTU/lb
Specific heat	1 J/kgK	= 1 m^2/s^2K = 2.3884*10^{-4} kcal/kg grd = 2.3884*10-4 BTU lb. °F
Thermal conductivity	1 W/mK	= 1 kg m/s^3K = 0.859824 kcal/m h grd = 6.934 BTU inch/sq. ft. hr. °F
Heat transfer coefficient coefficient of heat transmission	1 W/m^2K	= 1 kg/s^3K = 0.859824 $kcal/m^2h$ K = 0.1754 BTU/sq. ft. hr. °F
Temperature	x/[K]	= 273.15 + X /[°C]
	X [°F]	= 32 + 1.8 X [°C]

Table 35: Unit Conversion

10.9 Tables of Properties

The materials covered in the following tables find widely different applications. For this reason some of the data are not given. As a general rule, **electrical** and **mechanical** applications can be differentiated. Those materials classified according to **DIN EN 60 672-1** are given minimum specifictions for application in **electrical and electronic engineering**, but are also applied elsewhere. Flexural strength for technical ceramic materials are determined according to DIN EN 60 672-2 (see p. 263 ff.).

10.9.1. Materials according to DIN EN 60 672-3

10.9.2. Non-standardised high-performance materials

Due to the wide range of property values quoted by manufacturers, the values given in the following tables are indicative or minimum specification values. The actual values are often much better! It is therefore advisable to request reliable values from the manufacturers.

Note:
The values for bending strength, σ_B, determined by the 3-point bending test, are about 30 % greater than those obtained from the 4-point bending test!

10.9.1 Materials According to DIN EN 60 672-3

10.9.1.1 Alkali - Aluminium Silicates (C 100)

Identifcation according to DIN EN 60 672			C 110	C 111	C 112	C 120	C 130	C 140
			Quartz porcelain	Quartz porcelain	Cristobalite porcelain	Alumina porcelain	Alumina porcelain	Lithium porcelain
Mechanical:	**Symbol**	**Unit**	plastically formed	pressed			high strength	
Open porosity		[Vol %]	**0**	**< 3.0**	**0**	**0**	**0**	**0.5**
Density, min.	ρ	[g/cm^3]	**2.2**	**2.2**	**2.3**	**2.4**	**2.6**	**2.0**
3-point bending strength, unglazed	σ_{ft}	[MPa]	**50**	**40**	**80**	**90**	**140**	**50**
3-point bending strength, glazed	σ_{fg}	[MPa]	**60**	**--**	**100**	**110**	**160**	**60**
Elastic modulus	E	[GPa]	**60**	**--**	**70**	**--**	**100**	**--**
Hardness	HV_{10}	[GPa]	**--**	**--**	**--**	**--**	**--**	**--**
Stress intensity factor	K_{IC}	[MPa $\sqrt{m}$]	**--**	**--**	**--**	**--**	**--**	**--**
Electrical:								
Breakdown strength	E_d	[kV/mm]	**20**	**--**	**20**	**20**	**20**	**15**
Withstand voltage	U	[kV]	**30**	**--**	**30**	**30**	**30**	**20**
Permittivity 48-62 Hz	ε_r	[---]	**6 - 7**	**--**	**5 - 6**	**6 - 7**	**6 - 7,5**	**5 - 7**
Loss factor at 20 °C, 48-62 Hz	tan δ_{pf}	[10^{-3}]	**25**	**--**	**25**	**25**	**30**	**10**
Loss factor at 20 °C, 1 MHz	tan δ_{1M}	[10^{-3}]	**12**	**--**	**12**	**12**	**15**	**10**
Specific resistance at 20 °C	$\rho v_{>20}$	[Ωm]	**10^{11}**	**10^{10}**	**10^{11}**	**10^{11}**	**10^{11}**	**10^{11}**
Specific resistance at 600 °C	$\rho v_{>600}$	[Ωm]	**10^{2}**	**10^{2}**	**10^{2}**	**10^{2}**	**10^{2}**	**10^{2}**
Thermal:								
Mean coefficient of linear expansion at 30-600 °C	$\alpha_{30\text{-}600}$	[$10^{-6}K^{-1}$]	**4 - 7**	**4 - 7**	**6 - 8**	**4 - 7**	**5 - 7**	**1 - 3**
Specific heat capacity at 30-600 °C	$C_{p,30\text{-}600}$	[$Jkg^{-1}K^{-1}$]	**750 - 900**	**800 - 900**	**800 - 900**	**750 - 900**	**800 - 900**	**750 - 900**
Thermal conductivity	$\lambda_{30\text{-}100}$	[$Wm^{-1}K^{-1}$]	**1 - 2.5**	**1.0 - 2.5**	**1.4 - 2.5**	**1.2 - 2.6**	**1.5 - 4.0**	**1.0 - 2.5**
Resistance to thermal shock		assessed	**good**	**good**	**good**	**good**	**good**	**good**
Maximum temperature of use	T	[°C]	**--**	**--**	**--**	**--**	**--**	**--**

Table 36: Properties of alkali – alumina silicates (C 100)

