LABORATORIUM FÜR TECHNISCHE MECHANIK
UNIVERSITÄT PADERBORN

10. Workshop
Composite Forschung in der Mechanik
December 9-10, 1997
Paderborn, Liborianum

o. Prof. Dr. rer. nat. K.P. Herrmann
Laboratorium für Technische Mechanik
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PROGRAM

Tuesday, December 9, 1997

8:30-8:40 Opening of the Conference

SESSION I: Analytical and Numerical Methods - Homogenization and Damage
(Chairman: D. Leguillon)

8:40-9:05 **K. Türke**, Karlsruhe: “Numerical Homogenization of Anisotropic Effects in Continuum Damage Mechanics“

9:10-9:35 **W. Dreyer**, Berlin: “The Imbroglio of Mean Values in Micro-Mechanics“

9:40-10:05 **R. Meske**, Karlsruhe: “Self-Consistent Models for Composite Materials-Analytical and Numerical Evaluation“

10:10-10:30 Coffee breake

SESSION II: Analytical and Numerical Methods - Damage
(Chairman: E. Schnack)

10:30-10:55 **R. Pandorf**, Bochum: “Simulation of Matrix Damage in Particle Reinforced Metal Matrix Composites“

11:00-11:25 **F. Hild**, Cachan: “On the Continuum Description of Damage in Brittle Matrix Composites“

11:30-11:55 **S. Benke**, Aachen: “Thermoplasticity of MMC’s Undergoing Large Deformations“

12:00-12:25 **O. Hesebeck**, Karlsruhe: “Consistent Formulation of Damage Mechanics Material Models within a Thermomechanical Framework“

12:30-14:00 Lunch break

SESSION III: Analytical and Numerical Methods - Damage and Fracture
(Chairman: W. Hufenbach)

14:00-14:25 **J. Zhang**, Paderborn: “A Predictive Methodology for the Elastic Properties of General Symmetric Laminates Containing Multilayer Ply Cracks“

14:30-14:55 **A. Haddi**, Aachen: “Three-Dimensional Analysis of Crack-Inclusion Interactions in Composites“

15:00-15:25 **D. Leguillon**, Paris: “Delamination Onset in Composite Laminates“

15:30-15:55 Coffee break

SESSION IV: Modeling of Fibre-Reinforced Composites
(Chairman: W. Müller)

16.00-16.25 **J.M. Quenisset**, Bordeaux: “Modeling and Designing F/M Interfacial Zones in Metal Matrix Composites“

16.30-16.55 **F. Ohmenhäuser**, Stuttgart: “Interface Failure Between Concrete and a Pre-Stressed Aramide Reinforcement Bar“

17.00-17.25 **W.Weikl**, Karlsruhe: “Identification of Delaminations in Carbon-Fibre Reinforced Plastic by Shearographic Measurements at the Surface - an Inverse Problem“

17:30-17:55 **A. Langkamp**, Dresden: “Thermo-Elastic Properties and Damping Behaviour of Anisotropic Fibre-Reinforced Ceramics“

19:00 Banquet at the Liborianum

Wednesday, December 10, 1997

SESSION V: Experimental/Numerical Investigations of Composites
(Chairman: P. Peters)

8:30-8:55 **C. Marotzke**, Berlin: “Singularities and Interface Cracks in Micromechanical Tests“

9:00-9:25 **A. Noe**, Paderborn: “Evaluation of Sub-micrometer Deformation Measurements at a Fibre Composite obtained by Scanning Tunneling Microscopy (STM)“

9:30-9:55 **E. Martin**, Talence: “Influence of an Interface on the Mechanical Behaviour of a Monofilament“

10:00-10:25 **W. Hintze**, Aachen: “Holographic-Interferometric Investigations of Microdeformations in Heterogeneous Materials“

10:30-10:55 Coffee breake

SESSION VI: Experimental/Numerical Investigations of Composite Structures
(Chairman: K. P. Herrmann)

11:00-11:25 **P. Peters**, Köln: “Interfacial Stress Transfer in SiC-Fibre Reinforced Titanium Alloys Due to Thermal and Reaction Residual Stresses“

11:30-11.55 **T. Hauck**, München: “Fatigue Life Estimation of Solder Joints for Electronic Packages“

12:15-13:45 Lunch break

ABSTRACTS

Thermoplasticity of MMC's Undergoing Large Deformations

***S. Benke*, T. Pandorf, D. Weichert**

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Metal matrix composites (MMC's) are more and more used for the construction of machine parts subjected to complex mechanical and thermal loading. To predict the material response under such conditions the application of the finite element method has received considerable attention.

During the deformation of a solid body a temperature change can be observed which is caused by thermoelastic and dissipative (thermoplastic) effects. At the same time these temperature changes lead to thermal strains and stress redistributions. For a full description of the material behaviour and especially its damage behaviour these effects have to be considered.

This presentation aims to describe the influence of these temperature changes on the damage behaviour of MMC's. At the locations of stress and strain concentrations large deformations may occur which are taken into account. Discrete damage models like particle cracking, debonding between the hard phase and the metal matrix, and the evolution of pores in the matrix are incorporated in the presented model. The results from the so determined damage evolution are compared with continuum damage models (Gurson, Chaboche).

