Mathematisches Forschungsinstitut Oberwolfach

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# Mechanics of Materials

May 5th – May 11th, 2002

The conference was organized by R. Kienzler (Bremen), D. McDowell (Atlanta) and E. Werner (München). U. Nordbrock (Bremen) served attentively and efficiently as secretary of the meeting which attracted 44 participants from 10 countries.

Mechanics of Materials covers a wide field of research activities ranging from elementary physics over material science to applied mechanics. It is by nature interdisciplinary. The conference provides a platform for the scientists to learn from and interact which each other in a friendly and constructive atmosphere.

On the basis of the submitted abstracts, the organizers formed groups of participants under the following head lines

- Material Laws, Elasticity
- Homogenization, Micromechanics, Numerical Mechanics
- Phase Transformation, Miscellaneous
- Configurational Mechanics
- Creep, Damage, Fracture
- Plasticity and Related Fields

Depending on the group size, each group was allotted one or two sessions. The group member were completely free to organize the session(s) the day prior to their scheduling with the guidance of an experienced coordinator. The outcome was a variety of quite differently arranged sessions. For example, some used one or two overview lectures supplemented by several smaller contributions. Some were conducted in "classical style" with equally sized lectures. Some sessions consisted of prepared extensive discussions following introductory lecutres. Although plenty of time was reserved for discussion during the sessions, the coffee and lunch brakes and the evenings were extensively used for this purpose. Two–page abstracts for all talks were posted on the bulletin board, helping to stimulate this exchange.

On Thursday night an informal gathering took place with an after–dinner talk of O. Mahrenholtz on the History of Mechanics followed by a chamber–music concert involving viola, violoncelli and piano. It was a great pleasure that the RiP guests accepted the invitation to participate.

In a general round–table discussion on Friday afternoon the participants concluded that the meeting was extremely fruitful and inspiring. The unique Oberwolfach–atmosphere was particulary gratefully acknowledged as contribution to a successful meeting. Both the new director and his staff are commended for providing an optimal framework for the success of the conference. Thank you all!

# Points of departure for the general discussion: "Key Issues in Mechanics of Materails with Microstructure"

I. Change — "*The only thing constant is change.*"

- What has changed in the last 10–15 years in this field ? Has it mattered? How fast are things changing? Are they accelerating or decelerating?
  - Perceptions
  - Interactions between materials science and mechanics disciplines is much enhanced
  - Much more interplay of numerics with microstructure features
  - New fields may be developing at this interface
- Do we leave continuum field models at some point in hierarchy of length/time scales? Where? How much statistical mechanics can be injected into continuum mechanics, and what are the limitation?

II. Model realism — "*If it looks like a duck, quacks like a duck, and waddles like a duck, it just might be a duck*"

- How do we select parameters to represent microstructure?
- Do we explicitly or implicitly model interactions?
- Model/parameter validation
- What microstructure features are essential/appropriate to model. Which tend to dominate structure–property relations?
- What is the sensitivity of relevant response functions to our choice of model parameters and to their variation?
- Behaviour of interfaces in system

III. Terminology — *is it really just words*?

- What do we mean by "microstructure"? We should perhaps decompose:
  - Intrinsic – characteristics of material structure/ordering (composition, phase, arrangement/morphology, interface details, ...)
  - Extrinsic – changes of state attributed to solutions of initial–boundary value problems that depend on constitutive construct and numerical scheme (schear bands, cracks, phase volume fractions in first order micture theory, ...)
- Should it be standardized to some extent? Does this process occur maturally? Does it have implications?

IV. Inverse methods — finding the ingredients to "bake your cake"

- Inverse problems do not typically have unique solutions — multiple microstructures produce same result

    - How do we attempt to proceed to explore these ranges of microstructures, even with approximations?
    - How do we address uncertainty of local properties? Uncertainty associated with constitutive idealization or model implementation?
- Inverse problems over multiple length scales (macro to micro) cannot be done without proper coupling between them (e. g. long range forces)
- In the presence of multiple mechanisms, how do we identify
    - Relative importance
    - Scale of action
    - Coupling between them
- What are the real prospects for inverse problem solutions in various materials?
- To better estimate local properties, perhaps sub–problems over more narrow ranges of scales (length and time) will be possible when combined with appropriate resolution measurements (e. g. nanoindentation is meso to micro)

V. Coupling of numerical implementation with theoretical model – *famous last words ...' well, the code compiles*'

- How do we preserve the theoretical structure of a model when implementing numerically. Is this possible in all cases?
- Boundary conditions should ultimately be physically–based, not just consistent with numerical scheme or theoretical idealization. In nonlocal realm, they can't be separated from constitutive models.
- What should be the boundary between regularization or localization control for the sake of computational efficacy and obtaining physical solutions. Where is the common ground?
- How do we deal with the issue of software infrastructure support for solving constitutive equations with microstructure (additional kinematical DOF, boundary conditions for flux terms, etc.)

VI. Applications — *dolllars (euros) and sense*

- How can concepts of microstructur be carried over to use in actual applications? What are the limitations?

VII. Education — *Will there be Oberwolfach 2030 on Mechanics of Materials*?

- What kind of training/background is necessary for mechanics of materials to blossom? Are we doing right?
- Are students exposed to computers for problem solving too early? Too late?
- Are faculty capable? Are textbooks and supporting references proper?
- How specialized is the field?
- How much of the classical mechanics should be conveyed? Where are lines drawn in this regard?

# Abstracts

### Creep analysis of beems, plates and shells considering damage

H. Altenbach

Modern design rules for thin–walled structures which operate at elevated temperatures are based on the demand that the creep and maybe the damage behavior should be taken into account.Performing the creep–damage analysis of beams, plates and shells three items must be considered: the choice of a suitable material model, the choice of a suitable structure mechanics model, and the choice of a suitable numerical solution technique. Assuming the simplest creep–damage model of the Kachanov–Rabotnov type added by a modified Hayhurst's damage evolution, the influence of the choice of the creep–damage equations on the solution of bending problems is demonstrated.

A simple analysis of a pipe bend problem shows that the results of 2D and 3D finite element calculations are sensitive with respect to the boundary conditions and the damage evolution law. The reason for such differences is the first order shear deformation theory which is the base of the shell elements. For the beam problem an improvement is proposed since in the case of creep–damage problems the shear correction factor is time– and material–dependent. This allows an adequate description of the non–symmetric stress state in the beam due to the different behavior under tension and compression conditions.

### A gradient plasticity model for polycristaline metals

J. Bammann

A gradient model of finite deformation plasticity is developed within the framewordk of the thermodynamics of internal state variables. Beginning with the multiplicative decomposition of the deformation gradient into elastic and plastic parts of crystal plasticity, two internal state variables are introduced to represent the elastic strain associated with statistically stored dislocations (SSD) and geometrically necessary dislocations (GND). A simple scalar measure is introduced to describe the SSDs and an appropriate evolution equation is developed. The GNDs are represented by the incompatibility of the elastic deformation gradient in the intermediate configuration. The curl of the elastic deformation gradient can be evaluated directly since the plastic spin is accurately predicted by the crystal plasticity model. The crystal plasticity model is extended to a macroscopic phenomenological model by manipulating the orientation distribution function of the texture vector for double planar slip model.

