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KOMMENTAR CRITIQUE VIEWPOINT

How can we improve the (mechanical) reliability of ceramic components?

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Wie kann die (mechanische) Zuverlässigkeit der keramischen Bauteile verbessert werden?

Comment améliorer la fiabilité (mécanique) des pièces céramiques?

Introduction

As all ceramists know, a strong relationship exists between the processing and properties of ceramics. This relationship is particularly significant in dealing with the question of reliability, which was addressed in a workshop during the 2nd European Ceramic Society Conference, held in Augsburg, Germany, 11–14 September 1991. Although it was not stated explicitly during the conference, reliability was assumed to be mechanical reliability.

In this note, it is intended to make a few remarks on the most important aspects of reliability. These remarks are made from the viewpoint of a ceramist dealing with mechanical behaviour and having some experience in processing. The discussion will be limited to (semi-) brittle behaviour. Some of the remarks, in particular those more distant from my immediate practical experience, will be overstated in order to encourage discussion. In order to assess the various issues relevant to the problem, an attempt is made in Fig. 1 to put some structure in the discussion. The metaphor used is a tree, the reliability tree. The various branches and twigs grow, dependent on each other but not necessarily knowing very much of one another. Moreover they tend to grow apart. The basic division in reliability is between materials and design. Relating various branches of the tree to the strength equation, which relates fracture and residual stress, defect size and a material's properties, a division (Fig. 2) can be seen: the right-hand side deals with materials while the left-hand side deals with the design. In the following, the division as indicated in the tree is closely followed.

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Materials

Within the materials branch, processing, machining and non-destructive evaluation (NDE) are the main items.

Non-destructive evaluation

A multitude of NDE methods exist, e.g. X-ray techniques, ultrasonic techniques (US), optical techniques (OM). It seems that the defects that are relevant in ceramics ($< 100\,\mu m$) are still too complicated for NDE. It has been stated that the problem of small defect size can be solved though at considerable cost. It seems also that considerable time is involved. For routine checks, only macro-NDE is economically feasible. Therefore we have to lower the price and increase the speed before full scale implementation is possible. **At present NDE for small defects plays no significant role.**

Processing

Processing deals with improvement of existing fabrication technologies and the invention of new

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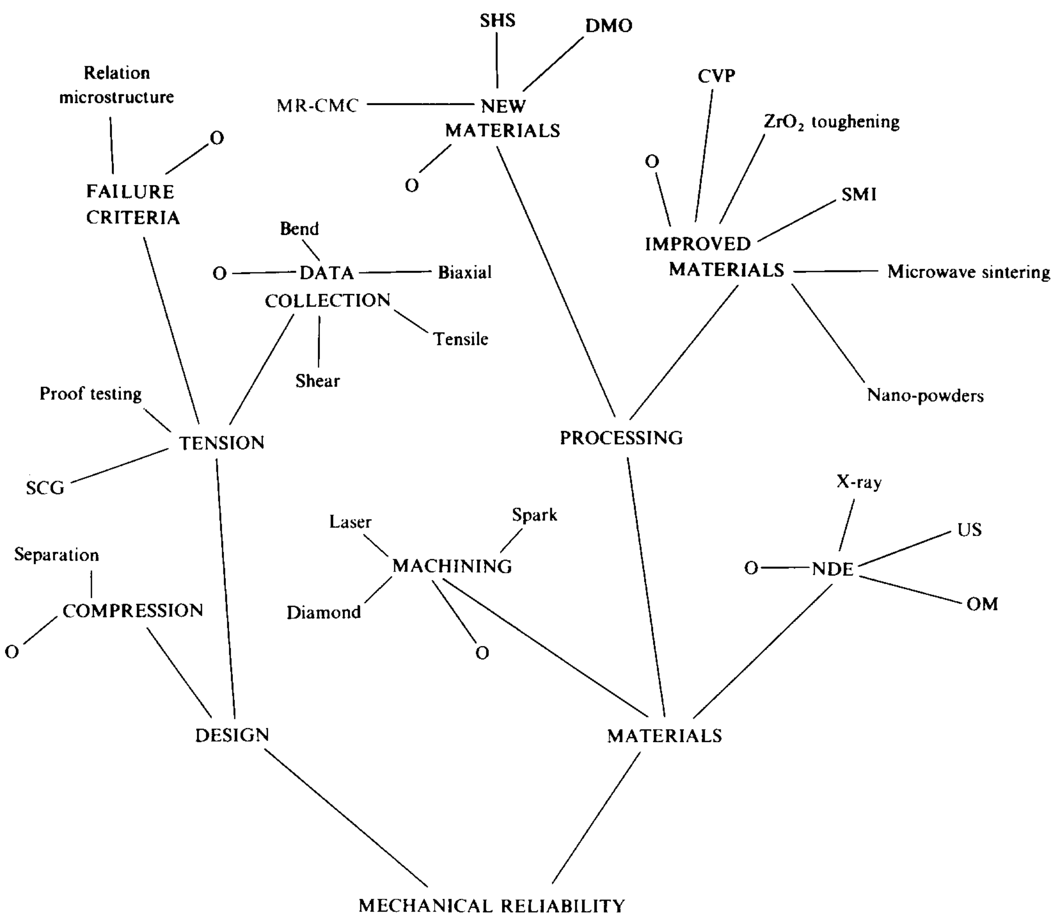

