2 Programme

2.1 Timetable

Time	Monday 18.09.2023	Tuesday 19.09.2023	Wednesday 20.09.2023	Thursday 21.09.2023	Friday 22.09.2023
09:00		Lecture 5	Lecture 15	Lecture 20	Lecture 31
09:30		Lecture 6	Lecture 16	Lecture 21	Lecture 32
10:00		Lecture 7	Lecture 17	Lecture 22	Lecture 33
10:30		Coffee-break	Coffee-break	Coffee-break	Coffee-break
11:00		Lecture 8	Lecture 18	Lecture 23	Lecture 34
11:30		Lecture 9	Lecture 19	Lecture 24	Closing
12:00	Registration	Lecture 10	Excursion	Lecture 25	
12:30		Lecture 11		Lecture 26	
13:00	Opening	Lunch		Lunch	
13:30	Lecture 1				
14:00	Lecture 2				
14.30	Lecture 3	Lecture 12			
15:00	Lecture 4	Lecture 13		Lecture 27	
15:30	Come Together	Lecture 14		Coffee-break	
16:00		City Tour		Lecture 28	
16:30				Lecture 29	
17:00				Lecture 30	
17:30					
18:00				Banquet	
18:30					
19:00					
19:30					
20:00					
20:30					
21:00					
21:30					
22:00					

2.2 Sessions Overview

2.2.1 Lectures

Lecture 1

Holm Altenbach, Konstantin Naumenko, Johanna Eisenträger, Katharina Knape see Sect. 3.2 on p. 23 (30 minutes including discussion)

Lecture 2

Eike Blum, Yevgen Kostenko, Konstantin Naumenko, see Sect. 3.18 on p. 31 (30 minutes including discussion)

Lecture 3

Dmytro Breslavsky and Oksana Tatarinova, see Sect. 3.3 on p. 23 (30 minutes including discussion)

Lecture 4

Jian-Feng Wen, Yang Shu, Jia-Wen Fei, Cong-Xiang Zheng, and Shan-Tung Tu, see Sect. 3.33 on p. 38 (30 minutes including discussion)

Lecture 5

Yuri Kadin and Richard Schake, see Sect. 3.16 on p. 30 (30 minutes including discussion)

Lecture 6

Takeshi Iwamoto, Chong Gao, Bo Cao and Tsutomu Umeda, see Sect. 3.15 on p. 30 (30 minutes including discussion)

Lecture 7

Alexander Dyck, Alexander Kauffmann, Martin Heilmaier, and Thomas Böhlke, see Sect. 3.6 on p. 25 (30 minutes including discussion)

Lecture 8

Robert Fleischhauer, Le Zhang, and Michael Kaliske, see Sect. 3.8 on p. 26 (30 minutes including discussion)

Lecture 9

Jörg Hohe and Sascha Fliegener, see Sect. 3.14 on p. 29 (30 minutes including discussion)

Lecture 10

Claudio Findeisen, Zalikha Murni, Abdul Hamid, Benedikt Rohrmüller, Dominik Spancken, Dominik Laveuve, and Jörg Hohe, see Sect. 3.7 on p. 25 (30 minutes including discussion)

Lecture 11

Oksana Tatarinova, Holm Altenbach, and Dmytro Breslavsky, see Sect. 3.29 on p. 36

Lecture 12

Fabian Welschinger, Argha Protim Dey, Benjamin Schneider, Matti Schneider, Sebastian Gajek, and Thomas Böhlke, see Sect. 3.32 on p. 38

Lecture 13

Sorin Vlase, M. Katouzian, M. Marin, C. Itu, and A. Toderita, see Sect. 3.30 on p. 37 (30 minutes including discussion)

Lecture 14

Bilen Emek Abali, see Sect. 3.1 on p. 23 (30 minutes including discussion)

Lecture 15

Kerstin Weinberg and Marcel Fischbach, see Sect. 3.31 on p. 37 (30 minutes including discussion)

Lecture 16

Yoji Shibutani, Linju Liu, Kazuma Ito, Hideaki Sawada, Masaaki Sugiyama, and Naoki Maruyama, see Sect. 3.28 on p. 36 (30 minutes including discussion)

Lecture 17

Seishiro Matsubara, Akira Takashima, So Nagashima, Shohei Ida, Hiro Tanaka, Makoto Uchida, and Dai Okumura, see Sect. 3.20 on p. 32 (30 minutes including discussion)

Lecture 18

Patrick Michels, Christian Dresbach, Esther Ramakers-van Dorp, Holm Altenbach, and Olaf Bruch, see Sect. 3.21 on p. 32 (30 minutes including discussion)

Lecture 19

Olivier Castelnau, Patrick Cordier, Karine Gouriet, Timmo Weidner, James van Orman, Jennifer M. Jackson, and Philippe Carrez, see Sect. 3.5 on p. 24 (30 minutes including discussion)

Lecture 20

Ehab Hamed, Sen Zhang, Ali Amin, and Ian R. Gilbert, see Sect. 3.12 on p. 28 (30 minutes including discussion)

Lecture 21

Lukas Richter, Holger Sparr, and Matthias Ziegenhorn, see Sect. 3.25 on p. 34 (30 minutes including discussion)

Lecture 22

Elisabetta Gariboldi, Matteo Molteni, Diego Vargas, and Konstantin Naumenko, see Sect. 3.10 on p. 27 (30 minutes including discussion)

Lecture 23

Michael Brünig, Sanjeev Koirala, and Steffen Gerke, see Sect. 3.4 on p. 24 (30 minutes including discussion)

Lecture 24

Romana Schwing, Stefan Linn, Christian Kontermann, and Matthias Oechsner, see Sect. 3.27 on p. 35 (30 minutes including discussion)

Lecture 25

Guozheng Kang, Yujie Liu, and Qi Li, see Sect. 3.17 on p. 30 (30 minutes including discussion)

Lecture 26

Mikhail Guzev, A.M. Golosov, E.P. Riabokon, M.S. Turbakov, E.V. Kozhevnikov, and V.V. Poplygin, see Sect. 3.11 on p. 28 (30 minutes including discussion)

Lecture 27

Timm Schultz, Ralf Müller, and Angelika Humbert, see Sect. 3.26 on p. 35 (30 minutes including discussion)

Lecture 28

Hsiao-Wei Lee, Noushad Bin Jamal M, Stanisław Mroziński, Adam Lipski, Michał Piotrowski, and Halina Egner, see Sect. 3.19 on p. 31 (30 minutes including discussion)

Lecture 29

Hideo Hiraguchi, see Sect. 3.13 on p. 28 (30 minutes including discussion)

Lecture 30

Bilal Rafiq, Xuming Zheng, Qiang Xu, see Sect. 3.24 on p. 34 (30 minutes including discussion)

Lecture 31

Dai Okumura, Atsuya Ogino, Seishiro Matsubara, and So Nagashima, see Sect. 3.23 on p. 33 (30 minutes including discussion)

Lecture 32

Jingyu Zhang and Huiling Duan, see Sect. 3.34 on p. 39 (30 minutes including discussion)

Lecture 33

Artur Ganczarski, see Sect. 3.9 on p. 27 (30 minutes including discussion)

Lecture 34

Mbombo Amejima Okpa, Qiang Xu, Zhongyu Lu, see Sect. 3.22 on p. 33 (30 minutes including discussion)

2.3 Social Programme

2.3.1 Come Together

On Monday (4.30 pm) a *Come Together* will be organized in the Building 44.
There is no additional fee.

2.3.2 City Tour

On Tuesday (4.30 pm) there is offered an English guided *City tour* (approximately 1,5 hours).
The starting point is at Lecture hall.
There is no additional fee.

2.3.3 Excursion

On Wednesday (12.30) there is offered a bus tour to Quedlinburg (added to the UNESCO World Heritage List in 1994 because of their exceptional preservation and outstanding Romanesque architecture). Return to Magdeburg at 19.30.
There is no additional fee.

2.3.4 Banquet

On Thuersday (18.00) the Conference Dinner will held at the Restaurant Franx (Hegelstr. 39).
There is no additional fee.