## Material laws on the basis of Taylor–theories considering martensitic phase transitions

D. Besdo

Many kinds of austenitic steels have a strong tendency to martensitic phase transitions. This transition influences the mechanical behaviour strongly. In case of crack propagation induced inner stresses can support it, but the increased yield limit can also hinder it. The presentation shows how the transition itself and its influence on the mechanical behaviour was described basing on 40% tensile tests. Especially material of type 1.4301 was treated where small changes of the chemical ingredients can create large effects concerning the tendency of phase transitions.

The applied method was a mixture of a Taylor and a Sachs model. An initial isotropy of the orientation distribution was guaranteed by use of random quanternions with a restriction to those in the unit hypersphere. They were projected to the surface of it finally.

A discretization of the ODF was necessary and, hence, was applied. The effective stresses were assumed to be equal to a 50%–mixture local elastic stresses of a uniform deformation and global stresses which were the mean values of the local ones.

The phase transition took into account that three types of matensite could be produced according to three transition criteria similar to yield criteria but including hydrostatic stress parts. A re–transition from martensite to austernite was not provided. Some shearing during the phase transition was considered by minimizing the stress differences before and after the transition.

Results were produced and compared with experimental data for tensile tests. The theory is able to describe the process but, unfortunately, large differences of fitted parameters were necessary to describe effects which depend on very small differences of the chemical composition. Also too much transition was predicted during the unloading phase. In every case, measured changes of Young's modulus could easily be explained.

## Texture induces anisotropy in metals

T. Boehlke

On the macroscale the constitutive behavior of polycrystalline metals is generally governed by the crystallographic texture as well as the morphology of the grains, and the hardening state in the aggregate. In the present work we restrict the investigation to macroscopic anisotropies due to inhomogeneous distributions of crystal orientations, i.e. a crystallographic texture.Polycrystalline copper ist considered which is subjected to finite inelastic deformations. Single crystalline copper exhibits a strong anisotropy of both the elastic and the viscoplastic behavior. This fact causes the effective elastic and viscoplastic properties of the polycrystal to become anisotropic if a crystallographic texture evolves.

First the macroscopic elastic anisotropy is considered. A fourth–order moment of the orientation distribution function (odf) is identified, which governs the macroscopic elastic anisotropy for all types of volume averages (arithmetic, geometric, harmonic, etc). It is shown that this fourth–order moment exhibits index symmetries which go beyond the classical relations given for all hyperelastic linear laws. These symmetries allow the derivation of evolution equations for the anisotropic part of the effective elasticity tensor. The coefficients are calibrated by Taylor type texture simulations and experimental data.

Furthermore, experiments and theoretical considerations show that the anisotropy of the plastic behavior of metals is correlated with the elastic anisotropy. Therefore, the

anisotropy of the plastic behavior can be analyzed by means of the elastic anisotropy for moderate textured polycrystals. We consider the implications of the assumption, that the elastic anisotropy and the yield function of the polycrystal are governed by the same fourth–order moment of the odf. It is shown that such a model allows for predicting the plastic anisotropy of rolled sheets and the cyclic Swift effect which can be observed in torsion experiments.

### A unified description of nucleation, propagation and proliferation of cracks under creep conditions

M. Chrzanowski

(joint work with B. Bodnar and K.Nowak)

Structures that operate in high temperature environment undergo a number of time–dependent processes, which may lead to their catastrophic failure. One of the most important is progressive gradual deterioration of material continuity. It may not be associated with large deformations, and therefore no visible warning can be observed before structures' collapse. Three stages can be distinguished within this time–dependent process. The first one is that of micro–cracks nucleation and coalescence, terminated by the formation of one or more macro–cracks at time called first crack appearance (FCA). The following stage of failure process consists of these macro cracks to grow until they span a characteristic dimension of a structure's elements; this time is called through–body crack appearance (TCA). The final stage is that in which the development of cracks leads to the final collapse of a structure at time called time to structure collapse (TSC). The relationships between the three characteristic time instances terminating above–mentioned stages are discussed and used as measure of safety margin of a structure.

In the paper the numerical analysis of failure process in creeping plates within the frame of Continuum Damage Mechanics has been made. It is worthy to underline that this approach allows analysis in consistent way the whole failure process of structure without any pre–assumption on pre–existing cracks of given position, length and orientation.

As result of numerical calculation the formation of macro–crack networks as well the profiles of main cracks propagating throughout the structure body are shown.

### Diffusion in multi–component systems with no or dense sources and sinks for vacancies

F. D. Fischer

(joint work with J. Svoboda, P. Fratzl and A. Kroupa)

General equations for the multi–component diffusion in crystalline systems are derived in the framework of Onsager's non–equilibrium thermodynamics. The aim is to provide explicit equations needed for computer–modeling of, e. g., diffusion–controlled phase transformations, but avoiding the usual simplifying assumptions, such as the independence of the fluxes of different atomic species. An additional difficulty is introduced into the problem by the fact that the concentration of vacancies, which mediate diffusion of substitutional atoms, may follow different rules, depending on whether there is a sufficient density of forces and sinks to keep the local vacancy concentration in equilibrium. We treat two limiting cases, one where the total vacancy number is conserved (that is, there are no available sources and sinks) and one where the vacancy concentration is kept in equilibrium

(the case of dense sources and sinks). First, the diffusive fluxes of all components and of vacancies are expressed by the well known Onsager relation. The kinetic coefficients $L_{ik}$ from the Onsager relation are derived by means of an extremal thermodynamic principle with respect to the atomic mobilities of individual components and taking into account the constraint amongst fluxes resulting from the vacancy diffusion mechanism. In the case where a dense network of sources and sinks of vacancies is active, the number of lattice positions is not necessarily conserved in every region of the specimen. This means, that the second Fick law, derived for the local conservation of lattice positions, is not applicable in this case. Using mass conservation considerations, the second Fick law is modified to account for this effect. The lattice may shrink or expand for two reasons –either due to the generation or annihilation of vacancies or to the change of the molar volume connected with the change of chemical composition. The deformation of the system is expressed quantitatively by strain rates. Finally, the equations for the system evolution are expressed in both the lattice–fixed and in the laboratory–fixed frames of reference.