10.9.1.2 Magnesium Silicates (C 200)

Identifcation according to DIN EN 60 672			C 210	C 220	C 221	C 230	C 240	C 250
			Steatite for	Steatite	Steatite	Steatite	Forsterite	Forsterite
Mechanical:	**Symbol**	**Unit**	low voltage	standard	low loss	porous	porous	dense
Open porosity		[Vol %]	**0.5**	**0**	**0**	**35**	**30**	**0**
Density, min.	ρ	[g/cm^3]	**2.3**	**2.6**	**2.7**	**1.8**	**1.9**	**2.8**
3-point bending strength	σ_B	[MPa]	**80**	**120**	**140**	**30**	**35**	**140**
Elastic modulus	E	[GPa]	**60**	**80**	**110**	**--**	**--**	**--**
Hardness	HV_{10}	[GPa]	**--**	**--**	**--**	**--**	**--**	**--**
Stress intensity factor	K_{IC}	[MPa $\sqrt{}$m]	**--**	**--**	**--**	**--**	**--**	**--**
Electrical:								
Breakdown strength	E_d	[kV/mm]	**--**	**15**	**20**	**--**	**--**	**20**
Withstand voltage	U	[kV]	**--**	**20**	**30**	**--**	**--**	**20**
Permittivity 48-62 Hz	ε_r	[---]	**6**	**6**	**6**	**--**	**--**	**7**
Loss factor at 20 °C, 48-62 Hz	tan δ_{pf}	[10^{-3}]	**25**	**5**	**1.5**	**--**	**--**	**1.5**
Loss factor at 20 °C, 1 MHz	tan δ_{1M}	[10^{-3}]	**7**	**3**	**1.2**	**--**	**--**	**0.5**
Specific resistance at 20 °C	$\rho_{V>20}$	[Ωm]	**10^{10}**	**10^{11}**	**10^{11}**	**--**	**--**	**10^{11}**
Specific resistance at 600 °C	$\rho_{V>600}$	[Ωm]	**10^{3}**	**10^{3}**	**10^{5}**	**10^{5}**	**10^{5}**	**10^{5}**
Thermal:								
Mean coefficient of linear expansion at 30-600 °C	$\alpha_{30\text{-}600}$	[10^{-6}K^{-1}]	**6 - 8**	**7 - 9**	**7 - 9**	**8 - 10**	**8 - 10**	**9 - 11**
Specific heat capacity at 30-600 °C	$C_{p,30\text{-}600}$	[Jkg^{-1}K^{-1}]	**800 - 900**	**800 - 900**	**800 - 900**	**800 - 900**	**800 - 900**	**800 - 900**
Thermal conductivity	$\lambda_{30\text{-}100}$	[Wm^{-1}K^{-1}]	**1 - 2.5**	**2 - 3**	**2 - 3**	**1.5 - 2**	**1.4 - 2**	**3 - 4**
Resistance to thermal shock		assessed	**good**	**good**	**good**	**good**	**good**	**good**
Maximum temperature of use	T	[°C]	**1000$^{*)}$**	**1200**	**1200**	**1000$^{*)}$**	**1000$^{*)}$**	**1200**

$^{*)}$ According to hardness, which is dependent on the annealing temperature

Table 37: Properties of magnesium silicates (C 200)

10.9.1.3 Titanates (C 300)

Identifcation according to DIN EN 60 672			C 310	C 320	C 330	C 331	C 340	C 350
			Titanium-dioxide	Magnesiumtitanate	Titanium-dioxide	Titanium-dioxid	Bismuth-titanate	Perovskite
Mechanical:	**Symbol**	**Unit**	main constituent		with other oxides	with other oxides	base	medium ε_r
Open porosity		[Vol %]	**0**	**0**	**0**	**0**	**0**	**0**
Density, min.	ρ	[g/cm^3]	**3.5**	**3.1**	**4**	**4.5**	**3**	**4**
3-point bending strength	σ_B	[MPa]	**70**	**70**	**80**	**80**	**70**	**50**
Elastic modulus	E	[GPa]	**--**	**--**	**--**	**--**	**--**	**--**
Hardness	HV_{10}	[GPa]	**--**	**--**	**--**	**--**	**--**	**--**
Stress intensity factor	K_{IC}	[MPa $\sqrt{m}$]	**--**	**--**	**--**	**--**	**--**	**--**
Electrical:								
Breakdown strength	E_d	[kV/mm]	**8**	**8**	**10**	**10**	**6**	**2**
Withstand voltage	U	[kV]	**15**	**15**	**15**	**15**	**8**	**2**
Permittivity 48-62 Hz	ε_r	[---]	**40 - 100**	**12 - 40**	**25 - 50**	**30 - 70**	**100 - 700**	**350 - 3000**
Loss factor at 20 °C, 48-62 Hz	tan δ_{pf}	[10^{-3}]	**6.5**	**2**	**20**	**7**	**--**	**--**
Loss factor at 20 °C, 1 MHz	tan δ_{1M}	[10^{-3}]	**2**	**1.5**	**0.8**	**1**	**5**	**35**
Specific resistance at 20 °C	$\rho v_{>20}$	[Ωm]	**10^{10}**	**10^{9}**	**10^{9}**	**10^{9}**	**10^{9}**	**10^{8}**
Specific resistance at 600 °C	$\rho v_{>600}$	[Ωm]	**--**	**--**	**--**	**--**	**--**	**--**
Thermal:								
Mean coefficient of linear expansion at 30-600 °C	$\alpha_{30\text{-}600}$	[$10^{-6}K^{-1}$]	**6 - 8**	**6 - 10**	**--**	**--**	**--**	**--**
Specific heat capacity at 30-600 °C	$C_{p,30\text{-}600}$	[$Jkg^{-1}K^{-1}$]	**700 - 800**	**900 - 1.000**	**--**	**--**	**--**	**--**
Thermal conductivity	$\lambda_{30\text{-}100}$	[$Wm^{-1}K^{-1}$]	**3 - 4**	**3.5 - 4**	**--**	**--**	**--**	**--**
Resistance to thermal shock		assessed	**--**	**--**	**--**	**--**	**--**	**--**
Maximum temperature of use	T	[°C]	**--**	**--**	**--**	**--**	**--**	**--**

Table 38: Properties of titanates, etc. (C 300)

10.9.1.4 Alkaline Earth – Aluminium Silicates (C 400)

Identifcation according to DIN EN 60 672			C 410	C 420	C 430	C 440
			Cordierite	Celsian	Calcium-based	Zircon-based
Mechanical:	**Symbol**	**Unit**	dense	dense	dense	dense
Open porosity		[Vol %]	**0.5**	**0.5**	**0.5**	**0.5**
Density, min.	ρ	[g/cm^3]	**2.1**	**2.7**	**2.3**	**2.5**
3-point bending strength	σ_B	[MPa]	**60**	**80**	**80**	**100**
Elastic modulus	E	[GPa]	**--**	**--**	**80**	**130**
Hardness	HV_{10}	[GPa]	**--**	**--**	**--**	**--**
Stress intensity factor	K_{IC}	[MPa $\sqrt{m}$]	**--**	**--**	**--**	**--**
Electrical:						
Breakdown strength	E_d	[kV/mm]	**10**	**20**	**15**	**15**
Withstand voltage	U	[kV]	**15**	**30**	**20**	**20**
Permittivity 48-62 Hz	ε_r	[---]	**5**	**7**	**6 - 7**	**8 - 12**
Loss factor at 20 °C, 48-62 Hz	tan δ_{pf}	[10^{-3}]	**25**	**10**	**5**	**5**
Loss factor at 20 °C, 1 MHz	tan δ_{1M}	[10^{-3}]	**7**	**0.5**	**5**	**5**
Specific resistance at 20 °C	$\rho v_{>20}$	[Ωm]	**10^{10}**	**10^{12}**	**10^{11}**	**10^{11}**
Specific resistance at 600 °C	$\rho v_{>600}$	[Ωm]	**10^{3}**	**10^{7}**	**10^{2}**	**10^{2}**
Thermal:						
Mean coefficient of linear expansion at 30-600 °C	$\alpha_{30\text{-}600}$	[10^{-6}K^{-1}]	**2 - 4**	**3.5 - 6**	**--**	**--**
Specific heat capacity at 30-600 °C	$C_{p,30\text{-}600}$	[Jkg^{-1}K^{-1}]	**800 - 1200**	**800 - 1000**	**700 - 850**	**550 - 650**
Thermal conductivity	$\lambda_{30\text{-}100}$	[Wm^{-1}K^{-1}]	**1.2 - 2.5**	**1.2 - 2.5**	**1 - 2.5**	**5 - 8**
Resistance to thermal shock		assessed	**very good**	**good**	**good**	**good**
Maximum temperature of use	T	[°C]	**1200**	**--**	**--**	**--**

