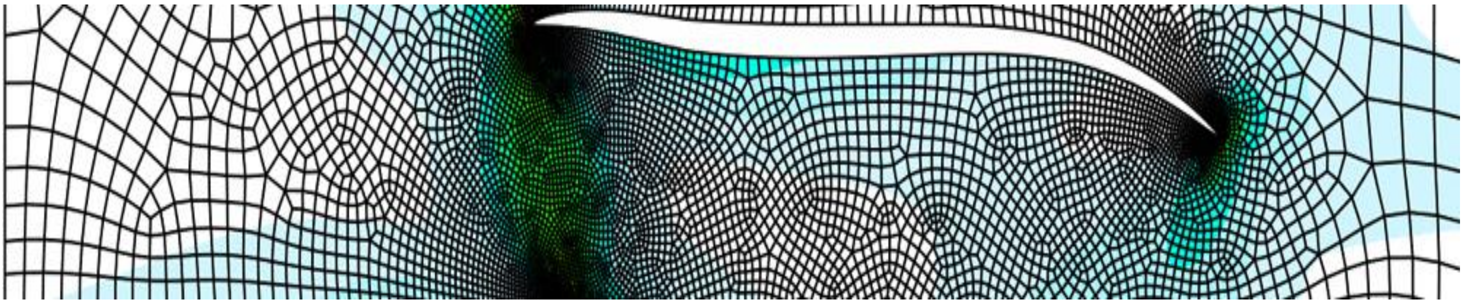

Subproject A2: Near-Surface Regions - development of loading adapted property profiles

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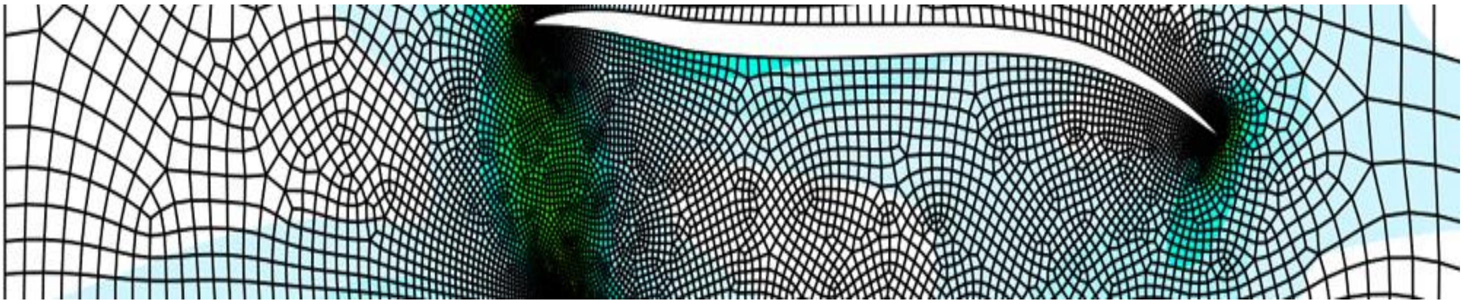
Summary description of the project:

Near-surface regions are of essential importance for the damage development during fatigue loading. These regions are the highest loaded areas of components and therefore generally starting points for capital damage mechanisms due to different Influences (notch effect, surface roughness, corrosion etc.). Heat treatment and mechanical surface treatment, like deep rolling, are able to increase the resistance against failure in near-surface regions. A combination of the treatments mentioned leads for example to a stabilization of beneficial residual stress states due to coupled effects and therefore to higher fatigue lifetime, as well as the safety and reliability of components. However, a consecutive or simultaneous combination of two processes usually implies a further step in the process chain, resulting in higher effort and costs. A systematic study regarding the influence on the microstructure of the material and an integration of functions to reduce the length of the process chain are the central points of the project.

Current status of the project:

One particular aspect of the subproject is the characterization of the near surface region which is influenced by the combination of elevated temperature and plastic deformation regarding safety and reliability. Significant properties of the surface regions which are so far investigated are residual stress states and integral width values measured by x-ray diffraction, development of the surface and core hardness and the quality of the surface (roughness). The results are considered regarding the lifetime of components, demonstrated by Wöhler curves which are generated by the evaluation of fatigue tests with uniaxial tension-compression loading. The investigated near surface regions are created by the variation of significant process parameters, like deep rolling force and temperature but also by changing the material state after tempering at higher temperature.