3 Abstracts

3.1 Damage Mechanics in Metamaterials by Using Phase-field Modeling

Bilen Emek Abali

Damage in heterogeneous structure like composite materials is challenging to model. Even if each constituent is isotropic, the microstructural alignment induces often an anisotropic character at a macroscale. Furthermore, by homogenizing this microstructure at the macroscale, for example by using a classical laminate theory, we may model damage mechanics in viscoplasticity by using a phase-field modeling. Whenever the homogenization is applied at a length-scale, which is near to the microstructure, the accuracy of the classical laminate theory decreases. Actually, overall the assumption is in danger that the deformation energy depends only on the strain (first gradient of displacement). By using generalized mechanics, where the deformation energy depends also on the second gradient of displacement, we obtain the necessary accuracy. In this way we construct a so-called metamaterial and need to discuss its adequate damage modeling. In this talk, we shed light on determining parameters in metamaterials by using asymptotic homogenization techniques [**Abali2021a**, **Vazic2021**, **Yang2022**] and simulating generalized damage mechanics [**Abali2021b**] by using opensource packages [**Abali2017**].

3.2 Creep Mechanics - Some Historical Remarks and New Trends

Holm Altenbach, Konstantin Naumenko, Johanna Eisenträger, and Katharina Knape

Creep mechanics is a branch of continuum mechanics that began to develop in the late 19th century. In the 1930s the first theories were developed that allowed the analysis of structures and the description of material behavior [**Altenbach2020**]. The viscoelasticity theory introduced approaches that could be linked to rheological models. Therefore, rheological models and their perspectives will be discussed in the concluding part.

3.3 Creep and Irradiation Effects in Reactor Vessel Internals

Dmytro Breslavsky and Oksana Tatarinova

Creep accompanied by the accumulation of hidden damage is a complex phenomenon. In nuclear reactor vessel internals (RVI) it is also accompanied by effects associated with the action of irradiation. Deformation and damage accumulation caused by irradiation effects in the material, such as irradiation creep, irradiation swelling, embrittlement, when interacting with the effects caused by thermal creep, can significantly limit the safe operation of RVI.
The paper is devoted to the presentation of the calculation method of determining the stress-strain state and long-term strength of RVI and the description of the results obtained with its

help. The method is based on a complete mathematical formulation of the boundary- initial value problems of creep accompanied by irradiation effects. Elastic, thermoelastic, plastic, thermal and irradiation creep, irradiation swelling strains, damage due to thermal and irradiation creep are considered. The numerical solution of the boundary value problems is performed by the FEM, and the initial value problems are solved by time integration. To estimate cyclic deformation and fracture, the procedures of asymptotic methods and averaging over cycle periods are used. As examples of the use of this calculation method, the results of modeling the creep of fuel claddings, T-joints of pipes and baffles of a nuclear reactor are given. The issues of interaction of strains and damages of different nature under complex stress state are discussed.

3.4 Analysis of Damage and Fracture in Anisotropic Sheet Metals Based on Biaxial Experiments

Michael Brünig , Sanjeev Koirala, and Steffen Gerke

Many experiments have indicated the dependence of strength as well as damage and fracture behavior of anisotropic sheet metals on loading direction and on stress state. Therefore, in the presentation the influence of stress state and loading direction with respect to the principal axes of anisotropy on damage and fracture behavior of anisotropic sheet metals is investigated. New experiments with biaxially loaded specimens and corresponding numerical simulations have been performed. Series of forces with different load ratios act on biaxially loaded specimen leading to different damage and failure mechanisms. Digital image correlation is used to monitor evolution of strain fields in critical parts of the specimens. Failure modes on fracture surfaces are visualized by scanning electron microscopy. In addition, numerical simulations on the micro- and the macro-level have been performed to analyze stress states. The results are used to develop a damage criterion and a damage rule depending on the stress state and the loading directions.

3.5 Periclase Deforms more Slowly than Bridgmanite under Earth Mantle Conditions

Olivier Castelnau, Patrick Cordier, Karine Gouriet, Timmo Weidner, James van Orman, Jennifer M. Jackson, and Philippe Carrez

Transport of heat from the interior of the Earth drives convection in the mantle which involves the deformation of solid rocks over billions of years. The lower mantle of the Earth is mostly composed of iron-bearing bridgmanite $MgSiO_3$ and $\sim$25% volume periclase MgO (also with some iron). It is commonly accepted that ferropericlase is weaker than bridgmanite. Considerable progress has been made in recent years to study assemblages representative of the lower mantle under the relevant pressure and temperature conditions. However, the natural strain-rates are 8 to 10 orders of magnitude lower than in the laboratory, and are still inaccessible to us. Once the deformation mechanisms of rocks and their constituent minerals have been identified, it is possible to overcome this limitation thanks to multiscale numerical modeling, and to determine rheological properties for inaccessible strain rates. In this work we use 2.5D dislocation dynamics to model the low-stress creep of MgO periclase at lower mantle pressures and temperatures. We show that periclase deforms very slowly under these conditions, in particular much more slowly than bridgmanite deforming by pure climb creep. This is due to slow diffusion of oxygen in periclase under pressure. In the assemblage, this secondary phase hardly participates in the deformation, so that the rheology of the lower mantle is very well described by that of bridgmanite.

Our results show that drastic changes in deformation mechanisms can occur as a function of the strain-rate.

3.6 Efficient Simulation of Creep in Lamellar Structures

Alexander Dyck, Alexander Kauffmann, Martin Heilmaier, and Thomas Böhlke

In this talk we use homogenization theory to predict the effective creep behavior of lamellar metal composites. To incorporate the complex microstructure of lamellar materials in computations is usually infeasible, due to the required high resolution necessary to capture the materials response. However, laminate theory offers the possibility to consider the complex lamellar microstructure and effectively predict the material response via homogenization. The homogenization scheme ensures kinematic compatibility of strains and static admissibility of stresses. Both linear elastic and more complex, viscoplastic materials can be considered in the scale transition approach.

We start our talk with a brief introduction in laminate theory and establish the necessary equations. We proceed by presenting an efficient numerical implementation of the derived equations. Finally we apply the scheme to lamellar composites to numerically predict the creep response, e.g. in terms of minimum creep rates and strains, and study the influence of the lamellar morphology on the overall creep response.

3.7 A Viscoelastic Continuum Damage Model to Model the Creep and Fatigue Failure Behavior of Fiber Reinforced Polymers

Claudio Findeisen, Zalikha Murni Abdul Hamid, Benedikt Rohrmüller, Dominik Spancken, Dominik Laveuve, and Jörg Hohe

In this presentation we investigate in the derivation, implementation, and validation of a continuum damage creep-fatigue model to describe the failure of fiber reinforced polymers under creep and combined constant (creep) and cyclic (fatigue) loads. The model is based on a linear viscoelastic three-parameter Kelvin-Voigt base model. The base model is enhanced by introducing a scalar damage variable describing the stiffness degradation. Failure of the material is assumed to be described by a Tsai-Hill type failure envelope. Based on experimental observations on the creep response of a short glass fiber reinforced polyamide 6 material, the criterion is re-written to a strain space formulation rather than the original stress space formulation. The damage evolution is assumed to be driven by the approach of a state point in strain space towards the failure envelope. For the damage evolution, a power-law formulation is assumed.

For discontinuously fiber reinforced composites featuring a spatially variable, process dependent microstructure, the model is generalized to general fiber orientation states by using the eigenvalues of the fiber orientation tensor as additional predefined field variables. In order to keep the amount of input variables within acceptable limits, the material parameters are interpolated from three predefined reference fiber orientation states. Finally, the model is critically reviewed by presenting a strategy to determine the material parameters and some validation experiments.

3.8 A Temperature Dependent Viscoelastic Approach to the Constitutive Behavior of Semi-crystalline Thermoplastics at Finite Deformations

Robert Fleischhauer, Le Zhang, and Michael Kaliske

A special class of polymers with entangled but un-crosslinked macromolecules are thermoplastics. They show significant creep phenomena, when subjected to static mechanical loads, due to their microstructure. The contribution at hand aims at a thermo-dynamically consistent constitutive modeling of the material behavior of semi-crystalline thermoplastics at finite deformations. The material behavior, that is especially focused on, is characterized by an elastic and viscous deformation, in order to model the creep behavior of thermoplastics.

The concept of the split of the deformation gradient into volumetric and isochoric parts is applied. The isochoric part is further split into elastic and viscous contributions and the volumetric part is considered to account for thermal and elastic deformations. Based on these multiplicative kinematics, the isochoric elastic right Cauchy-Green deformation tensor is introduced such that it is not influenced by a change of temperature. The determinant of the volumetric part of the deformation gradient is used to account for the thermal expansion and stress-inducing volumetric elastic deformations. This kinematic approach is based on the work of [**Miehe1992**].

