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FAILURE ANALYSIS OF TEXTILE-REINFORCED CERAMIC MATRIX COMPOSITES

The high lightweight potential of modern long-fibre reinforced ceramics for the application in components under complex thermo-mechanical loads can only be used optimally, if the anisotropic fibre reinforcement is designed according to the acting loads. For the component optimisation adapted analytical and numerical simulation techniques as well as suitable realistic failure criteria are required. By applying analytical and numerical computing methods developed so far for fibre- and textile-reinforced ceramics, the thermo-mechanical induced stresses and strains can be sufficiently determined. In contrast, undertaking the failure analysis adapted to textile ceramic structures still remains a source of considerable difficulty. One principal reason for this is that the use of the „homogenisation technique" in the sense of a „blurred" continuum is not permissible for a realistic description of the fracture behaviour of textile-reinforced ceramics. The often applied generalising fracture criteria, such as, for example, the quadratic failure criteria of Sacharov and Tsai-Wu cannot be used to simulate the actual fracture behaviour realistically and there remains a great uncertainties in the interpretation of the results of fracture tests. Only the development of a new type of so-called fracture mode criteria can enable a physically based description of the prevailing failure modes of fibre- and textil-reinforced ceramics. Subsequently, the action plane criterion of Hashin-Puck and the invariant criterion of Cuntze are applied to the failure analysis of fibre- and textile-reinforced SiC ceramics and correspondingly modified.

The objective of this paper is to improve the strength analysis of fibre- and textile-reinforced ceramic structures applying novel fracture mode related failure criteria. By means of multi-axial failure tests carried out on reinforced ceramics, the failure mode criteria were able to be verified in the (σ_2, τ_{21})- and (σ_1, σ_2)-stress planes.

Key words: **ceramic composites, failure behaviour, simulation, verification**

ANALIZA PĘKANIA KOMPOZYTÓW CERAMICZNYCH WZMOCNIONYCH WŁÓKNAMI TEKSTYLNYMI

Właściwości nowoczesnych materiałów ceramicznych wzmocnionych włóknami tekstylnymi stwarzają potencjalne możliwości konstruowania ultralekkich elementów, podlegających złożonym naprężeniom termomechanicznym. Potencjał tych materiałów może być optymalnie wykorzystany tylko wtedy, jeżeli cechy ich anizotropowego wzmocnienia włóknistego dobrane zostaną na podstawie występującego stanu naprężeń. Optymalizacja konstrukcji wymienionych elementów wymaga zastosowania odpowiednich analitycznych i numerycznych technik symulacji oraz realistycznych kryteriów zniszczenia. Istniejące metody obliczeń naprężeń i odkształceń pozwalają na ich wystarczająco dokładne określenie. W odróżnieniu od tego analiza pękania rozważanych materiałów stwarza istotne problemy. Wynika to z faktu, że zastosowanie „technik homogenizacji" nie pozwala na rzeczywisty opis zniszczenia w tych materiałach. Często stosowane uogólniające kryteria zniszczenia, takie jak np. kwadratowe kryterium Sacharowa i Tsai-Wu również nie pozwalają na uzyskanie dokładnych wyników. Jedynie rozwój nowego typu kryteriów zniszczenia uwzględniających tzw. tryby pękania może prowadzić do uzasadnionego fizycznie opisu materiałów ceramicznych wzmacnianych włóknami i tkaninami w realnych warunkach zniszczenia. Następnie, zastosowano kryteria Hashin-Puck i kryterium wartości niezmiennych według Cuntze do analizy uszkodzeń zaistniałych we wzmacnianych włóknami i tkaninami SiC i odpowiednio je zmodyfikowano.

W artykule przedstawiono ulepszoną metodę weryfikacji wytrzymałości jedno- i wielowarstwowo wzmocnionych struktur ceramicznych przy zastosowaniu nowych kryteriów zniszczenia uwzględniających różne rodzaje pękania materiału. Wieloosiowe próby wytrzymałościowe, przeprowadzone na kompozytach ceramicznych, pozwoliły zweryfikować wyżej wymienione kryteria w płaszczyznach naprężeń (σ_2, τ_{21}) i (σ_1, σ_2).