The numerical simulations are performed on the meso-scale. Starting with a given initial temperature distribution, the elastic-plastic response and the resulting temperature changes due to the thermoelastic and dissipative effects are calculated. The external load is incrementally applied and displacement controlled. The instationary temperature distribution as well as the resulting thermal strains are determined, and a new load-free increment is applied to calculate the new stress-strain distribution. At the end of an increment, several local failure criteria are checked. If one of these is satisfied, a load-free increment is applied next to better account for stress redistribution effects. The overall behaviour is predicted by application of the representative volume element (RVE) technique and compared with the results of the incorporated continuum damage models.

The Imbroglio of Mean Values in Micro Mechanics

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Bodies that are macroscopically almost homogenous at first sight may have a complex micro- structure on a microscopic scale.

For example, the mechanism of failure of ductile steels is largely dominated by generation, growth and coalescence of voids. Therefore ductile steel belongs to the class of porous media. The thermo-mechanical behavior of porous bodies can be described on a micro-scale, where each individual void is considered, or alternatively on the macro-scale, where the presence of voids is described exclusively by a mean volume fraction of voids. Thus, on the micro-scale, the body consists of voids and of the undamaged matrix, whereas the body appears to be homogenous on the macro scale.

Usually the thermo-mechanics of those bodies is described by the method of representative volume elements (*RVE*). A *RVE* represents a macroscopically small volume element $\Delta V(X)$ of the body at any macro point X. The *RVE* $\Delta V(X)$ exhibits in its interior the microstructure.

From a macroscopic point of view, there are single values of macro stress, macro strain and volume fraction assigned to the *RVE* at X. From a microscopic point of view, the *RVE* at X will be decomposed into small volume elements $\Delta v(Y)$ at the local points Y of the *RVE*. A boundary value problem for the *RVE* gives rise to fields of micro stresses and micro strains and these must be related to the single values of the macro stress, the macro strain and the volume fraction of voids at X.

The relations between micro- and macro -quantities are established by forming mean values of the microscopic quantities. This is a subtle and non-unique procedure and has lead to a long controversy in the literature. We shall discuss the topic carefully and in detail.

Three-Dimensional Analysis of Crack-Inclusion Interactions in Composites

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The crack propagation in composites is investigated by studying the problem of a homogeneous, isotropic elastic body containing an inclusion and a symmetric cluster of inclusions under mode I loading. It is known that the microstructure affects the initiation and propagation of cracks which in turn influences the overall fracture toughness of the material. In order to address practical material problems, the effect of various Young's moduli and locations of the inclusion on the crack front are examined in the three-dimensional case. Also, the influence geometrical factors such as crack length, particle size and crack-inclusion distance is investigated. A comparison is made between a crack penetrating a compact inclusion and a crack penetrating a cluster of inclusions.

In fracture mechanics, criteria for failure are generally based on the analysis of stress and strain states near the crack-tip. To characterise the stress concentration near a crack tip, Rice (1968) proposed the well-known path-independent J-integral. However, path-independence is lost in the case of inhomogeneous materials and the extension of the J-integral concept is needed (see, e.g., Haddi and Weichert, 1995). This extended J-integral is used here to characterise crack-inclusion interactions. The numerical algorithm can be incorporated into a large class of finite element programs and can be used together with post-processing programs such as IDEAS, using stress and displacement data from a finite element analysis to calculate the J-integral. The mesh in the presented examples contained 7530 nodes and 1410 twenty-node, isoparametric quarter-point elements for centre cracked elastic materials, with a symmetrically located elastic inclusion and four layers of elements through the half thickness. The 3D J-integral is calculated over a chosen volume by means of a two-points Gaussian integration in each co-ordinates directions. After analysing the crack-inclusion interaction along the crack front we investigate what difference it makes if a crack penetrates a compact, square inclusion or a cluster of inclusions of the same total volume. The results of these computations show that the J-integral retains its characteristic features, namely its path-independence and its physical meaning of an energy release rate, for inhomogeneous materials, if additional terms are taken into account. The value of the extended integral strongly varies with shape and elastic moduli of the inclusion and less strongly with crack-inclusion distance and crack length. The J-integral is maximum near the centre of the crack front and becomes minimum at its side. The effect of the location of the inclusion indicates that soft inclusions positioned in the crack plane in front of a crack attract cracks.

References

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Fatigue Life Estimation of Solder Joints for Electronic Packages

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The purpose of reliability analysis and fatigue life prediction is to optimise package designs, to predict field use limits and to analyse failure of products. One of the most important failure mechanisms in electronic devices is creep rupture induced in thermal cycling. Therefore, thermal fatigue of solder joints is critical to electronic package performance and lifetime. Associated methodologies for lifetime estimation utilize empirical damage laws based on inelastic strain energy density or inelastic strain accumulated per cycle during thermal cycling testing. Finite element calculation can be used in order to simulate the inelastic deformation behavior of devices under the associated test conditions.

The paper will present an approach for reliability assessment and fatigue life estimation of solder joints in a flip chip die attachment. The electronic package was subjected to temperature cycles between -56 and +125°C. The resulting thermally induced stress and strain state as well as the associated energy density accumulation in solder joints were determined by the use of 3D- nonlinear finite element analysis. The applied lead/tin solder alloy was modled as viscoplastic solid based on Anand's model for rate dependent plasticity. In order to obtain results in the surroundings of one bump of the flip chip structure, the submodeling technique was applied. Submodeling is based on St. Venant's principle, which states that if an actual distribution of forces is replaced by a statically equivalent system, the distribution of stress and strain is altered only near the regions of load application. Therefore, if the boundaries of the submodel are far enough from the stress concentration, reasonably accurate results can be calculated in the submodel.

