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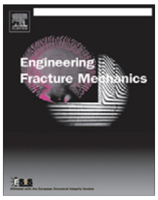

# Reliability prediction for contact strength and fatigue of silicon nitride high strength components using an R-curve approach

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ABSTRACT

The following paper will highlight the contributions of probabilistic reliability assessment to the failure prediction of brittle materials exhibiting so-called R-curve behaviour. Experimental findings of the authors and in the literature are related to the stepwise refinement in the accuracy of numerical approaches. Special emphasis is put on the fracture mechanics description using the weight function approach and corresponding modifications in the weakest link formulation of the failure prediction. As a verification example, a contact fatigue experiment is used to assess predictions of the weakest link finite element post-processor STAU.

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## 1. Introduction

The present status of reliability analysis for load-bearing components fabricated from high-strength engineering ceramics like silicon nitride, silicon carbide and other non-oxide ceramics is the result of a long series of empirically based investigations, directed research, and, finally, numerical modelling, all going more or less in parallel and with more or less consideration of the respective different approaches.

The purpose of the following paper is to highlight the current status of fracture mechanics based reliability analysis of high-strength ceramics using weakest link ideas based on advanced variants of the Weibull theory. This kind of approach has a long history, starting with very general arguments on weakest link failure for cotton yarn [1], glass [2], or generally stress dependent failure description for static fracture [3,4] or fatigue failure [5]. A more detailed fracture mechanics treatment of the material flaws that lead to failure of a component under sustained loading was obtained by a fracture mechanics treatment of the flaws as micro-cracks [6–9]. For time-dependent (static or cyclic) loading, mechanism-based models for the kinetics of crack propagation [10–12] allow a model-based prediction of complex-shaped engineering components under transient loading. The relevant inert strength data base is usually obtained from four-point bending tests giving the characteristic strength together with the Weibull modulus. Fatigue crack propagation data is obtained from lifetime tests under a constant amplitude using a special evaluation procedure [13]. Parallel to the development of understanding of the physical mechanisms of crack propagation and fracture, numerical tools for reliability assessment were developed. First attempts to relate R-curve behaviour to strength characteristics were mainly based on analytical approaches thus limited to relatively simple static mechanical loading conditions [14]. Presently, weakest link finite element postprocessors like STAU [15] and CARES/Life [16] provide reliability analysis of components under complex transient thermo-mechanical static and cyclic loading. However, incorporation of high-strength micromechanical properties into numerical assessment of crack propagation [17–19] and reliability [20–22] requires an advanced fracture mechanics description of the failure behaviour of micro-cracks in the vicinity of stress concentrators, e.g., in the case of thermal or contact loading [23] or for failure due to interface

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## Nomenclature

| | |
|---|---|
| $a$ | crack size |
| $a_c$ | critical crack size |
| $A$ | surface area of the component |
| $A_0$ | unit area |
| $C_1$, $C_2$ | fit parameters for R-curve |
| $D_n$ | coefficients for the weight function series |
| $E'$ | plane strain Young's modulus |
| $F$ | load |
| $F_C^{(i)}$ | maximum load in cyclic test |
| $h$, $h_{edge}$ | weight function |
| $K_{I\ appl}$ | applied stress intensity factor |
| $K_{I\ br}$ | bridging part of the stress intensity factor |
| $K_{I\ tip}$ | crack tip stress intensity factor |
| $K_{Ic}$ | fracture toughness |
| $K_{IR}^{\mathrm{degr}}$ | degraded R-curve |
| $K_{I0}$ | intrinsic threshold value |
| $K_{I0}^{\mathrm{degr}}$ | intrinsic fatigue threshold value |
| $m$ | Weibull modulus |
| $n$ | crack growth exponent |
| $N$ | number of interpolation points |
| $N_C$ | number of load cycles to failure |
| $P_f$ | failure probability |
| $R$ | load ratio |
| $Y_I$ | geometry factor |
| $\delta$ | crack opening displacement |
| $\delta_0$ | parameter of bridging stress function |
| $\delta_0^{\mathrm{degr}}$ | parameter of bridging stress function for the degraded R-curve |
| $\Delta a$ | crack extension |
| $\lambda_1$, $\lambda_2$ | fit parameters for R-curve |
| $\mu$ | friction coefficient |
| $\sigma_{appl}$ | applied stress |
| $\sigma_{br}$ | bridging stress |
| $\sigma_{eq}$ | equivalent stress |
| $\sigma_0$ | characteristic Weibull strength |
| $\sigma_0$ | parameter of bridging stress function |
| $\sigma_0^{\mathrm{degr}}$ | parameter of bridging stress function for the degraded R-curve |
| $\Omega$ | crack orientation |

cracks in ceramic joints [24]. For high strength industrial applications silicon nitrides are successfully used as ball bearing material, but also for, e.g., tools for high temperature applications like wire rolling [25,26]. The microstructure of silicon nitrides leads to crack bridging effects on a very short length scale of several microns. Crack bridging effects lead to so-called R-curve behaviour. Re-notching experiments by [27] gave first experimental evidence for rising crack resistance curves in alumina but did not reveal the exact mechanism of crack bridging. Crack bridges were first observed during in situ experiments by [11]. Its implications for static and cyclic crack propagation are extensively discussed by [28]. The effect of the local bridging stress field [29] for a single crack tip on the global fracture behaviour of a polycrystalline aggregate was considered by [30] using a random distribution for the characteristic range of bridging stresses. An extensive treatment on various general aspects of R-curve modelling and measurement is given in the review paper of [31]. For the special case of silicon nitrides [32,33,17,34] give experimental results and corresponding theoretical analyses.

In the following paper, we shall use results on R-curve behaviour of silicon nitride from the literature sources together with own results on contact strength and fatigue measurements to demonstrate how prediction of the failure probability of a component can be done using experimental results from bending tests on simple geometries. The contact strength and fatigue measurements will thus serve as a verification example for the reliability prediction. The strategy in setting up the prediction analysis as well as the limits will be described and implications on transferability of the results will be given. In dealing with fatigue prediction, fatigue effects will be predicted using a degraded R-curve approach with bridging stresses from R-curve analyses of pre-fatigued specimens [35].

The conventional Weibull theory is based on some simplifications regarding the fracture mechanics model: the stress over the dimension of a natural flaw is regarded constant. This leads to significant under-estimation of strength and lifetime for components under thermal shock or contact loading. An extended Weibull theory which allows for considering stress

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