The specific heat capacity of thermoplastics is incorporated into the Helmholtz energy and assumed to be a material constant. The heat flux vector is assumed to follow Fourier's law and is a function of the thermal conductivity coefficient for the appropriate thermoplastics, compare [**Fleischhauer2023**]. A suitable specific formulation of the Helmholtz energy is introduced, based on [**Zerbe2017**], consisting of volumetric, isochoric, thermal and latent parts. The energy formulation is used to derive the first Piola-Kirchhoff stresses as well as the external power, which is used to define the change of entropy inside of the thermoplastic material. Furthermore, the energy is used to specify the dissipative behavior of the material for considering a change of mechanical into thermal energetic parts, compare [**Miehe1988**].

The viscous part of the deformation gradient is driven by its thermodynamic consistent evolution equation. This evolution equation is based on a constitutive viscous flow potential with respect to the viscous intermediate configuration and the respective Mandel stresses. The second internal variable, the hardening strain is driven by the latent part of the Helmholtz energy and its thermodynamic consistent evolution equation. The presented contributions are based on the developments in [**Zerbe2017**].

All constitutive descriptions and developments are incorporated into a two-field global finite element solver, considering the balance laws of non-linear thermo-inelasticity at finite deformations, compare [**Fleischhauer2023**], with respect to the reference configuration. The Newton-type solver is based on the consistently linearized field equations for the displacement and the temperature field, which form the global unknown fields. The implicit function theorem is applied to consider the change of these global unknowns, due to a change of the local internal variables, namely the viscous part of the deformation gradient and the hardening strains. All computational developments and constitutive descriptions are numerically verified, with respect to quadratically converging global and local Newton-type solvers.

Finally, experimental creep data for polyoxymethylene (POM) at 60°C, taken from [**Zerbe2017a**], is used to identify the introduced material constants and to successfully validate the material model as a whole.

3.9 The Strain Rate Dependent Model Based on Micropolar Theory Implemented in Discrete Element Method

Przemysław Nosal and Artur Ganczarski

Modelling of high strain rates processes with large deformations can be a very demanding task when using finite element method. On the other hand, we can use the discrete element method (DEM), which naturally overcomes some disadvantages of mesh based methods. Recently, this method has also been used for modelling of metallic materials [**nguyen21**].

In present work, we focused on appropriate description of interaction forces between discrete elements. We introduce the new formulation of this description, based on micropolar theory [**cosserat09**, **nowacki86**]. To take into account the influence of high strain rates on material behavior we adopted the Johnson-Cook model [**johnson83**]. Numerical calculations of stresses in the viscoplastic range are carried out by using the return mapping algorithm with the cutting plane method [**ortiz86**].

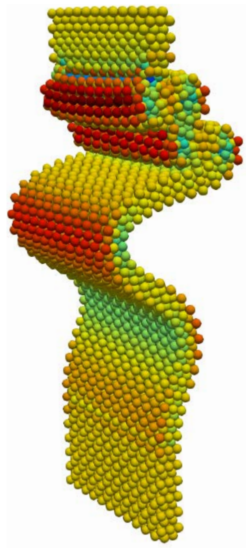

Figure 3.1: Buckling using presented model.

The outcomes confirm qualitatively material sensitivity on the strain rate. The quantitative aspect of the results can be achieved after calibration of the model parameters. Figure 3.1 presents the result of compression of aluminium bar, where the new model was used.

3.10 Development of a microstructure-based finite element model of thermomechanical response of a fully metallic composite Phase Change Material

Elisabetta Gariboldi, Matteo Molteni, Diego Vargas, and Konstantin Naumenko

Latent heat Phase Change Materials (PCM), which can store heat during their melting and release it during their solidification, are suitable materials for thermal storage and thermal management of structures. In order to confine the molten phase PCM are combined with other materials with higher melting point. The resulting composite structures, with regular or irregular arrangement of phases, are known as Composite PCM (C-PCM) and can be modulated in their heat storage capability and thermal conductivity by arranging phase amount and distribution.

When services at temperatures just below or above the melting point of the PCM phase, creep phenomena and phase volume changes occur. Under these conditions, the analysis of PCM composite behaviour requires not only thermal, but also mechanical considerations. A representative part of a regularly arranged C-PCM was considered in the present contribution. Below the melting temperature of PCM, both phases were modelled considering their thermal, elastic, plastic and creep strains. For PCM phase, in the temperature transition range and above, its volume change during phase transformation, compressibility and thermal expansion were considered. A finite element analysis of the first thermal cycle from RT to above the melting temperature was carried out for different holding times and maximum temperature. The results indicate that when PCM phase is confined by the matrix no leakage is expected, rather voids formation is observed. Analysis for some cycles illustrate that the phase can rearrange and stress distributions can be different from the initial thermal cycle. This provides the possibility to optimize the first thermal cycle in view of the service conditions expected for the C-PCM material.

3.11 The Effect of Dynamic Loads on the Creep of Geomaterials

Mikhail Guzev, A.M. Golosov, E.P. Riabokon, M.S. Turbakov, E.V. Kozhevnikov, and V.V. Poplygin

The samples of geomaterial are tested under constantly applied loading. Under the combined action of a static preload and an additional dynamic load, a linear increase in the axial strain of the sample is observed even at the initial stage of the experiment. Dynamic loading activates an intense in the creep of the geomaterial and leads to a decrease in the Young's modulus.

3.12 Effect of Fibres Content on the Creep of Fibre Reinforced Concrete – A Meso-Scale Approach

Ehab Hamed, Sen Zhang, Ali Amin, and Ian R. Gilbert

A 2D meso-scale numerical investigation of creep in fibre reinforced concrete is presented. The model runs direct image-based analysis in which the internal structure of concrete is either obtained from X-ray micro-CT scanning or numerically generated. An automatic and robust quadtree decomposition algorithm is employed to convert digital images into meshes, which are then solved using the scaled boundary finite element method based on a continuum approach. Concrete is treated as three-phase composite, that comprises of viscoelastic mortar, elastic coarse aggregates and elasto-plastic steel fibres. Zero-thickness interface elements with appropriate traction separation laws are inserted to model the potential damage and separation along the interfacial transition zone (ITZ) around the aggregates. The fibres are modelled using line beam elements that can resist axial loading, bending and shear. The creep model is based on a rate-type rheological model corresponding to a Kelvin chain. Validation of the proposed meso-scale model is conducted through validation with experiments at the macro-scale of concrete. A parametric study that examines the effects of the fibres content on the creep response is conducted. The model is capable to explain several structural aspects that cannot be captured in a macro-scale analysis, such as the effect of the fibres length and orientation, existence of pores, and other parameters.

3.13 A Novel Simulation Method for Phase Transition of Single Crystal Ni based Superalloys in Elevated Temperature Creep Regions via Discrete Cosine Transform and Maximum Entropy Method

Hideo Hiraguchi

Single crystal Ni based superalloys are composed of cubic γ' phases and γ phase channels. It is known that the γ' phases gradually connect each other and change into rafting perpendicular to the tensile direction during the first, second and third high temperature creep regions in this type of the structure composed of these two phases of the single crystal Ni based superalloys. This time, the phenomenon of the γ' phase rafting was able to be simulated via the Discrete Cosine Transform and the Maximum Entropy Method. Therefore, we are planning to make a presentation on this novel simulation method at this symposium.

3.14 Anisotropic Creep Analysis of Fiber Reinforced Load Point Support Structures for Thermoplastic Sandwich Panels

Jörg Hohe and Sascha Fliegener

Structural sandwich panels are found in a variety of technological fields where extreme lightweight solutions are required. In addition to the classical fields of the aerospace industry or the wind energy sector, sandwich structures become increasingly popular in transport applications of both the rail and road sector. In contrast to aerospace components with limited numbers of components to be manufactured, especially the automotive sector is characterized by industrial scale mass production with large numbers of components to be manufactured with an extreme demand for short cycle times. For this purpose, polymeric composite and sandwich components consisting of thermoplastic base materials are popular materials for future composite automotive designs. On the other hand, one of their major shortcomings is their inherent tendency towards creep deformation.