Consistent Formulation of Damage Mechanics Material Models Within a Thermomechanical Framework

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The present paper is concerned with the formulation of damage mechanics material models. Many standard models describing elasto-plastic and visco-plastic material behaviour can be realized within a thermomechanical framework. Based on the hypothesis of maximum rate of dissipation work we can derive pseudo-potentials governing the irreversible evolution of state variables [1,2,3]. This approach imposes restrictions on the form of the evolution equations, so that less heuristical assumptions are required to develop the phenomenological model, and similar numerical methods can be applied to models of this class.

The time evolution can be expressed by a variational inequality. For a simple elasto-plastic model the inequality resembles a parabolic variational inequality of the second kind. The mathematical properties and a solution algorithm for this problem are well known [4,5].

The extension of the elasto-plastic model to damage mechanics is not straightforward. Most damage mechanics models do not refer to thermodynamical considerations (e.g.[6]). The damage mechanics models of Chaboche, Lemaitre *et al.* claim to base on the thermomechanical concepts [7]. However, it will be shown that their elasto-plastic damage model violates the postulate of maximum dissipation work. The possibilities of a consistent treatment of a damage variable in plasticity will be discussed.

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On the Continuum Description of Damage in Brittle-Matrix Composites

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The basic mechanisms related to the degradation of brittle matrices reinforced by continuous or discontinuous fibers and submitted to monotonic load histories are matrix–cracking, interfacial debonding and sliding, and eventually fiber breakage and fiber pull–out (Burr *et al*., 1995). These mechanisms induce stiffness losses and inelastic strains. The latter are studied within the framework of continuum damage mechanics by using micromechanical analyses. An explicit expression of the Helmholtz free energy density is derived in the case of monotonic load conditions. In particular, internal variables are carefully chosen to describe the degradation mechanisms (e.g., a damage parameter characterizing matrix–cracking, another one modeling interfacial debonding) and written in a more appropriate format to allow the derivation of constitutive equations applicable to structural calculations (Burr *et al*., 1997).

The model is used to analyze experimental data obtained on SiC matrices unidirectionally reinforced by continuous fibers. The evolution laws are derived by using micromechanical information. In particular, dimensionless groups are exhibited and identified from experiments.

The same model is used to study the behavior of a unreinforced concrete. To avoid localized damage, the prismatic concrete specimen is loaded by aluminum bars glued on two opposite lateral faces (Berthaud and Mazars,1989). In particular, the effect of glue between the aluminum bars and the concrete specimen is discussed and modeled.

Furthermore, the model is utilized to analyze the behavior of concrete specimen reinforced by short fibers made of steel (Boudon-Cussac, 1996).This composite is loaded by using a similar technique as that used to study unreinforced concrete. The different interfacial contributions (i.e., the short fiber/concrete interface, the aluminum/reinforced concrete interface) are identified. Comparisons are carried out for different fiber volume fractions (i.e.0., 0.1%, 0.3% and0.6%) and fiber orientations (0°, ±15° and 30°).

Finally, the effect of distributions of fibers is discussed. An extension of the previous model is proposed in order to account for the distribution. The tensorial nature of each internal variable is carefullyanalyzed and discussed.

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Holographic-Interferometric Investigations of Microdeformations in Heterogeneous Materials

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The damage evolution in heterogeneous materials highly depends on the mutual influence of the participant material components. Typical examples are composite laminates, but also metallic materials consisting of coarse hard phases, like the ledeburitic high speed steel X 210 Cr 12. Its microstructure shows a very irregular, netlike dispersion of carbide structure embedded in a rather ductile metal matrix. It is known that, first the hard carbides fail before microscale damage in the matrix occurs.

In this paper we investigate the lokal deformation field of the microstructure using holographic interferometric sandwich-holograms. The holographic material used in the experiments is sensitized with ammonium-dichromate, which has a diffraction efficiency of nearly 100% and a greater resolution, than commercially available plates with silver halogenides.

The double exposed reflection-interferograms record the three-dimensional displacement field of the microstructure. Here, a notched cantilever bar is stepwise loaded with a single force until complete failure. At each step two dichromated gelatin holograms are taken simultaneously to investigate the region at the bottom of the notch. One holographic plate is in a rest position, the other is fixed on the moving part of the test piece. The advantage of such an holographic process is its capacity to show simultaneously the deformation state in form of interference fringe patterns and the changes of the surface structure. Another advantage of the holographic principle is the possibility to enlarge hologram areas of interest after having performed the experiments, because of the great area of several cm^2 of the plates covered by the photography: When a processed hologram is illuminated with the original reference beam, one can use a microscope focused right through the depth of the hologram to examine any plane of interest.

The displacement field at the bottom of the notch for one load step was calculated with the finite-element program CRACKAN. The numerical solution consists of a macroscopic model to simulate the bending test, and a microscopic model with the dimensions 0.375 x 0.5 mm^2, which takes into account the presence of the two-phase structure in order to simulate the rupture mecanisms. Particle fracture is explained to occur if the normal stress in the carbides reaches a critical value. Stress and strain distributions are also calculated from the displacement information.

