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INTRODUKTION TO CERAMICS

High purity technical ceramics have unique properties. Advanced methods for analysing the strength of the material in combination with known thumb rules in designing help us make the most out of the material.

The use of ceramic components increases every year due to the outstanding properties of the material. These properties provide extended lifetime and added value to the final product.

Ceramics are an important alternative to plastics and metals. The increasing range of ceramic materials will however never replace metal, nevertheless they are important complements to the supply of today’s materials and have a good potential for the future.

When choosing a material for mechanical engineering the choice more frequently fall on ceramics. For optimal problem solving all physical data of the material must be interpreted properly for the various components. The technique of joining ceramic to metal for different applications requires high standards on the design. Therefore, it is important to consider the coefficient of thermal expansion for the different materials, as well as the hardness of the ceramic in relation to its brittleness.

Definition

The common definition of ceramics is: Ceramic materials are inorganic, non metallic, water insoluble and consists of at least 30 % crystalline. It is shaped in room temperature from raw material powder and obtains its typical properties by temperature treatment, most often above 800 °C.

Product- and material groups

Classification in product groups can be done according to the following: porous ceramics, refractory ceramics, chemical ceramics, mechanical ceramics, nuclear ceramics, electro ceramics, opto ceramics, bio ceramics and magnetic ceramics. You can also distinguish “active” ceramics from “passive” ceramics within the different groups, but there are further ways to subdivide ceramics, e.g. according to material groups:

- Silicate ceramics
- Refractory ceramics
- Oxide ceramics
- Non oxide ceramics
- Electro ceramics
- Magnetic ceramics
- Glass ceramics and special ceramic materials
- Exotic ceramics (mixed ceramics)

Today, 80 % of all machined high purity ceramics are used as electro ceramics, produced of the most frequently used material aluminium oxide. In this wide range of ceramic materials it is important to look into the areas that are still relatively small but technically very interesting within the engineering ceramics. This is one of the areas where we find the future growth potential.

Technical ceramics can be divided into three subgroups: oxide ceramics, stabilized ceramics and non oxide ceramics. This is only a general grouping, since even the slightest amount of additives affects the properties positively or negatively.
APPLICATION AND REQUIREMENTS GOVERN CHOICE OF MATERIAL

Prerequisites
Users and producers of ceramics must carefully consider the area of application as well as what the product is expected to withstand, and based on that choose the most suitable material.

It may take several years from starting up a project, via prototypes and tests, to serial production. When developing new designs “trial and error” is often applied and the design will generally be empirically optimised.

It is still rather cumbersome and expensive to use the FEM-method for analysing the construction. The choice of a suitable material is based on the system solution considering relevant design criteria of the material. In addition to the material properties, it is important to understand the production process to be able to consider economical manufacturing techniques and production steps already at the construction stage. This will help avoid complicated operations and reduce costs already from the beginning.
This production scheme shows the core of the process for the most common ceramic materials; aluminium oxide, zirconium oxide, silicon carbide and mix ceramics.

**THE PRODUCTION PROCESS**

- **Powder Preparation**
- **Laboratory Control**
- **Shaping**
  - Extrusion • Isostatic pressing
  - Injection moulding • Automatic pressing
- **Green Machining**
  - Cutting • Turning • Milling • Drilling
- **Sintering**
  - Presintering • Sintering • Annealing
- **Inspection**
  - Crack detection (Colour penetration test)
- **Hard Machining**
  - Grinding • Polishing • Drilling • Tumbling
- **Final inspection**
  - Crack-, dimensional and visual control
- **Joining techniques**
  - Soldering • Welding • Gluing • Shrinking in
- **Final inspection and control**
  - Ceramic to metal parts
- **Finished product**
- **Delivery**
POWDER PREPARATION AND SHAPING

Powder preparation
The heart of every ceramic production lies within the powder preparation. The purchased powder has to be prepared to a specific composition, grain size and shape. During the preparation, additives are added to achieve a powder adapted for the specific forming, machining and sintering process. These additives and aids burn out completely during sintering. The powder is spray dried to achieve a granulate which is possible to press.

The heart of all ceramic production is the powder preparation
To secure the quality it is important to characterise the basic material very carefully, since a mistake in this early stage can have a huge impact on, and even spoil, the finished product.

