ICED13
INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

DESIGN FOR DURABILITY – DESIGNING WITH ADVANCED CERAMICS

Anna Kerstin USBECK, Dieter KRAUSE
Hamburg University of Technology (TUHH), Germany

ABSTRACT

The demand of sustainable products - not only in transport, but in manufacturing and building industry - results to the necessary of improving the reliability. The MTBF-index (mean time between failures) and MTBM (mean time between maintenance) have been introduced, to include the reliability of products in the profitability analysis. On the technical side, international standards describe how to test the reliability of a product or component by means of constant failure rate or constant failure intensity.
The demand of sustainable products results in a redesign with new targets. The challenge for the designer is to (re-)design the technical system with improved material and/or optimized shape. Therefore the paper will discuss the material selection methods for a “design for durability”. As a consequence it will show the influence of embodiment design when designing with advanced ceramics.
The autor has worked on failure criteria of multi-axial loaded ceramics and investigated several cyclic and static load cases on ceramic structure specimen. Based on this experiences a guideline will be proposed for the embodiment design evaluation of cermic parts.

Keywords: advanced ceramics, material selection, sustainable design

Contact:
Anna Kerstin Usbeck
Hamburg University of Technology (TUHH)
PKT (Product Development and Mechanical Engineering Design)
Hamburg
21073
Germany
Usbeck@tuhh.de

1 INTRODUCTION

Demand for sustainable products results in a redesign with new targets. The challenge for the designer is to (re-)design the technical system with improved material and/or optimized shape. The challenge for designers is to take a risk with unknown material properties and, in particular, a lack of long-term experiences. This paper focusses on “design for durability” and shows the challenges of embodiment design when designing with Advanced Ceramics used for structural parts.

1.1 When do we decide to use Advanced Ceramics in design?

Increasing industrialization and decreasing availability of raw materials bring the need for sustainable development of new products. While the manufacturer considers the total cost of a product by cost management, the overall costs to the user are not that evident. The more energy-consuming and maintenance-intensive the product is, the lower the relation between capital cost (purchase price) and lifecycle costs (see Figure 1).

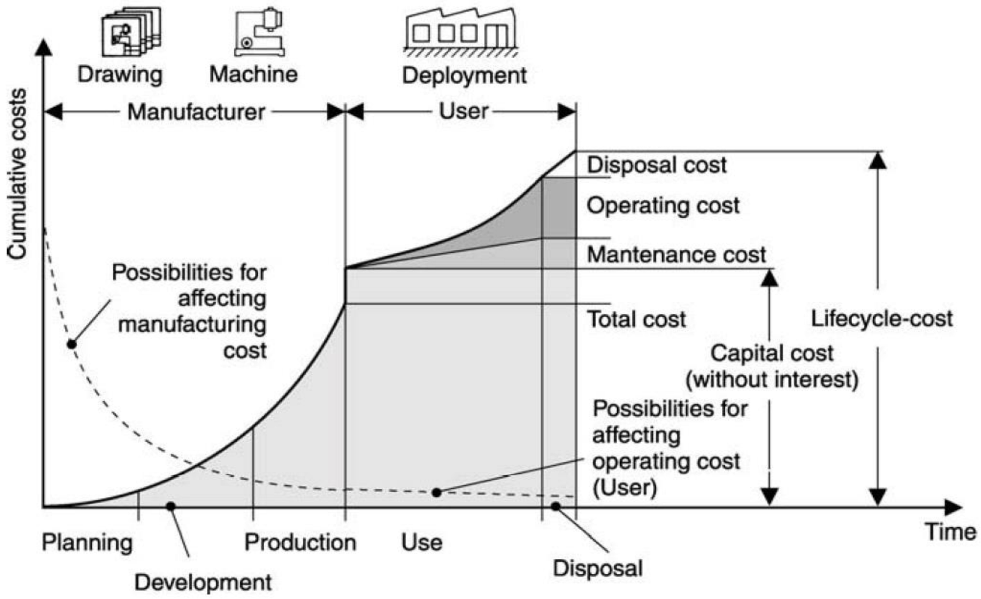


Figure 1. Lifecycle costs during the individual product life span (Ehrlenspiel 2007)

Ehrlenspiel (2007) states that “...very often the buyer does not value high efficiency; they pay attention only to low capital expenditure…This kind of short-term thinking is widespread, but very shortsighted and essentially uneconomical.” He considers the following rules for reducing lifecycle costs:

1) **General:** Choose low-loss, reliable, life-span-optimal design principles
2) **Low one-off costs:** Low transportation costs, low set-up and training costs
3) **Low operating costs:** Save energy, reduce losses, reduce costs of operational and auxiliary materials
4) **Low maintenance costs:** Inspection and service, repair costs
5) **Low disposal costs**

Advanced ceramics is a material with high wear resistance, high stiffness, high temperature resistance, low friction rate, adjustable thermal and electrical properties and low corrosion. Material selection methods suggest advanced ceramics to reduce lifecycle costs due to its properties, particularly low maintenance, operating and disposal costs. But Ceramics are also known to be very brittle, so they are rarely used for structural parts even if there is much improvement in the performance of Advanced Ceramics (Figure 2, Moeller 2008).