Furthermore, the integration of inductive heat treatment and deep rolling at elevated temperature in a combined, integrated process is a key issue of the subproject. For this purpose, a process chain was developed where the three temporally and locally separated processes (inductive hardening, tempering and high temperature deep rolling) can be executed consecutively or simultaneously. This process chain is the basis for further studies regarding an optimization of process parameters depending on process – material structure – property – relationship. An investigation of the human factor, for example with eye – tracking – systems, is intended because the mentioned processes unite two disciplines of material science and therefor demand high standards on operators.



Subproject A3: Mineral adhesive for high performance concrete

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Summary description of the project:

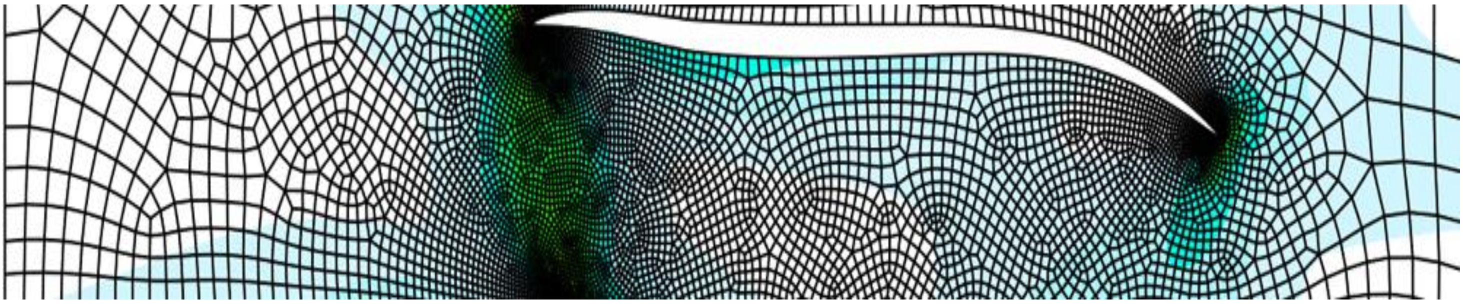
Since the middle of the last century, adhesive bonding has been successfully used in the aerospace industry. In addition, in the past, the need for energy savings ("lightweight construction") also led to the establishment of adhesive production processes in road and rail vehicle construction. In the construction industry, especially the broader application of ultra-high performance concrete (UHPC) offers enormous potential for structural bonding. The outstanding properties of this high-tech material enable filigree, material-saving, but also highly resilient constructions that can be produced economically as prefabricated parts in modular construction. By applying the adhesive technology, these components can be joined directly after delivery to the construction site. This method allows a better exploitation of the potential of the UHPC, both constructively and economically.

Applications of structural bonding are the bridge construction, here, for example, the prefabricated UHPC plates of the bridge deck can be joined to the upper chords made of UHPC or steel (see Gärtnerplatzbrücke in Kassel). Furthermore, the load bearing capacity and durability of solid or steel bridges can be restored or even increased by joining thin prefabricated UHPC panels. The effort of repairs to damaged bridge decks might be drastically reduced. Similarly, the use of high-performance mineral adhesives is feasible in modular building construction with prefabricated UHPC parts.

Current status of the project:

The aim of the TP A3 is to achieve a load transfer between components which have been joined by means of mineral adhesive. Specifically, the composite zone should be sustainably strengthened so that the failure takes place in the reinforced substrate. In experiments with epoxy adhesives, a similar behaviour could be detected, but these products are only applicable under severe restrictions. The achieved results of the project in material-technical adaptation, the optimization of the joining zone layout, the quantification of the human influence (in cooperation with TP A1 / B4) as well as the tests for direction depending strength determination (in cooperation with TP B3) resulted in the finding, how a ductile failure behaviour of joined material connections can be achieved. The overall objective of safe and reliable materials was basically ensured by the defined micro-reinforcement of the joining zone.

The final modification of the mineral adhesive system is to raise its adhesion properties to the performance level of the epoxy-based adhesives. The processing properties were adjusted and the spectrum of redispersible polymer dispersions (RPP) to be investigated was further expanded. For the first time it could be shown that the bond between material-technically modified mineral adhesive and defined substrate surface exceeds the matrix tensile strength of the UHPC substrate. These very promising results are followed by test series in which, among other things, mechanical characteristics under normal climatic conditions and under varying conditions are checked.