The comparison of the theoretically calculated micro-displacement fields with the obtained experimentally fields shows a fairly good agreement of the qualitative form of the fringes and the order of magnitude of the displacements.

Thermo-Elastic Properties and Damping-Behaviour of Anisotropic Fibre-Reinforced Ceramics

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Advanced applications using long fibre-reinforced ceramics enable to develop multifunctional constructions, which have to satisfy extreme light-weight requirements under complex thermo-mechanical and dynamical loads. The high light-weight potential of fibre ceramic composites can only be used for technical applications in an optimal way, if the structure of the fibre ceramic composite and the component is designed according to the loads. For this purpose, the anisotropic material properties have to be determined experimentally in dependence on the temperature. These data are needed in the form of so called characteristic parameter functions for the analysis of the stress and strain fields as well as for the structural dynamical analysis.

At the Institut für Leichtbau und Kunststofftechnik (ILK) the temperature dependent anisotropic elastic properties of fibre reinforced ceramics are measured in tension, compression, bending and torsion tests. A specially developed high-temperature testing system allows the performance of material tests for combined loading conditions in vacuum or in an inert gas atmosphere at temperatures from 20 °C up to 1600 °C.

The determination of the dynamic material properties e.g. dynamic Young's modulus and damping coefficient is efficiently done applying a resonance bending technique. Using fast fourier transformation (FFT) and adapted curve fitting analysis, the dynamcial characteristic material values in dependence on the fibre orientation are investigated.

The anisotropic thermo-elastic and dynamical property profiles of various fibre-reinforced ceramic composites made by gradient chemical vapour, liquid silicon and liquid polymer infiltration techniques are discussed. The results show clearly, that the material behaviour of fibre ceramic composites essentially depends on the production procedure. Whereas the elastic structural behaviour of silicon carbide (SiC) fibre reinforced SiC ceramics made by the chemical vapour infiltration technique is nearly isotropic, liquid silicon infiltrated SiC materials show a high degree of anisotropy, which has to be principally considered within the design process of fibre ceramic structures.

Delamination Onset in Composite Laminates

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Tensile tests on cross-ply laminates $[\pm\theta]_S$ are analysed using a composite plate model with, in addition, the study of free edge effects appearing in the boundary layers. As in Pagano's model, it is sufficient to examine cross sections of the specimens with fictitious loads on their boundaries. The solutions can be split into two parts, the first one is due to the inhomogeneous (fictitious) applied loads and the second one undergoes edge singularities. These singularities cause stress concentrations but it is impossible to recover experimental results concerning ply thickness sensitivity to delamination by simply comparing the intensity factors of these singularities. The theoretical model thus obtained is by far less sensitive than the experiments.

To get a better agreement with the experiments, it is necessary to introduce surface defects such as interface micro-cracks or notches. These are, in a way, idealized geometries but they emphasize on the role of surface flaws in initiation of delamination. It is thus possible to determine a notch angle which fits experimental and numerical results in terms of thickness sensitivity (tests are performed on $[\pm 10]_S$ and $[\pm 20]_S$ laminates of T300/914).

Nevertheless, this analysis remains a relative one, sensitivity to delamination is the ability of a specimen to delaminate earlier or later than another depending on their relative thicknesses. To go further and get a prediction of critical delamination stress is difficult, since, as weak singularities are involved, the Griffith criterion cannot be used directly (it is a usual feature in case of crack initiation). There are two ways to overcome this difficulty. Whether one assumes that there exist micro-cracks prior to any test or one has to consider a crack jump instead of a continuous growth. Corresponding lengths are obtained by an energy balance equation but the delamination tests do not allow to decide if one assumption is better or more realistic than the other. In both cases, prediction of the critical delamination stress is satisfying. However, studies in other situations (blunt cracks) tend to prove that the crack jump is the right option. On the other hand, the same studies lead to the conclusion that the corresponding lengths are not characteristic of the material or of the assembly of materials but linked to the structure and that, there are size effects in some situations.

Singularities and Interface Cracks in Micromechanical Tests

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In micromechanical tests such as pull-out and fragmentation tests, stress singularities arise in the interface between fiber and matrix at specific points. The order of the singularities depends on the angle of the two phases as well as on the elastic properties. In this paper, the dependency of the order of singularity on these parameters is shown for different interfacial regions based on the solutions for bimaterial wedges.

The fracture process is analysed using contact elements allowing friction in the debonded interface. For the pull-out test it is shown that the mode ratio changes dramatically during the first phase of the crack from dominating mode I to mode II. The mixed mode energy release rate as well as the mode I and mode II parts are calculated for glass and carbon fibers embedded in thermoplastic matrices. It turns out that the strain energy stored during the cooling process, which is usually neglected, significantly increases the energy release rate and has to be taken into account in the evaluation of the test data. A second parameter with great influence on the released energy is the interfacial friction in the debonded interface as a result of the thermally induced radial compressive stresses. The frictional stresses are directly taken into account in the analysis using contact elements with friction and are not derived indirectley as often found in the literature. It is shown that the interfacial friction significantly decreases the energy release rate. Additionally, some experimental results of pull-out tests performed under a microscope are presented showing the stable propagation of the interface crack.

