EMMC case study:

Residual stresses in aviation components

Interview of Dr Andreas Drexler, Materials Center Leoben Forschung GmbH (MCL)

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Open turbine with turbine disk. Source: MTU Aero Engines.

About the Company

MCL is an applied research institute offering competence in materials, process, and product engineering. MCL's key advantages lie in the combination of advanced experimental analysis with high level materials modelling and it comprises state-of-the-art technical facilities and wide-ranging specialist knowledge of materials. MCL combines this interdisciplinary expertise in its IC-MPPE (Integrated Computational Materials, Process and Product Engineering) approach to drive material-based innovations. It performs long time cooperative projects together with universities where research topics are developed. Building on this expertise, the center offers targeted support in practical material, process and product development questions with a variety of industrial partners. 80% of the centre's R&D effort is related to developing, processing and applying advanced materials.

170 employees work at the centre and about 55 of them in simulation department which was initiated about 12 years ago. MCL's materials modellers can be found on all level of education, ranging from bachelor master and PhD students to post-doctoral and highly experienced staff researchers. The educational background of the employees ranges from materials science, mechanical engineering, physics, mathematics and computer science. The majority of professional staff development happens internally, but training is out-sourced to 3rd parties if a member of staff

requires it. In specific cases MCL actively hires staff for their modelling skill set to widen their expertise when needed. Young people are very attracted to MCL's activities and they are actively engaged with students.

About modelling – the nuts and bolts

MCL is familiar with electronic, atomistic, mesoscale, continuum and data driven modelling which are often integrated into multiscale approaches for deriving microstructure evolution and structure-property relationships. In addition, MCL is capable of performing e.g. mechanical or thermo-physical material testing and detailed microstructure characterisation in house. The combination of multi-scale modelling and multi-scale material characterisation makes MCL a one stop shop for application near material modelling and allows developing physical based as well as phenomenological material models. To perform calculations the centre uses commercial, in-house software and freeware on a daily basis. In addition, MCL also actively develops software for targeted purposes. See https://www.mcl.at/software/. In addition to physical-based modelling and more and more data-driven materials modelling approaches are being pursued. For this purpose, also databases of materials properties are hosted and developed at the center.

The computational expertise is applied to a variety of different applications or problems. As a first step, MCL's experts investigate an industrial problem and develop clear expectations and give a sensible time line and financial estimate to a client. They do not shy away from complex questioning and will also embark on long-term projects involving one or more PhD students if required. MCL often embarks on collaborative programmes where partners bring in new knowledge or academics take over supervision of students. Materials modelling is often carried out with distinguished specialists in academia and in combination with advanced experimental analysis techniques.

About the Case Study

The case study was performed by MCL (providing the modelling expertise) and the Austrian company voestalpine BÖHLER Aerospace GmbH & Co KG, a specialist in high-quality forgings and a supplier to the aerospace and energy industry, and MTU Aero Engines AG, a German aircraft engine manufacturer.

For this particular case, which were your objectives as an industrial provider of modelling?

The aerospace industry is actively seeking new ways to decrease noise, weight and fuel consumption of their planes and to develop the powerful, environmentally friendly and quiet engines of tomorrow. To reach these ambitious goals suppliers and manufacturers of aero engines join forces to improve manufacturing routes of used materials and to integrate them into existing lifetime calculations. For this particular case, the emphasis was on the development of a digital twin for turbine disks. Turbine disks are highly stressed parts of a jet engine, in which the turbine blades are mounted. These are pertinent to produce the thrust with the aid of the combustion gas. The digital twin is a numerical model covering both the manufacturing as well as the service conditions to predict service lifetime of turbine disks. Thereby, the knowledge of residual stresses and local strength of the material is crucial. Especially, residual stresses have not been considered in previous models. Therefore, our objective was the development of a digital twin of a turbine disk, which includes residual stresses and local strength which helps engineers in industry to avoid distortion after the manufacturing process as well as improve service lifetime.

How did materials modelling play a key role in problem solving?

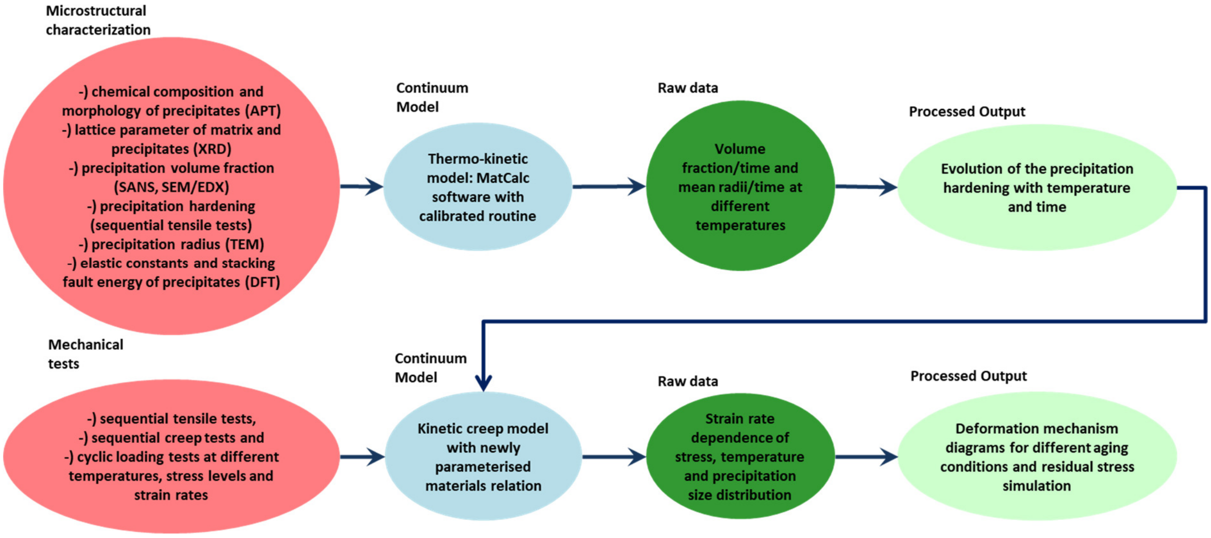
The aim of the project was the development of a fully parametrized digital twin covering the thermal conditions during the manufacturing process and service lifetime as well as a change of the material strength over time and temperature. Due to alternate heating and cooling cycles during the heat treatment process the thermal loading can be severe enough to cause internal plastification and thus residual stresses in the turbine disk. The core of the digital twin is the multi-physical material model. It enables expert users to simulate the viscoplastic material behaviour under a variety of thermomechanical loads in a turbine disk and to provide their constructing engineer colleagues with a powerful tool for the design optimization of aircraft turbines.

