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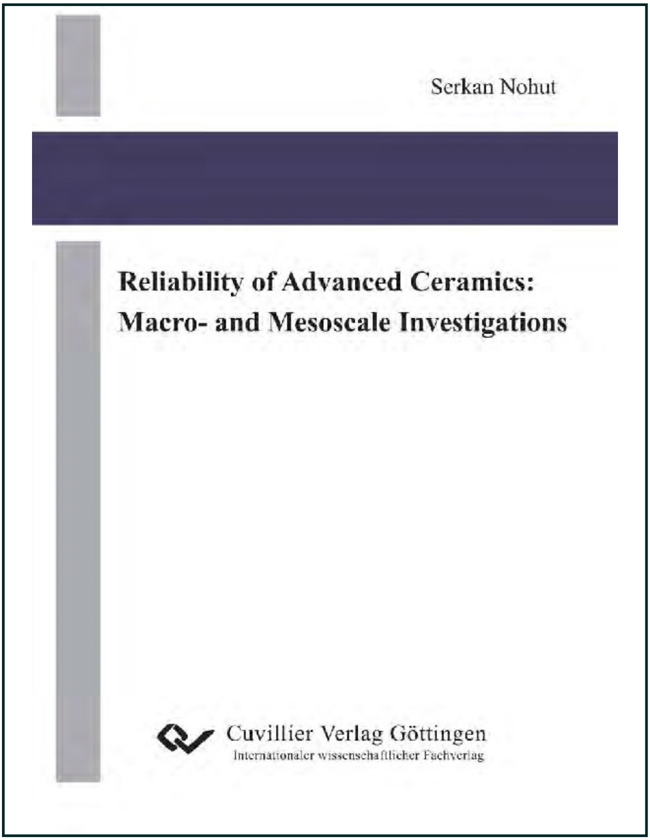
Reliability of Advanced Ceramics: Macro- and Mesoscale Investigations



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1 Introduction

The greatest advancements in material science has been produced in the 20^{th} century and as a result of these advancements, now almost every combination of metal alloys and capabilities of these alloys are fairly known. In the last years, since the limits of metal-based systems are exceeded, new materials capable of operating under higher temperatures, higher speeds, lower wear and corrosion rates, longer life factors and lower maintenance costs are required to maintain pace with technological advancements. Metals takes one of the most important places due to their unique properties; ductility, tensile strength, abundance, simple chemistry, relatively low cost of production, ease of forming and ease of joining, etc. By contrast, ceramics, brittle by nature, having a more complex chemistry and requiring advanced processing technology and equipment to produce, perform best when combined with other materials, such as metals and polymers which can be used as support structures. This combination enables large shapes to be made; the Space Shuttle is a typical example of the application of advanced materials and an excellent example of the capability of advanced materials.

In the last 30 years, the potential for advanced ceramics has been realised with the advances of understanding in ceramic chemistry, crystallography and the more extensive knowledge gained in regard to the production and design. Significant improvements in the fracture toughness, ductility, impact resistance of ceramics and design process have been realised.

Advanced ceramics, when used as an engineering material, afford several properties which can be viewed as superior to metal-based systems. These properties place this new group of ceramics in a most attractive position, not only in the area of performance but also cost effectiveness. These properties include high resistance to abrasion, high strength at high temperatures, chemical inertness and high speed machining capability(as tools). The properties of advanced ceramics need to be considered when designing structures, components and devices. The final design and material selection must ultimately be cost effective, reliable and ideally should be an improvement upon existing technology. In this regard material engineer works in close contact with the research team to cooperatively develop the new concept and this aspect has to be always kept in mind. New techniques such as Finite Element Analysis have proven beneficial in this regard. The use of computer modelling allows the structures to be created on screen without the need for costly prototypes.

In this dissertation, reliability analysis of advanced ceramics is performed on macro- and mesoscale. The failure probability analysis and design of ceramics will be discussed in macroscale and the effect of microstructural changes on macroproperties of ceramics will be examined in mesoscale. In order to increase the reliability of ceramic components, either the stress distribution on the component can be changed using some specific tools used in the design process or the strength distribution can be improved through the advancement of the microstructure of ceramic. This work will contain both of these facilities respectively in two different chapters.