Teilprojekt B2: Charakterisierung von Bio-Verbundwerkstoffen zur Simulation der mechanischen Eigenschaften

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Zusammenfassung:

With increasing environmental awareness the use of renewable reinforcement fibres - such hemp, jute or regenerated cellulose- increasingly comes to the fore. The mechanical properties of glass fibre reinforced composites are already reachable with the natural fibre reinforcement whereby their structures and properties deviate significantly to those of conventional reinforcement fibres.

Due to the significantly lower bending stiffness, the natural fibers differ significantly from glass fibers (GF) not only in their orientation, but also with regard to fiber length distribution, fracture behavior and fiber-matrix interaction. To simulate the fracture behavior of the bio-composites, it is essential to consider and characterize these influencing factors. In this subproject, the fracture behavior of bio-composite, which has so far only been considered integrally, is investigated with regard to micromechanics and the results are used for modelling the composite material in cooperation with subproject C3. This simulation is necessary to transfer the properties to complex components in order to ensure safe and reliable material behavior.

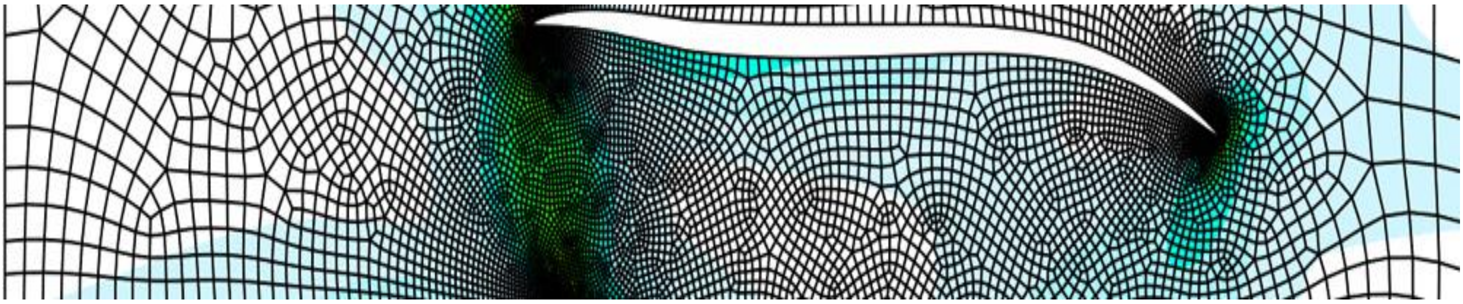
Stand des Projektes – Ziele und Perspektiven:

One of the main objectives of the subproject is the simulation and modelling of mechanical properties with regard to safe and reliable materials properties in order to expand the fields of application of alternative resources in technical areas. Especially the low bending stiffness and the non-linear alignment of the cellulosic fibers currently allow only an insufficient statement about the underlying micromechanics in natural fiber-reinforced plastics.

In order to determine these quantitatively, a composite made of polypropylene with 30wt.% CRF is examined and compared with PP 30GF. When characterizing fracture toughness using J-Integral on injection-molded CT specimens, the CRF-composite shows significantly higher values and a significant directional dependency (anisotropy) compared to PP 30GF. In addition to differences in fracture toughness, this also leads to deviating crack paths. More precisely, a computer tomography determined fiber orientation parallel to the direction of loading leads to a higher fracture toughness and a crack deflection of approx. 60°, which is also very well represented in the model-based simulation.

Besides the fiber orientation, which is very similar for GF and CRF, the ratio of the present fiber length distribution and the critical fiber length provides an explanation for the differences in material behavior. This shows that there are more long CRFs in the composite which exceed the critical fiber length and lead to a high reinforcing effect or which consume more energy when pulled out of the matrix. In this context, a limit value for an embedded fiber length is characterized, above which a fiber pull-out consumes more energy than a fiber breakage. A comparison of this value with the available fiber length distributions shows that considerably more CRF pull-outs occur than GF pull-outs with higher energy absorption.

These results provide a microstructural explanation for the higher fracture toughness of the CRF composites, as well as for the crack paths which deviate from the GF-reinforced PP and thus contribute significantly to the prediction of the failure behavior in addition to a better understanding of the material.