### Plasticity and history dependent elasticity in cohesive–frictional materials

H.–P. Gänser

An isotropic plasticity model for crushable foams with non–linear elasticity, two different flow rules and isotropic damage in tension and compression is explored that is suited for a wide range of materials. A pressure–dependent yield criterion for crushable foams is proposed that has its roots in the modified Cam–Clay model, commonly used for modeling wet soils. It is expected that, depending on the choice of the flow rule, this plasticity model will be able to predict the basic mechanical behavior of crushable foams as well as of cohesive–frictional materials. The first flow rule is the one of associated flow, originally used in the Cam–Clay model, and suitable for cohesive–frictional materials. Despite all similarities of the present model to the Cam–Clay model, it still differs with respect to the hardening law and to the non–zero tensile cutoff stress. Rate dependence is modeled either by a Perzyna–type overstress model, or via a consistency model. Damage accumulation is modeled in the compressive range by a phenomenological evolution law integrating a stress–dependent kernel along a plastic strain path. In the tensile range, the Colorado concept of an equivalent number of cracks is used. Total damage is assumed as the sum of tensile and compressive damage. With increasing damage, the elastic parameters as well as the tensile cutoff stress are reduced appropriately. Numerical aspects are briefly discussed.

### Homogenization techniques based on statistical continuum approaches

H. Garmestani

This paper focuses on the application of statistical continuum mechanics for the prediction of effective properties and their evolution in heterogeneous media. Mechanical properties of heterogeneous materials are highly dependent on the constituents' configuration and their distribution. At this point no formulation (other than Finite Element) exists to determine the mechanical properties unless the different phases are distributed periodically and the inclusions are of known geometries (spheres, ...). The distribution and morphology of the microstructure is represented by two and three point probability functions. The strain rate is taken to be proportional to the resolved local shear stress raised to a

power. In the case of elasticity, contributions to the strain rate due to elasticity are neglected and a Green's function solution is derived for the two isotropic media. A two–Green's function solution to the equations of stress equilibrium, originally proposed by Molinari, et al., is utilized to obtain the constitutive law for the heterogeneous medium. This relation links the local velocity gradient to the fields of the local viscoplastic modulus and the imposed strain rate. The concepts of statistical continuum theory are introduced into the localization relation to obtain a closed form solution. The resulting model calculates an effective modulus for the two–phase composite medium (elastic or plastic). Numerical results are presented which describe the evolution of certain morphological features of the microstructure.

### On the configurational force exerting on a non–uniformly moving source in an elastic medium

S. Gavrilov

In the paper, the effect of interaction of a source moving in an elastic medium with a non–stationary field radiated by the source is considered. As the simplest mechanical system, we consider the transversal oscillation of a string on an deformable foundation under a moving without a friction point mass.

The dynamics of this system can be considered from two different points of view. We can take or not take into account the possibility of longitudinal motion for points of the string. We call the corresponding mathematical models as extended model and truncated model, respectively.

In frames of the truncated model we show that in the general case the motion of the mass point along the string is impossible without dissipation. The expression for the dissipation can be represented as work of a quantity, which we call driving traction or configurational force, in the longitudinal displacement of the mass point.

In frames of the extended model we demonstrate that the dissipation observed can be associated with outflow of energy from transversal degrees of freedom to longitudinal ones, which can be considered as "hidden variables" in the truncated model. If there is no friction in the system, then there exists a longitudinal standard force exerting on the point mass. The magnitude of this standard force is equal to the magnitude of the configurational force found in frames of the truncated model. This force appears due to the asymmetry of elastic field radiated by the source, and plays in the case of accelerated motion of the source the role of are resistance force.

Finally we consider a problem concerning the deceleration of a free mass point due to a resistance force and give the solution.

### Gyromcontinua and ferromagnets

E. F. Grekova
(joint work with G. A. Maugin))

The aim of the paper is to model magnetic crystals having a complicated structure. These crystals have interesting magnetoacoustic properties. Each cell (a point–body) of such a crystal consists of many atoms, combined in clusters (subparticles) responsible for the magnetic properties of the crystal. The magnetic moment of the clusters is related to the angular momentum (including moment of momentum and spin). Subparticles are

considered as rotating point bodies, interacting with their neighbours, possessing rotational symmetry.

We apply two approaches: a phenomenological and a microstructural. The phenomenological approach is based on the law of energy balance. We obtain strain tensors for an inhomogeneous elastic polar medium (Kelvin's medium) and the constitutive equations. To write down the stress and couple tensor for a point–body corresponding to a cell we have to summarize those for point–bodies corresponding to all the subparticles in the cell. Thus, the strain energy has a complicated structure depending on various deformations and various internal parameters like relative rotation of subparticles in the natural configuration.

For the microstructural consideration, we model the interaction between subparticles as a potential interaction of sufficient general kind between rigid bodies both of force and moment nature, and calculate the force and moment acting from the neighbourhood upon a subparticle. To pass from the discrete to the continual consideration we expand all the quantities in space up to second order. We see that corresponding strain tensors appear. This research is not completed yet.

## Nonconvex inelastic materials and induced microstructures

K. Hackl

We look at a general class of dissipative materials described by a set of internal variables $z \in \Re^n$. . Within a single time–increment the evolution of the state of the body under consideration can be obtained by minimization of a functional of the form

$$I_{z0}(\Phi, z) \;=\; \int_\Omega \{\Psi(\nabla\Phi, z) \;+\; D(z, z_0)\}dx \;-\; l(\Phi)$$

with respect to the deformation $\Phi$ and the internal variables $z$ at the end of the time–increment, where $z_0$ denotes the value of the internal variables at the beginning of the time–increment. Here $\Psi(\nabla\Phi, z)$ is the specific free energy of the material and $D(z, z_0)$ the specific dissipation generated when $z_0$ is changed to $z$. .

If $D(z, z_0)$ is a convex fuction of $z$ then the minimization with respect to $z$ can be carried out in advance and we arrive at the reduced potential

$$\Psi^{red}_{z_0}(F) \;=\; min\{\Psi(F, z) \;+\; D(z, z_0)|z\} \;.$$

Now $\Psi^{red}_{z_0}(F)$ is a function of the deformation gradient $F$ only and can in every aspect be treated like the potential of a hyperelastic material. Especially the existence of minimizers is guaranteed by the quasiconvexity of $\Psi^{red}_{z_0}(F)$ (and a suitable growth–condition). For many materials, however, quasiconvexity does not hold, which results in the development of microstructures and mesh–dependent finite–element solutions.

These problems can be overcome by introducing so–called relaxed energies, which are (almost) quasiconvex again and yield regular finite–elemente results. The simplest relaxed energy is given by the $R_1$–convexification

$$R_1\Psi^{red}_{z_0}(F) = inf\{(1-\lambda)\Psi^{red}_{z_0}(F - \lambda a \otimes b) + \lambda\Psi^{red}_{z_0}(F + (1-\lambda)a \otimes b)|0 \le \lambda \le 1, a, |b| = 1\} \;,$$

which constitutes a relaxation with respect to all first–order laminates. This means microstructers are now modeled in a statistical sense via the volume–ratio $\lambda$. Higher–order relaxations can be introduced by iteration of the procedure above as . $R_k\Psi^{red}_{z_0}(F) =$

$R_1^k \Psi_{z_0}^{red}(F)$. We will study examples of various relaxed energies for elastoplastic materials undergoing martensitic phase transformations. Numerical results will be given and the question of the evolution of the internal variables, which now are only given in a statistical sense (as Young–measures), will be addressed.