Design with ceramics is not a straight-forward process as with the metals due to brittleness of the ceramics and scattering of strength. For that reason, design with ceramics is performed with statistical methods rather than deterministic design methods. In this work, statistical reliability analysis of advanced ceramics will be included first. In Chapter 4, the multiaxial Weibull criteria will be investigated experimentally and numerically. According to the experiments which are performed under conditions similar to service conditions, the multiaxial failure criteria will be analysed numerically and a comparison of the multiaxial failure criteria will be realised. Next, a failure probability analysis of ceramic coil springs will be applied. A formulation will be introduced for the ceramic coil springs which enables it possible to estimate the failure probability of ceramic coil springs with desired spring- and material parameters. Furthermore, according to the effective volume and effective surface calculations, it will be concluded whether the ceramic coil springs fail due to volume or surface defects. Afterwards, the importance of the form in design of ceramic components will be handled. The effect of shape optimization on the failure probability of ceramics will be investigated on two example applications: construction of a ceramic displacing piston of a stirling engine and design of a new ceramic finger-ring form. This work was assisted by an interdisciplinary project Graduiertenkollegs "Kunst and Technik" ("Art and Technic") and in the framework of this work design of a ceramic finger-ring will be next included. By using the gained information during workshops which were organized in order to understand the artistic evaluation criteria, a new ceramic-conforming finger-ring form will be designed by using the failure probability analysis.

The microstructure of ceramics has a big effect on the material properties. In Chapter 5 the effect of the grain size on the crack-tip toughness of alumina ceramics will be investigated in mesoscale. The main reason to analyse it in mesoscale is that the fracture of ceramics does not occur in atomistic scale due to for example dislocations but it occurs due to the pre-existing microdefects in the material. The experimentally observed increase of residual stresses in alumina with increasing the grain size will be included into Distinct Element Method (DEM) model and then the experimentally measured dependence of crack-tip toughness of alumina on grain size will be investigated. Depending on the similarity of the experimentally measured and numerically calculated results, it is then possible to estimate some microparameters which are not easy to measure experimentally.

2 Principles of Brittle Fracture

Failure analysis and prevention of failure are important functions to all of the engineering disciplines. The material engineers deal with the analysis of failures, whether a component fails in service or if failure occurs in manufacturing processes. In any case, one must determine the type of failure, the causes of failure in order to prevent future occurring possible failures and improve the performance of the components by using more suitable design methods.

Mechanical failure means the loss of load-carrying capacity of a component within a structure or of the structure itself. Failure occurs when the material is stressed to its strength limit and thus causing a fracture of excessive deformations. There are different failure types, some of which can be seen in most of the materials and some of which are special for some materials. The most commonly observed failure types in practical applications are: fatigue failures, corrosion failures, wear failures, impact failures, creep failures, ductile rupture and brittle fracture. More detailed explanations of these failure types can be found in the literature [1].

At low and ambient temperatures, fracture of ceramics is always brittle and occurs without any significant plastic deformations. Brittle fracture occurs due to unavoidable presence of microscopic defects (e.g. micro-cracks, internal pores and atmospheric contaminants) that results during cooling from the melt. For example, ceramics are used in electronics industry as substrates and dielectrics due to their electrical properties. The failure in these applications is often caused by brittle fracture which results from thermal expansion mismatch between the ceramic and metallic parts of electronic packages. Failure process in ceramics is dependent on chemistry and microstructure of the material, material properties (e.g. toughness, strength, R-curve behavior etc.) and also stress field in the material according to loading type. Some crack propagation mechanisms are also to be observed (e.g. sub-critical crack growth, fatigue or corrosion). Although ceramics can experience plastic deformation to a limited extend by slip which occurs at very high temperatures or at extremely slow deformation rates or when the cracks are sharp to atomic level of the solid or at high contact pressure, it is in most cases not important for practical applications. In this chapter, the principles of brittle fracture mechanics will be discussed in detail in order to understand the causes and the treatment of brittle failure in advanced ceramic materials.

2.1 Importance of Fracture Mechanics

In the 19^{th} century and the first half of 20^{th} century, the full-scale industrial revolution resulted in an increase in the usage of ductile metals (e.g. irons, steels) in order to overcome the problem of brittle fracture. Nonetheless, there occurred some accidents with loss of life due to some reasons including inadequacies in design, deficiencies in construction or uncertainties in the loading and environment. It was discovered that most of the failures were due to the growth of pre-existing defects (e.g. flaws, cracks etc.) in the material which could initiate cracking and fracture.

The first example is the **Tay Rail Bridge** disaster. **Tay Rail Bridge** is a railway bridge which lies between the city of Dundee and the suburb of Wormit in Fife and has a length of three and a half kilometres. During a storm on the evening of 28 December 1879, the center section of the bridge collapsed taking with it a train which was running on it. After some investigations, it was realised that many faults in design, material and processes caused the failure. It was reported that its downfall was due to the inherent defects in the structures which were not taken into account correctly during the design. The pictures which show the bridge after disaster from north- and south side are shown in Fig. 1.