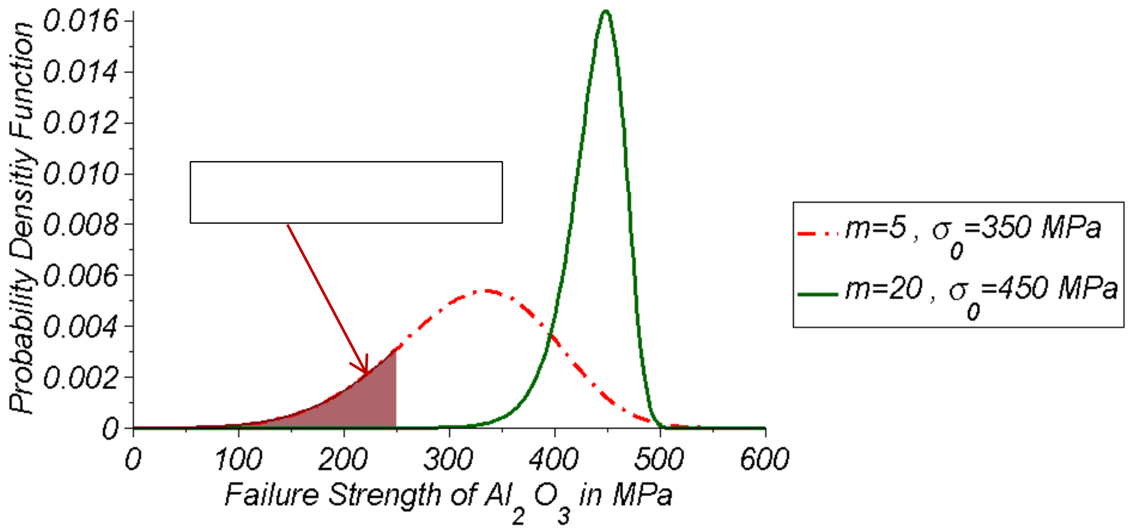


Figure 2. Weibull distribution of Al_2O_3 State of the Art: m=5 (1970), m=20 (2005)

1.2 Durable design with advanced ceramic material

Spark plugs
Petrol engines require a spark plug for the ignition of the fuel-air mixture. The improvement in motor efficiency was accompanied by the development of high performance spark plugs. The spark plug has to resist high temperatures and has to ensure electrical insulation between the ignition cable and the motor block. Only Ceramics can meet these requirements completely. Figure 3 shows a differential design with various materials, including ceramics as an insulation part.

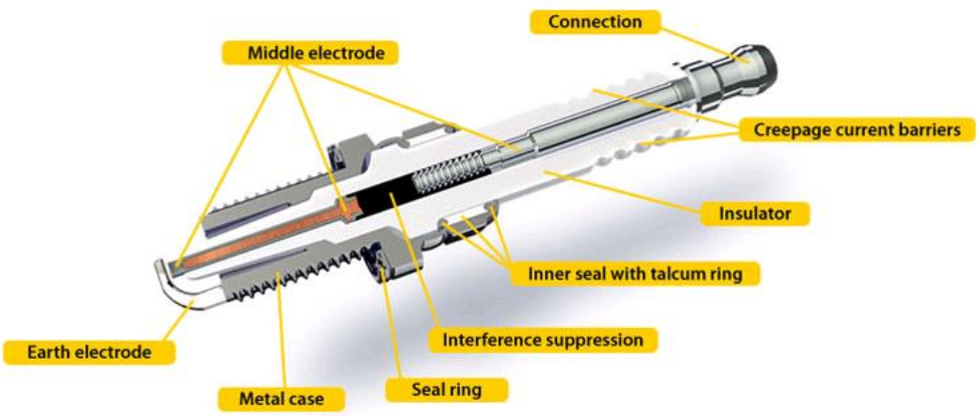
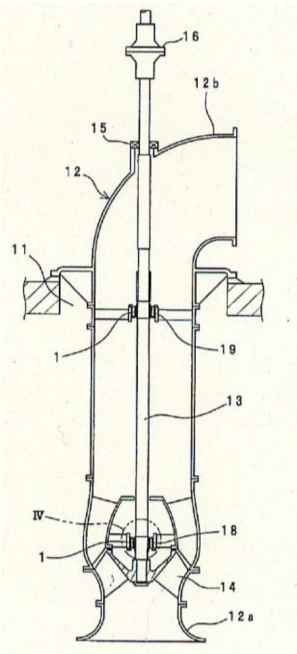


Figure 3. Design of a Spark plug (NGK 2013)

Mechanical seals
Mechanical seals are now indispensable in rotating machines in systems engineering. Mechanical seals have replaced most of the stuffing box applications due to the development of advanced ceramics and improved design with balanced seal faces and an almost contact-free operation. Again the “Ceramic solution” is more complex than stuffing boxes. The design is a differential design with different materials (advanced ceramics, elastomer and metal). Sealing under high velocity and low friction and wear is ensured by ceramic versus ceramic (silicon carbide) or carbon graphite antimony impregnated.