Table 39: Properties of alkaline earth - aluminosilicates (C 400)

10.9.1.5 Aluminium and Magnesium Silicates (C 500)

Identifcation according to DIN EN 60 672			**C 510**	**C 511**	**C 512**	**C 520**	**C 530**
Mechanical:	**Symbol**	**Unit**	Alumino-silicate based	Magnesium-Alumino-silicate based	Magnesium-Alumino-silicate based	Cordierite based	Alumino-silicate based
Open porosity		[Vol %]	**30**	**20**	**40**	**20**	**30**
Density, min.	ρ	[g/cm^3]	**1.9**	**1.9**	**1.8**	**1.9**	**2.1**
3-point bending strength	σ_B	[MPa]	**25**	**25**	**15**	**30**	**30**
Elastic modulus	E	[GPa]	**--**	**--**	**--**	**40**	**--**
Hardness	HV_{10}	[GPa]	**--**	**--**	**--**	**--**	**--**
Stress intensity factor	K_{IC}	[MPa $\sqrt{m}$]	**--**	**--**	**--**	**--**	**--**
Electrical:							
Breakdown strength	E_d	[kV/mm]	**--**	**--**	**--**	**--**	**--**
Withstand voltage	U	[kV]	**--**	**--**	**--**	**--**	**--**
Permittivity 48-62 Hz	ε_r	[---]	**--**	**--**	**--**	**--**	**--**
Loss factor at 20 °C, 48-62 Hz	$\tan \delta_{pf}$	[10^{-3}]	**--**	**--**	**--**	**--**	**--**
Loss factor at 20 °C, 1 MHz	$\tan \delta_{1M}$	[10^{-3}]	**--**	**--**	**--**	**--**	**--**
Specific resistance at 20 °C	$\rho v_{>20}$	[Ωm]	**--**	**--**	**--**	**--**	**--**
Specific resistance at 600 °C	$\rho v_{>600}$	[Ωm]	**10^3**	**10^3**	**10^3**	**10^3**	**10^4**
Thermal:							
Mean coefficient of linear expansion at 30-600 °C	α_{30-600}	[10^{-6}K^{-1}]	**3 - 6**	**4 - 6**	**3 - 6**	**2 - 4**	**4 - 6**
Specific heat capacity at 30-600 °C	$C_{p,30-600}$	[Jkg^{-1}K^{-1}]	**750 - 850**	**750 - 850**	**750 - 900**	**750 - 900**	**800 - 900**
Thermal conductivity	λ_{30-100}	[Wm^{-1}K^{-1}]	**1.2 - 1.7**	**1.3 - 1.8**	**1 - 1.5**	**1.3 - 1.8**	**1.4 - 2.0**
Resistance to thermal shock		assessed	**very good**	**very good**	**very good**	**very good**	**very good**
Maximum temperature of use	T	[°C]	**1200**	**1200**	**1200**	**1200**	**1200**

Table 40: Properties of porous aluminium silicates and magnesium silicates (C 500)

10.9.1.6 Mullite (C 600) and Aluminium Oxide (C 700)

Identifcation according to DIN EN 60 672			C 610	C 620	C 780	C 786	C 795	C 799
			Mullite ceramics	Mullite ceramics	Alumina	Alumina	Alumina	Alumina
Mechanical:	Symbol	Unit	50-65 % Al_2O_3	65-80 % Al_2O_3	80-86 % Al_2O_3	86-95 % Al_2O_3	95-99 % Al_2O_3	> 99 % Al_2O_3
Open porosity		[Vol %]	**0**	**0**	**0**	**0**	**0**	**0**
Density, min.	ρ	[g/cm^3]	**2.6**	**2.8**	**3.2**	**3.4**	**3.5**	**3.7**
4-point bending strength	σ_B	[MPa]	**120** *)	**150** *)	**200**	**250**	**280**	**300**
Elastic modulus	E	[GPa]	**100**	**150**	**200**	**220**	**280**	**300**
Hardness	HV_{10}	[GPa]	**--**	**--**	**--**	**--**	**--**	**--**
Stress intensity factor	K_{IC}	[MPa $\sqrt{m}$]	**--**	**--**	**--**	**--**	**--**	**--**
Electrical:								
Breakdown strength	E_d	[kV/mm]	**17**	**15**	**10**	**15**	**15**	**17**
Withstand voltage	U	[kV]	**25**	**20**	**15**	**18**	**18**	**20**
Permittivity 48-62 Hz	ε_r	[---]	**8**	**8**	**8**	**9**	**9**	**9**
Loss factor at 20 °C, 48-62 Hz	tan δ_{pf}	[10^{-3}]	**--**	**--**	**1**	**0.5**	**0.5**	**0.2**
Loss factor at 20 °C, 1 MHz	tan δ_{1M}	[10^{-3}]	**--**	**--**	**1.5**	**1.5**	**1**	**1**
Specific resistance at 20 °C	$\rho_{V>20}$	[Ωm]	**10^{11}**	**10^{11}**	**10^{12}**	**10^{12}**	**10^{12}**	**10^{12}**
Specific resistance at 600 °C	$\rho_{V>600}$	[Ωm]	**10^{4}**	**10^{4}**	**10^{5}**	**10^{6}**	**10^{6}**	**10^{6}**
Thermal:								
Mean coefficient of linear expansion at 30-600 °C	α_{30-600}	[10^{-6}K^{-1}]	**5 - 7**	**5 - 7**	**6 - 8**	**6 - 8**	**6 - 8**	**7 - 8**
Specific heat capacity at 30-600 °C	$C_{p,30-600}$	[Jkg^{-1}K^{-1}]	**850 - 1050**	**850 - 1050**	**850 - 1050**	**850 - 1050**	**850 - 1050**	**850 - 1050**
Thermal conductivity	λ_{30-100}	[Wm^{-1}K^{-1}]	**2 - 6**	**6 - 15**	**10 - 16**	**14 - 24**	**16 - 28**	**19 - 30**
Resistance to thermal shock		assessed	**good**	**good**	**good**	**good**	**good**	**good**
Maximum temperature of use	T	[°C]	**1200**	**1200**	**1200 - 1400**	**1400**	**1400 - 1500**	**1400 - 1700**