Słowa kluczowe: **kompozyty ceramiczne, mechanizm pękania, weryfikacja doświadczalna**

INTRODUCTION

The design of complexly loaded components made of textile-reinforced ceramic composites requires reliable dimensioning concepts in order to take best advantage of the high degree of lightweight potential inherent in these new group of high temperature materials. By applying analytical and numerical computing methods developed so far for fibre- and textile-reinforced ceramics, the thermo-mechanical induced stresses and strains can already be sufficiently determined [1].

In contrast, undertaking the failure analysis adapted to textile ceramic structures still remains a source of

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considerable difficulty. One principal reason for this is that the use of the „homogenisation technique" in the sense of a „blurred" continuum is not permissible for a realistic description of the fracture behaviour of textile- -reinforced ceramics. Experiences show that the failure of fibre ceramic composites initially takes place at the heterogeneous microlevel, and it is in particular the micro- -structural failure mechanism that takes on importance.

Although the micro-mechanical act of fracture has been extensively analysed in numerous studies and has also been realistically described using physically plausible models, only so-called „generalising fracture criteria" are currently applied to the description of heterogeneous anisotropic textile ceramics, which assume a non-permissible observation of a completely „blurred" fibre matrix continuum without considering the micro-mechanic effects. The often applied generalising fracture criteria, such as, for example, the quadratic failure criteria of Sacharov and Tsai-Wu combine fundamentally different fracture modes in an approximate comparison in the form of interpolation polynomials. However, this method cannot be used to simulate the actual fracture behaviour realistically and there remains a great uncertainties in the interpretation of the results of fracture tests.

The objective is therefore to improve the computed verifications of strength of single and multi-layered fibre- and textile-reinforced ceramic structures based on micro-mechanical phenomena as viewed from a macro-mechanical engineering perspective. In this regard the Institut für Leichtbau und Kunststofftechnik (ILK) at the Dresden University of Technology within the framework of a research project [2] sponsored by the Deutsche Forschungsgemeinschaft (DFG), is employing for the first time novel, physically based failure criteria established by Hashin-Puck and Cuntze, that enable not only the determination of the relative material loading, but also a differentiation between the fracture modes.

FRACTURE MODE CRITERIA

Only the development of a new type of so-called fracture mode criteria can enable a physically based description of the prevailing failure modes of fibre- and textil-reinforced ceramics using realistic fracture conditions. Subsequently, the action plane criterion of Hashin-Puck and the invariant criterion of Cuntze are applied to the failure analysis of fibre- and textile- -reinforced SiC ceramics and correspondingly modified.

The action plane related fracture criterion of Hashin-Puck

In order to formulate the action plane related fracture criterion for an evaluation of the 3D stress states, Hashin-Puck have introduced a completely novel approach in respect of the standard generalising interaction criteria. This criterion allows not only the critical difference between the fracture modes „fibre failure" (FF) and „inter-fibre failure" (IFF), but also incorporates, in addition, a fracture angle as a free parameter that characterises further fracture modes in the fibre-parallel plane. Furthermore it is observed that in accordance with the expected mechanical properties of the material and the phenomenological observations as well as in unison with experiments, compression stresses vertical to the fibres prevent inter fibre failure from developing. The starting point for such an approach has already been made by Mohr, who has formulated the following fracture hypothesis for brittle isotropic materials: *The act of fracture of a material is determined by the stresses of the fracture plane* [3].

On the basis of this hypothesis, Hashin-Puck record the failure modes fibre failure and inter fibre failure by different failure conditions, which take into account only the acting stresses in the fracture plane. This assumes that the fibre failure is solely triggered by the fibre-parallel stress σ_1 and remains unaffected by other stresses that occur. For the mathematical description of the fibre failure, a maximum normal stress criterion is applied.

The fracture conditions for inter fibre failure are, in comparison to the FF criterion, clearly more complex as different forms of failure such as adhesive failure of the fibre matrix border surface or cohesive failure of the matrix as well as different failure modes such as tension, longitudinal shear and transverse shear failure need to be realistically described. Here, Puck for formal purposes assumes a fracture mechanical cause for the failure in his formulation of the IFF conditions [3], that was first listed by Hahn et. al. According to this, micro-mechanical defects such as pores and hardness cracks form the basis of macro-mechanical cracks. It can be shown that by adopting an approach based on the strain energy release rate, a fracture criterion can be developed for combined (σ_1, τ_{21})-loading. The normal and shear stresses that arise are then related to each other by means of a quadratic polynomial.