### Finite linear viscoelasticity of incompressible isotropic materials

Peter Haupt

For a variety of real materials, the idealisation of incompressibility is a good characterisation of their behaviour, at least under appropriate loading histories. Among these materials are Newtonian and non–Newtonian fluids and a broad class of solids, such as filled rubbers and other elastomers.

Starting from the incompressibility assumption, a free energy functional is formulated, which is governed by two relaxation functions to be identified from experimental data. The associated stress relation can be understood as a generalisation of the Mooney–Rivlin model to finite linear viscoelasticity. The only restriction towards thermodynamic consistency (minimum property of the free energy and positive dissipation) is that the relaxation functions must have a negative slope and positive curvature. In order to motivate a concrete representation of relaxation functions, a series of Maxwell models in parallel may be considered, which leads to a discrete or continuous relaxation spectrum. As an application of the constitutive theory, a small time–dependent deformation superimposed to a finite static deformation is discussed. In the case of harmonic incremental deformations this leads to a boundary value problem of linear elastostatics containing the data of the static predeformation and the frequency–dependent storage and dissipation modulus as parameters.

### Four–dimensional formalism in continuum mechanics

G. Herrmann, R. Kienzler

The authors found recently that if the stress equation of motion are written in the form of a 4 x 4 matrix, it is seen that the balance of linear momentum is intimately related to the mass conservation. To place this finding (heuristically found) on a firm foundation, special theory of relativity was considered. Approximate relativistic balance and conservation laws were derived by expanding the exact relativistic basic expressions in series of powers of the ratio of the velocity of motion and the velocity of light. Several orders of approximation were examined in detail, employing both the Eulerian and Lagrangian description, leading to the classical, but coupled relations of the balance of linear momentum and conservation of mass, as well as to the linearized energy–momentum tensor of the theory of elasticity, as already given by Morse & Feshbach. The static part of this tensor as become known as the Eshelby tensor, which is the basis of mathematical modelling of defects (cracks, voids) in elastic continua. As a by–product, a hierarchy of approximate theories of continua is established where velocities are comparable in magnitude to the velocity of light.

## Multilayer ply cracking and associated delaminations in multidirectional composite lamintes

K.P. Herrmanna
(joint work with J. Zhang)

The fracture process of composite laminates under monotonic tension and tension fatigue loading involves sequential accumulation of damage in the form of matrix cracking, edge delamination prior to catastrophic failure. Local delamination initiates at matrix ply cracks due to a high interlaminar stress concentration at the crack tips, whereas edge delaminations originate from the load– free edge of a composite plate. These through–thickness failure modes can be detrimental to the strength and stiffness of composite laminates. Therefore, a prediction of their onset strain and growth is of a certain importance.

In this paper the socalled equivalent constraint model (ECM) has been applied to a quantitative examination of constraining effects on the transverse ply cracking and its induced delamination. Three equivalent contraint model laminates, a five layer model (FLM) and two three–layer laminates were proposed to examine the constraining mechanics of the constraining plies of the center 90° – plies group on due to transverse cracks induced delaminations. An in site damage effective function IDEF has been introduced for characterizing the extension stiffness reduction of the constrained 90– plies with respect to the delamination length and the crack spacing, respectively. In summary it could be stated that the three–layer laminate consisting of the 90°– ply group and its next neighbouring ply groups could be used to analyse the in situ reduced stiffness of the constrained transverse plies and the strain energy release rates due to a delamination and a matrix cracking in the more complicated $[\ldots|\varphi_i|\Phi_m|90_n]_S$ laminates. Several numerical examples are given.

## Constitutive modeling of Anisotropic hyperelastic material

M. Itskov
(joint work with N. Aksel)

Various biological soft tissues as well as many man–made reinforced rubber–like structures are characterized by strongly anisotropic material properties and can furthermore undergo large elastic deformations. The numerical simulation of such materials at large elastic strains requires a highly non–linear constitutive formulation. To this end, we propose in the present contribution two kinds of anisotropic hyperelastic models.

The first constitutive model represents a generalized hyperelastic formulation for fiber–reinforced structures. These structures are assumed to be made of an isotropic elastic matrix reinforded by a number of arbitrarily oriented fiber families. The strain energy function of such a structure takes into account not only the deformation of single fibers but also their interaction with each other and the isotropic matrix. Each of these components is described by a non–linear scalar function of the corresponding strain invariant. These functions are approximated by power series with an arbitrary number of terms. The coefficients of these terms are related to material constants and can be evaluated on the basis of experimental data. In the case of only one fiber family the model exhibits the transversely isotropic and in the case of two or three families of mutually orthogonal fibers the orthotropic material symmetry.

The second formulation represents a generalized orthotropic hyperelastic constitutive model more appropriate to fiber–free materials. The model is obtained as a non–linear

extension of the orthotropic St. Venant–Kirchhoff material and is described in each principal material direction by an isotropic tensor function coupled with the corresponding structural tensor. Similar to the first constitutive model, these isotropic tensor functions are approximated by tensor power series with an arbitrary number of terms. In the special case of isotropy, this constitutive formulation reduces to the Valanis–Landel hypothesis and can therefore be considered as its orthotropic generalization. The model matched for the numerical simulation of a rat abdominal aorta has demonstrated good agreement with experimental results available in literature for this biological tissue.

### Trapped models of thin elastic ligaments

J. Kaplunov

Trapped vibration modes are considered for thin elastic ligaments. Long–wave approximations are derived near resonance frequencies of shortest transverse fibres. It is established that localisation occurs provided that relevant waves have negative group velocities. Natural vibration forms are presented in terms of known special functions. The effects of ligament shape, pre–stress and anisotropy are involves. Further prospects are discussed.

### Uniqueness in simple problems of homogeneous non-linear elasticity

F. J. Knops

Conservation laws, which from one aspect may be regarded as generated by the Eshelby energy– momentum tensor, are developed for nonlinear elastodynamics. These laws, together with those already known in elastostatics, are applied to obtain uniqueness of classical solutions in nonlinear elasticity. The elastostatic laws are here used to extend previous uniqueness results to classical solutions of affine displacement boundary value problems in star–shaped bounded regions with different phases, and to cone–like unbounded regions occupied by homogeneous material. The strain–energy is restricted to be, for example, quasi–convex and strictly rank–one convex, or merely rank–one convex for the unbounded body.

The initial boundary value problem studied involves affine data and a star–shaped bounded homogeneous body whose strain energy is, for example, strictly quasi–convex and rank–one convex. The technique adopted uses the kinematical conservation laws to derive a sequence of inequalities preparatory to establishing a differential inequality for the mean square of the difference between displacements satisfying the same data. Uniqueness follows by contradiction for sufficiently small time and may be extended by iteration to the whole interval of existence of smooth solutions. The conclusion complements those by Dafermos; Hughes, Kato and Marsden; and Wheeler.