Subproject B3: Influence of geometry of biogenic fillers

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Summary description of the project:

Fillers and reinforcing materials made from renewable raw materials offer a wide range of applications in plastics technology. However, unlike synthetic fillers, they don't have constant properties, but vary depending on the year of harvest, growing region or sort. Along with the different processing parameters there is a significant influence on the mechanical properties of the final component.

The subproject investigated the relationships between the particle geometry of biogenic fillers and the mechanical properties of composites. The matrix material used was polypropylene, which was compounded with wood flour. By fractionating the fillers by size before compounding, blends with different mean particle sizes were produced and investigated. Fillers from different plant sources with variable process parameters were processed.

In cooperation with other subprojects, the human influences on the properties of biogenic fillers were determined and a model for the simulation of the influence of different particle geometries was developed. The investigations in the subproject should lead to a precise statement on the material behaviour and thus make a contribution to safe and reliable materials.

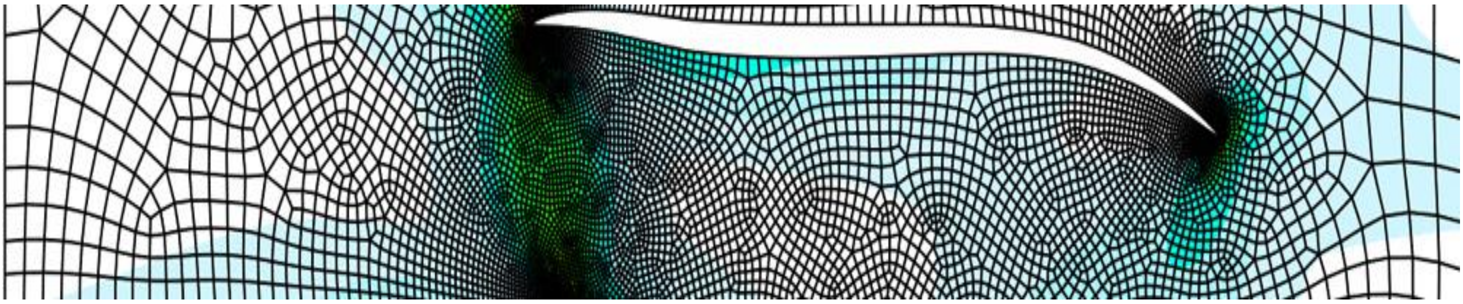
Current status of the project:

The overall objective of the project is to investigate the relationships between particle geometry of the fillers and the mechanical properties of the composites with regard to safe and reliable material properties.

Using a semi-crystalline thermoplastic matrix material and the filler wood flour, it was shown that the impact strength of such composites is linearly related to the particle size of the fillers used. The particle shape has no significant effect on these properties. In contrast, the strength of the material (e.g. under a tensile load) clearly depends on the particle shape of the fillers used. These results were supplemented by investigations of the damage behavior (crack investigation) using computer tomographic methods.

The analysis of the process parameters used shows that temperature and shear during processing can contribute to homogenization of the material and to a certain extent improve the composite properties. The material degradation caused by increased temperature only has a negative effect on the materials after longer periods of time, e.g. downtimes during injection molding.

In cooperation with the Fachgebiet Arbeits- und Organisationspsychologie, the influence of humans in the selection and processing of raw materials is also investigated. For this purpose, a method for planning and decision support was developed, which includes human activities and decisions in material development.



Subproject B5:

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Summary description of the project:

The aim of this project is to characterize recycled aluminum cast alloys, in order to use them for high structural applications under reliability conditions. For this purpose, the effect of heat treatments on the fragmentation and dissolution of the detrimental Fe-rich intermetallic inclusions is studied as well as the effect of these inclusions on the mechanical properties.

Moreover, the interaction between process conditions, microstructure and structural defects in the resulting mechanical behavior is analyzed. Statistical design of experiments is used in order to achieve appropriate correlations and optimize heat treatments. It is also investigated the 3D morphology of different casting defects by the use of high-resolution Micro-CT in addition to the conventional metallographic examinations.