Objective of the present contribution is the design and evaluation of load point support structures for thermoplastic sandwich panels, involving hybrid designs of discontinuously and continuously fiber reinforced polymer matrix composite materials. For this purpose, creep material models for anisotropic fiber reinforced materials are developed and implemented. Based on a classical threeterm Kelvin-Voigt approach, a preliminary isotropic viscoelastic material model is formulated. Using a Schapery type extension, a stress dependence is implemented. The isotropic base model is extended to anisotropic fiber reinforced materials in a twofold manner. For discontinuously longfiber reinforced materials, a simple generalization based on anisotropy factors is employed. To account for creep effects in continuously unidirectionally fiber reinforced materials, the isotropic base model is superimposed with an isotropic Hooke's law. In this context, the isotropic viscoelastic part represents the matrix response whereas the rate independent anisotropic Hooke's law with (almost) vanishing stiffness perpendicular to the fibers represents the response of the unidirectionally continuous fibers. The different models are implemented as user-defined material models into a commercial finite element program.

In a first application, the numerical approach is validated against experimental data obtained in unidirectional coupon experiments considering unreinforced thermoplastic materials as well as discontinuously and continuously fiber reinforced materials, both tested in different spatial directions at different temperatures. In a second step, the model is applied to load point support structures made from compression molded long fiber reinforced thermoplastics for sandwich panels. The sandwich face sheets are made from multidirectional laminates consisting of unidirectional carbon fiber reinforced thermoplastic plies bonded to a thermoplastic foam core. Different design options for the load point support structure are considered. The results of the simulations are validated against experimental data obtained in creep experiments on square sandwich plates with a central loading point featuring the respective support structure. The numerical predictions are found in good agreement with the numerical predictions.

3.15 A Consideration of Damage Initiation and Evolution Coupling with Strain-induced Martensitic Transformation During Small Punch Tests of SUS304 at Various Deformation Rate

Takeshi Iwamoto, Chong Gao, Bo Cao, and Tsutomu Umeda

The authors published the computational results on the damage evolution during the small punch testing of the austenitic stainless steel SUS304. The damage is considered in just austenitic phase by a modified Johnson-Cook model. The mode change in the fracture with respect to the deformation rate is successfully reproduced. However, the area where fracture is initiated is different from austenite-dominant region. In this study, not only initiation but also evolution of the damage are considered in either phase or both phases by a modified Johnson- Cook model and a modified Lemaitre model, respectively. Discussions on the damage suitably generated in the either phase are made.

3.16 Modeling of Cyclic Creep in PEEK with the Parallel Rheological Framework

Yuri Kadin and Richard Schake

Although creep is usually regarded as the quasi-static phenomenon, in multiple engineering applications the load, applied for the long time interval, is not constant. In this case, loading conditions resemble fatigue, and the cyclic creep phenomenon can be considered. The current work presents the theoretical and experimental study on the polymer, which is used for roller bearing application. It is used for cages, which main function is to isolate and to guide rolling elements. In this application the polymer cage is subjected to the long-term load, which alternates in time, meaning that in such conditions classical creep (under constant load) cannot be presumed. The cage is made of PEEK (Polyether ether ketone), which is used for bearing applications due to good chemical and thermal stability. Nevertheless, this material exhibit viscous behavior leading to creep deformations. In the current study, non-linear viscosity is included into the generalized Maxwell model, employing the Eyring equation, which pustulates that the viscosity coefficient is not constant but is dependent on stress. The model is implemented by the Parallel Rheological Framework (the numerical technique recently implemented in the commercial software ABAQUS), which is used to construct the generalized Maxwell model with hyper-elastic springs and dashpots of non-linear viscosity. Initially, the viscoelastic material parameters are identified from the uniaxial test, and later these parameters are used to simulate the PEEK response under cyclic loading, to predict the time to creep/fatigue failure. Eventually, the numerical predictions are compared to the test results.

3.17 Experimental Observation and Modelling of Creep-Ratchetting Interaction for the Notched-specimen of Copper

Guozheng Kang, Yujie Liu, and Qi Li

Based on the full-field measurement of strain by DIC, the evolution of strain field near the notch of copper specimen is first observed during the stress-controlled cyclic tests with different hold times at peak stress by addressing the creep-ratchetting interaction of the notched specimen at

130°C. The evolution characteristics of strain field near the notch are comparatively analyzed by performing the ratchetting tests with and without the peak stress hold and clarifying the contribution of creep strain at peak stress hold stage. Then, the creep-ratchetting interaction of the notched specimen of copper and the corresponding evolution of strain filed near the notch are modelled by using the finite element simulations in ABAQUS with the material models built-in and homemade, respectively. Finally, the effects of notch shape and size on the creep-ratchetting interaction of the notched copper specimen are investigated from the finite element simulations and necessary experimental observations. The conclusions obtained here can provide a guidance for analyzing and assessing the creep-ratchetting interaction of relative structure components.

3.18 Various state-of-the-art methods for creep evaluation of power plant components in a wide load and temperature range

Eike Blum, Yevgen Kostenko, and Konstantin Naumenko

Many power plant components are exposed to high temperature environments and complex loading conditions over long period of operation. An important part in the life-time assessment is the reliable prediction of strain/stress state using robust creep modeling to avoid possible integrity or functionality issues and failures in such components. The goal of this work is to apply different state-of-art creep models including the empirical Norton-Bailey, modified Garofalo equations and the advanced constitutive visco-plastic model KORA to the analysis of typical high-temperature power plant components in a wide range of loads and temperatures. Among other things, an advantage of each model and its robustness is discussed, which should reflect both inelastic deformation and stress relaxation. The material parameters were identified from experimental data for 10%CrMoV heat resistant steels in the creep range. The results of non-linear Finite Element Analysis (FEA) were used for the subsequent integrity assessment of benchmark examples as well of the practical example of the steam turbine component. The material laws were implemented in the commercial software NX CAE. The results for long-term assessment of real steam turbine component are presented and discussed. In addition, an outlook on further developments of the material modeling and assessment procedure is also provided.

3.19 Modeling Degradation Phenomena in Metals with Unified Mechanics Theory

Hsiao-Wei Lee, Noushad Bin Jamal M, Stanisław Mroziński, Adam Lipski, Michał Piotrowski, and Halina Egner

Constitutive modeling of dissipative phenomena in steel (plasticity, damage, fatigue etc.) primarily relies on test data for curve fitting a degradation evolution function, because the Newtonian space–time coordinate system does not include an axis for dissipation, degradation mechanism, or irreversible processes. As a result, stress, strain, or dissipated energy are usually used as a variable of an empirical function to establish life prediction models.

On the other hand, unified mechanics theory [**Basaran2022**], unifies the universal Newton laws of motion and the second law of thermodynamics at the ab-initio level. As a result, the governing differential equation of any system automatically includes entropy generation. The Newton universal laws of motion define the space–time coordinates of a material point in a physical system subjected to a loading, while the laws of thermodynamics define the coordinate of a

physical system on the additional thermodynamic state index axis. All the physical objects travel along this axis from the point of initial degradation until failure, governed by the the thermodynamic fundamental equation of the entropy production.
In the present research a unified mechanics theory-based model is used for predicting durability of P91 steel samples subjected to nonisothermal low-cycle fatigue [**Egner2020**], and the very high cycle fatigue life of A656-grade steel under ultrasonic vibration operating at 20 kHz [**Lee2022**]. The thermodynamic fundamental equation of the entropy production is derived in each case.
It is shown that in the case of P91 steel, which belongs to the materials that do not exhibit stabilization of cyclic properties, the entropy generation-controlled fatigue damage description allows avoiding sensitivity to the loading scheme (either stress or strain control) and obtaining proper durability estimations. In the case of ultrasonic vibration fatigue of A656 steel also a very good agreement between the experimental and predicted durability is obtained.

3.20 Time-swelling Superposition Principle for the Linear Viscoelastic Properties of Polyacrylamide Hydrogels

Seishiro Matsubara, Akira Takashima, So Nagashima, Shohei Ida, Hiro Tanaka, Makoto Uchida, and Dai Okumura

In this study, we investigate the linear viscoelastic properties of polyacrylamide hydrogels over a wide range of swelling states. The experimental data for dynamic moduli demonstrate that deswollen hydrogels exhibit linear viscoelastic behaviors while swollen hydrogels behave as purely elastic material. Based on the swelling-dependent linear viscoelasticity model, the time-swelling superposition principle is advocated to quantify the linear viscoelastic nature of deswollen hydrogels. The Williams-Landel-Ferry equation and the scaling law characterize the horizontal and vertical shift factors as a function of the volume swelling ratio, respectively, which successfully organize the dynamic moduli in the deswelling state. The resulting master curves elucidate that the dynamic moduli have a positive power-law correlation to the angular frequency. In addition, two shift factors reveal that deswelling enhances both frequency dependence and elastic property of the dynamic moduli. The scaling exponents of the elastic moduli in the deswelling state are larger than those in the swelling state, regardless of the contents of monomer and cross-linker. The generalized Maxwell model with identified material parameters captures the frequency and swelling dependencies of the linear viscoelastic behaviors.