*) Value according 3-point bending test

Table 41: Properties of mullite (C 600) and alumina (C 700)

10.9.1.7 Other Oxides (C 800) and Non-Oxides (C 900)

Identifcation according to DIN EN 60 672			**C 810**	**C 820**	**C 910**	**C 920**	**C 930**	**C 935**
			Beryllium oxide	Magnesium oxide	Aluminium nitride	Boron nitride	Silicon nitride	Silicon nitride
Mechanical:	**Symbol**	**Unit**	dense	porous			reaction bonded	dense
Open porosity		[Vol %]	**0**	**30**	**0**	**2**	**40**	**0**
Density, min.	ρ	$[g/cm^3]$	**2.8**	**2.5**	**3**	**2.5**	**1.9**	**3**
4-point bending strength	σ_B	[MPa]	**150**	**$50^{*)}$**	**200**	**20**	**80**	**300**
Elastic modulus	E	[GPa]	**300**	**90**	**300**	**--**	**80**	**250**
Hardness	HV_{10}	[GPa]	**--**	**--**	**--**	**--**	**--**	**--**
Stress intensity factor	K_{IC}	$[\mathrm{MPa}\sqrt{m}]$	**--**	**--**	**--**	**--**	**--**	**--**
Electrical:								
Breakdown strength	E_d	[kV/mm]	**13**	**--**	**20**	**--**	**--**	**20**
Withstand voltage	U	[kV]	**20**	**--**	**30**	**--**	**--**	**30**
Permittivity 48-62 Hz	ε_r	[---]	**7**	**10**	**--**	**--**	**--**	**8 - 12**
Loss factor at 20 °C, 48-62 Hz	$\tan \delta_{pf}$	$[10^{-3}]$	**1**	**--**	**2**	**2**	**2**	**2**
Loss factor at 20 °C, 1 MHz	$\tan \delta_{1M}$	$[10^{-3}]$	**1**	**--**	**2**	**2**	**2**	**2**
Specific resistance at 20 °C	$\rho_{V>20}$	$[\Omega m]$	**10^{12}**	**--**	**10^{12}**	**10^{12}**	**--**	**10^{11}**
Specific resistance at 600 °C	$\rho_{V>600}$	$[\Omega m]$	**10^{7}**	**--**	**10^{6}**	**10^{6}**	**--**	**10^{2}**
Thermal:								
Mean coefficient of linear expansion at 30-600 °C	α_{30-600}	$[10^{-6}K^{-1}]$	**7 - 8.5**	**11 - 13**	**4.5 - 5**	**--**	**2.5 - 3.5**	**2.5 - 3.5**
Specific heat capacity at 30-600 °C	$C_{p,30-600}$	$[Jkg^{-1}K^{-1}]$	**1000 - 1250**	**850 - 1050**	**800 - 900**	**900 - 1050**	**750 - 850**	**750 - 850**
Thermal conductivity	λ_{30-100}	$[Wm^{-1}K^{-1}]$	**150 - 220**	**6 - 10**	**> 100**	**10 - 50**	**5 - 15**	**15 - 45**
Resistance to thermal shock		assessed	**good**	**very good**	**good**	**good**	**good**	**good**
Maximum temperature of use	T	[°C]	**--**	**--**	**--**	**--**	**--**	**--**

$^{*)}$ Value according 3-point bending test

Table 42: Other oxide ceramic materials (C 800) and non-oxide materials (C 900)