Radial plain bearings
Ceramic journal bearings in vertical pumps are lubricated by the pumped fluid itself (Fig. 4). No additional water or grease lubrication bearings are needed. Again, a highly sophisticated differential

design with metal, elastomer and ceramic material leads to higher investment costs but keeps life cycle costs down. The bearings in tubular casing pumps are state-of-the-art.



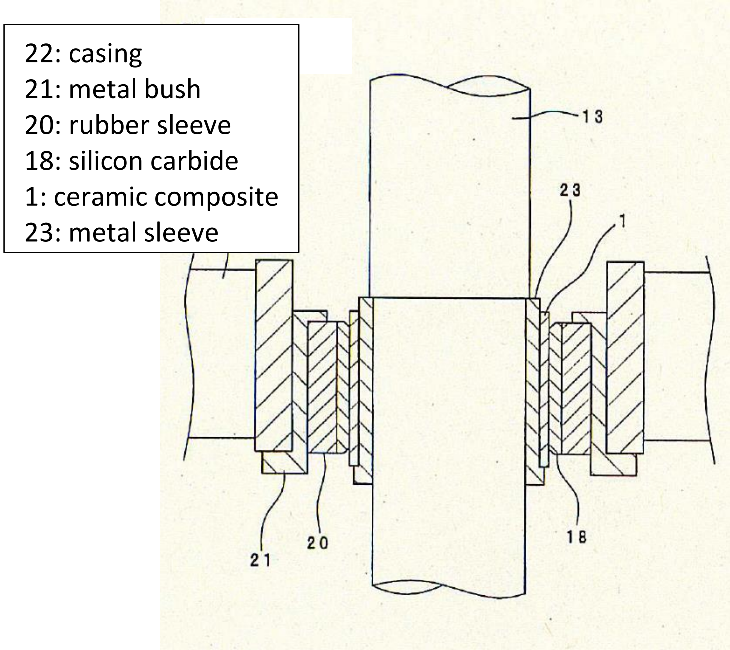


Figure 4. Tubular casing pump with ceramic sliding bearings, Japanese patent no. 2006038029

2 ADVANCED CERAMICS IN PRODUCT DEVELOPMENT

During the conceptual design process the engineer sets up a function structure and translates the requirements of a product into working principles. Some aims of the requirements are contradictory to others (e. g. maximum permissible manufacturing costs, long servicing intervals, high safety). The designer has to solve this conflict of objectives. In the case of durability, there will be a focus on minimizing service costs or enlarging operating time and reliability (e. g. reducing wear, reducing corrosion and increasing temperature resistance). Determination of the material takes place occasionally at different stages of the design process as per product development procedure according to VDI 2221.

a) *Develop the principle solution*: In some cases the material is essential for a principle solution of a function. The material is selected within the conceptual design phase (e. g. piezo-electric actuators).
b) *Develop the construction structure*: Generally, the material is chosen while developing the construction structure, the early stage of embodiment design. The designer determines the spatial constraints and sets up the preliminary form design. Therefore he needs to know certain properties of the material. Also material-determining requirements are fulfilled (such as resistance to wear and corrosion, service-life, etc.).
c) *Define the construction structure*: In the case of advanced ceramics, the material is often selected in the upgrade or redesign process to eliminate weak spots.
For example bottling plants change the material and thickness of the bottles. Therefore the bottling process had to be changed. As a consequence, the flow measuring devices needed a higher accuracy under pressure. The device manufacturer changed from rubber-sealed metal to advanced ceramic.

The embodiment design with Advanced Ceramics differs from the ordinary metal design. The brittleness of the material has a major influence on the shape design; the design solution is more complex and often ends up in a highly differential design, as shown in Albers (2010) for ‘Lubricated Multi-Disk Clutch Systems’. The main target of the designer is to minimize stresses within the ceramic parts to reduce failure probability. Nevertheless, quantitative design criteria are necessary to evaluate the technical criteria of a design and to improve the layout during the development process. These criteria are introduced in the following section.

3 ANALYTIC DESIGN CRITERIA FOR CERAMIC STRUCTURE PARTS

While the design criteria for metals are standardized and commonly taught in engineering education, designers are rarely familiar with new materials. Material researchers develop new materials and characterize them by different material test methods, like the four-point-bending test, static tensile test, indentation hardness (Vickers, Rockwell) and sub-critical crack growth. The designer then has to interpret the new material properties on a part-size level. For metal parts, common engineering design standards, such as ASME, and DIN EN, are available. These engineering standards consider size-effects, multi-axial loading conditions, temperature and corrosion as well as dynamic and cycling loading. The international design standards for metal parts are affected by empirical data collected over the entire last century. Effects of size, load condition (static, cycling), temperature, corrosive surrounding and welding influence are broadly explored for metals. In contrast, only limited empirical data are available from parts made from new materials, including advanced ceramics. The design criteria are deduced from failure theory and the macro-scale behavior is extrapolated from micro-size investigations. Hence the following section discusses the theoretical approach to evaluating ceramic parts, comparing the results with derived empirical data and introducing a new design standard according to common engineering standards.