### An anisotropic, finite deformation viscoplastic overstress theory (FVBO)

E. Krempl

A small strain viscoplasticity theory based on overstress is extended to finite deformation. Previously, the Eulerian approach to plasticity showed difficulties such as dissipation in a closed path in a purely elastic region and oscillations in simple shear. The recently invented and developed logarithmic approach permits a consistent Eulerian formulation. This method is applied to formulate an anisotropic viscoplasticity theory based on overstress for

finite deformation (FVBO). A closed path in the elastic region can be obtained without dissipation and no spurious oscillations are found in simple shear.

Similar to incremental, small strain plasticity, FVBO does not contain a strain measure in its constitutive equation. Rather, the rate of deformation is equal to the sum of two terms, namely: The objective, total time derivative of the product of elastic compliance times the Cauchy stress and an expression that depends on an increasing function of the overstress multiplied by an inelastic compliance matrix. The overstress is the difference between the stress and the equilibrium stress. It controls, together with the kinematic and isotropic stresses, the stress level.

Unlike an ideal elastic material, materials that need viscoplasticity for their constitutive equation do not have a natural reference configuration to which they return. In the deformation history of a metal or alloy many reference configurations are possible. FVBO is written for an Eulerian approach. The objective logarithmic method is used.

FVBO applies to displacement or stress boundary conditions and does not use a yield surface or loading and unloading conditions. There is a gradual transition from quasi–elastic behavior to fully established inelastic flow. The flow law includes fourth order elastic and inelastic compliance tensors and the state variables, the tensor–valued equilibrium, kinematic and drag stresses and their growth laws. They contain only stress and stress–like quantities and their first order, logarithmic, objective, time derivatives. This formulation avoids the difficulties encountered when the Jaumann rate is combined with hypo–elasticity.

## 2–D theory of dislocation nucleation

K. C. Le
(joint work with V. L. Berdichevsky)

Thermal nucleation of two–dimensional dislocations is studied. It is argued that probablility of $N$ dislocation pairs to appear has a simple asymptotics for large $N$:

$$p_N = [q(c,\beta,\mu)]^N / Z(\beta,\mu),$$

where $q(c,\beta,\mu)$ is a function of dislocation concentrating $c$, inverse temperature $\beta$, and chemical potential $\mu$, and $Z(\beta,\mu)$ is the partition function. We present $q(c,\beta,\mu)$ as a limit value of some functional integral and find an approximate value of this limit. This provides a thermodynamic description of nucleation transition. The probability distribution of dislocation position is studied within the same approximation. The behaviour of the probability distribution indicates that for small dislocation concentration the transition of Kosterlitz–Thouless type, i. e., the dipoles nucleated dissociate and form a neutral plasma, while at larger dislocation concentration, the transition corresponds to nucleation of dipoles which may remain bounded. A transition with respect to chemical potential is observed: for $\mu < \mu_{cr}$ the dislocation nucleation is a transition of infinite order, while for $\mu > \mu_{cr}$ it becomes a first order transition. The case of non–neutral system is also discussed.

## Contributions to metal plasticity and mining mechanis

H. Lippmann

This is an account of part of the corresponding research work, done during the last few years by the author and his group i. e., P. Adler, S. Guserle, Y. King, M. Reigl, M. Thalmair and H. P. Truong Qui. Regarding metal plasticity at first an experimental method,

originally proposed by BOEHLER & KOSS was extended in order to check whether grain rotation, to be understood as the rotation of the crystalline orientation is, in combination with isotropic and kinematic hardening, a significant quantity for describing the evolution of sheet metal anisotropy under multidirectional stretching or not; actually it is. Secondly the plastic Air Forming of slender parts was further developed, theoretically and experimentally as a new metal forming process under conditions of plane and spatial deformation. Regarding mining mechanics, laboratory experiments of the boring into rock were carried out in order to test this method for the prediction of high stress states, dangerous for men and material in deep underground mines. It was verified that the quantity of the fines of drilling is a representative stress measure indicating, mutually with the boring noise, also the danger of the initiation of so called mine bumps. Finally literature reports, according to which the danger of bumps could be reduced by the long time action of vibrations, artificially induced into the stratum have been checked in the laboratory. However they could not be confirmed.

### Rubber at cyclic loading and high preload

O. Mahrenholtz

Steel rings sitting on a rubber foundation which is connected to a – nearly rigid – circular disk and subjected to a radial load show a very particular behaviour when the load is cyclic in time.

The design allows and requires a high preload of the rubber ring which is prestressed during assembling and keeps the pressure after relaxation (WINKLER foundation).

It is possible to solve the (EULER) ring problem under the assumption of linear behaviour of the WINKLER (rubber) foundation in a closed form (ODE of 6th order in N (normal force)) and to identify the foundation stiffness parameter.

Intriguing is the fact the system shows in experiment not only the expected ring vibration (force excitation) but exhibits – on a second time scale so to say – vibration induced relaxation of the displacement which will recover after ending of excitation. A complex model of the time dependent behaviour may describe the phenomenon.

### Pseudo–plasticity and pseudo–inhomogeneity effects in the mechanics of materials

G. A. Maugin

It is shown that a large variety of physical effects such as continuously distributed defects, heat conduction, anelasticity (plasticity in finite–strains, growth), phase transitions, more generally shock–waves, can be viewed as pseudo–material inhomogeneities when continuum thermomechanics is completely projected onto the material manifold itself . Main ingredients in this approach are the notions of local structural rearrangements (Epstein and Maugin) and of its thermodynamical dual, the Eshelby material stress tensor. An outcome of this is the unification of the theories of inhomogeneity of Eshelby on the one hand, and of Kroener–Noll–Wang on the other hand. The notion of configurational forces as understood nowadays in solid–state physics and engineering mechanics follows necessarily from these developments.

### Homogenization concepts for granular and particle systems

D. L. McDowell
(joint work with J. D. Clayton and M. Zhou)

The present work addresses a decomposition of the deformation gradient of a polycrystal, based on principles of volume averaging, focusing on crystalline elastoplasticity and ductile damage in the form of intergranular cracking . Furthermore, the framework offers a convenient setting from which to evaluate continuum–type failure criteria in terms of homogenized variables and mesoscopic incompatibility fields. The kinematic description in the present work is based upon volume averaging of the local deformation gradient $\mathbf{f}$ of an aggregate of metallic grains and damage entities comprising a Statistical Volume Element (SVE). In this approach, we can distinguish between contributions of volume preserving slip and dilatational damage. We also briefly review the recent development of a concept for an equivalent continuum for dynamically deforming atomistic particle systems that are treated using concepts of molecular dynamics.