10.9.2 Non-classified high-performance materials

10.9.2.1 Oxide Ceramics

			Al_2O_3	Al_2O_3	Al_2O_3	Al_2O_3	ZTA	PSZ
Mechanical:	**Symbol**	**Unit**	Aluminium oxide < 90 %	Aluminium oxide 92-96 %	Aluminium oxide 99 %	Aluminium oxide > 99 %	Aluminium oxide/ZrO_2-toughened	Partially stabilised ZrO_2
Open porosity		[Vol %]	**0**	**0**	**0**	**0**	**0**	**0**
Density, min.	ρ	[g/cm^3]	**> 3.2**	**3.4 - 3.8**	**3.5 - 3.9**	**3.75 - 3.98**	**4.0 - 4.1**	**5 - 6**
4-point bending strength	σ_B	[MPa]	**> 200**	**230 - 400**	**280 - 400**	**300 - 580**	**400 - 480**	**500 - 1000**
Elastic modulus	E	[GPa]	**> 200**	**220 - 340**	**220 - 350**	**300 - 380**	**380**	**200 - 210**
Hardness	HV_{10}	[GPa]	**12 - 15**	**12 - 15**	**12 - 20**	**17 - 23**	**16 - 17**	**11 - 12.5**
Stress intensity factor	K_{IC}	[MPa $\sqrt{m}$]	**3.5 - 4.5**	**4 - 4.2**	**4 - 4.2**	**4 - 5.5**	**4.4 - 5**	**5.8 - 10.5**
Weibull modulus	m	[---]	**10 - 15**	**10 - 15**	**10 - 15**	**10 - 15**	**10 - 15**	**20 - 25**
Electrical:								
Breakdown strength	E_d	[kV/mm]	**10**	**15**	**15**	**17**	**--**	**--**
Withstand voltage	U	[kV]	**15**	**18**	**18**	**20**	**--**	**--**
Permittivity 48-62 Hz	ε_r	[---]	**9**	**9**	**9**	**9**	**--**	**22**
Loss factor at 20 °C, 48-62 Hz	$\tan \delta_{pf}$	[10^{-3}]	**0.5 - 1.0**	**0.3 - 0.5**	**0.2 - 0.5**	**0.2 - 0.5**	**--**	**--**
Loss factor at 20 °C, 1 MHz	$\tan \delta_{1M}$	[10^{-3}]	**1**	**1**	**1**	**1**	**--**	**--**
Specific resistance at 20 °C	$\rho v_{>20}$	[Ωm]	**10^{12} - 10^{13}**	**10^{12} - 10^{14}**	**10^{12} - 10^{15}**	**10^{12} - 10^{15}**	**10^{14}**	**10^{8} - 10^{13}**
Specific resistance at 600 °C	$\rho v_{>600}$	[Ωm]	**10^{6}**	**10^{6}**	**10^{6}**	**10^{6}**	**10^{6}**	**10^{3} - 10^{6}**
Thermal:								
Mean coefficient of linear expansion at 30-1000 °C	$\alpha_{30-1000}$	[10^{-6}K^{-1}]	**6 - 8**	**6 - 8**	**6 - 8**	**7 - 8**	**9 - 11**	**10 - 12.5**
Specific heat capacity at 30-1000 °C	$C_{p,30-1000}$	[Jkg^{-1}K^{-1}]	**850 - 1050**	**850 - 1050**	**850 - 1050**	**850 - 1050**	**800**	**400 - 550**
Thermal conductivity	λ_{30-100}	[Wm^{-1}K^{-1}]	**10 - 16**	**14 - 24**	**16 - 28**	**19 - 30**	**15**	**1.5 - 3**
Resistance to thermal shock		assessed	**gut**	**gut**	**gut**	**gut**	**gut**	**gut**
Maximum temperature of use	T	[°C]	**1200 - 1400**	**1400 - 1500**	**1400 - 1500**	**1400 - 1700**	**1500**	**800 - 1600**

Table 43: Properties of oxide ceramics

10.9.2.2 Carbides

			LPSIC	SSIC	SISIC	RSIC	NSIC
Mechanical:	**Symbol**	**Unit**	Liquid-phase sintered silicon carbide	Sintered silicon carbide	Silicon-infiltrated silicon carbide	Re-crystallised silicon carbide	Nitride bonded silicon carbide
Open porosity		[Vol %]	**< 1**	**0**	**0**	**10 - 15**	**10 - 15**
Density, min.	ρ	[g/cm^3]	**3.20 - 3.24**	**3.08 - 3.15**	**3.05 - 3.12**	**2.6 - 2.8**	**2.7 - 2.82**
4-point bending strength	σ_B	[MPa]	**600**	**260 - 500**	**180 - 450**	**80 - 120**	**180 - 200**
Elastic modulus	E	[GPa]	**420**	**350 - 450**	**270 - 400**	**230 - 280**	**150 - 240**
Hardness	HV_{10}	[GPa]	**22**	**23 - 26**	**14 - 25*)**	**25**	**--**
Stress intensity factor	K_{IC}	[MPa √m]	**6.0**	**3.0 - 4.8**	**3 - 5**	**3 - 4**	**--**
Weibull modulus	m	[---]	**10 - 15**	**9 - 19**	**14 - 16**	**10 - 12**	**10 - 12**

Electrical:

Specific resistance at 20 °C	$\rho v_{>20}$	[Ωm]	**$10^3 - 10^4$**	**$10^3 - 10^4$**	**$10^1 - 10^3$**	**--**	**--**
Specific resistance at 600 °C	$\rho v_{>600}$	[Ωm]	**10^1**	**10^1**	**5**	**--**	**--**

Thermal:

Mean coefficient of linear expansion at 30-1000 °C	$\alpha_{30-1000}$	[$10^{-6}K^{-1}$]	**4.1**	**4.0 - 4.8**	**4.0 - 4.8**	**4.7 - 4.8**	**4.5**
Specific heat capacity at 30-1000 °C	$C_{p,30-1000}$	[$Jkg^{-1}K^{-1}$]	**600**	**600 - 1000**	**650 - 1300**	**600 - 900**	**800 - 900**
Thermal conductivity	λ_{30-100}	[$Wm^{-1}K^{-1}$]	**100**	**40 - 120**	**100 - 160**	**18 - 20**	**14 - 15**
Resistance to thermal shock		assessed	**good**	**good**	**very good**	**very good**	**very good**
Maximum temperature of use	T	[°C]	**1200 - 1400**	**1400 - 1750**	**1380**	**1600**	**1450**

Table 44: Properties of carbides

10.9.2.3 Nitrides

			SSN	HIPSN	RBSN	BN	AIN
Mechanical:	**Symbol**	**Unit**	Sintered silicon nitride	Hot isostatic pressed silicon nitride	Reaction bonded silicon nitride	Boron nitride	Aluminium nitride
Open porosity		[Vol %]	**--**	**0**	**--**	**0**	**0**
Density, min.	ρ	[g/cm^3]	**3.2 - 3.3**	**3.2 - 3.3**	**1.9 - 2.5**	**2.0 - 2.1**	**3.0 - 3.3**
4-point bending strength	σ_B	[MPa]	**700 - 1000**	**800 - 1100**	**200 - 330**	**--**	**200 - 360**
Elastic modulus	E	[GPa]	**290 - 330**	**290 - 330**	**80 - 180**	**--**	**320**
Hardness	HV_{10}	[GPa]	**14 - 16**	**15 - 17**	**8 - 10**	**--**	**11**
Stress intensity factor	K_{IC}	[MPa $\sqrt{m}$]	**5 - 8.5**	**8.5**	**1.8 - 4.0**	**--**	**3.0 - 3.5**
Weibull modulus	m	[---]	**10 - 15**	**12 - 20**	**14 - 16**	**10 - 12**	**10 - 12**
Electrical:							
Breakdown strength	E_d	[kV/mm]	**20**	**20**	**--**	**7**	**> 20**
Withstand voltage	U	[kV]	**--**	**--**	**--**	**--**	**--**
Permittivity 48-62 Hz	ε_r	[---]	**8 - 12**	**8 - 12**	**--**	**--**	**8.6**
Loss factor at 20 °C, 48-62 Hz	tan δ_{pf}	[10^{-3}]	**2**	**2**	**2**	**2**	**--**
Loss factor at 20 °C, 1 MHz	tan δ_{1M}	[10^{-3}]	**2**	**2**	**2**	**2**	**0.4 - 0.5**
Specific resistance at 20 °C	$\rho v_{>20}$	[Ωm]	**10^{11} - 10^{12}**	**10^{13}**	**10^{13}**	**--**	**10^{13} - 10^{14}**
Specific resistance at 600 °C	$\rho v_{>600}$	[Ωm]	**10^{9}**	**10^{9}**	**10^{10}**	**--**	**10^{12}**
Thermal:							
Mean coefficient of linear expansion at 30-1000 °C	$\alpha_{30-1000}$	[$10^{-6}K^{-1}$]	**2.5 - 3.5**	**3.1 - 3.3**	**2.1 - 3**	**2.2 - 4.4**	**4.5 - 5.6**
Specific heat capacity at 30-1000 °C	$C_{p,30-1000}$	[$Jkg^{-1}K^{-1}$]	**700 - 850**	**700 - 850**	**700 - 850**	**--**	**700 - 760**
Thermal conductivity	λ_{30-100}	[$Wm^{-1}K^{-1}$]	**15 - 40**	**15 - 50**	**4 - 15**	**< 1**	**180 - 220**
Resistance to thermal shock		assessed	**very good**	**very good**	**very good**	**very good**	**very good**
Maximum temperature of use	T	[°C]	**1300**	**1400**	**1400**	**800 - 1000**	**1000**

