FRACTURE OF SiSiC-CERAMICS UNDER BIAXIAL LOADING

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A new procedure was developed to proof the strength of engineering ceramics under biaxial loading. This test procedure enables simultaneous loading of thin-walled tubular specimens by internal hydraulic pressure and an axial force. Therefore realization of a wide range of biaxial stress states of combined tension/compression stresses is possible. First test results on dense and porous silicon infiltrated silicon carbide show different behaviour of the selected materials. Furthermore,fracture and strength of the tubular specimens are strongly dependent on applied stress ratio.

INTRODUCTION

The majority of potential engineering ceramic components are intended to serve under complex stress states. This lends extreme importance to the experimental determination of ceramic fracture conditions under multiaxial loading and to the development of adequate models for failure prediction, see for example Arone (1). By contrast, most experimental data on the strength of engineering ceramics relate to bending and to uniaxial compressive or tensile loading. The lack of reliable data on the mechanical behaviour of the engineering ceramics under multiaxial loading requires more effort to this problem.

Since the general multiaxial loading leads to complicated experiments and difficult interpretation of the results, usually biaxial stress states were prefered.

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The advantage of the tubular specimen tests combining pressuration and axial loading is due to the fact that significant stress gradients through the specimen thickness can be avoided if wall-thickness is small enough, and that a wide range of biaxial stress states can be achieved with one and the same specimen geometry. For this reasons a test system with combined internal hydraulic pressure and axial load was built up. The principles of operation are described elsewhere by Staskewitsch and Stiebler (2).

EXPERIMENTAL PROCEDURE

First series of tests were performed using three different stress ratios R:

$R = -\infty$ pure axial compression
$R = -3$ combined compression/tension
$R = 0$ pure tension by internal pressure

where R is defined as follows:

$$R = \frac{\sigma_z}{\sigma_\theta} \tag{1}$$

The loading velocities during the tests were chosen so that the specimen failure occured between 30 to 60 s. This time is short enough to avoid subcritical crack growth because SiSiC (silicon infiltrated silicon carbide) is not very sensitive to this effect, as shown by Röttenbacher and Heider (3). At the other hand time is long enough to control the test run.

Ten tension tests ($R = 0$) and biaxial tests ($R = -3$) on tubular specimen of dense and porous SiSiC-ceramics with 2.0 mm wall-thickness and 26.0 mm inner diameter were performed. To characterize the strength of the material the circumferential fracture stress at the inner side of the tubular specimen was calculated.

RESULTS OF BIAXIAL TESTS

The fracture strength of the dense SiSiC is plotted in Figure 1, where each circle represents one specimen loaded by pure tension ($R = 0$). The stars stand for the fracture strength of the biaxial tests with stress ratio $R = -3$. The dependence of the fracture probability from fracture stress is described by the following equation based on Weibull-statistics (4):

$$h = 1 - \exp\left[-\left(\frac{\sigma_{\theta f}(r_i)}{\sigma_0}\right)^m\right] \tag{2}$$

A special fitting procedure (maximum-likelihood-method) yields the parameters m and σ_0 so that the S-curves in Figure 1 can be plotted.

To characterize the tensile or compressive stress at fracture of investigated ceramics the value at the fracture probability of h = 0.5 (equivalent to 50 %) is chosen. In the following this value is designated as σ_{50}.

The test results of the porous SiSiC-ceramics (material was modified by flaws containing excessive carbon) are also shown in Figure 1. Each x-symbol represents the fracture stress $\sigma_{\theta f}(r_i)$ at the inner side of a tubular specimen broken by pure tension (R = 0). The cross-symbols reveal that superposition of a compressive stress, in the course of biaxial testing with stress ratio R = -3, lowers the tensile fracture stress. The S-curve is shifted to smaller stress values.

Plotting the double ln of $(1 - h)^{-1}$ versus ln of fracture stress the S-curves change into straight lines, Figure 2. The slope of the lines correspond to the Weibull modulus m, which is used to describe scattering of strength as a material specific parameter. The lines for the porous material and the line for the dense material tested biaxially are nearly parallel, that means, m is in a good agreement, if the small number of tests is taken into account. Only the dense SiSiC under pure tension loading shows a distinct smaller slope, indicating a small Weibull modulus and more variable fracture stresses.

Characteristic material data of the dense and porous SiSiC are summarized in a compressed form in Table 1.

TABLE 1 - Mean values of fracture strength σ_{50}, Weibull modulus m and parameter σ_0 of dense and porous SiSiC-ceramics

material	stress ratio R	σ_{50} (MPa)	m	σ_0 (MPa)
dense SiSiC	0	173	4	190
dense SiSiC	-3	207	12	213
dense SiSiC	$-\infty$	4120	24	4180
porous SiSiC	0	157	16	161
porous SiSiC	-3	117	12	121

Under pure compression the dense SiSiC-ceramic showed fracture stresses exceeding 4000 MPa. Due to the limited capacity (max. 400 kN) of the universal testing machine a reduction of the wall-thickness from 2.0 mm to 0.8 mm was necessary for this kind of testing. Furthermore it was expected that the flaws contained in the porous material would reduce the strength dramatically, say to the half. First compression tests on porous material however did not show this effect. Consequently the wall-thickness of this tubular specimens have to be reduced, too.