### Cyclic thermal loading of duplex steels

C. Messner
(joint work with E. A. Werner)

Ferritic–austenitic duplex steels demonstrate a complex deformational behaviour even in the absence of mechanical loads. Purely thermal cycling in the temperature interval from 20°C to 900°C can cause either accumulation of inelastic strains (thermal ratchetting) or plastic shakedown, depending on microstructure morphology and/or the strength and thermal properties of the constituting phases. The structural macroscopic response of an entire specimen is investigated by means of cyclic thermal loading of specimens in a dilatometer. Thermal cycling is performed for various temperature amplitudes. The influence of the loading parameters as well as the microstructure orientation are investigated. The microscopic deformation of the ferrite and austenite and the influence of the traction free surfaces are examined by means of measuring the evolution of surface roughness with fully three–dimensional profile scans. Besides the increase in the roughness parameters, the measured surface profiles also reveal a strong anisotropy. The local distribution of the asperities directly corresponds to the orientation of the microstructure, i.e. anisotropy due to the forging during production. Several spatial surface roughness parameters based on the autocorrelation function and power spectral density allow for a quantitative comparison with the microstructure.

### Socio–thermodynamics – integration and segregation in a populatin

I. Müller

An analogy is constructed between thermodynamics and sociology. The sociological system is one of hawks and doves who compete for the same resource. In the analogy the price of the resource corresponds to the temperature of a liquid or solid and the two species correspond to the constituents of a liquid solution or an alloy. Different phases of a solution are analogous to different strategies of competition in the population. It turns out that in good times, when the price is low the species mix homogeneously while in bad times when the price is high, there is segregation into hawk–rich and dove–rich colonies.

## Systematic construction of conservation laws

U. Nordbrock

Different possibilities exist to obtain conservation laws. Depending on whether or not a Lagrangian function is available for the system of interest, the classical approch employing Noethers Theorem or the recently developed so–called Neutral Action (NA) method is useful. Some other methods are also possible but will not be discussed in detail in this lecture.

Noether's method for calculating conservation laws makes use of the fact that a Lagrangian function, if it exists, solves the Euler–Lagrange equation. This equation, in turn, is obtained by demanding that the so–called action integral is stationary, i.e., its variation is zero. The action integral is defined as the integral of the Lagrangian function over an arbitrary domain in the space of independent variables. The variation can be performed by a transformation of the dependent variables with the domain remaining fixed during variation ("local variation"). For an additional variation on a changing domain ("convective variation"), the indepenent variables must be transformed too. This leads to an additional set of equations for determinating this transformation. These transformations are based on the theory of continous groups by Lie. Nevertheless, even though group theory underlies Noether's theorem, this branch of mathematics will not be dealt with in the lecture.

In case that for a given mechanical system a Lagrangian function is not known or not available, and the system is only described by a set of differential equations, the so called Neutral Action (NA) method might be applied. The basic idea of this relatively new method is that no characteristic has to be calculated as done using Noethers method. Instead, a function has to be determined demanding that its product with this set of equations is a so–called null Lagrangian, i.e. it satisfies the Euler–Lagrange equation identically. The action integral of such a null Lagrangian has vanishing variation for any dependent variable, i.e. it behaves neutrally under its variation. Therefore, the name "Neutral Action" (NA) method was given to this procedure.

## On motion of elastic solids with friction, heat generation and wear

Z. S. Olesiak

Since the relative motion cannot exist without fiction between the solids — the friction forces are taken into account. The friction forces in turn generate heat which induces the voluminal changes and thermal stresses. On the other hand the friction forces and the friction heat make that the surfaces in contact wear, and change their shapes. One might think that the friction and frictional heat generates only quantitative changes, perhaps important, however no new phenomena could be expected. It is not the case. In a few papers we were interested in finding the answer to the following questions:

1. are there cases of a stick–slip motion when the increase of temperature plays an important role,
2. a case of a motion when it stops due to heat generation, and starts moving after the system cools down,
3. nonlinear effects, problems with stability and chaotic motion.

## Fracture of cellular metal

R. Pippan
(joint work with C. Motz)

Improvements in manufacturing processes in the last few years have increased the quality and the reproducibility of metallic foams and made them commercially available. This has opened new fields of applications, like in load bearing structural elements. Therefore, besides the well investigated compression and energy absorbing behavior of metallic foams, further mechanical properties, like tension behavior, the fracture toughness and the fatigue behavior are important. The aim of the paper is to give at first a short overview of the mechanical behavior of cellular materials and then to discuss in detail the deformation behavior in tension, the fracture toughness and the fatigue crack growth behavior of closed–cell aluminium foams.

The questions addressed in the paper are:

- What are the dominant deformation processes in tension?
- What are the failure mechanisms?
- What is the effect of notches on the strength?
- How can we characterize the fracture toughness?
- Which parameters influence the fracture toughness?
- Which mechanisms are responsible for fatigue crack propagation?

In order to discuss these questions beside the results of common stress–strain measurements in tension experiments, standard fracture toughness and fatigue crack propagation tests, local deformation measurements on the different level of the architecture (i.e. on cell wall and the structural level) and finite element simulations are used.

## Theoretical and numerical modeling of fibre–reinforced composites

S. Reese

Experimental data for structures made of heterogeneous materials are expensive and often incomplete. It is therefore useful to enhance the understanding of the material behaviour by means of computational modelling. For this purpose, a computer model is set up where the fibres and the embedding matrix are discretized by non–linear truss and 3D elements, respectively. Based on the stress–strain data computed in classical loading situations as uniaxial, biaxial tension and shear, an anisotropic inelastic continuum mechanical model is derived. The present work focuses on fabric structures made of aramid as well as shape memory alloy fibres, both embedded in a polymer matrix. The anisotropic model employs the concept of structure tensors. Using a new idea to describe the push–forward of the structural vectors to the intermediate confguration, one comes to the conclusion that the inelastic deformation can be described by means of a *symmetric* internal variable. The continuum mechanical model is finally implemented into a new finite element technology based on the concept of reduced integration plus hourglass stabililization. The finite element simulations show that the macromechanical model displays the “test data“ very well. In the case of the SMA composite, however, the differentiation between the cases of pseudoelasticity, pseudoplasticity and the shape memory effect is highly nontrivial. Special techniques to bifurcate into the correct branches have to be applied. The simulation of practically relevant examples as e. g. an adaptive plate gives qualitatively reasonable results.

## Improved reduced degree of freedom elements based on the theory of a Cosserat point

M. B. Rubin

Cosserat theories are special nonlinear continuum theories that can be used to model the response of shells, rods and points. In this seminar it is shown how the theory of a Cosserat point can be used as a finite element for the formulation of the numerical solution of problems in nonlinear elasticity. In contrast with standard Bubnov–Galerkin procedures, the resultant forces and moments in the Cosserat theory are related to derivatives of a strain energy function and the constitutive constants are determined by comparison with exact solutions of the linear theory for bending, torsion and higher order hourglassing. This procedure produces a Cosserat element that eliminates common locking phenomena when one or two of the element dimensions become small.