Fig. 1. The reliability tree. Missing items are indicated by O.

ones. Systematic improvement of microstructures (SMI) through better control of powders, consolidation and sintering is an economically attractive route. It seems, however, that in many cases only small improvements are brought about. Therefore the realisation of new processing routes and principles is of the utmost importance. However, many of the new routes are intrinsically of a high cost, e.g. nano-sized powders, chemical vapour precipitating powders (CVP). Others seem more cost effective, e.g. self-propagating high-temperature synthesis (SHS), direct melt oxidation (DMO). Also metal-reinforced ceramic matrix composites (MR-CMC) are interesting for low and intermediate temperature applications. **Attention to intrinsically cost effective processes will be most rewarding.**

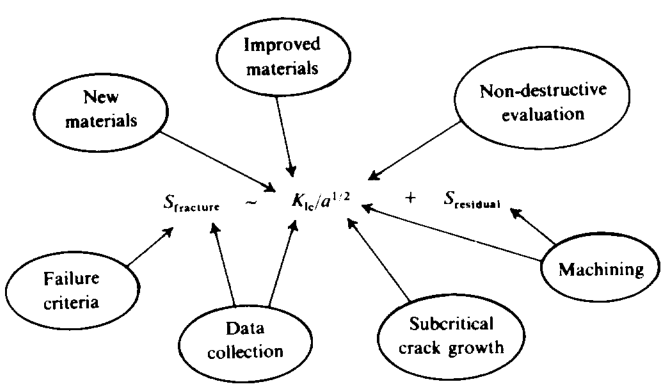

Fig. 2. The main influences of the various branches of the reliability tree on the strength, $S_{fracture}$, of ceramics. The fracture toughness, K_{Ic}, the defect size, a, and the residual stress, $S_{residual}$, are all affected though by different branches.

Although not entirely the area of ceramics, joining of metals to ceramics is important. At present the Weibull modulus of joints is far below that of monolithics. Therefore metal ceramic joining techniques should be improved.

Machining

Although (near) net shape processing is a popular goal, machining remains an important issue. The reproducibility of machining processes should be increased. This applies to the conventional diamond machining as well as to more modern techniques like laser cutting. There has been too little interest from materials people in machining. **There is a need for better characterization techniques for machined surfaces in relation to the mechanical properties.** This characterization should include damage as well as residual stress introduced during machining. Normalization of the machining procedure for test pieces is therefore relevant as long as the influence of machining is not fully understood.

Design

Within the design branch we can distinguish between compressive and tensile loading.

Compression

A simplistic view in design in ceramics would be to design everything in compression. Sometimes this is feasible, e.g. shroud rings. In other cases a separation of functions can be pursued, e.g. a metal part loaded in tension and a ceramic part loaded in compression. Here a lot can be learned from nature. Natural geometries as encountered in wood and the human body can offer substantial advantages.