3.21 Application of Nonlinear Viscoelastic Material Models for the Shrinkage and Warpage Analysis of Blow Molded Parts

Patrick Michels, Christian Dresbach, Esther Ramakers-van Dorp, Holm Altenbach, and Olaf Bruch

The prediction of shrinkage and warpage of extrusion blow molded plastic parts is a topic of high industrial demand. Nevertheless, simulation results are still associated with uncertainties. One of the major difficulties is the description of the complex time-, temperature- and process-dependent material behavior of semicrystalline polymers like high density polyethylene (HDPE). It is state of the art to use linear viscoelastic material models for the shrinkage and warpage analysis. However, linear viscoelastic behavior can only be assumed if the stresses are small. To increase the prediction accuracy of the current simulation models, nonlinear viscoelastic material models, such as the Abaqus Parallel Rheological Framework (PRF), are investigated. The calibration of the PRF model can be quite challenging, especially if a higher number of networks is used. Consequently, we present a calibration strategy that uses functional relations to describe the parameters along the network elements in order to reduce the dimensions of the design space for model calibration. To find the best possible solution, the global optimization algorithm Adaptive Simulated Annealing (ASA) is used. A simplified one-dimensional representation of the PRF model is implemented in Matlab to further reduce the computational effort of the model calibration. The calibration workflow is successfully tested using a set of relaxation tests with subsequent unloading at different strain and temperature levels. A good agreement between the experimental material tests and the simulation results, using the calibrated PRF model, is observed.

3.22 The Development of a Cavitation-Based Model for Creep Lifetime Prediction Using Cu-40Zn-2Pb Material

Mbombo Amejima Okpa, Qiang Xu, Zhongyu Lu

The occurrence of creep induced cavitation can considerably shorten the lifespan of numerous high-temperature applications. A contemporary problem in structural mechanics and materials science is the inadequate mathematical description of creep deformation and rupture time. This situation stems not only form the lack of accurate quantification and incorporation of cavitation damage in current theoretical models, but it is compounded by the strong stress level dependency of the creep lifetime.
Cavitation is the rate-controlling mechanism during creep. To this end, this study has developed a cavitation-based method for creep rupture lifetime prediction. For accuracy and a representative data, cavitation data measured using x-ray synchrotron tomography, are chosen for the study. Cavitation damage modelling precisely cavity nucleation, growth and size distribution are present. Functional relationship between creep exposure time and cavitation damage are developed to aid creep lifetime prediction. This approach has the advantage of traceability as it developed based on quantifiable physical changes in the material (cavity nucleation and growth).
This study reports the latest progress in the development of a cavitation model for a specific material under testing condition. It is planned to incorporate it, to develop a creep lifetime prediction and extrapolation model. This paper offers a theoretical foundation for a time-based extrapolation method to predict creep lifetime. Furthermore, the cavitation modelling approach used in this study may be applied in other failure modes like fatigue.

3.23 Effects of Surface Tension on Crease Nucleation and Evolution in an Elastomer Subjected to Uniaxial, Plane Strain, and Equibiaxial Compressions

Dai Okumura, Atsuya Ogino, Seishiro Matsubara, and So Nagashima

This study investigates the effects of surface tension on crease nucleation and evolution in an elastomer subjected to uniaxial, plane strain, and equibiaxial compressions. Two-dimensional finite element analysis is performed assuming an incompressible neo-Hookean hyperelastic media. A perturbation force-based approach (not initial imperfection approaches) is used to introduce a crease in the metastable state prescribed before the onset of wrinkling instability, leading to estimating the energy barrier and the energy release. The former is the energy needed to nucleate the crease and the latter is the energy that is released by the evolution of the

crease. The dominant periodic distance between creases is also analyzed as a function of the amount of the applied strain. Because the energy release is assumed to balance the energy increase due to surface tension, which is caused by crease nucleation and evolution, the effects of surface tension is simply analyzed via the results of the finite element analysis. It is found that the predictions are in good agreements with experimental data and further elucidate the tendency depending on uniaxial, plane strain, and equibiaxial compressions. Further, it is found that because surface instability has the scale-free nature, the nucleation of the crease causes the mesh sensitivity whereas the evolution of the crease can be normalized by the thickness of the hyperelastic media.

3.24 The Development and Application of Optimisation Technique for the Calibrating of Creep Cavitation Model Based on Cavity Histogram

Bilal Rafiq, Xuming Zheng, and Qiang Xu

It is generally accepted that the creep rupture is primarily determined by the creep cavitation at grain boundaries, hence it is vital important to develop an accurate cavitation model. Most of the existing creep cavity models used some simplifications such as using average diameter of cavities, assumed nucleation, et al. Recently, the concept of calibrating the creep cavity models using 3D cavity histogram without any aforementioned simplifications was conceived and practical trial and error method was devised and used. Whilst the use of such trial and error method had produced results, arguably very accurate too, but its use heavily relies on the user's insight knowledge of the characteristics of the cavity density distribution function and intervention. Here, we present the development and application of optimisation techniques for the calibration of creep cavitation model using Excel Solver, via the minimising the difference of the predicted cavity distribution density over cavity size and the experimental measured one. Its application produces an updated creep cavitation model without any suspicions doubt of its mathematical accuracy. We anticipate this optimisation implementation via Excel Solver will be widely used in future.

3.25 Self-heating Analysis with Respect to Holding Times of an Additive Manufactured Aluminium Alloy

Lukas Richter, Holger Sparr, and Matthias Ziegenhorn

Materials exhibiting a rate-dependency in a mechanical loading regime enclose a variety of deformation mechanisms depending on their microstructure. This holds true for material classes from plastics to metals and is increasingly important for high-performance structural components. Material models covering viscoplastic deformation with hardening effects for metals have been widely studied in the last decades. The deformation mechanisms contribute to stored energy and dissipation and are reflected in the balance of energy. The current temperature measurement techniques give new opportunities to exploit an accurate temperature field to prove and validate material models. Especially, contact-free thermography with a small resolution range up to 1 mK is becoming more popular in mechanical testing set-ups. The paper examines a thermo-mechanical approach and an experimental concept for a material law verification and validation for self-heating in small temperature ranges. The focus lies on loading regimes incorporating holding times and the unloading path. An advanced thermographic measurement method is applied. It is pointed out that the thermomechanical approach is valuable and informative to assess the observed deformation processes and to describe the material behaviour with a thermodynamically valid parameter set.

3.26 Simulation of Firn Densification Using a Cell Model Approach

Timm Schultz, Ralf Müller, and Angelika Humbert

In polar regions and at high altitudes the amount of snow fall over the course of a year can exceed the amount of snow melting during the melt season. This multi-annual snow is called firn. It is the intermediate product between snow and glacier ice. Firn, a mixture of ice and air, compresses due to the continuing accumulation of snow over consecutive years and the resulting overburden stress. The simulation of this densification process on Earth's ice sheets, Greenland and Antarctica, is of interest for serveral reasons.
Air can circulate through the porous material firn. Therefore, an age difference between glacier ice and air enclosed in the ice in form of bubbles exists. For this reason reconstructions of the past climate from ice cores rely on knowledge of the point in time of pore close-off. This can be obtained by simulating the densifications process of firn. Simulations further allow to describe the density distribution of the firn layer on the Greenland Ice Sheet and in Antarctica. Volume changes of the ice sheets, obtained for example by consecutive satellite measurements, can be translated into mass changes using this density distribution.
In natural conditions on Earth firn exists at temperatures relatively close to its melting point. This makes firn an interesting material as it densifies due to creep. The process shows several similarities to sintering. In [**gagliardini1997**] Gagliardini & Meyssonnier adopted a model for the consolidation of power law creeping materials, based on a cell model. The model can be applied to firn, as its creep behavior can be described by a power law. This approach for the simulation of firn densification is reviewed and improved, by including a broader data basis and considering additional data. To determine the model parameters, data from firn cores, obtained in Greenland and Antarctica, are analyzed regarding their density as well as their stress and strain states.