Table 45: Properties of nitrides

10.9.2.4 Other Materials

			ATI	MGO	MGO	SiO2	BC
Mechanical:	**Symbol**	**Unit**	Aluminium-titanate	Magnesium oxide, dense	Magnesium oxide > 90 %	Silicon dioxide (Silica)	Boron carbide
Open porosity		[Vol %]	**10 - 16**	**0**	**25 - 45**	**7**	**0**
Density, min.	ρ	[g/cm^3]	**3.0 - 3.7**	**3.4**	**2.0 - 2.7**	**1.9 - 2.0**	**2.5**
4-point bending strength	σ_B	[MPa]	**15 - 100**	**165**	**8 - 50**	**30 - 40**	**400**
Elastic modulus	E	[GPa]	**10 - 50**	**250**	**90**	**30 - 40**	**390 - 440**
Hardness	HV_{10}	[GPa]	**5**	**--**	**--**	**--**	**30 - 40**
Stress intensity factor	K_{IC}	[MPa √m]	**3 - 5**	**--**	**--**	**--**	**3.2 - 3.6**
Weibull modulus	m	[---]	**10 - 12**	**10 - 12**	**10 - 12**	**10 - 12**	**10 - 15**
Electrical:							
Breakdown strength	E_d	[kV/mm]	**--**	**--**	**--**	**--**	**--**
Withstand voltage	U	[kV]	**--**	**--**	**--**	**--**	**--**
Permittivity 48-62 Hz	ε_r	[---]	**--**	**10**	**10**	**--**	**--**
Loss factor at 20 °C, 48-62 Hz	$\tan \delta_{pf}$	[10^{-3}]	**--**	**--**	**--**	**--**	**--**
Loss factor at 20 °C, 1 MHz	$\tan \delta_{1M}$	[10^{-3}]	**--**	**--**	**--**	**--**	**--**
Specific resistance at 20 °C	$\rho v_{>20}$	[Ωm]	**10^{14}**	**10^{14}**	**10^{14}**	**--**	**--**
Specific resistance at 600 °C	$\rho v_{>600}$	[Ωm]	**10^{9}**	**10^{9}**	**10^{9}**	**--**	**--**
Thermal:							
Mean coefficient of linear expansion at 30-1000 °C	$\alpha_{30\text{-}1000}$	[$10^{-6}K^{-1}$]	**0.5 - 2**	**13.5**	**12 - 13**	**0.5 - 0.9**	**6**
Specific heat capacity at 30-1000 °C	$C_{p,30\text{-}1000}$	[$Jkg^{-1}K^{-1}$]	**800**	**850 - 1050**	**850 - 1050**	**--**	**--**
Thermal conductivity	$\lambda_{30\text{-}100}$	[$Wm^{-1}K^{-1}$]	**1.5 - 3.0**	**7 - 11**	**6 - 10**	**--**	**28**
Resistance to thermal shock		assessed	**extremely good**	**good**	**very good**	**very good**	**--**
Maximum temperature of use	T	[°C]	**900 - 1.600**	**--**	**--**	**1.000**	**700 - 1.000**

Table 46: Properties of other materials

10.9.3 Summary of Chemical Resistance

Table 47 compares the corrosion resistance of ceramic materials. The corrosion resistance of SISIC, SSIC and aluminium oxide to a large number of reagents is illustrated in Table 48.

	Oxides		Carbides		Nitrides		Silicates		
	Al_2O_3	ZrO_2	SSIC	SISIC	SSN	HPSN	Stoneware	Hard porcelain	Steatite
Hydrochloric acid HCl (dilute)	+ (*)	-	+	+ (100 °C)	+ (*)		+ (*)	+ (*)	+ (*)
Hydrochloric acid HCl (conc.)	+ (*)	o	+ (*)	+	-	+	+ (*)	+ (*)	+ (*)
Nitric acid HNO_3 (diluted)	+		+ (*)	+ (*)	+ (*)	+	+ (*)	+ (*)	+ (*)
Nitric acid HNO_3 (conc.)	+ (*)	o	+ (*)	+ (*)			+	+	+
Sulphuric acid H_2SO_4 (diluted)	+			+ (100 °C)	+		+ (*)	+ (*)	+ (*)
Sulphuric acid H_2SO_4 (conc.)	+ (*)	- (*)	+	+			+ (*)	+ (*)	+ (*)
Phosphoric acid H_3PO_4	+ (20 °C)	o (*)	- (250 °C)	+	o	+	80 % H_3PO_4 + (*)	80 % H_3PO_4 + (*)	80 % H_3PO_4 + (*)
Hydrofluoric acid HF	-	- (20 °C)	+	+	-	-	-	-	-
Sodium hydroxide NaOH solution	o (*)		+	o (100 °C)	+	+	- (*)	- (*)	- (*)
Caustic potash solution KOH solution	+ (*)	+ (*)	+ (*)	o (80 °C)	+ (*)	+			
Sodium chloride NaCl	+ (*)			+ (900 °C in air)			+ (*)	+ (*)	+ (*)
Potassium chloride KCl	+			+ (900 °C in air)			+		
Copper chloride $CuCl_2$	(*)						+	+	+