3.1 Common design criteria for ceramics

Manufacturers of Advanced Ceramics do not indicate allowable stresses for the material. There is no possibility of making a preliminary design with estimated stresses. With the lack of analysis standards, descriptive design rules are used for ceramics. Many of them are similar to the design rules for cast iron. Both are brittle materials which have little ductility and do not tolerate flaws.

Common design rules

- Avoid structures that change from thick walls to thin walls
- Simplify geometry; Smooth edges
- Design for compressive stresses, Avoid tensile and bending stresses, if possible
- Limit the projected area, keep the location techniques simple
- Specify surface finishes as lapped, ground or, preferably, sintered
- Reduce the section thickness of the component (only use the ceramic where it is doing ceramic work)
- Overload of ceramic parts is strictly to be avoided by assembly design

The designer tries to fulfill these design rules but does not generally evaluate the design stresses. Some manufacturers emphasize that no tensile stresses are allowed on the parts at all. As a very extensive evaluation, proof tests are considered in high performance applications.

3.2 Scientific approach on evaluating ceramic part design

The scientific approach to evaluating a ceramic part design is to determine the stress distribution within a ceramic part and sum up the stressed volume of the part for the material scatter, which is assumed to be Weibull-distributed. (Weibull modulus m, V_{eff}: effective volume, $\sigma_{I,max}$: maximum principle stress in the part and σ_0, V_0: nominal strength and volume of standardized material data).

$$\left(\frac{\sigma_0}{\sigma_{I,max}}\right) = \left(\frac{V_{eff}}{V_0}\right)^{\frac{1}{m}} \tag{1}$$

For a multi-axial stress distribution either the Principle of Independent Action (PIA) or the Principle Stress distribution including Crack direction (PSC) is applied to determine the effective volume.

Principle of Independent Action (PIA)

$$V_{eff} = \int_V \left(\frac{\sigma_I}{\sigma^*}\right)^m dV + \int_V \left(\frac{\sigma_{II}}{\sigma^*}\right)^m dV + \int_V \left(\frac{\sigma_{III}}{\sigma^*}\right)^m dV \tag{2}$$

Principle Stress with Crack direction (PSC)

$$V_{eff} = \int_V \frac{1}{4\pi} \int_0^{\pi} \int_0^{2\pi} \left(\frac{\sigma_{eq}(\varphi,\vartheta)=\left(\sigma_I \cos^2(\varphi)+\sigma_{II} \sin^2(\varphi)\right) \cos^2(\vartheta)+\sigma_{III} \sin^2(\vartheta)}{\sigma^*}\right)^m \cos\vartheta \, d\vartheta d\varphi dV \tag{3}$$

The effective volume V_{eff} can be determined numerically by summing up the effective stresses in each finite-element. All partial $\sigma_{eq}$are references to the maximum stress $\boldsymbol{\sigma}^*$of the part stress distribution. Finally the evaluation results in a failure probability for the designed part.

$$P_f = 1 - exp\left(-\int \left(\frac{\sigma_I}{\sigma_0}\right)^m \frac{V_{eff}}{V_o}\right) \tag{4}$$

As an example, a sliding bearing of a vertical tubular casing pump is investigated in Usbeck (2013). The variation of segments and the failure probability of each variant are shown in Figure 5. While maximum surface pressure is halved by paralleling the surface pairs, the maximum principle stress will reduce to nearly one third and failure probability is reduced to 1/10.

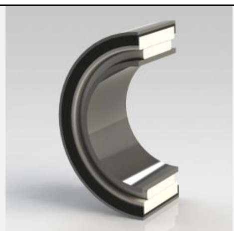
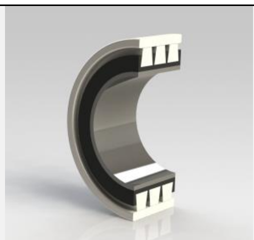
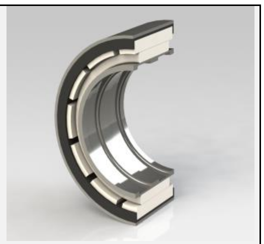
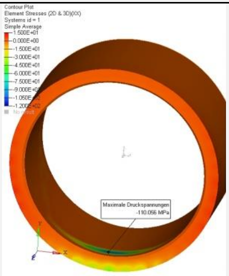
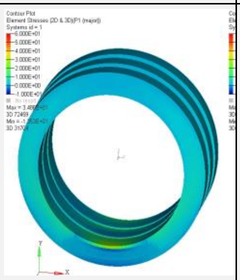
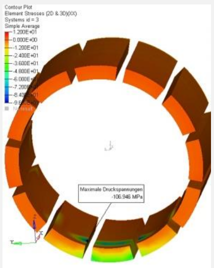
Design variants			
Stress analysis			
Maximum surface pressure	110 MPa	61 MPa	107 MPa
Maximum principle stress	89 MPa	35 MPa	148 MPa
Failure probability	0,016%	0,00021%	0,31 %

Figure 5. Sliding bearing segment variants

The summarized evaluation procedure is used in many scientific investigations of ceramic parts. But the evaluation is very elaborate and can only be carried out after final design of the part. Additionally, the material data of specimen size are theoretically extrapolated to part size without empirical proof.