## Rubber – like and soft materials at very high strains

G. Saccomandi

Many rubber–like materials and soft tissues exhibit a significant stiffening or hardening in their stress–strain curves at large strains. The accurate modelling of this phenomenon is a key issue for the better understanding of the mechanics of materials such as elastomers or arterial walls.

To describe this effect, molecular models based on a probability density function for the end to end distance of the polymeric chains with compact support has been proposed. These models, known as limiting chain extensibility models, are very complicated because they involve the inverse Lagevin function.

Here we propose a simple approach based on the classical phenomenological theory of nonlinear elasticity. In the case of isotropic generalized neo–Hookean materials, we introduce a strain–energy density which depends on a constant $I^*$ such that when $I_1$ tends to $I^*$ the strain–energy blows up ($I_1 = trace\ (\mathbf{C})$). This means that $I_1 < I^*$ and the stress components are unbounded when $I_1$ approaches $I^*$. This approach allows to have an accurate qualitative and quantitative description of primary loading paths and this along with mathematical feasibility. On the basis of this dimple models it is possible to build more complex constitutive equations that allow to describe pseudoelastic phenomena as the Mullin's effect.

## On anisotropic formulations of multiplicative inelasticity

C. Sansour

The formulation of an anisotropic elastic constitutive law within the framework of multiplicative finite strain inelasticity is discussed. Explicit expressions are given for the specific case of orthotropic anisotropy. As a fundamental result it is shown that the structural tensors to characterize the anisotropy at hand should be first transformed as mixed–variant tensors under the action of the inelastic part of the deformation gradient, in case of a description with respect to the intermediate configuration, or under the action of the deformation gradient itself in case of a description with respect to the actual configuration. The reduced dissipation inequality takes a radically different form than that established in the purely isotropic case. Specifically, the formulation provides an access to a plastic spin which depends directly on the elastic anisotropy and vanishes by passing to a purely

isotropic formulation. As a possible application, the evolution equations of the unified type due to Bodner and Partom are incorporated in the formulation. A numerical example is presented showing the numerical effect of the anisotropy under consideration.

### Subgrain formation and non–local plasticity

R. Sedláček
(joint work with J. Kratochvil, W. Blum and S. Forest)

Formation of periodic misorientations of crystal lattice during plastic deformation is treated in the framework of continuum crystal plasticity as a bifurcation from a uniform to a non–homogeneous mode of plastic deformation. Continuum theory of dislocations is utilized to derive the dislocation patterns corresponding to the emerging misorientations which are interpreted as initial stages of deformation–induced misoriented cell or subgrain structures.

Once formed, the boundaries of the subgrains lead to hardening as they present a hard phase which induces long–range internal back stresses in the interiour of the subgrains by forcing the mobile dislocations to take a bowed configuration. Simple dislocation–based and Cosserat models are proposed to explain the size–dependent subgrain hardening, where smaller subgrains are stronger.

### Deformation response of Hadfield steel single and polycrystals

H. Sehitoglu
(joint work with D. Canadinc, I. Karaman, Y. I. Chumlyakov and H. J. Maier)

In this work, we are focusing on low stacking fault energy (SFE) materials (Fe–Mn–C alloys) which exhibit twinning or slip or their combination depending on the single crystal orientation and loading direction. The slip is often planar, especially at low strains, because cross slip is limited in these class of materials. The stress–strain response of these materials exhibit an unusual upward curvature with very high strain hardening coefficients ($\sim$ G/10 where G is shear modulus). We have recently introduced a unique strain–hardening approach within a visco–plastic self–consistent crystal plasticity framework incorporating length scales associated with spacing between twin lamellae and grain boundaries. Twin boundaries are treated as hard but penetrable obstacles. The model successfully predicts the stress–strain response and texture evolution of these low SFE austenitic steels in both single and polycrystalline form. In this presentation, we will also describe a simple model for the energy required to form a constriction from two parallel partial dislocations as a function of stacking fault energy, and solute concentration.

### Effect of materials' Stochasticity on macroscopic deformational behaviour and failure

V. V. Silberschmidt

Direct observations of material microstructures vividly manifest their considerable randomness due to different microscopic and/or mesoscopic defects (voids, microcracks etc.), variations in sizes and orientations of grains of polycrystalline aggregate, presence of precipitates or other phases, grain boundaries and interfaces. To a certain degree, non–randomness is rather an exception than a rule in the world of real both natural and

artificial materials. The effect of microstructure on macroscopic response to various loading types is demonstrated for a range of materials and processes. In ferritic–austenitic duplex steels the change of morphology (e.g. matrix–inclusion relation) can cause a transition between two principally different types of material's behaviour under purely thermal cyclic loading: plastic shakedown and thermal ratchetting. The spatial non–uniformity in distributions of ferritic and austenitic domains results in formation of characteristic surface roughness.

Damage evolution and crack propagation in brittle materials (e.g. alumina ceramics) demonstrate a high grade in spatial randomness: neither numbers nor shape of fragments coincide for twin–specimens loaded under equal conditions due to differences in the ensembles of microdefects. The difference in local paces of damage accumulation and crack propagation needs an introduction of local stress intensity factors and of new concepts of local and global reliability for such materials.

### On spatial and material settings in continuum mechanics

P. Steinmann

Conceptually, in the spatial setting of continuum mechanics we consider the response to variations of spatial placements of "physical particles" with respect to the ambient space, whereas in the material setting of continuum mechanics we consider the response to variations of material placements of "physical particles" with respect to the ambient material. Thus the former establishes (Newtonian, mechanical) forces that drive "physical particles" through the ambient space whereas the latter establishes (Eshelbian, configurational) forces that drive "physical particles" through the ambient material. Here the relevant relations pertaining to continuum (thermo) mechanics are developed in spatial and material setting. These are besides the kinematics essentially the appropriate formulations of the balance of momentum and the resulting balance of kinetic energy for the mechanical part and the balances of energy and entropy for the thermomechanical part. The approach taken here is to mirror the thermomechanics underlying the spatial setting by the corresponding thermomechanics of the material setting. Thus a number of interesting and new relations between the two setting or rather motion problems, that would have been overlooked otherwise, are discovered.

Summarizing, the main aim of this work form the theoretical viewpoint is twofold: on the one hand to highlight the intriguing duality of the spatial and the material setting of continuum (thermo) mechanics and on the other hand to provide the necessary tools for an elegant transition between these two settings. Thereby, the underlying strong interest of the material setting rests in particular in the interpretation of the corresponding material forces as the thermomechanical driving quantities for the motion of general defects relative to the ambient material. This interpretation of the material setting is finally exploited to render an algorithmic impact on computational defect mechanics as highlighted with a number of numerical examples.

## Competition between recovery and recrystallisation

H. P. Stüwe

The latent energy stored in metals after plastic deformation is mainly due to an enhanced dislocation density. During a subsequent anneal it will be diminished by recovery and by recrystallisation.