Key:

\+ resistant (up to the indicated temperature)
\- corrosive attack (at indicated temperature)
(*) boiling
o a reaction takes place

Table 47: Comparison of corrosion resistance of ceramic materials

Corrosion resistance of SISIC, SSIC and aluminium oxide

Material			SISIC		SSIC		Al_2O_3 (99,7 %)	
Reagent	**Formula**	**Concentration**	**RT**	**50°C**	**RT**	**50°C**	**RT**	**50°C**
4-chlortoluene	$C_6H_4ClCH_3$	concentrated	++	++	++	++	y)	y)
Acetone	CH_3COCH_3	concentrated	++	++	++	++	y)	y)
Acetyl chloride	CH_3COCl	concentrated	++	++	++	++	y)	y)
Aluminium chloride	$AlCl_3$	10 %	++	++	++	++	++	++
Ammonia	NH_4OH	concentrated (25%)	++	+	++	++	++	++
Ammonium chloride	NH_4Cl	25 %	++	++	++	++	++	++
Ammonium fluoride	NH_4F	20 %	+	-	++	++	++	++
Ammonium nitrate	NH_4NO_3	50 %	++	++	++	++	++	++
Aniline	$C_6H_5NH_2$	concentrated	++	++	++	++	y)	y)
Benzene	C_6H_6	concentrated	++	++	++	++	y)	y)
Benzoic acid	C_6H_5COOH	alkali solution	++	++	++	++	y)	y)
Boric acid	H_3BO_3	cold saturated solution	++	++	++	++	++	++
Calcium oxide	CaO	cold saturated solution	++	++	++	++	y)	y)
Carbon tetrachloride	CCl_4	concentrated	++	++	++	++	y)	y)
Caustic potash solution	KOH	30 %	-	-	++	++	y)	y)
Caustic potash solution	KOH	20 %	+	o	++	o	y)	y)
Chromic-sulphuric acid mixture	H_2SO_4-CrO_3	concentrated	++	++	++	++	y)	y)
Citric acid	$C_6H_8O_7$	50 %	++	++	++	++	y)	y)
Copper-II chloride	$CuCl_2$	40 %	++	++	++	++	++	++
Copper-II sulphate	$CuSO_4$	25 %	++	++	++	++	++	++
Dioxan	$(CH_2)_4O_2$	concentrated	++	++	++	++	y)	y)
Ethanol	C_2H_5OH	concentrated	++	++	++	++	y)	y)
Ethyl acetate	$CH_3COOC_2H_5$	concentrated	++	++	++	++	y)	y)
Formic acid	$HCOOH$	concentrated	++	++	++	++	y)	y)
Fuming sulphuric acid	$H_2SO_4+SO_3$	30 % free SO	++	++	++	++	y)	y)
Glacial acetic acid	CH_3COOH	concentrated	++	++	++	++	y)	y)
Glycerine	$C_3H_8O_3$	concentrated	++	++	++	++	y)	y)
Hexafluorosilicic acid	H_2SiF_6	concentrated	++	++	++	++	y)	y)
Hydrochloric acid	HCl	concentrated, 36 %	++	++	++	++	++	++
Hydrofluoric acid	HF	concentrated, 40 %	+	-	++	++	++	-
Hydrofluoric acid nitric acid	HF-HNO_3	concentrated, 3:1	-	-	++	+	y)	y)

Material			SISIC		SSIC		Al_2O_3 (99,7 %)	
Reagent	**Formula**	**Concentration**	**RT**	**50°C**	**RT**	**50°C**	**RT**	**50°C**
Hydrogen bromide	Br	cold saturated solution	++	++	++	++	++	y)
Hydrogen peroxide	H_2O_2	30 %	++	++	++	++	y)	y)
Iron II sulphate	$FeSO_4$	25 %	++	++	++	++	++	++
Iron-III chloride	$FeCl_3$	45 %	++	++	++	++	++	++
Lithium hydroxide	$LiOH$	10 %	++	+	++	++	y)	y)
Magnesium sulphate	$MgSO_4$	4 %	++	++	++	++	++	++
Methanol	CH_3OH	concentrated	++	++	++	++	y)	y)
Mercury nitrate	$Hg(NO_3)_2$	10 %	++	++	++	++	y)	y)
Nitric acid	HNO_3	concentrated, 65 %	++	++	++	++	++	+
Nitrohydrochloric acid	$HCl-HNO_3$	concentrated, 3:1	++	++	++	++	++	-
Nitrosulphuric acid	$H_2SO_4+HNO_3$	concentrated, 1:1	++	++	++	++	y)	y)
Oleic acid	$C_{17}H_{33}COOH$	concentrated	++	++	++	++	y)	y)
Oxalic acid	$(COOH)_2$	cold saturated solution	++	++	++	++	y)	y)
Phosphoric acid	H_3PO_4	concentrated, 85 %	++	++	++	++	++	-
Phthalic acid	$C_6H_4(COOH)_2$	alkali solution	++	++	++	++	y)	y)
Potassium chloride	KCl	cold saturated solution	++	++	++	++	++	++
Potassium chromate	K_2CrO_4	35 %	++	++	++	++	y)	y)
Potassium nitrate	KNO_3	20 %	++	++	++	++	++	++
Potassium permanganate	$KMnO_4$	5 %	++	++	++	++	++	++
Propanoic acid	$C_2H_5(COOH)$	concentrated	++	++	++	++	y)	y)
Salicylic aldehyde	$C_7H_6O_2$	concentrated	++	++	++	++	y)	y)
Silver nitrate	$AgNO_3$	10 %	++	++	++	++	y)	y)
Sodium carbonate	Na_2CO_3	15 %	++	++	++	++	y)	y)
Sodium chloride	$NaCl$	cold saturated solution	++	++	++	++	++	++
Sodium fluoride	NaF	4 %	++	+	++	++	y)	y)
Sodium hydroxide	$NaOH$	10 %	+	-	++	++	++	+
Sodium hydroxide	$NaOH$	30 %	-	o	++	o	++	+
Sodium hypochloride	$NaClO$	12.5 % free Cl	++	++	++	++	++	y)
Sodium metaborate	$NaBO_2$	20 %	++	++	++	++	y)	y)
Sodium peroxide	Na_2O_2	10 %	++	++	++	++	++	++
Sodium sulphide	Na_2S	50 %	++	++	++	++	++	++
Sodium thiosulphate	$Na_2S_2O_3$	40 %	++	++	++	++	++	++
Sulphuric acid	H_2SO_4	50 %	++	++	++	++	++	++