3.3 Empirical investigations of ceramic structural parts under static and cycling load

Investigations of ceramic parts under static and cycling load have been carried out to re-evaluate the above analytic evaluation based on fracture mechanics and to develop simplified practices for designers as per the technical evaluation of metal parts.

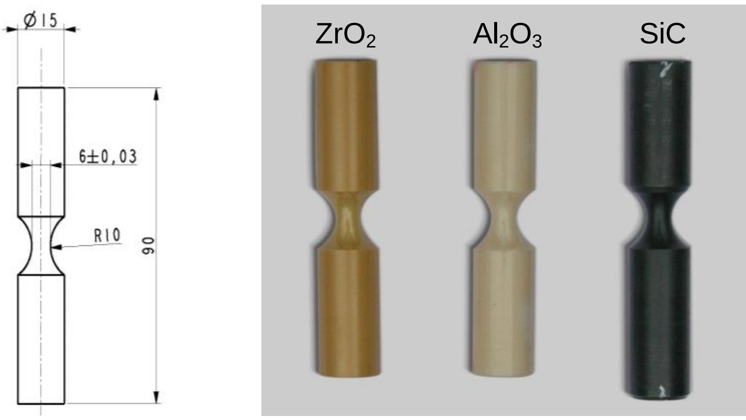


Figure 6. Specimen of part size for torsion-pressure tests

Three commercial ceramics, zirconia, alumina and silicon carbide (Figure 7), have been tested as structural parts under torsion and torsion with additional pressure (Usbeck 2013). Some of the results are presented in Figures 8 and 9. As a result of the static fracture tests (Figure 8), different load cases (and consequentially different effective volumes) cause different Weibull lines for alumina, zirconia and also silicon carbide. This size effect can be explained with Equation (4).

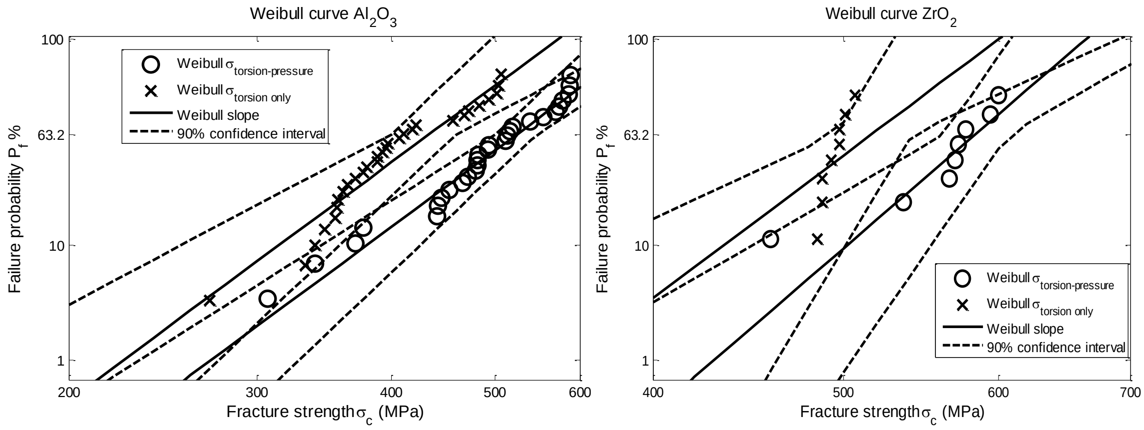


Figure 7. Fracture strength under torsion and torsion-pressure for alumina and zirconia