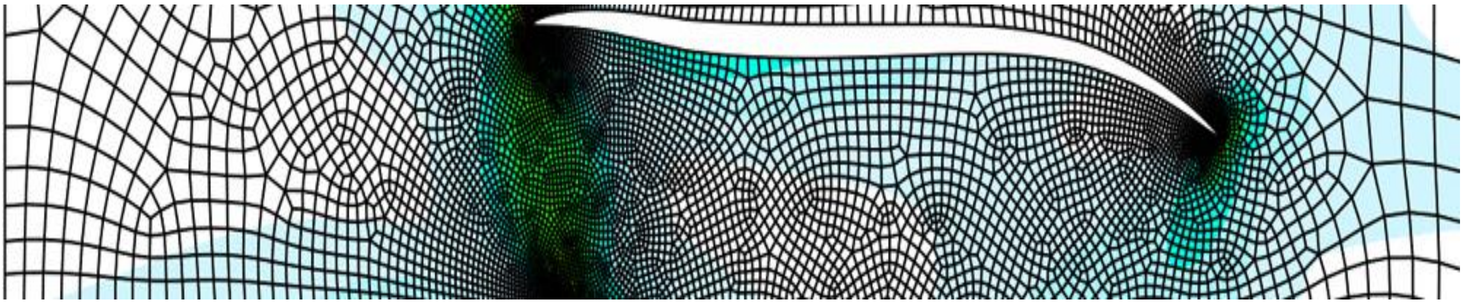
In a second stage of the project, cast components with different iron content are produced under real casting conditions and under variation of important process parameters. The objective is to determine the purity requirements of the studied in order to assure the reliability of the components.

Current status of the project:

Fatigue tests were performed on recycled samples and the fracture surface SEM analysis showed that the β-Al5FeSi inclusions have no direct impact on the damage mechanism. In addition, a high number of these particles were found in the inner material, which may explain their limited effect on fatigue life. The 3D reconstructions show the arrangement of these Fe-rich particles in agglomerations of complex clusters of inclusions distributed along the samples. Therefore, the inclusions that are considered as single needle-like particles in 2D metallographic images may actually belong to larger single inclusions consisting of plate-like particles.

The size of these particles increases exponentially with the Fe content, resulting in a dramatic decrease in mechanical properties. Nevertheless, a significant increase in mechanical properties after heat treatment can be seen as a consequence of fragmentation and dissolution of these particles.

This phenomenon can also be observed in the REM analyzes of the fracture surfaces of high Fe content samples before and after the heat treatment. A cleavage fracture of massive, brittle ß-Al5FeSi inclusions was observed in a non-heat-treated sample with 1.85% Fe content and a ductile fracture with a significant reduction in the proportion of Fe-rich inclusions.



Subproject C1: Thermal Stability of Ultra High Performance Concrete (UHPC)

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Summary description of the project:

Ultra-high performance concrete (UHPC), exhibits a significantly increased compressive strength (> 150 MPa) compared to ordinary concrete and is characterized by a very low water content, a high amount of closely packed solids and, as a consequence, an almost capillary pore-free, impermeable microstructure. On the one hand, this structure density desirably increases the strength and durability. On the other hand, it reduces the resistance of the UHPC under temperature loads in particular in the range of > 250 °C. If a critical temperature is exceeded, the material fails brittle, indeed almost explosive, and above all, not predictable. In addition to phase transformations in the microstructure, in particular the rising partial vapour pressure effects the formation of micro cracks when the local tensile strength of the dense microstructure is exceeded. Under constant stress these cracks combine to form macro cracks and thus lead to the loss of mechanical strength of the concrete structure.

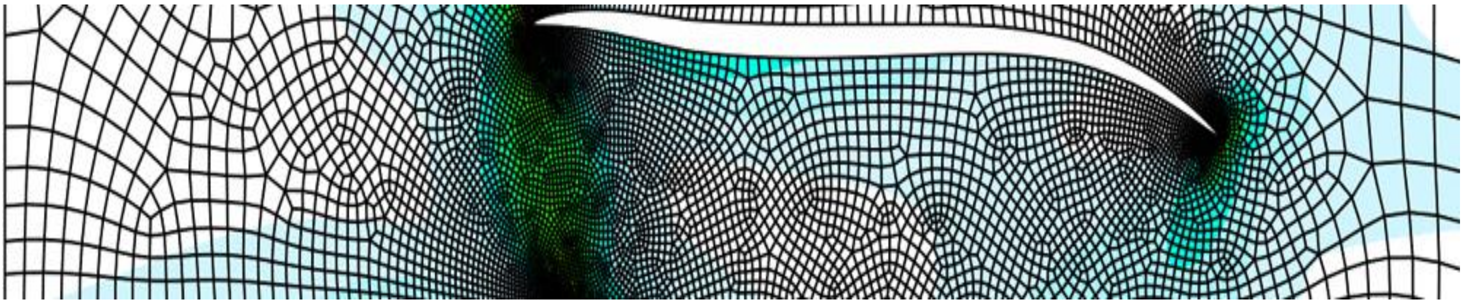
The specific failure mechanisms in case of fire with maximum temperatures up to 1,000 °C are widely known. Nevertheless, the area of special mechanical engineering and industrial plant construction requires components made of UHPC, which are able to resist cyclic thermal stresses in the range up to 500 °C in long-term while the mechanical strength is still maintained. To attain the aforementioned stability, commonly known procedures to improve the thermal stability of ordinary concrete are mostly inappropriate for the use in ultra-high performance concrete. For example, the addition of PP-fibres is usually associated with loss of mechanical strength of the UHPC.