What tools and methodologies have been applied?

The method implemented relies on a multi-physical material model. More specifically, mechanical, thermal and thermo-kinetic models have been linked together in a finite element modelling framework. On the mechanical side, a cyclic plasticity model was implemented in user-defined routine and parametrized for the full temperature range from room temperature up to the forging temperature. The challenge of the thermal simulation was the determination of the inhomogeneous cooling conditions on the surface. Thermo-kinetic models were applied to describe precipitation and related hardening which not only affects the yield strength but also the creep deformation at elevated temperatures.

The main challenge was to find a material relation to describe the structure property relationship between the local precipitation evolution and hardening. To give a closer insight into the plasticity model, let's look into the microstructurally based creep model accounting for the precipitation strengthening in a turbine disk. The creep model describes the strain rate dependency of the macroscopic variables stress, temperature and precipitation hardening. The evolution of the internal variables volume fraction and mean radius of the precipitates are simulated with thermo-kinetic model. For the parametrization and validation of this thermo-kinetic model a large number of experimental tests were performed. The combination of the thermo-kinetic simulation with our creep model makes it possible to determine deformation mechanism diagrams for any heat treatment process applied to a turbine disk. Thus, we can integrate heat treatment and machining processes into the design development and lifetime predictions of industrial components, and thereby facilitate near net-shape production.

Finally, the digital twin is able to study the property distributions in the turbine disk under different conditions. The expert user will run tests to see how the production process or the disk's shape should be designed to give it optimal local properties in order to gain to full light weight potential, for example.



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What were the expected improvements of the material behaviour simulation?

The improvement is a model which takes residual stresses into account to predict service lifetime and distortions more reliably. Industry partners wanted to understand the origin of the residual stresses and its distribution in the turbine disk. Once it is understood what causes them and where the residual stresses are severe, one can change the manufacturing and machining process and optimise them. This should lead to a longer lifetime of the disks and increase the service intervals of the aircrafts.

For this particular case, did modelling affect your value chain?

The material model was developed in a way that it integrates the manufacturing process of the supplier voestalpine BÖHLER Aerospace smoothly into the lifetime simulations of the manufacturer MTU Aero Engines. No additional mapping of internal variables is needed, which would lead to a loss of information. With the aid of the model, the industrial partners could understand properties of a known material better and suggest changes to fulfil the needs of the manufacturer. This enables integrated product and process development of turbine disks, with the well-known advantages of shorter development cycles and increasing variety as well as technical product complexity.

For this particular case, what was the quantitative value of materials modelling?

Before new disks with a new optimised shape can be consider for the use in aero engines, several prototypes have to be tested in a test engine to ensure it performs in real life conditions. Each prototype costs the equivalent of a small car, but more important is that a failure of a prototype delays the design process of an engine by up to 1.5 years. Thus, modelling can lead to higher success rates of these tests and the aerospace industry saves person time and testing costs.

What investments were made during the project?

The project was carried out in the framework of a PhD thesis. The main investments were made for the model development, and parametrization of the models to experiment.

For this particular case, how did you measure the impact of Materials Modelling as a tool to assist in problem solving, process optimisation, product development?

We had a statement of work with defined deliverables. Our main KPI was the customer satisfaction. The company partners we work with are encouraged to give us feedback, how the generated insights are used to improve processing steps and materials concepts. Other KPIs, for example, are the number of projects that can be generated from an activity or the number of submitted patents. We are also encouraged to publish some of our results, so we report the number of publications and monitor the number of citations.

What technical and technological benefits resulted from the project?

With the multi-physical modelling approach, we could improve our know-how and workflows in the field of process simulations. The technical benefits for our industrial partners are the improved predictive power in service lifetime and near net shape production.

What where the economic benefits/impacts when you did use modelling?

The economic benefit for us is that we have now sophisticated workflows to embark on follow-up activities, like development projects or service-contracts. The material relations and routines, which were developed in the project, can also be parametrized for a wider range of materials and processes. The customers can use the digital twin and study it in silico thoroughly before embarking on the real-life tests. This will lead to more successful experiments, shorter development times and thus, save them time and money.

Did modelling improve your competitiveness/innovation power?

Due to papers and success stories, we got more visibility which will distinguish ourselves as the go-to partner for similar projects in the field of materials for aerospace applications. We are pushing ourselves to be innovative by taking on these industrial challenges and do not shy away from entering new areas in material modelling, as we did in the present project with multi-physical approaches.

What sort of obstacles or barriers did you have to overcome to use modelling?

In this particular case, the barrier was very small. The two companies were already aware that materials modelling is a useful tool for integrated computational material, process and product engineering (IC-MPPE). However, we did have to provide a solid validation for our numeric models to show that they are trustworthy and have predictive power. Our model passed several tests on predicting properties of samples and turbine disks in real life conditions.