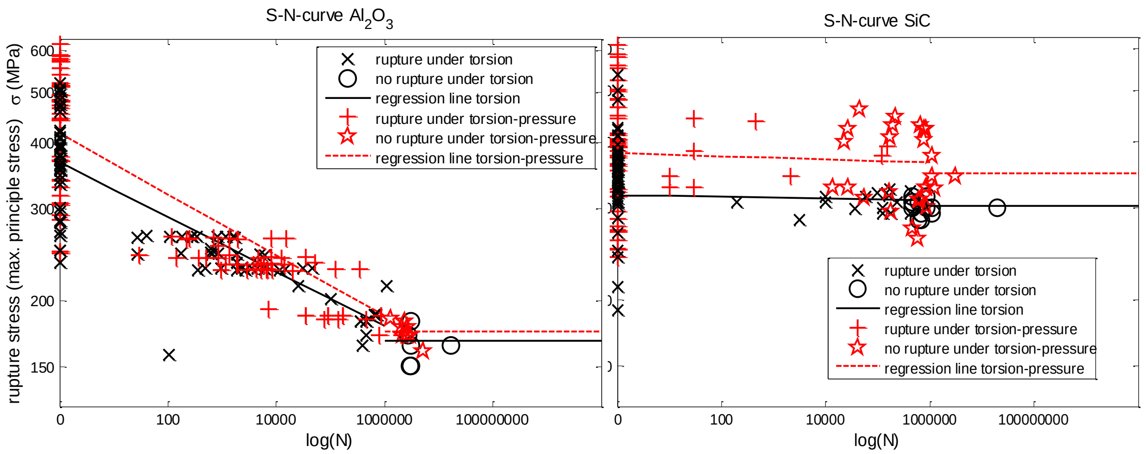


Figure 8. S-N-curves under cycling torsion loading (with and without additional pressure)

The cycling tests in Figure 9 show very different behavior of alumina and silicon carbide. This is explained by the different crack growth behavior. Alumina has got a very low crack growth exponent *n*, so above a certain stress level, the crack intensity factor is exceeded and the cracks start to grow. This behavior is similar to metal S-N-curves while crack growth factors are different (more extrinsic than intrinsic crack growth effects). Silicon carbide has almost no crack growth effects, so no S-N-curves can be obtained. Static scatter is similar to scatter of rupture after certain cycles. Fatigue strength of silicon carbide equals static strength, while parts of alumina have got poorer endurance strength. These effects have to be considered in the outlined new evaluation procedure.

3.4 New design procedure for ceramic parts

Developing the construction structure, designers carry out basis calculations to estimate the durability of a layout. Evaluating metal parts, the permissible stress of the material $\sigma_{permiss}$ has to be higher than the effective stress equivalent $\sigma_{eq,stucture}$ within the structure caused by operating loads.

$$\boldsymbol{\sigma_{permiss}} > \boldsymbol{\sigma_{eq,stucture}} \qquad (5)$$

Several guidelines exist to calculate the admissible stress as well as the stress equivalent for multi-axial loads on a structure. Those guidelines exist for metals and other materials, but not for advanced ceramics. In Usbeck (2013) an analytic evaluation procedure is proposed to determine allowable stresses of ceramic parts as per the FKM-guideline for metal parts (Forschungskuratorium Maschinenbau, 2003). The following section summarizes the analytic procedure to evaluate stress and fatigue within ceramic parts.

Static analysis

Generally, the strength of a material must be higher than the applied stress on the specimen. Referring to a designed part, the permissible stress of the structure $\sigma_{admiss,struct}$ must be higher than the effective stress equivalent occurring within in the structure $\sigma_{eq,struct}$ under operating conditions.

$$\sigma_{permiss,struct} > \sigma_{eq,struct} \tag{6}$$

Determination of the effective stress equivalent $\sigma_{eq,struct}$

The effective stress equivalent can be determined analytically or numerically with finite-element methods. According to Usbeck and Krause (2010), the principle stress criteria has to be chosen.

$$\sigma_{eq,struct} = \sigma_{I,max,structure} \tag{7}$$

Determination of the permissible stress on the structure $\sigma_{admiss,struct}$

The permissible stress of the structure depends on the material strength, the scatter of material, the size of the structure and the load case. Similar to the guidelines for metal design, the material strength $\sigma_{97,5\%}$ is defined for 97.5 % survival probability of the material test data. Two additional factors will consider stress distribution K_S and nominal size K_D of the structure.
Note: safety factors are not included!

$$\sigma_{permiss,structure} = K_D \cdot K_S \cdot \sigma_{97,5\%} \tag{8}$$

Determination of material strength $\sigma_{97,5\%}$

Because of the high scatter of strength in ceramics, failure probability has to be taken into account. The probability of failures is assumed as Weibull distributed. The characteristics of this distribution are the inert strength σ_c and the Weibull modulus m. The parameters are generally determined by the 4-point-bending test. The lower the Weibull modulus m the higher the scatter of strength within the material. In Figure 10 the scatter of advanced ceramic material (m=10) is opposed to steel and cast iron. Steel is assumed with m=30 and cast iron m=15 according to Hertel (2010).