A totally different fracture process is encountered in fragmentation tests. The intensity of the stress concentrations at the broken fiber end are much higher compared with pull-out tests, reveal that the fiber break must be followed by an interface or matrix crack, depending on the strength of the interface. Both types of cracks are simulated and the respective energy release rates are calculated. Contrary to the pull-out test, the interfacial failure is due to shear stresses. The role of the initial stresses due to cooling or curing as well as the influence of friction on the interfacial crack propagation is studied. Furthermore, the stress field in the vicinity of the interface is calculated and compared with results of the simple data reduction schemes. It shows that the neglection of the radial stresses in the interface as well as of the variation of the axial stresses in the matrix lead to significant deviations between the simple theories and finite element analysis.

Influence of an Interphase on the Mechanical Behaviour of a Monofilament

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Interfacial zones have been shown to play a crucial role on the mechanical behaviour of composite materials. In titanium alloy matrix composites, the formation of a reaction zone at the filament / matrix interface during the processing step introduces a brittle component which initiates damage in the matrix (Majumbar and Newaz, 1992). When the reinforcing filament consists of silicon carbide deposited on a tungsten core, such a reaction zone can also be present at the W/SiC interface reducing the strength of the filament (Gambone and Gundel, 1997). Interfacial design taking into account physico-chemical and thermo-mechanical aspects have to be carried out to improve the mechanical performance of those materials (Guo and Derby, 1995). Interphases selected for their barrier diffusion role can be deposited at interfaces to prevent the formation of reaction zones (Lepeticorps *et al.*, 1994).

The present work is aimed at evaluating the influence of an interphase on the mechanical behaviour of a W/SiC filament. Experimental investigation include tensile tests performed on coated tungsten filaments and fractographic observations. A fracture mechanics approach is used to estimate the influence of flaws located within the interfacial zone and demonstrates the role of interfacial bonding conditions on the fracture behaviour of the filament.

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Self-Consistent Models for Composite Materials - Analytical and Numerical Evaluation

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The mechanical properties of composite materials can be evaluated by theoretical models which utilize assumptions about the concentration, geometry and interaction of the different phases of the composite. One of this models is the self-consistent method, in the form introduced by Hill (1965). In this method, the mechanical properties of a two-phase composite consisting of particles embedded in a matrix are calculated by embedding one particle direclty in a matrix with the properties of the composite material which are to be determined. These properties can then be evaluated using the results of Eshelby (1957) for an ellipsoidal inclusion. One problem of this approach is that the representative volume element is not properly defined. This is improved by the generalized version of the self-consistent method, which is also know as three phase sphere and cylinder model (Christensen & Lo, 1979). In this method a composite sphere consisting of a particle with radius *a* and a concentric matrix shell of radius *b* is embedded in the effective medium. The ratio *a/b* is chosen such that the volume concentrations of particles and matrix are satisfied.

The mechanical properties of the effective medium can be evaluated numerically by an iterative FE-simulation of a composite sphere embedded in a large enough region of the unknown effective medium. The mechanical properties are calculated iteratively from the stress and strain in the inclusion and the matrix shell under a given loading. An advantage of this method in comparison to the analytical treatment is that nonlinear material behaviour and complex inclusion shapes can be simulated.

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Evaluation of Sub-Micrometer Deformation Measurements at a Fiber Composite Obtained by Scanning Tunneling Microscopy (STM)

***Alfons Noe**[1] **and Wolfgang G. Knauss**[2]*

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Standard carbon fiber composites are fabricated from fibers with a diameter of 5-10 µm. The length scale introduced by the fiber diameter implies that deformation and displacement fields of the fiber-matrix domain enter the sub-micrometer range. The analysis of deformations and displacements allows for a direct characterization the fiber-matrix performance. However, the resolution limitation of optical methods excludes the measurement of detailed fields at this length scale. Scanning tunneling microscopy (STM) is a relatively new experimental method for the quantitative measurement of surface deformations at the micrometer or sub-micrometer scale.

A specially designed scanning tunneling microscope (Vendroux) was utilized to record the surface topographies of the far end of a carbon fiber reinforced composite beam subjected to a sequence of transverse beam deflections. The scanning process was performed over a square of 8.0 µm on a side.

This contribution reports on the quantitative evaluation of the sequence of STM images related to the load steps. First, appropriate post processing tools for the quantitative evaluation of STM images are presented. Visual characterization, spectral analysis, statistical measures, least square techniques and cross correlation methods have been applied to the images. Second, out-of-plane displacements and inplane displacement fields as well as the associated surface strain and rotation tensors have been computed. Finally, the post processing results are cross-checked and discussed based on the physical rationale for the observed microscopic deformations.

Interface Failure Between Concrete and a Pre-Stressed Aramide Reinforcement Bar

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Aramide-reinforced concrete is used as an alternative to steel reinforcement in civil engineering structures in corrosive environments. To improve the interfacial strength between concrete and the re-bar, the aramide bar is sand coated. The manufacturing process of a concrete bar, reinforced by a pre-stressed aramide rod, has been simulated numerically using the finite element method (FE).