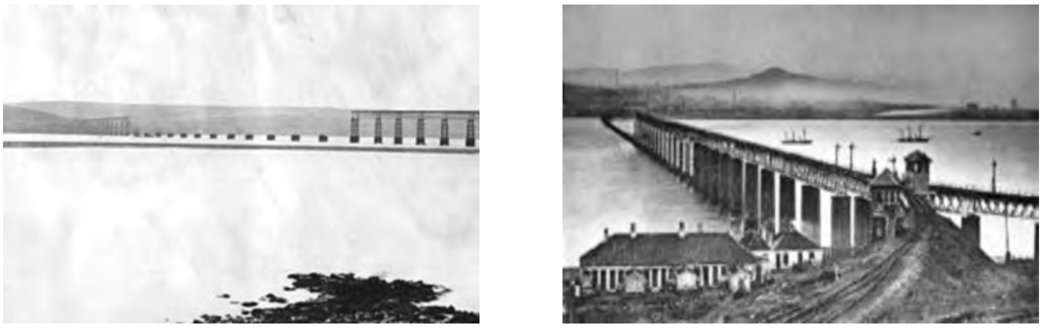

(a) (b)

Figure 1: Destroyed Tay Rail Bridge from (a) north side, (b) south side

Second example is **Liberty ships**. In the World-War II approximately 2500 Liberty ships were produced by using the technique of welding rather than riveting to assemble ships. Liberty ships were basic cargo ships with cargo carrying capacity of 9000 tons. Out of 2500 Liberty ships, built between 1940 - 1944, 145 broke in two and 700 experienced serious failures. In Fig. 2, failure of an one-day old Liberty ship, SS Schenectady is shown.

Moreover many other bridges and railway equipments also failed in this time frame. Mostly, the failures occurred under very low stresses and these fractures were brittle due to the flaws and stress concentrations. It was also discovered that brittle fracture in the types of steel used was promoted by low temperatures. Nowadays, the causes of these failures can be easily explained with the principles of fracture mechanics. For example, current manufacturing and design procedures can prevent the brittle fracture of welded

Figure 2: One-day old Liberty ship, SS Schenectady

steel structures by ensuring that the transition from ductile to brittle behavior occurs at low temperatures and the welding process does not raise it.

The main object of the fracture mechanics is to provide quantitative answers to problems regarding the cracks in structures. It uses methods of analytical solid mechanics in order to calculate the driving force on a crack and experimental solid mechanics to characterize the resistance of material against failure. Therefore, the term *"Fracture Mechanics"* refers to a specialization of solid mechanics in which it is assumed that there are pre-existing cracks in the material and the quantitative relations between the crack length, the materials inherent resistance to crack growth and the stress at which the crack propagates at high speed is investigated. This is the main reason for the need of fracture mechanics for the evaluation of strength of the materials which maintain cracks inside.

2.2 Strength of Defect Free Solids

Strength is the resistance of a material to failure and denotes the stress at which the material fails either by fracture in brittle materials or by plastic deformation in ductile materials. On the atomic level when sufficient stress is applied, the fracture occurs by breakage of bonds holding atoms together. Consequently, the theoretical strength of an ideal (defect-free) body is found to be the stress that is required to break these bonds. The theoretical strength of materials is important in order to assess the potential for improvements in processing and design of structures, especially with the increasing interests in nanostructured materials. A detailed derivation of theoretical strength can be found in [2, 3, 4].

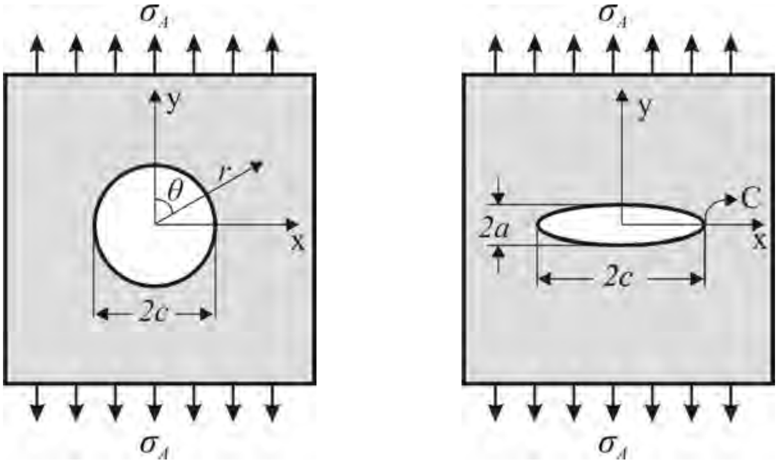
The theoretical strength σ_{th} of a material can be calculated as