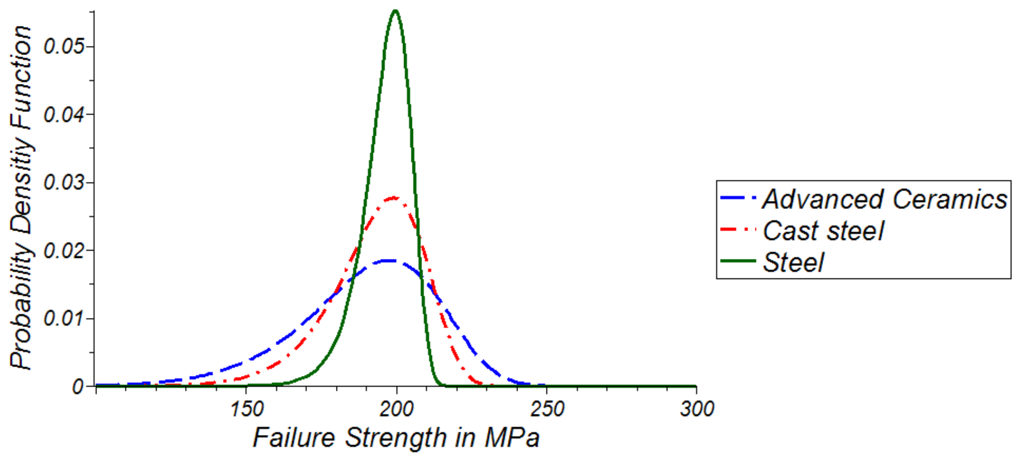


Figure 9. Probability of Failure Strength for Different Materials

The influence of scatter can be considered similar to the FKM-guideline (2003); the material strength is defined at a failure probability rate of P_f = 2.5 % (i.e. $\sigma_{97,5\%}$: 97.5% survival probability). In Table 1 the material strength $\sigma_{97,5\%}$ is stated for different scatter (Weibull modulus m) and inert strength σ_c.

Table 1. Material strength $\sigma_{97,5\%}$ for different Weibull scatter

Weibull m	**5**	**10**	**15**	**20**	**25**
σ_c *in MPa*	$\sigma_{97,5\%}$				
200	96	138	154	166	173
400	191	277	313	333	345
600	287	415	469	499	518
800	383	553	626	665	690

Determination of scale effect K_D

The scale effect, which is described in empirical equations for metal, is similarly introduced for ceramics, but derived analytically by the assumption of a Weibull-distibuted failure probability for uniaxial tensile loading on a 7.5 mm diameter specimen according Eq. (1). Figure 11 shows the scale effect for different Weibull scatters m in ceramics compared with the empirical values for metal from the FKM-guideline.

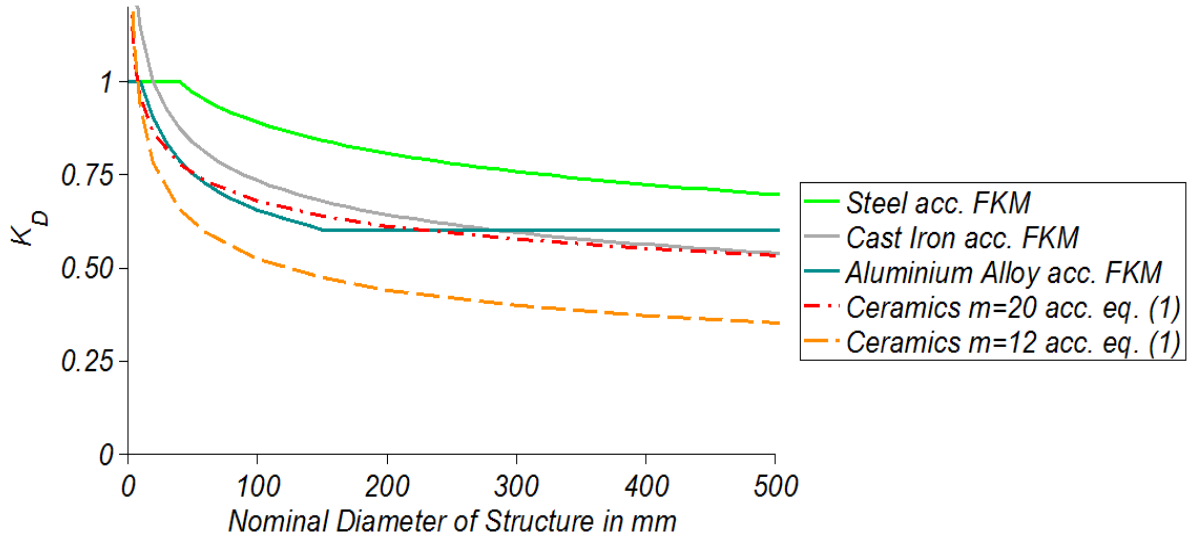


Figure 10. Scaling Effect of Different Materials

Determination of stress factor K_S

The 4-point-bending test is a uniaxial tension test, but structural parts feature multi-axial stress states. While compressive strength in one direction reduces failure probability, two-axial tensile stress will increase failure. The stress factor K_S is calculated by the relation between uniaxial and multi-axial stress according Equation (1) and (2) for a standardized volume.

$$K_S = \left(\frac{\sigma_{multiaxial}}{\sigma_{uniaxial}}\right) = \left(\frac{V_{eff,uni}}{V_{eff,multi}}\right)^{\frac{1}{m}} \tag{9}$$

with $$V_{eff} = \int_V \frac{1}{4\pi}\int_0^{\pi}\int_0^{2\pi}\left(\frac{\sigma_{eq}(\varphi,\vartheta)=\left(\sigma_I\cos^2(\varphi)+\sigma_{II}\sin^2(\varphi)\right)\cos^2(\vartheta)+\sigma_{III}\sin^2(\vartheta)}{\sigma^*}\right)^m \cos\vartheta \, d\vartheta d\varphi dV \tag{1}$$

The settings for uniaxial stress is $[\sigma_I = 1, \sigma_{II} = 0, \sigma_{III} = 0]$, for two-axial $[\sigma_I = 1, \sigma_{II} = 1, \sigma_{III} = 0]$, for three-axial $[\sigma_I = 1, \sigma_{II} = 1, \sigma_{III} = 1]$ and for tension-compression $[\sigma_I = 1, \sigma_{II} = -1, \sigma_{III} = 0]$. Figure 12 shows the stress factor $\boldsymbol{K_S}$ dependent on the Weibull scatter.