Current status of the project:

The safety and reliability of UHPC under thermal stress is ensured by two key strategies. Firstly, the use of innovative fibre reinforcement, which resulted from the cooperation with the TP B2. It causes an increase in the water vapour permeability of the UHPC. Second, the targeted modification of the binder of the UHPC formulation to reduce the vapour partial pressure while increasing tensile strength of the matrix.

In the case of fibre reinforcement, the resulting vapour partial pressure can be dissipated through a dense network of fine channels without the occurrence of micro cracks, which though does not result in total destabilization of the microstructure within the observed temperature range up to 500 °C. In the case of targeted adaption of the binder composition, the reaction products which are mainly responsible for the damage are reduced and so the resistance to thermal stress is increased. Thus, a dramatic improvement in the thermal stability of UHPC was proven, since the reference was only stable up to a maximum of 300 °C.

The project goal of a thermally stable ultra-high performance concrete with an increased damage tolerance as well as a largely predictable failure behaviour was achieved on a laboratory scale. Furthermore, the work has opened up additional fields of application, especially in the high-temperature sector. In cooperation with other project participants, however, the in-depth analysis of the human influence within the manufacturing process plays an important role in ensuring a consistently high and, above all, reproducible quality of this high-performance material.



Subproject C2: Evaluation of strength, reliability and life span applying numerical methods: multiscale damage-mechanical approaches

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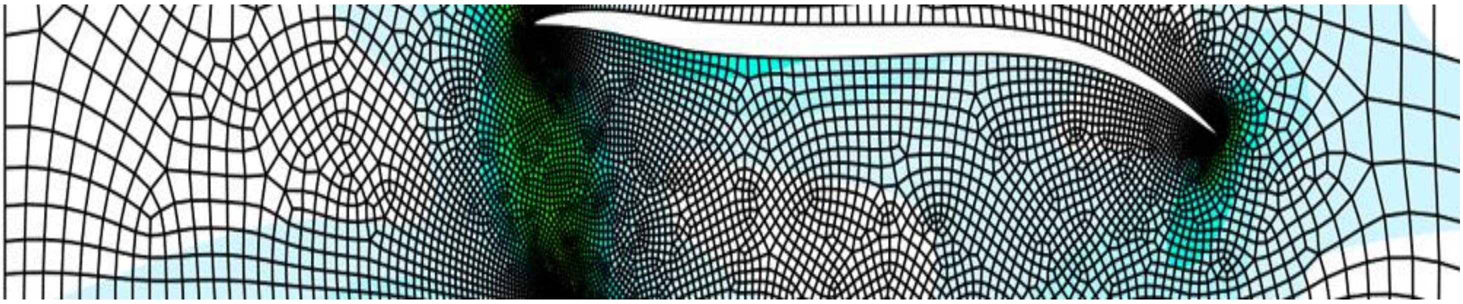
Summary description of the project:

A simulation tool is developed which is able to predict crack nucleation and the evolution of damage. The modeling is based on the concept of continuum damage mechanics. The growth of defects is described on microscopic and mesoscopic levels. Depending on the material, transcrystalline and intercrystalline cracks, voids or inclusions could be crucial. The numerical simulations are basically carried out on the macroscopic level. Incipient macroscopic cracks are formed due to the growth and coalescence of microcracks. In doing so, the multiple scales are connected via homogenization procedures. Microstructures are described within cell models which constitute representative volume elements. By means of averaging, the process of homogenization provides effective material constants. Phenomenologically motivated numerical concepts for crack nucleation are likewise developed and tested. In particular, the theory of configurational forces in the material space seems very promising, efficiently providing information about location and direction of crack nucleation in plane and spatial boundary value problems. Therefore material forces are suitable for the modeling of the sequential processes of crack nucleation and growth. A major issue of this subproject is the combination of approaches derived from fracture and damage mechanics. Taking both fields into account, predictions concerning the strength and reliability of technical structures will be substantially improved.

