Weakest-link failure prediction for ceramics

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WEAKEST-LINK FAILURE PREDICTION FOR CERAMICS

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ABSTRACT

Detailed problems associated with measurement and interpretation of the bend strength of ceramics are presented. The relationship between 3- and 4-point bend and biaxial test results is discussed in the light of current theoretical understanding. There remain a number of unresolved aspects and a new, 'damage mechanics' approach is mooted for further consideration.

INTRODUCTION

Weakest-link failure prediction for components is usually based on data obtained from 3- or 4-point bend tests but several pitfalls are encountered. First, the bend tests themselves have problems, not only due to the limited volume tested but also to the test procedure and the quality of the specimen surface. Once these data are reliably generated, the next question is the transformation of these uni-axial data to multi-axial data, but no universally applicable relation is yet available. In the next section we discuss the problems associated with the bend test and the transformation of uni-axial to multi-axial data. Once this procedure has been carried out, further problems emerge; it is concluded that alternative approaches may be worthy of consideration. Here we propose a damage approach based on microstructural insights and anisotropic deformation behaviour.

BEND TESTS

The problems associated with bend tests can be divided into three categories. Firstly, the problems directly related to the actual execution of the test:

- the application of simple beam theory
- friction effects at the supports
- local stresses at the supports
- unequal applied moments
- twisting and wedging of the specimen.

The problems associated with the performance of the test have been dealt with adequately (1-2). The general conclusion is that it is possible to obtain data reliable to about 1% if and only if all the above mentioned effects are taken into account properly.

Secondly, the problems related to the surface condition of the specimens. Here we refer to:

- roughness of the specimen surface
- damage introduced during grinding
- residual stresses in the specimen surface
- significance of the specimen surface for the actual component.

The situation here is less clear. Often for a component a certain (low) surface roughness is demanded. This is usually obtained by grinding and, if necessary, subsequent polishing. The surface damage introduced during grinding is not removed during polishing. Experiments with polished specimens show that by polishing the strength is increased somewhat but also that the Weibull modulus decreases. Moreover due to grinding, compressive residual stresses can occur which may disappear either partially or wholly during polishing.

Possibilities exist to improve the strength of specimens (and components) e.g. by ion implantation or by ductile or 'damage free' grinding. The former method (6) tries to remedy the damage done during grinding by introducing compressive stresses into the surface and, possibly, rounding off of the defect tips and healing of the defects. This has resulted in a higher strength (about 15%) and Weibull modulus (about 100%) for materials implanted with a dose of about 10^{17} cm^{-2} of noble gas ions. The latter method (4) is in principle much better suited since it minimizes the damage introduced during normal grinding. This can be realized by using an extremely stiff machine with 0.1 μm positioning capability and highly developed grinding wheel technology. Moreover, very low feed rates and cutting depths are used. Using this technique (4) for a particular type of sialon, an increase in strength from 480 for normally ground material to

875 MPa for ductile ground material was observed. Also the roughness decreased from 0.35 μm to 8 nm.

Residual stresses are important to consider. Unfortunately only for a few materials a more or less complete analysis of the residual stresses is performed, but these few studies indicate that a substantial influence is possible. For certain materials which show a phase transformation, e.g. ZrO_2 or $BaTiO_3$, the influence can be even larger due to the difference in thermal expansion coefficient and specific volume for the two phases involved.

Probably superfluously, it should be remarked that all predictions for components can only be done reliably if the surface of the component has received the same treatment as the specimens tested.

Thirdly, all aspects related to the interpretation of the test data. Here we can refer to:

- estimation of the failure probability
- extraction of the model parameters by different methods like least-squares, maximum-likelihood or method of moments.

A concise survey of these aspects has recently been given (7).

MULTI-AXIAL STRESSES

After the completion of the data collecting procedure and the identification of the type (surface or volume) and number of defects involved, a procedure is required to transform the uni-axial data into multi-axial data. For this transformation stress volume/surface integrals from the bend test have to be known. It has been shown (3) that the information from bend tests can be generated by using the analytical formulae for the stress integrals, within an error of $\sim$ 1%. Thus no finite element calculations are necessary, at least if the bend test specimen satisfies certain size requirements.