Shaping
The prepared granulate is formed under high pressure to compact parts. The most common methods for shaping ceramics are automatic pressing (dry pressing), isostatic pressing, extruding, and injection moulding. The choice of method depends on the size and geometry of the part as well as the required quantity since all methods are not suitable for all technical ceramic components.
The most common shaping methods

Automatic pressing (Dry pressing)
Double sided pressing (tablet pressing) is mainly used where an upper punch and a bottom punch compress the granulate in a die forming a “green body” (= detail before sintering). Undercut is, as with injection moulding, not possible to press. However it is possible to produce holes (round, oval, square etc.) and steps in axial direction. The pressing tools, made of hard metal, are relatively expensive and pay off only at larger quantities. Since the tools have limited compressing force, the largest surface possible to produce is approximately 80 mm² and heights up to 50 mm. Geometrically the parts become very consistent and will usually be sintered without further machining.

Isostatic pressing
Isostatic pressing is a compaction from all sides in an elastic, often rubber, mould with high hydraulic pressure up to 4 000 bar. The outer profile, shaped by the mould, is not very precise and has to be machined before sintering. The moulds are relatively cheap but the pressing cycle takes a long time, consisting of three steps: raising pressure, keeping pressure and reducing pressure. This method is used for smaller series or larger dimensions. The machining required after isostatic pressing is, compared to automatic pressing, considerably more complicated.

Extruding
A plastic workable ceramic dough is prepared and pressed by a piston pump through a nozzle, thus creating tubes, rods and similar parts in lengths up to 2 meters, with diameters up to 20 mm. Parts for high temperature applications like protection tubes, multi bore tubes for thermo couples etc. do not normally need any further machining. For mechanical parts the final shapes and tolerances are reached by cutting and grinding.

Injection moulding
This way of producing is in many ways similar to injection moulding of plastics. After moulding the additives are removed chemically or with thermal treatment whereby the remaining material is sintered to a dense ceramic part. Hard machining is normally not required.

Casting
The ceramic powder is suspended in water and poured into a gypsum mould. The gypsum absorbs the water and the remaining powder forms the part.
GREEN MACHINING ALLOWS COMPLICATED GEOMETRIES

Green Machining
The dry- and isostatic pressed parts have chalk-like characteristics and can be green machined through grinding, cutting, drilling, milling and turning. The machining methods, borrowed from the metal industry, allow producing complicated details. At this stage only rough tolerances can be achieved but it is rather easy, fast and cost effective to machine.

Sintering
Sintering is a densification of a green body to a compact ceramic part through thermal treatment below the melting point of the powder. High purity and polycrystalline ceramic materials have no binding phase. These materials are sintered at temperatures around 1 800 °C which makes them shrink up to 50 % in volume. During sintering the ceramic material obtains all desirable properties for technical usage.

Through these described methods of shaping, tolerances within the area of ± 1 % from nominal measurements (dimension < 10 mm minimum tolerance ± 0.1 mm) can be reached. To avoid costly machining of defect parts a crack control test is performed on all details after sintering.

Summary: Narrow tolerances should only be used where absolutely necessary for the function. On flat and cylindrical surfaces, the surface quality can be significantly improved with lapping and honing, as well as polishing to reasonable costs.

During sintering the ceramic material obtains the desirable strength properties.

Hard Machining
For the areas of applications where the tolerances achieved “as fired” (not machined after sintering) are not good enough, a hard machining will give the required tolerances and surface finish. The machining is made with diamond tools, -emulsions and -pastes.

By hard machining it is today possible to manufacture according to ISO-tolerances in quality T7 (holes) or t6 (shafts). More precise tolerances can be achieved with additional work at a higher cost. Always consider the use of high surface quality and narrow tolerances and only use where absolutely necessary for the function. It is, for example, possible to fit a shaft into a hole with less than 5 μm clearance. However, we should mention that the better tolerances require longer time for production,
Each individual design has to be examined to determine what is required from the part based on the conditions of the application. The best suitable ceramic material will be chosen and the design has to be optimised to the chosen material. Ceramics have many beneficial properties that give high security, high reliability and long lifetime to the designed part, due to:

- Excellent hardness and wear resistance
- Excellent corrosion resistance
- High mechanical strength
- High pressure and bending strength
- Excellent chemical resistance
- Superior high temperature properties
- Electrical insulation
- Low coefficient of expansion
- Low specific weight
- Superior surface quality
MATERIAL PROPERTIES

The price for ceramics is normally higher than for other materials because of higher raw material costs and a more advanced and expensive production. This is compensated by an extended lifetime and the unique properties of the ceramic material. One example is ceramic slide bearings where low friction, high corrosion resistance and high wear resistance is required. Cheap materials with good sliding properties are available as well as cheap materials with good corrosion resistance, but there are few alternatives where several properties are combined in the same material.