Failure mode concept of Cuntze

To improve the practical handling of physically based failure criteria, Cuntze has developed a new approach which also aims at circumventing the problematical aspects of the Hashin-Puck criterion. On account of the practical factors involved, Cuntze considers the establishment of a new approach for a realistic strength analysis which goes beyond the action plane approach of Hashin-Puck as an urgent necessity. On the one hand, the action plane resistance $R_{\perp\perp}^{A}$ introduced by Puck cannot be directly measured experimentally so that no direct statistical verification of strength can be carried out. On the other hand, a composite failure does not always involve a fracture plane in the sense of the hypothesis proposed by Mohr, such as can be the case for textile-reinforced ceramics for example. Subsequently Cuntze assumes that micro-mechanical and statistical interactions in particular in the case of overlaid loading cannot be distinctly differentiated from each other. Taking these factors into account, Cuntze worked out a failure mode related strength criterion that he formulated as invariant depiction in order to enable a universal application and simple mathematical use [4].

The fundamental difference of the criteria considered here derives in particular from a simplified use. This allows the failure mode concept of Cuntze not only to enable the calculation of reserve factors but also to clarify important problems regarding the types of fracture that occur without having to solve arduous extreme values tasks. An advantage of the action plane related criterion is, however, that the fracture angle can be calculated as additional information if the extreme value can be calculated, which is of particularly elemental importance for the description of gradual acts of failure.

ADAPTED TESTING METHODS FOR THE VERIFICATION OF THE NEW FAILURE CRITERIA

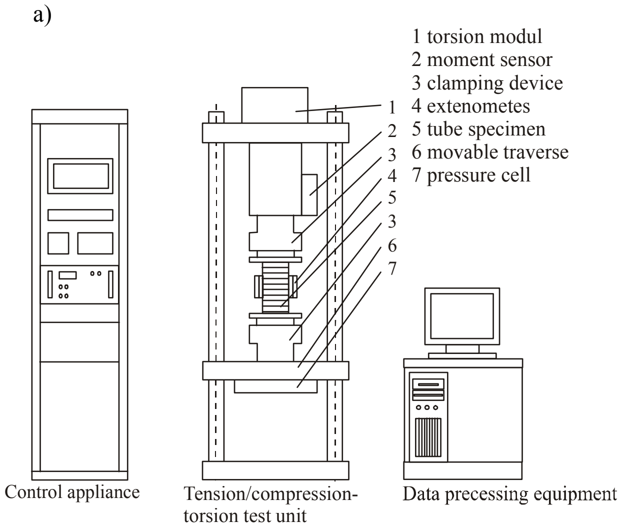
In order to be able to verify the failure mode related criteria experimentally, it is necessary to develop adapted testing methods that enable a measured multi-axial application of load. Therefore, as part of the DFG research project to conduct strength studies in the (σ_1, σ_2, τ_{21})-stress space, testing methods were developed for tension/compression torsion tests (T/C-T tests) and compression-inner pressure tests (C-p tests) of unidirectional (UD) and bi-directional (BD) reinforced pipe test pieces made of fibre- and textile-reinforced ceramics.

Tension/compression torsion tests

In the case of the T/C-T fracture tests the failure-critical stress combination along the prescribed loading path was produced by a load-controlled multi-axial test machine specially developed by the Institute with adapted strain twisting extensometer (Fig. 1). This extensometer permitted both the strain and the distortion to be recorded as well as the gradual course of failure.