Unfortunately, once these integrals are given, no general prescription exists how to apply them to a multi-axial stress state. Even for a transformation to a bi-axial situation the situation is not clear (5). Well known are the models of Weibull (normal stress criterion), Stanley (independent stress criterion) and Lamon (maximum strain energy release rate criterion). On the assumption that 4-point bend data are available, these models do predict identical results for 3-point bend test. However, for the equi-biaxial stress state, e.g. as used in a ball-on-ring test, the situation is completely different. The estimated strength for the ball-on-ring test from 4-point data can differ as much as 10% for the three models, dependent on the value of the Weibull modulus, Figure 1. This may not seem large but it must be recognized that these differences lead to far larger differences in the failure probabilities, e.g. a factor 10. Experimental work to establish whether a certain model is applicable and under what conditions is necessary. Extension to multi-axial stress states is the next aspect to consider.

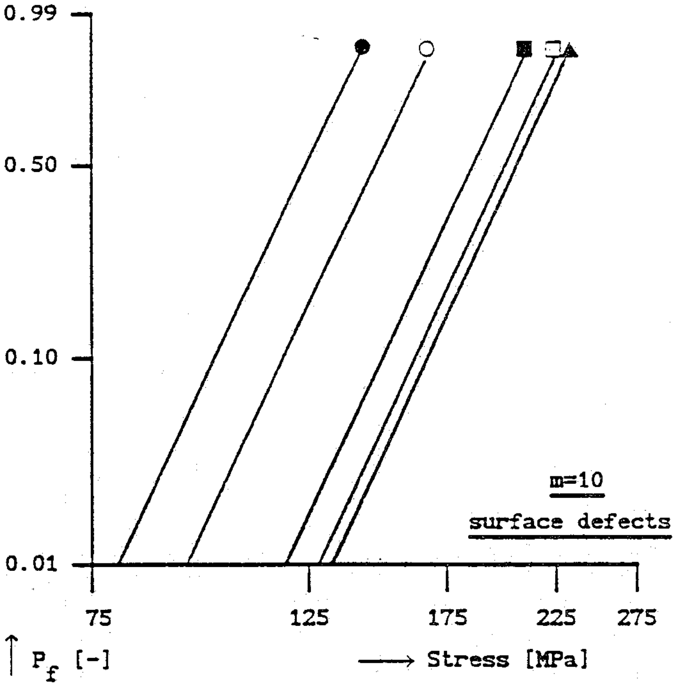

Figure 1. Weibull plot with predictions for models of Lamon, Stanley and Weibull for uni-axial (3- and 4-point) and bi-axial (ball-on-ring) bend tests: ● = 4-point bend test; 0 = 3-point bend test; □ = ball-on-ring test model of Lamon; Δ = ball-on-ring test model of Stanley; ▨ = ball-on-ring model of Weibull.

FURTHER PROBLEMS

Even if the problems with the statistical approach could be solved, some remaining items remain unaddressed. To mention just three:

- slow crack growth
- corrosion
- creep.

The first two phenomena change the nature of the defects continuously during loading in ways that are not completely defined. Introduction of these aspects into a statistical approach seems cumbersome. While slow crack growth and corrosion can operate at room temperature, creep operates only a high temperature. Again incorporation into the statistical approach seems rather difficult. Separate approaches are therefore necessary for mechanically loaded components when the above mentioned phenomena play an important role. From the problems encountered it seems fair to conclude that alternative solutions would be welcome.

A POSSIBLE ALTERNATIVE

The statistical approach is based on fracture mechanics applied to microscopic defects. It neglects to a large extent the information that is available from the microstructure of the tested specimens. A completely opposite approach is continuum damage mechanics (8). In this formalism, in its simplest form, a damage parameter is introduced describing the amount of isotropically distributed damage in the material. An associated damage evolution law is postulated. When a certain critical value for the damage parameter is reached, the material fails. Originally the theory was completely phenomenological; no clear statements were made about the nature of the defects or the basis of the damage evolution law; the information from microstructures was neglected. Recently, however, some micromechanical models have been put forward which can form a basis for the constitutive behaviour of brittle materials (9-10). A combination of the constitutive behaviour of these models with continuum damage mechanics could result in a 'damage mechanics' approach, taking into account microstructural data but nevertheless firmly rooted in an anisotropic continuum deformation theory. It is clear though, that the success of such an approach is critically dependent on the possibility of extracting from microstructural analysis the relevant parameters in a concise form.

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