3.27 Creep Behavior Under High Temperature Thermal Cycling and Low Mechanical Loadings

Romana Schwing, Stefan Linn, Christian Kontermann, and Matthias Oechsner

Operators of industrial furnaces often report premature failure of thin walled components accompanied by large creep deformations. The components show a significantly shorter lifetime than expected by calculations using a linear damage accumulation model.
In addition to very high temperatures, which are up to 80% of the melting temperature [K] of the deployed materials, and the corrosive and oxidative ambient atmosphere the complex loading conditions in such industrial furnaces often include temperature changes due to burner on-off-cycle, batch operation or belt infeed.
Experiments under corresponding conditions of very high temperatures and low mechanical loadings showed that the creep strain of some typical metallic materials under anisothermal testing turned out to be much higher than the creep strain of an isothermal creep test at maximum cycle temperature. This creep behavior is rather unexpected and further investigations of this effect of accelerated creep strain under anisothermal conditions were systematically made.

Several material grades were tested under different temperature cycles at low mechanical stresses and it can be concluded that the observed effect is no material-specific issue. Rather, it seems to be a hitherto uninvestigated creep effect, which deserves further attention, even though the occurrences are limited to a specific parameter range.
In this study the results of a systematically performed experimental campaign are outlined. The results reveal relevant parameters that show to have a specific influence on the effect of accelerated creep strains under anisothermal temperature. As well the relevance of microstructural properties and a formed dislocation structure will be discussed. Here, microstructural processes may cause the observation of repriming, which was observed after every temperature change. Furthermore, an approach for explaining these underlying creep mechanisms will be briefly introduced.

3.28 Effect of Atomistic Diffused Carbons in Fe-C Alloy to Stress-induced Phase Transformation

Yoji Shibutani, Lijun Liu, Kazuma Ito, Hideaki Sawada, Masaaki Sugiyama, and Naoki Maruyama

Clustering of diffused carbons in steel (Fe-C alloy) much affects the strength and ductility because the internal lattice structure may be largely distorted and it reduces to yield the self-equilibrium internal stress, which changes the defect interaction of dislocations mechanically. Activation barrier of carbon diffusion (0.45 eV for 0.1 at% C by the present calculation) is much lower than the self-diffusion of iron (3.11 eV) and thus it can easily diffuse during tempering process even close to room temperature. In the current research, the atomistic modeling to investigate the effect of diffused carbons in Fe-C alloy was employed using molecular dynamics simulations. Phase transformation to martensitic phase produces the several phases of alpha-prime (bcc or bct), fct and epsilon (hcp). This behavior is complexly driven as a function of temperature and its rate, content of carbon, applied stress and so on. The study mainly takes the effect of applied stress at several circumstance temperatures and anisotropic diffusion effect of carbon. And the residual epsilon phase after a stress cycle, which broke the reversible Bain distortion between fcc and bcc, was focused from the view on the embryo of carbide.

3.29 Creep-damage Processes in Cyclic Loaded Double Walled Structures

Oksana Tatarinova, Holm Altenbach, and Dmytro Breslavsky

Recent years have been characterized by increased interest in the use of cooled blades operating at elevated temperatures in gas turbine engines (GTE). The large number of cooling channels and the complex geometric shape of the blades lead to the fact that direct numerical analysis often cannot be satisfactorily applied to elucidate the qualitative patterns of their deformation and damage accumulation leading to fracture.
GTE blades used on vehicles operate under conditions of complex temperature-force cyclic loading, which is also characterized in forced modes by stresses exceeding the elasticity limits. For effective numerical simulation of such structural elements, it is necessary to use adequate constitutive equations that can reflect all the effects that occur in their material over time. The paper is devoted to the description of the developed constitutive equations for modeling cyclic creep-damage processes, as well as the use of these equations in the numerical analysis of models of GTE blades. To obtain the constitutive creep-damage equations which are valid in

the stress range not exceeding the elastic limit, asymptotic methods and methods of averaging over periods are used. To take into account cyclic overloads that lead to the occurrence of plastic strains in a hardening material, a method that makes it possible to obtain averaged creep curves has been developed. Examples of using the obtained equations for modeling the creep of heat-resistant alloys used in turbine machinery are considered.

For numerical simulation of deformation and fracture, the FEM is used in combination with a numerical method of time integration. To estimate the patterns characteristic of the alloys under consideration in a complex stress state, a number of simplified two-dimensional models are considered, the temperature-force regimes of which are close to real ones. A model of a doublewalled blade, which is located in a non-uniform temperature field and loaded with gas flow pressure and centrifugal forces, has been developed and investigated. The laws of deformation and fracture due to damage accumulation, obtained by analyzing the numerical results, are discussed.

3.30 Finite Element Models in the study of Creep Behavior of Carbon-Fiber-Reinforced Composites

Sorin Vlase, M. Katouzian, Marin Marin, C. Itu, and A. Toderita

Usually, a polymer composite with a viscoelastic response matrix has a creep behavior. To predict this phenomenon, a good knowledge of the properties and mechanical constants of the material becomes important. Schapery's equation represents a basic relation to study the nonlinear viscoelastic creep behavior of composite reinforced with carbon fiber (matrix made by polyethrtethrtketone (PEEK) and epoxy resin). The finite element method (FEM) is a classic, well known and powerful tool to determine the overall engineering constants. The method is applied to a fiber one-directional composite for two different applications: carbon fibers T800 reinforcing an epoxy matrix Fibredux 6376C and carbon fibers of the type IM6 reinforcing a thermoplastic material APC2. More cases have been considered.

3.31 Effect of Physical Aging on the Flexural Creep in 3D Printed Thermoplastic

Kerstin Weinberg and Marcel Fischbach

Extrusion-based 3D printing has become one of the most common additive manufacturing methods and is widely used in engineering. This contribution presents the results of flexural creep experiments on 3D printed PLA specimens, focusing on changes in creep behavior due to physical aging. It is shown experimentally that the creep curves obtained on aged specimens are shifted to each other on the logarithmic time scale in a way that the theory of physical aging can explain. The reason for the physical aging of 3D printed thermoplastics is assumed to be the special heat treatment that the polymer undergoes during extrusion. Additionally, results of a long-term flexural creep experiment are shown, demonstrating that non-negligible creep over long periods can be observed even at temperatures well below the glass transition temperature. Such creep effects should be considered for designing components made of 3D printed thermoplastic.

3.32 Deep Material Networks for an Efficient Virtual Characterization of Long-term Creep in Short Fiber-reinforced Polymers

Fabian Welschinger, Argha Protim Dey, Benjamin Schneider, Matti Schneider, Sebastian Gajek, and Thomas Böhlke

In an increasingly competitive environment, a fast development process for products with high reliability requirements is the key to success. A significant acceleration can be achieved by virtualizing the product development process to a high degree. Shaping the reliability of complex systems in an early phase of the product development process requires the use of accurate simulation methods. Shaping the reliability means knowing and evaluating all possible failures of industrial products. For all design elements in a system subjected to harsh environments and loading conditions, this includes functional failure or loss of integrity. To answer these questions virtually, we need precise simulation methods for predicting the deformation and failure behavior for all materials involved. In particular for components made of fiber-reinforced polymers the prediction of relevant characteristics is a challenging task. The process-induced microstructure of the material heavily impacts the anisotropic thermo-mechanical behavior of the macroscopic component. This renders modeling approaches and the required experimental characterization effort very costly and time intensive. A significant acceleration can be achieved by replacing the physical experiments by material simulations carried out on the microstructural level of the composite.

These computations are executed on synthetically generated realistic three-dimensional images of the microstructure with statistical descriptors as input. A key to obtain high quality numerical results in a reasonable time is the use of efficient FFTsolvers that operate on regular grids with no need for explicitly meshing the complex microstructure. Following this philosophy, the macroscopic deformation and failure behavior as a function of the microstructural topology can be modeled with remarkable quality. The interaction between nonlinear micromechanical and macroscopic response, i.e., material and component behavior, can be realized using expensive FE2 or FE-FFT strategies or alternatively using efficient data-driven multiscaling techniques. At the core of these approaches are surrogate models that, compared to the full field FFT simualtions, provide the same modeling accuracy in a fraction of the computing time. These methods consist of an offline phase, in which numerous micromechanical simulations are performed to generate numerical data which are used for training deep material networks. In an online phase, for fiber-reinforced polymers, the deep material networks are first used to inversely identify the constitutive parameters for the individual phases based on sparse experimental data and then to generate virtual test data for arbitrary loading conditions. The enriched dataset, i.e., real and virtual test data, then serves as a basis for calibrating well-established anisotropic models used for component simulations. This contribution outlines the theory of deep material networks in the context of longterm creep in fiber-reinforced polymers and demonstrates the application of this concept in an industrial environment by comparing experimental investigations with numerical analyses.