DISCUSSION & CONCLUSIONS

Two different types of silicon infiltrated silicon carbide (SiSiC-) ceramics were chosen for this investigations. Besides the dense material,a porous material - modified by flaws containing excessive carbon - is used. From the results of biaxial tests of the porous SiSiC-ceramics it can be seen that superposition of a compression stress reduces the tensile fracture strength as expected. For a stress ratio R = -3 the S-curve is shifted nearly parallel to the curve corresponding to R = 0 in the domain of lower fracture strength. Therefore the characteristic strength σ_{50} is reduced by 40 MPa (see Table 1). In contrast to this the curves of the dense SiSiC-ceramics crosses at high stresses and σ_{50} of the biaxial tests exceeds that of the pure tension tests about 34 MPa.

Comparison of the tensile fracture strength from Table 1 shows, that σ_{50} of the dense material exceeds the strength of the porous material for both stress ratios.

The scatter of the fracture stresses, described by the Weibull modulus m between 12 and 16, lies in a medium range compared with ceramics available on the market.

Tension tests (R =0) of dense material represent an exception. In this case the Weibull modulus of about 4 indicates a large variation of fracture stresses. The reason for the unexpected behaviour of the dense material is not explicable yet. Maybe residual-stresses from machining or anisotropic microstructure from manufacture causes the difference. But also other possibilities connected with experimental procedure or specimen-design have to be taken into account. Therefore further investigations and more tests for a fully statistical treatment of data are necessary.

For strength and reliability assessment results of the biaxial tests have to be incorporated into calculations for determination of limiting fracture surfaces corresponding to different reliability levels.

SYMBOLS USED

h = fracture probability

m = Weibull modulus

r = radius of the tubular specimen (mm)

r_i = radius at the inner surface (mm)

R = stress ratio

σ_z = axial stress (MPa)

σ_θ = circumferential stress (MPa)

$\sigma_{\theta f}(r_i)$ = circumferential fracture stress at $r = r_i$ (MPa)

σ_0 = parameter (MPa)

σ_{50} = fracture strength at $h = 0.5$ (MPa)

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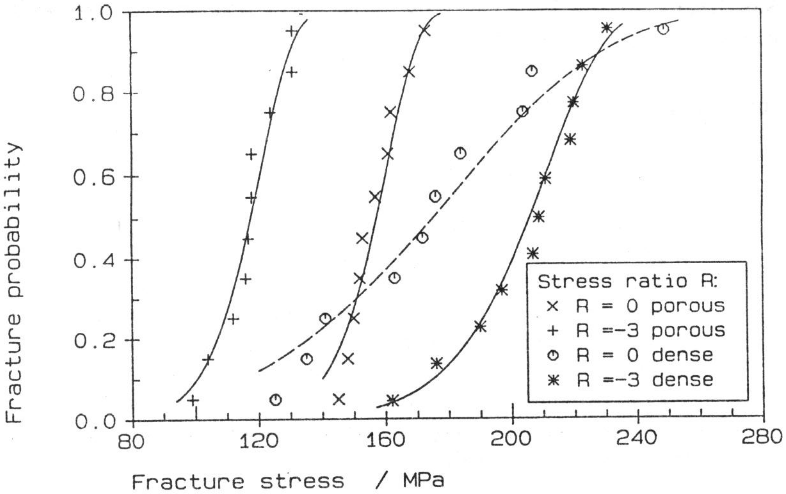

Figure 1: Fracture probability h as function of fracture stress $\sigma_{\theta f}(r_i)$ for dense and porous SiSiC-ceramics. Tubular specimen were loaded by tension (R = 0) and combined tension/compression (R = -3).

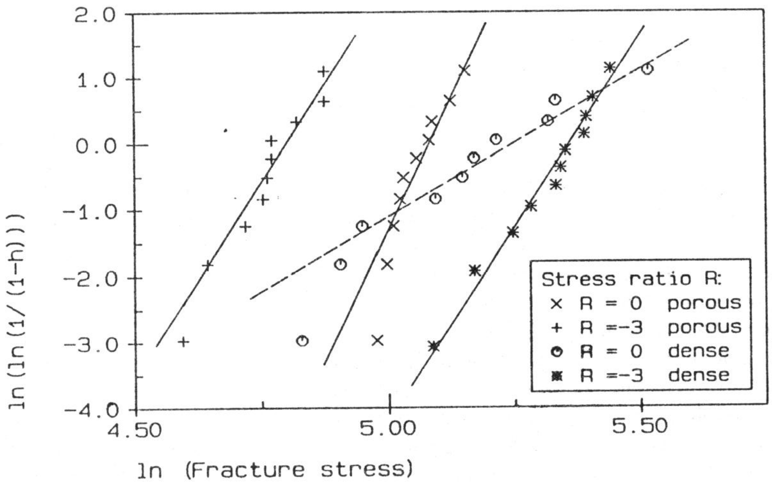

Figure 2: Weibull-plots of all tension and biaxial tests done on dense and porous SiSiC-ceramics