Tension

Although 'design in compression' is a solid piece of advice, following this advice is not always possible. We have to be able to deal with tensile loaded structures. In many applications nowadays, not only in the field of structural ceramics but notably in the field of functional ceramics, tensile stresses are present. From the many examples that can be quoted I only mention a few: actuators (bending stress), capacitors (thermal shock and bending stress), discharge lamp envelopes (thermal shock and thermo-mechanical load) and resistors with a positive temperature coefficient (thermal shock and thermo-mechanical load).

The first item that comes to mind is data collection. Conventionally this is done by bend testing, occasionally assisted by tensile testing or bi-axial testing. **The need for a carefully selected set of accurate strength measurements in order to characterize the strength of ceramics in multi-axially loaded situations is clearly present.**

A second item is the choice of the failure criteria involved. At present no unequivocal choice for failure criteria can be made. Essential in this is the definition of an appropriate effective stress in ceramics, comparable to the von Mises stress in metals. **The definition of such an effective stress, suitable for design purposes, is highly desirable.** It would be very helpful if, from an analysis of the microstructure, a proper choice for the effective stress could be made. Highly connected is the problem of extrapolation from a limited set of test specimens to high survival probabilities.

In addition to momentary fracture, subcritical crack growth (SCG) is most relevant. It is known that the conventional description in terms of a power law is unsatisfactory. Better based descriptions in terms of exponentials in stress are not fully developed. Moreover, the choice of effective stress is again relevant.

Prooftesting is often advocated as a solution to uncertainties in design. The main problem is to apply a load to a component in such a way that stress is raised a certain percentage homogeneously throughout the structure as compared with the actual situation. This is rather difficult and can only be realized for essentially tensile loaded components, e.g. optical fibres. Moreover subcritical crack growth during unloading may spoil the prooftest. For a homogeneously overloaded component the failure criterion is not important for the failure prediction. For inhomogeneous overloading the failure criterion enters the prooftest theory and the intrinsic advantage is lost. Therefore **prooftesting plays only a minor role at present**. For metal–ceramic joints similar arguments hold.

What To Do?

First of all, from the above it is clear that more reproducible, i.e. reliable, materials at a lower cost level must become available. Reproducibility can be best guaranteed by intrinsically stable processes, that is processes in which minor changes of the settings do not influence the properties of the resulting materials significantly. Therefore we have to look primarily for this type of process. Moreover, processing improvements and innovations must, from the very beginning, take the aspect of cost into consideration.

Secondly, a better awareness of the vices and virtues of ceramics on all levels would be very helpful. Let me quote two examples. The first, about 10 years ago, deals with hexa-ferrites for car starting motors. All requirements for the application are met except one. Adjusting the position of a starter motor in the garage is usually done with the first hammer within reach. The resulting impact is the only loading the ceramic does not survive. The second, about one year old, deals with silicon carbide pistons for the sugar industry. Steel pistons have to be replaced every week due to corrosion and wear. A silicon carbide piston has a lifetime of about a year. Checking the piston makes it necessary to unscrew the part. In case of a tightly fixed part, a blow with a hammer is used to 'frighten' the part which, for metals, usually has no detrimental effect. But again this is the only load the ceramic does not survive. In both cases a better awareness of the brittle behaviour of ceramics could have avoided the problem. Many other, though similar, events have been reported, usually in an anecdotal way. The awareness can only be created by proper education at all levels.

Thirdly, there is a need for cross-trained people in order properly to assess the variety of aspects that have to be considered. Engineers should know more of materials while material scientists should know more of engineering. Understanding each other's problems and capabilities is only possible if sufficient overlap in knowledge is present. Again this is a matter of education.

In conclusion, there is still a long way to go and there are many things that can be done. It seems, however, that some well-founded choices can be made. My choices have become clear. A brief summary is given in Table 1.

Table 1. Branches considered important for improved reliability

Materials	Processing	Cost effective new routes, e.g.
		Self-propagating
		High-temperature synthesis
		Direct-melt oxidation
		Metal-reinforced ceramic matrix composites
		Systematic microstructure improvement
		Metal–ceramic joining
	Machining	Characterization
		Normalization
Design	Tension	Data collection
		Failure criteria
		Subcritical crack growth