The tests carried out on fibre- and textile-reinforced ceramic pipes serve, on the one hand, to determine fracture stresses as well as the related fracture angle and, on the other hand, to characterise the elementary fracture types. Moreover, knowledge of the fracture angle and fracture mode enables a detailed description of the complicated failure phenomena of reinforced ceramic composites. The fracture curve of the (σ_2, τ_{21})-stress plane for unidirectional fibre-reinforced ceramics covers, for example, the fracture type cross-sectional-normal failure and cross-sectional-longitudinal failure. The wealth of information that the T/C-T supplies permits the first basic physical failure phenomena to be explained and subsequently also documents the deficiencies of the global failure criteria.

a)



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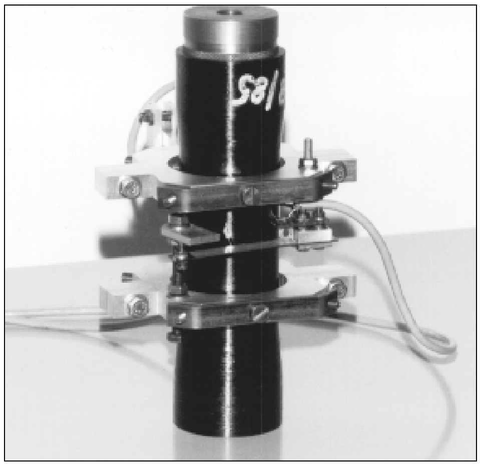

Fig. 1. Tension/compression-torsion-test: a) testing facility, b) specimen with extensometer

Compression-inner pressure tests

In order to analyse the failure behaviour in particular of textile-reinforced fibre ceramics in the case of combined tension-compression loading (σ_1^+, σ_2^--stress plane), a compression-inner pressure machine was developed for the study (Fig. 2) [5]. The tensional stress in direction of the fibre chain σ_1^+ is generated by the inner pressure while the axial compressive force induces the stress σ_2^-. The compressive loading σ_3^- of up to 10 MPa generated by the inner pressure is initially not considered in the failure analysis. Within the framework of these tests, it was investigated how far the failure modes of tensional brittle failure and compressive failure exert an influence on each other.

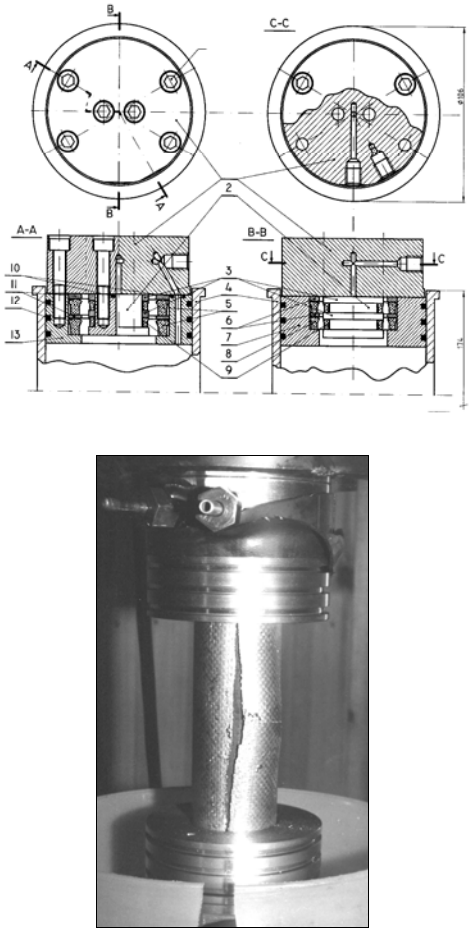

Fig. 2. Compression-inner pressure facility

FRACTURE TESTS ON UNI- AND BI-DIRECTIONALLY REINFORCED FIBRE CERAMICS

As part of the studies, the basic failure phenomena exhibited by different fibre- and textile-reinforced ceramics that had been manufactured by specialist producers by means of CVI-, PIP- and LSI processes were analysed in single and multi-axial failure tests.

An example of this is depicted in the following, which sets out the results of T/C-T tests on LSI uni-directional-reinforced carbon fibre silicon carbide composites for the (σ_2, τ_{21})-plane (Fig. 1). The increase in loading until fracture is effected uniformly in each case along the given loading path 1÷4. The recorded strengths reveal very little scatter for pure compressive loading, which suggests that the tests show a high degree of repro- ducibility. For pure torsional loading however, a perceptibly greater scatter can be observed. From the comparison of the different failure modes it follows that the statistical distribution of the strength parameters depends considerably on the respective fracture mode. This must be sufficiently considered in the failure analysis.