The kinetics of recovery is described by an empirical equation. The kinetics of recrystallisation is described by the Avrami–equation. in reality both mechanisms will frequently compete. It is shown that this leads to a modified Avrami–equation, which correctly describes "anomalous Avrami–exponents" and other effects.

## Continuum thermodynamic modeling and simulation of additional hardening in metallic polycrystals due to deformation incompatibility

B. Svendsen

Standard micromechanical modeling of the inelastic material behaviour of metallic single crystals and polycrystals is commonly based on the premise that resistance to glide is due mainly to the random trapping of mobile dislocations during locally homogeneous deformation. Such trapped dislocations are commonly referred to as statistically–stored dislocations (SSDs), and act as obstacles to further dislocation motion, resulting in hardening. As anticipated in the work of Nye (1953) and Krner (1960), and discussed by Ashby (1970), an additional contribution to the density of immobile dislocations and so to hardening can arise when the continuum lengthscale (e.g., grain size) approaches that of the dominant microstructural features (e.g., mean spacing between precipitates relative to the precipitate size, or mean spacing between glide planes). Indeed, in this case, the resulting deformation incompatibility between, e.g., hard inclusions and a soft matrix, is accomodated by the development of so–called geometrically–necessary dislocations (GNDs). Experimentally–observed effects in a large class of materials such as increasing material hardening with decreasing (grain) size (i.e., the Hall–Petch effect) are commonly associated with the development of such GNDs.

The purpose of this work is the formulation and investigation of a phenomenological constitutive model for the inelastic material behaviour of single crystals and polycrystals including the possible effects of incompatibility in the local inelastic deformation as represented by GNDs on this behaviour. In particular, this approach yields a multifield generalization of standard crystal plasticity as based in particular on a generalized Ginzburg–Landau or Cahn–Allen–type evolution/field relation for the scalar glide–system slip. Initial modeling and simulation results for the case of constrained simple shear of a crystalline strip containing one or more glide systems demonstrates the ability of the approach to predict the effect of local deformation incompatibility on hardening behaviour.

## Contact of elastic bodies with negative poisson's ratio

G. Szefer

In the paper, the statement and numerical solution of a class of large deformation frictional contact problems will be presented. Contrary to results known up to now in contact mechanics, we consider the case when the material of the contacting body is assumed to be elastic but with negative Poisson's ratio. Such type of materials rather seldom analysed in elasticity do not violate the assumptions of the theory which permit values of the Poisson number from the interval $-1 < \nu < 0.5$. .

Structures and devices produced (manufactured) from such kind of materials demonstrate interesting behaviour. We consider elastic blocks (slabes and plates) subjected to contact with a flat, rigid and rough foundation. Static and dynamic unilateral as well bilateral contact problems in terms of large deformations are analysed. The paper is organized as follows: we start with some remarks devoted materials with negative Poisson's ratio, then a static problem of a block compressed on the upper edge and clamped on the lower one is considered. For comparison extension of the upper edge is considered too. Then we pass to dynamics of a rubber block $\nu = +0.48$ with a layer on the bottom possessing elastic properties with the coefficient $\nu < 0$. Different values of the thickness of the layer are taken into account. Plots of contact stresses illustrate the obtained results. Comparison with the classical elastic materials is discussed.

## Crack initiation and crack stability – experiment and simulation

H. Vehoff

Computer simulations and in–situ scanning force microscopy were performed in order to investigate the influence of the geometry and the microstructure of macroscopic specimens on crack nucleation and the brittle–to–ductile transition. Orientation imaging technique was used to characterize the specimens. Based on these results, the stress concentration at grain boundaries (3–D elastic) was calculated. From these results, we predict the crack nucleation sites and compare them directly with the experimental results. Depending on the material, the cracks are either stable or unstable, which in turn depends on the dislocation emission criteria and on the velocity law. We studied the local deformation at crack tips experimentally and compared the results with mesoscopic simulations. The boundary condition of the mesoscopic model was obtained with an appropriate constitutive model by FEM. The fracture mode of the simulated specimen depends on the stability of microcracks of given length and orientation that are assumed to exist within the specimen. Cleavage fracture occurs when indicated by a simulation routine on the mesoscopic length scale. The dynamic crack tip shielding process of the dislocation–emitting crack that is loaded in mode I and II, generally, is simulated. Instead of the well–known model of the semi–infinite crack, constitutive equations are derived in order to analyze a finite crack in the macroscopic specimen.

### On the application of direct methods to the assessment of periodic composites

D. Weichert

It is shown, how shakedown– and limit analysis can be used to predict local failure of composites with at least one ductile constituent and how admissible domains of loading can be determined without carrying out step–by–step analysis. For this, the composite is modelled on the so–called meso–scale as a mechanical structure by itself. Then, shakedown– and limit analysis are carried out giving, in the here considered case of periodic composites, the admissible loading domains for the representative volume element. To bridge the gap to the macroscopic characteristics of the material, averaging techniques such as Homogenisation Technique or Tolerance Averaging Methods are used. The here assumed scenario of failure is as follows: during loading, on the meso–scale level unlimited accumulation of inelastic deformations occurs in some areas. The accumulated plastic deformations lead to material damage in the ductile matrix of the composite, causing the initiation of micro–cracks. These may in the sequel of the loading process propagate and initiate failure of the considered structural element. However, crack initiation and propagation are not specifically addressed: If in some part of the composite the unlimited accumulation of plastic deformations is detected, we say that the material fails. Similarly, brittle failure and debonding of reinforcements are assumed to initiate failure due to fatigue and are not admissible for safe states of the material.

### On the structural behaviour of textile reinforced concrete (TRC)

B. W. Zastrau
(joint work with I. Lepenies and M. Richter)

Textile reinforced concrete (TRC) is a composite made of long fibers (filaments), e. g. glass fibers, and a fine concrete (aggregate size less than 1mm). The bundles of fibers (roving) consist of a huge number of filaments (400–2000 filaments). These are acting as a tension reinforcement in the brittle concrete, which leads to an enhancement of the ductility of the whole composite.

The failure mechanisms of TRC are complex. Most important for the enhancement of the ductility is the successive debonding of the fibers from the surrounding matrix if the brittle matrix is cracked. Therefore, one of the main issues is the simulation of the bond behavior between the reinforcement and the matrix. Based on pullout tests, both analytically and numerically solvable interface bond models are developed. The analytically treatable interface model is slip–based with a piecewise linear shear stress–slip–relation. The related governing differential equation of the shear stress transfer mechanism can be solved in a closed form, which allows a simple identification of the bond parameters. For the analysis of more complex reinforcement structures (e. g. inclined fibers, multilayered structures) and subdivided profiles analytical solutions have their limits. Therefore, numerical solutions are used, whereas the shear stress–slip relation is implemented in a three–dimensional finite element approach as a damage model for an interface layer with a finite thickness.

*Edited by Reinhold Kienzler*

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