$$\sigma_{th} = \sqrt{\frac{E\gamma}{b_0}} \tag{1}$$

where E is the Young's modulus, γ is the specific surface energy per unit area and b_0 is the interatomic spacing at equilibrium. The high theoretical strength would appear to be favoured by large Young's modulus E, large specific surface energy γ and by close packing of atomic planes. Mecholsky [5] estimated the theoretical strength to be between the commonly quoted values of E/π and $E/8$. For polycrystalline ceramics, values of E are typically in the range 100 - 500 GPa.

2.3 Stress Concentrators

Some experimental measurements [6, 7, 8] performed with different ceramics, namely Al_2O_3, Si_3N_4 and SiC showed that the real strength of the ceramics are lower than the theoretical strength by a factor of 100 to 1000. This difference was experimentally explained for the first time by Griffith [8] who has made some experiments with glass threads of varying diameters. He proved that this discrepancy is due to the stress concentrations around small cracks or similar flaws, the presence of which can hardly be avoided. These small cracks cause a local stress concentration at the crack-tip which is several times higher than the applied stress and the crack grows when the stress at crack-tip is equal to the theoretical strength.
In 1898, Kirsch [9] derived the stress distribution around a circular hole and obtained a solution for the influence on the stresses of a hole with a radius of c placed in a much larger plate (see Fig. 3(a)) under remotely applied uniform tensile stress σ_A.



(a) (b)

Figure 3: (a)Plate containing a hole subjected to uniform applied stress, (b)Plate containing an elliptical cavity subjected to uniform applied stress

He started with the *Airy stress function* which introduces a general framework for two-dimensional problems and accomplished the stress field in an infinite plate containing a circular hole in polar coordinates as

$$\begin{aligned} \sigma_{rr} &= \frac{1}{2}\sigma_A \left[\left(1 - \frac{c^2}{r^2}\right) + \left(1 + \frac{3c^4}{r^4} - \frac{4c^2}{r^2}\right) \cos 2\theta \right] \\ \sigma_{\theta\theta} &= \frac{1}{2}\sigma_A \left[\left(1 + \frac{c^2}{r^2}\right) - \left(1 + \frac{3c^4}{r^4}\right) \cos 2\theta \right] \\ \sigma_{r\theta} &= -\frac{1}{2}\sigma_A \left[\left(1 - \frac{3c^4}{r^4} + \frac{2c^2}{r^2}\right) \sin 2\theta \right] \end{aligned} \tag{2}$$

where r is the polar radius and θ is the polar angle. The circumferential stress $\sigma_{\theta\theta}$ takes its maximum value for $\theta = \pi/2$ or $\theta = 3\pi/2$ and $r = c$. Using Eq.(2) if $r \to \infty$ then the maximum circumferential stress becomes the uniform applied stress, i.e. $\sigma_{\theta\theta} \to \sigma_A$ and if $r = c$ and $\theta = \pi/2$ then the maximum circumferential stress reads $\sigma_{\theta\theta} = 3\sigma_A$ which means that the *stress concentration factor* (SCF) is equal to 3. An important result of the Kirschs solution is that the SCF does not depend on the size of the hole. Any hole, no matter how small, increases the local stresses by a factor of three.

In 1913, Inglis [10] extended the Kirschs work to treat the stress field around a plate containing an elliptical cavity as shown in Fig. 3(b). This provides crack-like geometries to be handled by making the minor axis of the ellipse small. It is considered that an infinite plate containing an elliptical cavity with a major axis of $2c$ and a minor axis of $2a$ is subjected to a uniform applied tension σ_A along the y-axis. The maximum stress occurs at point C and is equal to

$$\sigma_C = \sigma_A \left(1 + 2\frac{c}{a}\right) \tag{3}$$

Note that the formula given in Eq.(3) recovers the stress concentration solution of a circular hole when $a = c$. An alternative representation can be achieved by introducing a radius of curvature ρ

$$\sigma_C = \sigma_A \left(1 + 2\sqrt{\frac{c}{\rho}}\right) \tag{4}$$

where

$$\rho = \frac{a^2}{c} \tag{5}$$

The result of Inglis predicts that sharp voids are worse than rounded ones (i.e. the local stress increases with decreasing radius of curvature ρ).