In Figure 3 the experimentally determined strengths are compared with the theoretically calculated curves in accordance with the action plane related failure criterion of Hashin-Puck and reveal a good degree of concurrence of mean values and theoretical values. A clear rise in the failure curve can be recognised in the compression/shear range on account of the „inner material friction” which accords with theoretical considerations. This clearly proves that, under increasing compressive loading, the shear failure as a consequence of τ_{21} is initially increasingly more difficult for fibre ceramics too. The increase in compressive stresses then leads to change of the slippage of the respective fracture surfaces from parallel to the direction of the fibre to vertical to the direction of the fibre, which, under a high compressive loading, leads to a relatively steep fall of the failure curve.

On account of the failure mode dependent statistical strength distribution, the calculation of failure curves with defined failure probability using the Hashin-Puck criterion is not immediately possible. For this purpose, the invariant criterion of Cuntze needs to be applied.

Apart from UD-reinforced wound test pieces, LSI-C/C-SiC-pipe test pieces with woven reinforcement were tested in T/C-T tests. The reinforced structure of these test pieces consists of a T800 plain weave wound around a cylindrical core so that the inner and outer wall of the pipes each displayed a discontinuity in their reinforcement caused by the two ends of the winding. In the tension-compression-torsion tests carried out, this discontinuity in the reinforcement proved to be, in many cases, a failure-relevant notch point, which is reflected in

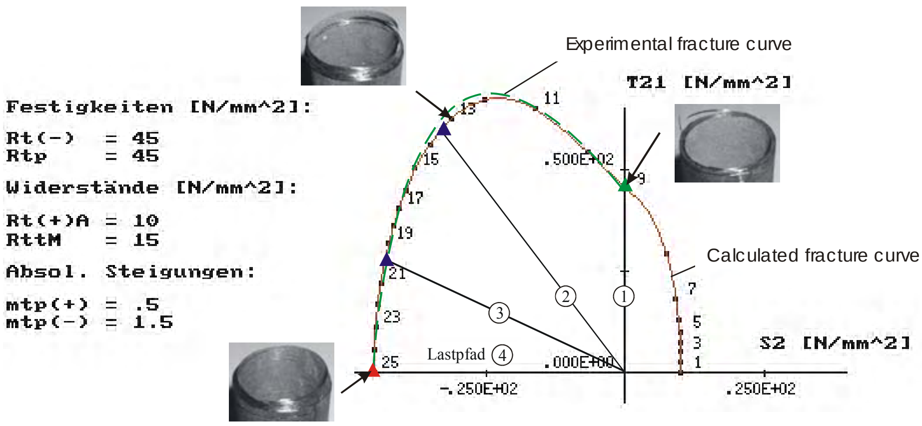

Fig. 3. Comparison of experimentally determined and theoretically calculated fracture profiles in accordance with Hashin-Puck

the relatively large scatter pattern of the experimentally recorded failure characteristics.

FRACTURE CONDITIONS FOR FIBRE CERAMICS WITH WOVEN REINFORCEMENT

The evaluation of the failure tests carried out on the textile-reinforced ceramics shows that such composite ceramics can be divided into two groups in respect of their failure behaviour. The first group is formed by the woven-reinforced ceramics that display a distinct fracture plane when they fail so that their failure behaviour can be described with the use of adapted action plane related failure criteria. The second group consists of the composite ceramics that fail under tensional and shear loading as a consequence of largest main normal stress, whereas under compressive loading a fibre instability failure exhibiting a distinct fissured fracture occurs.

SUMMARY

The main objective of the tests was to work out a mathematical basis for the verification of strength for fibre- and textile-reinforced ceramic composites. This included applying for the first time the failure mode concept proposed by Hashin-Puck and Cuntze to reinforced LSI ceramics and modifying the criteria correspondingly. By means of multi-axial failure tests carried out on reinforced ceramics, the modified failure mode concept was able to be verified in the (σ_2, τ_{21})- and (σ_1, σ_2)-stress planes, a finding of great practical importance.

This allows the failure mode concept to judge the induced spatial stress states more realistically than if conventional generalising criteria are used and thus enables an improved exploitation of the existing high degree of lightweight construction potential offered by fibre-and textile-reinforced ceramics.

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