3.33 Creep and Fracture of 316L under Uniaxial and Multiaxial Stress States: Comparison Between Finite Element Analysis and Digital Image Correlation Method

Jian-Feng Wen, Yang Shu, Jia-Wen Fei, Cong-Xiang Zheng, and Shan-Tung Tu

The stress state is one of the most notable factors that dominate the initiation of creep fracture. To examine the effects of stress state on creep and creep fracture, uniaxial and multiaxial creep rupture tests were carried out at 600°C on standard creep specimens and tension-shear specimens, respectively, for 316L stainless steel. The strain on the surface of the specimens was measured by digital image correlation (DIC) method. The displacement variations of the gauge section measured by the DIC method and calculated by the finite element method (FEM) based on the ductility exhaustion concept were compared with the creep test results; and the results of multiaxial creep fracture analysis based on DIC method and FEM were compared. The results shows that the variation of the displacement with time measured by the DIC method and the FEM is in good agreement with the results obtained by the extensometer on the uniaxial specimen, which verified the feasibility of the two methods. In addition, the creep strain field of the tension-shear specimen measured by the DIC method coincide with the that obtained by the FEM, which give us confidence in analyzing the creep fracture strain under different stress states. A fracture locus was finally constructed in the space of creep ductility and stress triaxiality for 316L based on a series of tests and calculations.

3.34 Modeling of Creep in Nickel-based Superalloys Based on Microtwinning Mechanism

Jingyu Zhang and Huiling Duan

Microtwinning mechanism dominates the creep of nickel-based superalloy in the certain environment due to the complex microstructure. In this study, creep theory based on microtwinning mechanism is established, including the creep constitutive equation based on crystal plasticity theory and the damage evolution equations. Furthermore, finite element algorithm and model are proposed with the developed creep theory, which are used to simulate the creep behaviors dominated by microtwinning mechanism of polycrystalline nickel-based superalloy under different aging treatments based on Abaqus/Explicit. The model predictions show a good consistency with experimental results. The research results indicate that the reference shearing slip rate and the multiplication of mobile dislocations mainly contribute to the creep strain, while the nucleation and growth rate of cavities determines the creep life. The reference shearing slip rate depends on the initial state of microstructure.

4 List of Authors and Participants

Bilen Emek **Abali**
Uppsala University, Sweden
bilenemek@abali.org

Holm **Altenbach**
Lehrstuhl für Technische Mechanik, Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany
holm.altenbach@ovgu.de

Ali **Amin**
University of New South Wales, Sydney, Australia
ali.amin@sydney.edu.au

Thomas **Böhlke**
Chair for Continuum Mechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
thomas.boehlke@kit.edu

Dmytro **Breslavsky**
National Techical University *Kharkiv Polytechnic Institute* & Lehrstuhl für Technische Mechanik, Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany
brdmkhpi@gmail.com

Olaf **Bruch**
Bonn-Rhein-Sieg University of Applied Sciences, Grantham Allee 20, 53757 Sankt Augustin & Dr. Reinold Hagen Stiftung, Kautexstr. 53, 53229 Bonn, Germany
Olaf.Bruch@h-brs.de; o.bruch@hagen-stiftung.de

Michael **Brünig**
Universität der Bundeswehr München, Neubiberg, Germany
michael.bruenig@unibw.de

Tieshan **Cao**
School of Materials Science and Engineering, Dalian University of Technology, Dalian 116085, P.R. China
tieshan@dlut.edu.cn

Philippe **Carrez**
Unité Matériaux et Transformations, Cité scientifique, Bât. C6, Université de Lille, 59655 Villeneuve d'Ascq, France
philippe.carrez@univ-lille.fr

Olivier **Castelnau**
PIMM / CNRS, Paris, France
olivier.castelnau@ensam.eu

Patrick **Cordier**
Unité Matériaux et Transformations, Cité scientifique, Bât. C6, Université de Lille, 59655 Villeneuve d'Ascq, France
patrick.cordier@univ-lille.fr

Argha Protim **Dey**
Robert Bosch GmbH, Corporate Sector Research and Advance Engineering, Germany

Christian **Dresbach**
Bonn-Rhein-Sieg University of Applied Sciences, Von-Liebig-Str. 20, 53359 Rheinbach, Germany
christian.dresbach@h-brs.de

Huiling **Duan**
State Key Laboratory for Turbulence and Complex Systems, Department of Mechanics and Engineering Science, BIC-ESAT, College of Engineering, Peking University, Beijing 100871, P.R. China
hlduan@pku.edu.cn

Alexander **Dyck**
Chair for Continuum Mechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
alexander.dyck@kit.edu

Halina **Egner**
Faculty of Mechanical Engineering, Cracow University of Technology, Al. Jana Pawła II 37,31-864 Kraków, Poland
halina.egner@pk.edu.pl

Johanna **Eisenträger**
Lehrstuhl für Technische Mechanik, Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany
johanna.eisentraeger@ovgu.de

Jia-Wen **Fei**

Claudio **Findeisen**
Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany
claudio.findeisen@iwm.fraunhofer.de

Marcel **Fischbach**
Universität Siegen, Siegen, Germany
marcel.fischbach@uni-siegen.de

Robert **Fleischhauer**
Institute for Structural Analysis, Technische Universität Dresden, Dresden, Germany
robert.fleischhauer@tu-dresden.de

Sascha **Fliegener**
Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany
sascha.fliegener@iwm.fraunhofer.de

Sebastian **Gajek**
Chair for Continuum Mechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Artur **Ganczarski**
Faculty of Mechanical Engineering, Cracow University of Technology, Al. Jana Pawła II 37,31-864 Kraków, Poland
artur.ganczarski@pk.edu.pl

Chong **Gao**
Ritsumeikan University, Japan
gaochong@fc.ritsumei.ac.jp

Elisabetta **Gariboldi**
Politecnico di Milano, Milan, Italy
elisabetta.gariboldi@polimi.it

Steffen **Gerke**
Universität der Bundeswehr München, Neubiberg, Germany
steffen.gerke@unibw.de

Ian R. **Gilbert**
University of New South Wales, Sydney, Australia
i.gilbert@unsw.edu.au

Andrei Mikhailovich **Golosov**
Perm National Research Polytechnic University, Perm, Russian Federation)
a-dune@mail.ru

Karine **Gouriet**
Unité Matériaux et Transformations, Cité scientifique, Bât. C6, Université de Lille, 59655 Villeneuve d'Ascq, France
karine.gouriet@univ-lille.fr

Mikhail **Guzev**
Perm National Research Polytechnic University, Perm & Institute for Applied Mathematics of the Far Eastern Branch of the Russian Academy of Sciences, Vladivostok, Russian Federation
guzev@iam.dvo.ru

Ehab **Hamed**
University of New South Wales, Sydney, Australia
e.hamed@unsw.edu.au

Martin **Heilmaier**
Institut für Angewandte Materialien - Werkstoffkunde, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
martin.heilmaier@kit.edu

Hideo **Hiraguchi**
The Institution of Professional Engineers, Japan, Tokyo, Japan
hideoh@abox2.so-net.ne.jp

Jörg **Hohe**
Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany
joerg.hohe@iwm.fraunhofer.de

Angelika **Humbert**
AWI Bremerhaven, Universität Bremen, Germany
angelika.humbert@awi.de

Shohei **Ida**

Kazuma **Ito**

C. **Itu**

Takeshi **Iwamoto**
Hiroshima University, Higashi-Hiroshima, Japan
iwamoto@mec.hiroshima-u.ac.jp

Jennifer M. **Jackson**

Noushad Bin **Jamal** M
Department of Applied Mechanics, Indian Institute of Technology, Madras, India
noushadbj@gmail.com

Yuri **Kadin**
SKF - Research Technology Development, Houten, The Netherlands
Yuri.Kadin@skf.com