The most important physical data for some typical ceramic materials, compared to steel and porcelain, is shown in diagram 1–6. The shown materials are:

- F99.7: 99.7 % alumina
- FZT: 90 % alumina + 10 % zirconia
- FZM: PSZ zirconia, partly stabilized
- FZM/K: TZP zirconia, partly stabilized
- SiC 198D: silicon carbide SsIC
- HP 79: silicon nitride, hot pressed
Temperature, density, pressure and bending strength, hardness, and thermal conductivity

Operating temperature range
Diagram 1
Ceramic materials have superior temperature properties. They keep all their unique properties within a large temperature range, for most of them from -273 °C to well above 1 200 °C.

Density
Diagram 2
Because of the low specific weight, ceramics can be considered a “light weight” material in the metallic comparison scale. Aluminium oxide has for example a specific weight of 3.9 gr/cm³ only half of the value for steel and less than 25 of the density of hard metal.

A lower density gives a faster reaction in, for example, hydraulic systems. In check valves opening- and closing times are shortened as the ceramic balls have less weight and will respond faster. For ceramic pistons and plungers less mass has to accelerate and decelerate compared to metal and therefore the force for mechanical operation can be reduced and energy is saved.

Valves of silicon nitride are used in today’s vehicle engines, which make the reaction time for the valves much faster due to the lower weight. This provides a more exact control and fuel savings.

Pressure- and bending strength
Diagram 3 and 4
Ceramic materials have an extremely high compression strength and, for a brittle material, a relatively good bending strength. These properties are valid at temperatures well above 1 000 °C. The high compression strength is especially useful in ceramic-to-metal components.

The compressive strength almost equals the bending strength of most metallic materials. This is not the case with ceramic materials. The bending strength of brittle materials is approximately a fifth to a tenth of the compression strength. When designing you have to take this into consideration. An important measurement for evaluating the properties of brittle materials is the fracture toughness, which shows values of the stress intensity factor.

In literature you divide materials into classes according to decreasing brittleness:

The stress intensity factor tell a lot about the fracture conditions for non ductile materials and is to be considered as bending strength.

Hardness
Diagram 5
Ceramic materials belong to the hardest of known materials. Ceramic retain its hardness even at high temperatures, far higher than, for example, high speed steel and hard metal, which lose their strength at temperatures of approximately 600 °C and up. The hardness is a strong prerequisite, beside others, for high wear resistance.

Thermal Conductivity
Diagram 6
Whilst silicon carbide has a thermal conductivity equal to copper, aluminium oxide has a value comparable to steel. It is beneficial for electro ceramics that the part, together with its electrical properties, has a good heat transportation capability to transfer the created heat away. On the other hand, zirconium oxide has a low thermal conductivity, close to porcelain, and good resistance to heat and is therefore an excellent thermal insulator.
MATERIAL PROPERTIES DIAGRAMS

1. Operating temperature range

2. Density

3. Pressure strength

4. Bending strength

5. Hardness

6. Thermal Conductivity
JOINING TECHNIQUES

To join a ceramic part together with another part, often in metal, you can use most known dismountable and non-dismountable joining methods. In this regard you should pay attention to the unique properties of the ceramics. The most common joining techniques for ceramics are: clamping, gluing, cementing, bolting, securing with plugs or groove and spring, as well as shrinking into metal, brazing and embedding with plastic. One essential method is the shrink in process, where with correct shrinking parameters the metal holder shrinks around the ceramic part. This method puts the ceramic under pressure which compensates for any possible tensile stress during use. You have to take the different thermal expansions of the materials into account and distribute the power in the part at the joint correctly.
**DESIGN ADVICES**

The known construction references for “pig iron, hard metal and powder metallurgy” can also be used as criteria’s for construction with ceramics. They can be applied to ceramics almost without exceptions:

- Even and sufficient wall thickness, not too thin, too thick or oversized. The usual over sizing of steel constructions for security gives no advantages for ceramics, rather disadvantages.

- Sharp and rough transitions should be avoided. Large radius, soft corners, concave inner edges as well as broken edges are preferred.

- Avoid convex radius and sharp edges, try to reach 45° chamfers.

- Compressive load on the component is preferred. Any tensile stress or punctual loads should be avoided and as with other materials grooves are critical.

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**Pressure load on the component is to be preferred**

- Oblong holes compensate dimensional deviations and serves as help when assembling.

- Narrow tolerances should only be used where absolutely necessary.

- Grinding is needed to obtain a good surface after sintering.

- Raised areas for grinding reduce grinding costs since a smaller area has to be grinded.