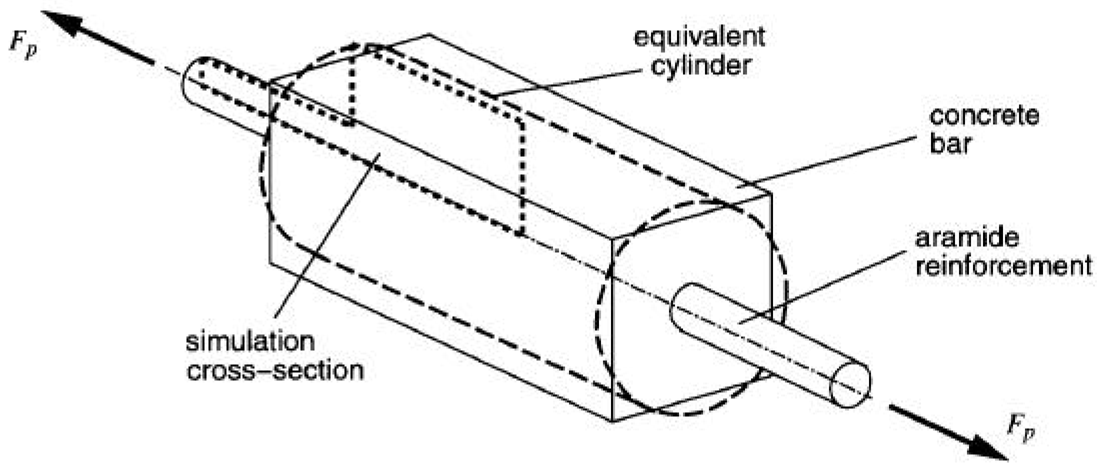

Figure 1: Aramide-concrete composite bar

For the FE model, axisymmetric conditions have been assumed. The interface constitutive behaviour is formulated in the framework of a cohesive zone model including the effects of stress triaxiality and crack closure, i.e. contact and friction.

As a first approximation, the material behaviour of both the aramide rod and the surrounding concrete has been assumed to be linear elastic. Hence, the only considered failure mechanism is the relaxation of the interface. The second approximation also includes concrete failure in planes perpendicular to the simulation cross-section (circumferential cracks). The resulting stress fields of these two simulations indicated that additional radial cracks eventually may occur. Thus, a third model considered radial cracks in the concrete as well.

The major results from these 3 different models are:

- The interface behaviour remains qualitatively identical for all three models; additional relaxation mechanisms (concrete cracking) reduce the amount of relaxation in the interface.
- The load transfer between concrete and re-bar concentrates in two locations: at the crack tip, and near the end of the specimen due to friction because of dilatancy-induced radial compressive stresses.
- Radial cracks suppress the initiation of circumferential cracks (crack shielding), indicating this to be the major relaxation mechanism in concrete within the composite.

Simulation of Matrix Damage in Particle Reinforced Metal Matrix Composites

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The use of particle reinforced Metal Matrix Composites (MMC's) results from their excellent stiffness-to-weight ratio, outstanding wear resistance as well as the reduced thermal expansion. In industrial applications, MMC's are used very often at elevated temperatures and due to this reason there is an increasing demand of constitutive relations in order to be able to describe the

creep behaviour numerically.

It is well known that the creep curve of most common materials in engineering applications can be divided into three stages. Experimental investigations showed for particle reinforced materials, especially for the Al_2O_3 reinforced AA 6061 (AlMg1SiCu), that the primary creep stage is immediately replaced by the tertiary region without showing a significant secondary creep rate. The physical reasons for the decreasing creep rate at the initial stage of the creep curve are the movement and accumulation of dislocations. The transition to the tertiary stage with an increasing creep rate is due to microscopic damage like particle cleavage followed by void nucleation and void growth in the metal matrix. Particle debonding was not observed in the composite AA 6061 + Al_2O_3.

Numerical simulations are performed on a microscopic scale with different arrangements of particles in unit-cells. The particles are modeled linear elastically and particle cracking is assumed to occur if the local first principal stress reaches a critical value. The matrix material was modeled by a combination of a viscoplastic material law with isotropic hardening [1] and a continuum mechanical damage criterion based on the Rabotnov-Kachanov equations:

$$\dot{\varepsilon}_{vp} = \left(\frac{\sigma - R - k}{K_a (1 - D)} \right)^{N_a}$$

The resulting macroscopic creep curve is compared with experimental data and stress, strain and damage fields will be presented.

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Interfacial Stress Transfer in SiC-fibre Reinforced Titanium Alloys Due to Thermal and Reaction Residual Stresses

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At the Institute of Materials Research (DLR) Titanium Matrix Composites (TMCs) are developed in cooperation with MTU for application in gas turbines. For the production of specimens (or components) a special technique is applied. Initially the SiC-(SCS-6)-fibres are coated with the titanium alloy by magnetron sputtering. For the present investigation the titanium alloy IMI834 is used. Unidirectionally reinforced specimens are produced by introducing a bundle of coated fibres into tubes of IMI 834 which are then consolidated (HIPed) at 950 °C under a pressure of 190MPa. The fibre producer provided a fibre with a 3 µm thick protection layer mainly consisting of carbon. This weak carbon layer prevents a reaction between titanium and SiC and gives rise to a low fibre matrix bond strength. For this reason stress transfer in the fibre matrix interface mainly takes place through interfacial frictional sliding, which has been shown with the aid of push-out experiments [1,2]. The most important parameter enabling frictional shear stresses are the residual radial compressive stress at the interface. Due to the difference in thermal expansion coefficient of fibre and matrix ($\alpha_m = 10 \times 10^{-6}$, $\alpha_f = 4 \times 10^{-6}$ m/m/°C) substantial thermal residual stresses are present in the material. Another type of residual stresses occur if the material is heat treated above 700 °C (simulating the service condition in a gas turbine) due to reaction of titanium with the carbon protection layer of the SCS-6 fibre according to $C + T_i \rightarrow T_iC$. This reaction gives rise to a volume reduction of 12.3 % leading to the so-called reaction residual stresses.