Material			SISIC		SSIC		Al_2O_3 (99,7 %)	
Reagent	**Formula**	**Concentration**	**RT**	**50°C**	**RT**	**50°C**	**RT**	**50°C**
Sulphuric acid	H_2SO_4	concentrated, 98 %	++	++	++	++	++	+
Sulphurous acid	H_2SO_3	5-6 % free SO	++	++	++	++	y)	y)
Tartaric acid	$C_4H_6O_6$	10 %	++	++	++	++	y)	y)
Tetrachloroethylene	C_2Cl_4	concentrated	++	++	++	++	y)	y)
Tetrafluoroboric acid	HBF_4	concentrated	+	+	++	++	y)	y)
Tri-sodium phosphate and	Na_3PO_4	10 %	++	++	++	++	y)	y)
Zinc chloride	$ZnCl_2$	60 %	++	++	++	++	++	++
Urea	H_2NCONH_2	cold saturated solution	++	++	++	++	y)	y)

++ resistant
+ some resistance
- not resistant
o boiling solution
y) no value available

Table 48: Corrosion resistance of SISIC, SSIC and aluminium oxide

Classifications made in Table 48 may vary due to differences in the microstructure and in the chemical composition. It is therefore advisable to request information from the manufacturers.

11 Bibliography

Bunk W.; Hansen J.; Geyer M.: Tribologie: Reibung – Verschleiß – Schmierung, Springer-Verlag, Berlin 1981

Czichos, H.; Habig, K.-H: Tribologie-Handbuch, Reibung und Verschleiß, Systemanalyse, Prüftechnik, Werkstoffe und Konstruktionselemente, Vieweg-Verlag, Braunschweig 1992

Fanzott, S. M.: Technische Keramik. Rohstoffe, Eigenschaften und Einsatzgebiete, Verlag Moderne Industrie, Landsberg/Lech 1987

Gläser, H.; Lori, W.; Schröpel, H.: Keramikgerechtes Konstruieren, Hoppenstedt Technik Tabellen Verlag, Darmstadt 1992

Hecht, A.: Elektrokeramik, Springer-Verlag, Berlin 1976

Höhne, L.: Honen technischer Keramik, Vulkan-Verlag, Essen 1999, zugl. Dissertation, TU Braunschweig 1998

Kriegesmann, J.: Technische keramische Werkstoffe, Blättersammlung, Deutscher Wirtschaftsdienst, Köln 1989–2003

Liebermann J.: Hydrophobes Oberflächenverhalten verbessert das elektrische Fremdschichtverhalten von Porzellanisolatoren und erlaubt vereinfachte Bauformen, in: Keramische Zeitschrift, 54 (2002), S. 554–559

Liebermann J.: Neue Entwicklungsvarianten hochwertiger kostengünstiger Hochspannungsisolationsporzellane, Dissertation, TU Bergakademie Freiberg, Freiberg 2000,

Pigores, O.: Werkstoffe in der Tribotechnik: Reibung, Schmierung und Verschleißbeständigkeit von Werkstoffen und Bauteilen. Dt. Verlag für Grundstoffindustrie, Stuttgart 1992

Salmang, H., Scholze, H.: Keramik, Teil 1: Allgemeine Grundlagen und wichtige Eigenschaften, Springer-Verlag, Berlin 1982

Salmang, H., Scholze, H.: Keramik, Teil 2: Keramische Werkstoffe, Springer-Verlag, Berlin 1982

Schneider, J: Schneidkeramik. Anwendungsgebiete und Einsatzmöglichkeiten, Verlag Moderne Industrie, Landsberg/Lech 1996

Telle, R.; Quirmbach, T.: Korrosion und Verschleiß von Keramischen Werkstoffen, Deutsche Keramische Gesellschaft e.V., Köln 1994

Tietz, H.: Technische Keramik, VDI Verlag, Düsseldorf 1994

Verband der Keramischen Industrie e.V.: Daten und Eigenschaften keramischer Werkstoffe, Selbstverlag, Selb 1997

Verband der Keramischen Industrie e.V.: Keramische Werkstoffe für die Elektrotechnik, Selbstverlag, Selb 1996

Verband der Keramischen Industrie e.V.: Keramische Werkstoffe für die Elektronik, Selbstverlag, Selb 1996

Verband der Keramischen Industrie e.V.: Keramische Werkstoffe für den Maschinenbau und die Verfahrenstechnik, Selbstverlag, Selb 1996

Verband der Keramischen Industrie e.V.: Keramische Werkstoffe für die Hochtemperaturtechnik, Selbstverlag, Selb 1996

Verein Deutscher Ingenieure: Konstruieren mit Keramik (VDI Bericht 1036), VDI Verlag, Düsseldorf 1993

Weigmann, U.-P.: Honen keramischer Werkstoffe. Berichte aus dem Produktionstechnischen Zentrum Berlin, Dissertation, TU Berlin, Berlin 1997

Willmann, G.: Biokeramik in der Orthopädie – Was haben wir aus 25 Jahren gelernt?, in: Med. Orth. Tech., 120 (2000), S.10–6

Wimmer, J.: Konditionieren hochharter Schleifscheiben zum Schleifen von Hochleistungskeramik, Dissertation, Universität Kaiserslautern, Kaiserslautern 1995

Woydt, M.: Beschaffung innovativer Werkstoffe, in Tribologie + Schmierungstechnik, 45 (1998), 37–41.

Woydt, M.: Werkstoffkonzept für den Trockenlauf, in: Tribologie + Schmierungstechnik, 44 (1997), 14–19.

Zum Gahr, K.-H.: Grundlagen des Verschleißes, (VDI Bericht Nr. 600.3), VDI Verlag, Düsseldorf 1987, S. 29–59.

Zum Gahr, K.-H.: Tribologie: Reibung – Verschleiß – Schmierung, in: Naturwissenschaften, 72 (1985),S. 260–267.

12 Register