Michael **Kaliske**
Institute for Structural Analysis, Technische Universität Dresden, Dresden, Germany

michael.kaliske@tu-dresden.de

Guozheng **Kang**
Southwest Jiaotong University, Chengdu, P.R. China
guozhengkang@swjtu.edu.cn

M. **Katouzian**

Alexander **Kaufmann**
Institut für Angewandte Materialien - Werkstoffkunde, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
alexander.kaufmann@kit.edu

Katharina **Knape**
Lehrstuhl für Technische Mechanik, Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany
katharina.knape@ovgu.de

Sanjeev **Koirala**
Universität der Bundeswehr München, Neubiberg, Germany
sanjeev.koirala@unibw.de

Christian **Kontermann**
Institut für Werkstoffkunde, TU Darmstadt, Darmstadt, Deutschland
christian.kontermann@tu-darmstadt.de

Yevgen **Kostenko**
Siemens Energy AG, Mülheim an der Ruhr, Germany
yevgen.kostenko@siemens-energy.com

Evgenii Vasilievich **Kozhevnikov**
Perm National Research Polytechnic University, Perm, Russian Federation
kozhevnikovevg@mail.ru

Dominik **Laveuve**
Professur Allgemeiner Maschinenbau, Fachbereich Management, Information, Technologie, Jade Hochschule Wilhelmshaven/Oldenburg/Elsfleth, Friedrich-Paffrath-Straße 101, 26389 Wilhelmshaven, Germany

Hsiao-Wei **Lee**
University at Buffalo, The State University of New York, USA
hlee53@buffalo.edu

Qi **Li**

Stefan **Linn**
Institut für Werkstoffkunde, TU Darmstadt, Darmstadt, Deutschland
stefan.linn@tu-darmstadt.de

Adam **Lipski**
Faculty of Mechanical Engineering, Bydgoszcz University of Science and Technology, Al. Prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland
adlippkm@pbs.edu.pl

Linju **Liu**

Yujie **Liu**

Zhongyu **Lu**
School of Computing and Engineering, Huddersfield University, Huddersfield HD1 3DG, UK
j.lu@hud.ac.uk

Marin **Marin**
Transilvania University of Brasov, Brasov, Romania
m.marin@unitbv.ro

Naoki **Maruyama**

Seishiro **Matsubara**
Nagoya university, Furo-cho, Chikusa-ku, Nagoya, Japan
seishiro.matsubara@mae.nagoya-u.ac.jp

Patrick **Michels**
Bonn-Rhein-Sieg University of Applied Sciences, Von-Liebig-Str. 20, 53359 Rheinbach, Germany
patrick.michels@h-brs.de

Stanisław **Mroziński**
Faculty of Mechanical Engineering, Bydgoszcz University of Science and Technology,Al. Prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland
stmpkm@pbs.edu.pl

Ralf **Müller**
TU Darmstadt, Darmstadt, Germany
ralf.mueller@tu-darmstadt.de

Zalikha **Murni**
Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany
zalikha.hamid@iwm.fraunhofer.de

So **Nagashima**

Konstantin **Naumenko**
Lehrstuhl für Technische Mechanik, Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany
konstantin.naumenko@ovgu.de

Vinh Van **Nghiem**
Thuyloi University, Hanoi, Vietnam
vinhfme@tlu.edu.vn

Matthias **Oechsner**
Institut für Werkstoffkunde, TU Darmstadt, Darmstadt, Deutschland
matthias.oechsner@tu-darmstadt.de

Atsuya **Ogino**

Mbombo Amejima **Okpa**
Department of Technology and Engineering School of Computing and Engineering University of Huddersfield, Huddersfield, HD1 3DH, UK
U2181632@unimail.hud.ac.uk

Dai **Okumura**
Nagoya University, Nagoya, Japan
dai.okumura@mae.nagoya-u.ac.jp

Hang Thi **Pham**
Thuyloi University, Hanoi, Vietnam
pthang@tlu.edu.vn

Michał **Piotrowski**
Faculty of Mechanical Engineering, Bydgoszcz University of Science and Technology,Al. Prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland
m.piotrowski@utp.edu.pl

Giacomo **Po**
University of Miami, Coral Ga, USA
gpo@miami.edu

Vladimir Valerievich **Poplygin**
Perm National Research Polytechnic University, Perm, Russian Federation)
poplygin@bk.ru

Bilal **Rafiq**
Department of Technology and Engineering School of Computing and Engineering University of Huddersfield, Huddersfield, HD1 3DH, UK
U2181632@unimail.hud.ac.uk

Esther **Ramakers-van Dorp**
Bonn-Rhein-Sieg University of Applied Sciences, Von-Liebig-Str. 20, 53359 Rheinbach, Germany
esther.vandorp@h-brs.de

Evgenii Pavlovich **Riabokon**
Perm National Research Polytechnic University, Perm, Russian Federation
riabokon.evgenii@gmail.com

Lukas **Richter**
BTU Cottbus Senftenberg, Senftenberg, Germany
richtluk@b-tu.de

Benedikt **Rohrmüller**
Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany
benedikt.rohrmueller@kit.edu

Hideaki **Sawada**

Richard **Schake**

Benjamin **Schneider**
Corporate Sector Research and Advance Engineering - Component Design, Reliability and Validation Polymers (CR/AMP5), Robert Bosch GmbH, 70465 Stuttgart
Benjamin.Schneider3@de.bosch.com

Matti **Schneider**
Chair for Continuum Mechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
matti.schneider@kit.edu

Timm **Schultz**
TU Darmstadt, Darmstadt, Germany
timm.schultz@tu-darmstadt.de

Romana **Schwing**
Institut für Werkstoffkunde, TU Darmstadt, Darmstadt, Deutschland
romana.schwing@tu-darmstadt.de

Yoji **Shibutani**
Osaka University, Osaka, Japan
sibutani@mech.eng.osaka-u.ac.jp

Yang **Shu**

Dominik **Spancken**
Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit LBF, Darmstadt, Germany
dominik.spancken@lbf.fraunhofer.de

Holger **Sparr**
BTU Cottbus Senftenberg, Senftenberg, Germany
holger.sparr@b-tu.de

Masaaki **Sugiyama**

Akira **Takashima**

Hiro **Tanaka**

Oksana **Tatarinova**
National Techical University *Kharkiv Polytechnic Institute*, Kharkiv, Ukraine
ok.tatarinova@gmail.com

A. **Toderita**

Shan-Tung **Tu**

Mikhail Sergeevich **Turbakov**
Perm National Research Polytechnic University, Perm, Russian Federation
msturbakov@gmail.com

Makoto **Uchida**

Tsutomu **Umeda**
Osaka Metropolitan University, Osaka, Japan
umedat@omu.ac.jp

James **van Orman**
Case Western Reserve University, 10900 Euclid Ave., Cleveland, OH 44106, USA
james.vanorman@case.edu

Sorin **Vlase**
Transilvania University of Brasov, Brasov, Romania
svlase@yahoo.com

Timmo **Weidner**
Unité Matériaux et Transformations, Cité scientifique, Bât. C6, Université de Lille, 59655 Villeneuve d'Ascq, France
timmo.weidner@univ-lille.fr

Kerstin **Weinberg**
Universität Siegen, Siegen, Germany
kerstin.weinberg@uni-siegen.de

Fabian **Welschinger**
Robert Bosch GmbH, Renningen, Germany
fabian.welschinger@de.bosch.com

Yuandi **Wu**
University of Huddersfield, Huddersfield, United Kingdom

Qiang **Xu**
University of Huddersfield, Huddersfield, United Kingdom
q.xu2@hud.ac.uk

Jingyu **Zhang**
College of Engineering, Peking University, Beijing, P.R. China
jingyuzhang@pku.edu.cn

Le **Zhang**
Institute for Structural Analysis, Technische Universität Dresden, Dresden, Germany
le.zhang@mailbox.tu-dresden.de

Sen **Zhang**
University of New South Wales, Sydney, Australia

Jie **Zhao**
Dalian University of Technology, Dalian, P.R. China
jiezhao@dlut.edu.cn

Xuming **Zheng**
Department of Technology and Engineering School of Computing and Engineering University of Huddersfield, Huddersfield, HD1 3DH, UK Xuming.Zheng@hud.ac.uk

Cong-Xiang **Zheng**

Matthias **Ziegenhorn**
BTU Cottbus Senftenberg, Senftenberg, Germany
ziegenho@b-tu.de