Experiments were performed at 850 °C (in vacuum) and interrupted after several periods of time in order to measure the thickness of the reaction layer and the dimensional (volume) change of the specimen.

A two-dimensional stress analysis (of radial and tangential stresses) was performed to calculate the thermal and reaction residual stresses and put in relation with the experimental results. On the basis of experiments and calculations it was concluded that the residual radial interfacial stress is not only the result of:

- thermal residual stresses
- interfacial reaction stress

but also of:

- shrinkage of the bulk matrix, which takes place at heat treatment temperatures above 700°C.

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Modeling and Designing F/M Interfacial Zones in Metal Matrix Composites

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In composite material, the fiber/Matrix (F/M) interfacial zone is well known to be a major parameter for controlling their properties.

When, on the one hand, in ceramic matrix composites (CMC), adjusting the F/M interfacial zone morphology and normal stresses that is controlling F/M frictional sliding, makes significant toughness improvement possible when compared to monolithic ceramics, on the other hand, in metal matrix composites (MMC), the conditions of F/M load transfer strongly influence the material durability and answers to various types of static, dynamic or cyclic loading.

The nature and main characteristics of F/M interfacial zones are dictated by the following driving factors:

1. the chemical interactions between fiber and matrix and also between various phases which can be interposed in the F/M interfacial zone,
2. the thermomechanical coupling between fiber and matrix which depends upon mismatch in fiber and matrix thermal expansion coefficients (CTE),
3. the effects of environment which are able to act in the F/M interfacial zone through the matrix or along the F/M interface,
4. and also, the initial design of the interfacial zone which can be guided by different objectives:
    - impeding the inter diffusion between fiber and matrix that is preventing reinforcement degradation and matrix embrittlement,
    - reducing residual thermal stresses induced by the fiber and matrix CTE mismatch,
    - favoring microcrack deviation in the F/M interfacial zone and better stress redistribution after fiber fractures.

As a consequence, the set up of a new composite requires the design of the F/M interfacial zone in order to achieve the specific properties suiting the expected applications.

Aiming at such a design, modeling the F/M interfacial zone has to take into account many a parameters whose values are often unavailable. It is particularly the case when the residual stresses induced by the volume deviations related to chemical interactions, are taken into account.

Nevertheless, modeling the F/M interfacial zone allows to point out tendencies which are helpful for designing or improving MMC’s such as titanium based matrix composites.

Numerical Homogenization of Anisotropic Effects in Continuum Damage Mechanics

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Continuum damage mechanics (CDM) will be defined in this context as a homogenization technique of micromechanic defects (inhomogenities such as cracks, pores, cavities, inclusions) and a macroscopic description by one or several internal variables, denoted by the damage operator **D** (Lemaitre and Chaboche, 1990). This strategy enables us to avoid the explicit description and evolution of the defects (cf. fracture mechanics models), but on the other hand leads to the problem of an adequate definition of the damage operator.

A thermodynamical analysis postulates the existence of a dissipation potential and an extended thermoelastic potential. But in most practical cases an explicit formulation of these potentials is not available. From the phenomenological point of view the damage operator can be interpreted as a reduction of the stiffness operator of the material, where a damage induced anisotropy has to be taken into account. Unfortunately an experimental determination of the reduced stiffness coefficients is possible only in very special and mainly academical cases.

These observations lead us to a micro mechanical analysis of the problem with a representative volume element on the meso-scale. On this level an experimental determination of the geometry of the defects is possible with optical methods, but a conclusion on the macroscopic reduction of stiffness remains a nontrivial problem.

In this lecture we will propose a numerical strategy to solve this problem based on a two grid method incorporating FEM and BEM (Schnack and Türke, 1997). Latest results (Hofmann, 1997) give us hope that a very effective method to model anisotropic effects in CDM will be available in the near future.

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Identification of Delaminations in Carbon-Fibre Reinforced Plastic by Shearographic Measurements at the Surface - An Inverse Problem

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The identification of defects such as delaminations in compound materials is of increasing importance due to the frequent use of such materials as structural components in modern mechanical systems. Especially the size and depth of a delamination are critical when determining the remaining strength of a component and appropriate repair strategies.

There are various methods for the detection of delaminations, most of which belong to nondestructive evaluation. In our group we use a relatively new nonlinear-optical method called shearography or image-sharing speckle-pattern interferometry. Utilizing this method relative surface displacements caused by certain loading conditions can be measured in a simple and accurate way by a subtraction of two speckle-pattern images (Klumpp, 1989).

The identification of the size and position of delaminations from measured surface displacements under given loading conditions can be described as an inverse problem. Corresponding to recent publications on a similar problem in electrostatics (Kubo, 1994 and Andrieux *et al*., 1996) we give an accurate mathematical description of our elastostatic problem. An introduction into the fundamental problems of existence, regularity and uniqueness of solutions will be given.