Current status of the project:

Works in the fields of micromechanically motivated damage mechanics have been carried out. Developments of approaches e.g. concerning multiscale FE simulations as well as numerical and analytical homogenisation techniques were enhanced. On the micro scale in particular microcracks and the delamination process of grain boundaries play an essential role. The goal of the subproject is the model-based investigation of crack nucleation and damage evolution mechanisms in heterogeneous anisotropic structures. The spectrum ranges from high-strength materials with low defect tolerances to heterogeneous structures made of renewable materials with rather high fluctuation of properties. On the microscale, the investigation is i.a. focused on the influence of different cell models of cracks on the simulation. The effective stiffness of different models, e.g. based on the dislocation method, are semi-analytically determined and compared. On the macro scale material laws and material tangents are developed, which exhibit a stable and convergent behavior in the numerical implementation. In particular, the softening process is an important part of the investigation. Another aspect of the model-based strength evaluation is the combination of both fracture and damage mechanics. Damage mechanical assessment provides information on the damage evolution from an early stage and thus on the crack nucleation within a component. On the other hand, approaches based on fracture mechanics are more accurate in predicting crack paths. Hence, the combination of both methods in the fracture process zone allows for the examination of microstructural processes, e.g. the trans- or intercrystalline growth of microcracks, in the crack tip region of a macro crack in connection with macro crack growth. Material forces are calculated on the macroscopic level and predict the crack initiation. The calculated location and direction are in accordance with the predictions of stress and energy based criteria. The numerical concept is currently extended to 3D applications.



Subproject C3: Evaluation of strength, reliability and life span applying numerical methods: fracture mechanical approaches

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Summary description of the project:

Classically, crack growth is investigated applying approaches of fracture mechanics. Here, sharp cracks are modeled by two opposing inner surfaces. To simulate growing cracks using numerical discretization methods three subtasks must be considered. First, a crack loading analysis is performed, e.g. by applying path-independent integrals. Based on the loading quantities, the second task is to determine the incremental crack growth direction. Finally, new crack surfaces must be created with respect to the predicted crack growth direction. If the material consists of microscopic inhomogeneities, an interaction between macroscopic crack and the fracture process zone is observed. Here, crack tip shielding due to phase transformations, the delamination of tiny inclusions or growing micro cracks are observed. In heterogeneous or compound structures interactions of cracks and strong or weak material interfaces play an important role just as anisotropic crack resistances.

In the first stage of the project, conventional numerical methods for an accurate loading analysis are extended to cope with the interaction of interfaces, e.g. between microfibers and matrix material, and the matrix crack. Anisotropic and graded properties of structures are taken into account. Furthermore, based on path-independent integrals, efficient approaches for the calculation of loading quantities at multiple-cracks systems are developed. In cases of delayed shear and tensile loadings a non-proportional crack tip loading is observed. For these load cases appropriate crack deflection criteria are investigated and experiments are carried out for their validation.

Current status of the project:

First papers have been published in the field of numerical and analytical crack tip loading analyses. Methods for an efficient numerical loading analysis at curved and multiple-cracks were developed. Investigations at cracks in anisotropic materials showed, that conventional crack growth and deflection criteria fail. Applying a new crack deflection criterion for anisotropic materials, crack paths were predicted accurately in aluminium alloy specimens with anisotropic fracture mechanical parameters. The sources of the anisotropy are identified to be mechanical processes during the material production, e.g. rolling, extrusion or injection moulding, inducing a texture and in general a predominant fracture mechanical direction.

In the model material of the subproject B2 (glass or cellulose fibre reinforce polypropylene) a distinct anisotropy was measured, resulting from the used injection moulding process and the filling of the mould. Applying the developed crack growth procedure, accurate predictions of crack paths depending on the orientation of the crack with respect to the predominant direction are possible.

Residual stresses, as investigated in the subprojects A2 and C4, provide the toughening of a structure but also go along with a non-proportional crack tip loading. Fatigue crack growth in such structures are in the main focus of current investigations, especially the accurate prediction of crack paths is challenging. A novel type of specimen is developed providing reproducible residual stress states and crack paths. With these experimental results, different hypothesis of crack deflection criteria in connection with non-proportional crack tip loadings are validated.