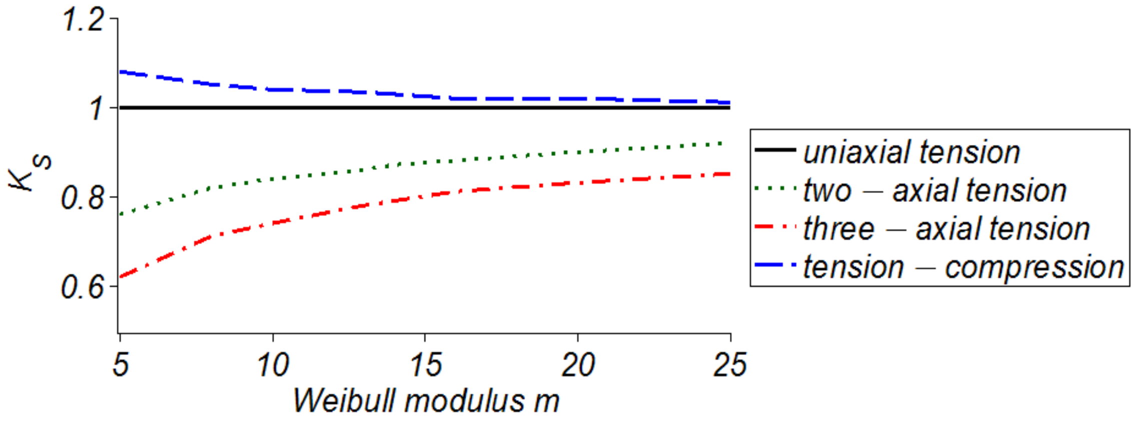


Figure 11. Scatter dependent Stress Factor K_S

Fatigue stress analysis

Fatigue stress analysis can be carried out similarly, but taking the subcritical crack growth into account. If the crack growth factor ***n*** is high, no fatigue stress has to be considered (for example silicon carbide), if the crack growth factor is small (for example alumina), crack growth reduces allowable stress. It is proposed to reduce the allowable stress by factor 0.3 as per FKM-guideline for brittle metal. Derivations of the analysis guideline and further calculation of subcritical crack growth are presented in Usbeck (2013).

4 CONCLUSION

The database for advanced ceramics are very small, but material selection methods often come up with advanced ceramic as a suitable material for engineering design. The durability of products can be increased by using advanced ceramics. Choosing Advanced ceramics, designers have to revise the embodiment design, often concluding with a more complex differential design. The proposed guideline assists the designer to evaluate preliminary form design and improve the layout without extensive finite element analyses.

REFERENCES

Albers, A. et al. (2010), 'Development and Validation of Lubricated Multi-Disk Clutch Systems with Advanced Ceramics' *in Mechanical Properties and Performance of Engineering Ceramics and Composites V*, John Wiley & Sons, pp. 309–315.

Ehrlenspiel, K. (2007), *Cost-Efficient Design*, Springer-Verlag, Berlin, Heidelberg.

Forschungskuratorium Maschinenbau (ed.) (2003), *Rechnerischer Festigkeitsnachweis für Maschinen-bauteile aus Stahl, Eisenguss- und Aluminiumwerkstoffen*, Frankfurt am Main.

Hertel, O.; Vormwald, M.(2010): Size effect in fatigue described by support factors derived from short crack growth consideration,*18th European Conference of Fracture*, Dresden, 2010.

Moeller, E (ed.) (2008), *Handbuch Konstruktionswerkstoffe*. *Auswahl, Eigenschaften, Anwendung,* Hanser Verlag, München.

NGK (2013), *NGK – Design of a spark plug* [online], http://www.ngk.de/en/technology-in-detail/spark-plugs/spark-plug-principles/design-of-a-spark-plug (2013/05/01).

Usbeck, A. K. (2013), *Auslegung von keramischen Strukturbauteilen unter mehraxialer statischer und zyklischer Beanspruchung*, Hamburger Schriftenreihe Produktentwicklung und Konstruktionstechnik Band 5/2013, TuTech Verlag, Hamburg, Institut für Produktentwicklung und Konstruktionstechnik.

Usbeck, A. K. and Krause, D. (2010), 'Fracture of structural ceramics under cycling load' in *18th European Conference of Fracture*, ed. DVM, Dresden.