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A Predictive Methodology for the Elastic Properties of General Symmetric Laminates Containing Multilayer Ply Cracks

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When a multidirectional composite laminate is subjected to a quasi-static or fatigue tensile loading, the intralaminar cracks (matrix cracks) appear parallel to the fibers in the 90^o-plies as well as in the off-axis laminae (if applicable) long before the catastrophic laminate fracture. The matrix cracking is one of the principal causes of the stiffness reduction of both GFRP and CFRP composite laminate plates. In this contribution, a theoretical model for the prediction of the elastic properties of a general symmetric laminate containing multilayer matrix cracks is proposed. For any known multi-ply crack patterns in a laminate, we focus, in particular, on estimating the degraded stiffness properties of a cracked ply group constrained by its neighboring plies within the laminate; the laminate stiffnesses are then easily calculated by using the laminate plate theory with the degraded ply stiffnesses obtained. A five-layer equivalent constraint model (ECM) laminate $[S^L/\varphi_p/\underline{\theta_q}/\phi_r/S^R]_s$ and seven others degenerated from such a model laminate by eliminating some of the sublaminates, $[\varphi_p]$, $[\phi_r]$, S^L and S^R, are designed for the analyses of the degraded stiffnesses of the cracked laminae in the laminate; the crack configuration in the θ-lamina is explicitly represented (designated by underline `_´) while the primary and secondary constraining effects are taken into account by the stiffness-equivalent homogeneous layers, $[\varphi_p]$ and $[\phi_r]$, as well as S^L and S^R. A sublaminate-wise first-order shear deformation laminate theory is developed to analyze the stress and strain fields in the ECM laminates under the combined tension-shear loading. The *in-situ* damage effective functions, Λ_{22} and Λ_{66}, for characterizing the in-plane stiffness reductions of a cracked lamina constrained, are then expressed as explicit functions of the transverse ply crack spacing in such a lamina, as well as of the stiffness properties and the geometric parameters of the constraining layers by using the obtained stress field. The predictions of the theory are in a good agreement with the experimental Young's modulus data for $[0/90/\pm45]_s$ glass fiber reinforced epoxy composite laminates under fatigue.

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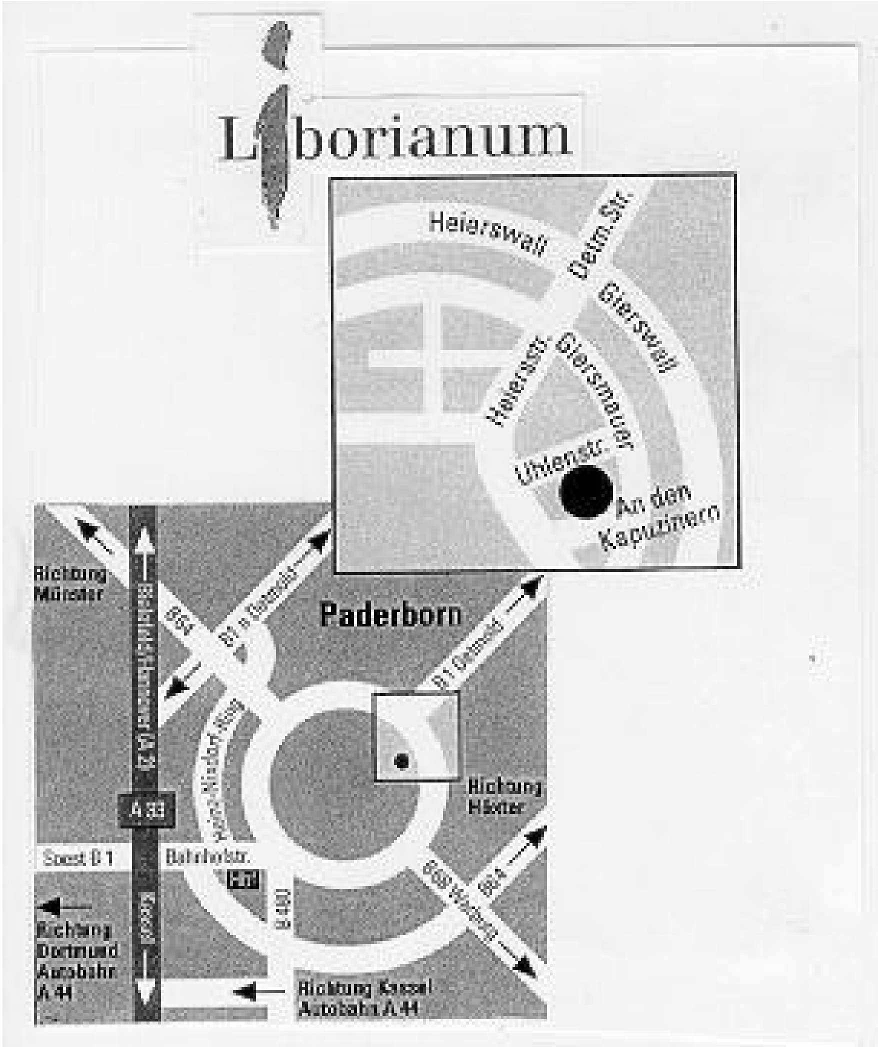

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