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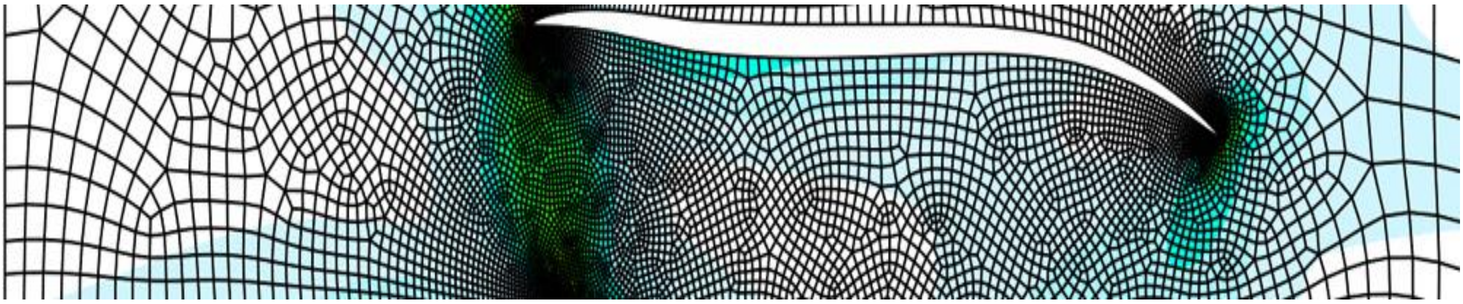

Subproject C4: Near surface regions - Reliable material properties under complex cyclic loading

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Summary description of the project:

Near surface regions play an important role in fatigue behavior. The properties of the near surface region can be changed by consecutive or simultaneous thermo-mechanical surface treatments such as shot peening, deep rolling or laser shock peening at elevated temperature. The resulting dislocation network exhibits a high stability and leads to an increased fatigue strength under cyclic loading. So far, detailed information about the effect of near surface properties after deep rolling related on microstructure, residual stress stability and plastic strain behavior under complex cyclic loading doesn't exist. Especially the material behavior in the regime of very high and low cycle fatigue is unknown. Also the influence of overloads should be investigated.
The central question of the project deals with the stability of near surface microstructures and residual stresses under complex fatigue loading conditions.

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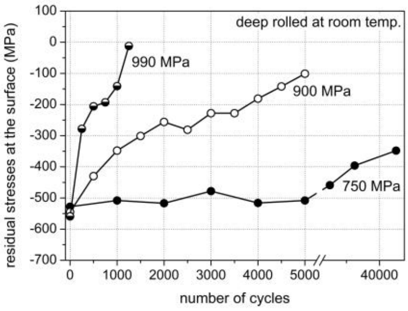
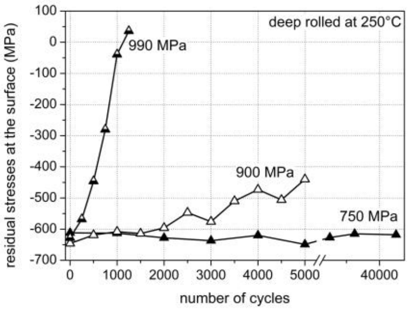
Current status of the project:

The aim of the project is to create basic knowledge about the effects of mechanical surface treatment in relation to residual stress stability and microstructure in the near surface region under complex cyclic loading. In this way the effectivity of mechanical surface treatment processes can be optimized.
At first, convenient heat treatment parameters and a beneficial deep rolling force were chosen. In the next step basic Wöhler-curves were established. The fatigue strength by deep rolling at room temperature was increased by 40% whereas the fatigue strength by deep rolling at 250°C rises up to 50%. In the low cycle fatigue regime, negative effects of deep rolling were detected. Residual stress relaxation proceeds rapidly and is a reason for the limited effect of deep rolling (see figures).





Overload tests have shown that deep rolled structures are more sensitive to overloads compared to untreated surfaces. In this case, the overload amount and also the number of overloads play a decisive role.
Future studies will deal with investigations of thermal residual stress relaxation and residual stress stability. Also tests in the very high cycle fatigue regime should deliver detailed information about the material behavior of deep rolled structures related to lifetime and residual stresses.