EMMC case study: MTU Aero Engines AG

Simulation of additive manufacturing of metallic components

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1. Which are your objectives as the industrial consumer of modelling?

a. *Description of the industrial problem:* Additive manufacturing is a highly complex process with a plurality of process parameters and different processing steps. Production of specific part geometries may lead to locally different mechanical properties. In addition, the part by itself shows high internal stresses and distortions. This makes the certification of an aircraft part produced by additive manufacturing challenging. In order to guarantee aviation specific requirements, it is fundamental to understand allowable process parameter variations without losing part integrity and stable mechanical properties.

b. *Classification of the project:*

   i. *Material:* Nickel-base and titanium-base alloys.
   ii. *Scale of the material phenomena to be described:* Microscale (100 nm - 1 mm) and macroscale (> 1mm).

iii. *Industrial application:* metallic components produced by additive manufacturing. Hence the application involves the fluid state, solidification, solid state component properties and eventually aero-engine parts (sub-systems).

iv. *Industrial sector:* Aero engines.

v. *Weakness of approach used up until now:* Experimental development and reaching MRL 10 for new parts is rather slow due to the complexity of the process, the large number of variables and the large number of outcomes that need to be assured.

c. *Requirements and expected results to understand the material behaviour.*

There is a need to understand and be able to control the interdependencies between Selective Laser Melting (SLM) processing, initial microstructure formation, evolution during heat treatment and resulting local mechanical strength. It is fundamental to understand allowable process parameter variations without losing part integrity and stable mechanical properties.

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

Detailed process understanding helps decision making in process development and testing. Due to the large parameter sets applicable in these AM manufacturing methods and their impact on achievable material properties and quality, support of the manufacturing process development by the use of simulation is highly attractive. With modelling, the various interactions and sensitivities can be investigated independently from each other. This is very important for aerospace applications with their high quality demands and controlled scatter in the resulting material properties.

3. What tools and methodologies have been applied?

Apart from intensive experimental testing and process monitoring, a simulation chain is developed which describes all steps of the manufacturing process on “all” relevant length scales. This “through process simulation” (section a. below) captures details of the microstructure, including grains, dendrites and crystal orientation, which in turn enable local materials properties to be determined (section b). These eventually feed into macroscale engine sub-system models (section c).

a. Different aspects of the process and microstructure evolution are described by different models as detailed below.

i. Melt Pool :
The local interaction between the laser beam and the powder bed during Selective Laser Melting (SLM) processing is modelled using a mesoscopic Lattice Boltzmann Method (LBM). The model describes the generation of the powder layer, melting and solidification, melt pool dynamic, capillary forces (Plateau-Rayleigh-effect), gravity, wetting, heat conduction and convection in laser beam melting.
The absorption of the beam by the powder bed is described by a continuum electromagnetic model.
Coupling of the mesoscopic powder bed model and the continuum electromagnetic model yields a tool that provides a good description of the melt pool physics and of the interaction between laser beam and powder bed.

The transfer of energy from laser beam to solid or liquid matter is successfully described. The tool can represent physical phenomena like melting and solidification, melt pool dynamics, wetting, capillary forces, gravity, heat conduction and convection, evaporation pressure, ray tracing as well as user defined scan strategies.

ii. Local Solidification

The initial stage of the solidification process is described by a continuum thermodynamics model. The local structure evolution during solidification, considering e.g. the dendritic structure and the crystal orientation formation, is described by a Phase Field (PF) model.

iii. Precipitation

The time dependent temperature profile resulting from the SLM process can be used as input to the Kampmann-Wagner model derived from classical nucleation and growth theory, which is a thermokinetic model describing nucleation, precipitation, growth and coarsening the which is. The thermodynamic driving forces and interfacial energies are calculated based on thermodynamic data from CALPHAD, and the system evolution follows the thermodynamic extremal principle. Simulations are carried out with the commercially available MatCalc software using a Monte Carlo (MC) solver.

b. The result of the above Melt Pool simulation is a microstructure with considerable local detail, and with the help of the following models local materials properties are determined:

A continuum model with a constitutive equation for crystal plasticity for yield and tensile strength solved by the Finite Element method (Crystal Plasticity FEM) is applied to the microstructure and the model is solved for representative volume elements in the order of 1 mm^3 fine enough to capture microscopic features. The continuum model calculates anisotropic plastic behaviour.

The results are post-processed into material relations that enter as input into continuum mechanical models that calculate macroscale mechanical property of the aero-engine part; where now one finite element represents the previous in detail investigated 1 mm^3.

c. The continuum mechanics model applied with this coarser resolution is used to describe macroscopic properties and to assess the design requirements of the final part, e.g. distortion, residual stress, life capability based on global material properties. The model is solved by a standard FEM solver.

The simulation includes transient calculation of heat transfer into already built material as well as radiation of energy to surrounding area. Thermal gradients induce strain gradients caused by thermal elongation of the material.

4. What investments were made during the project?

Total R&D investment in additive manufacturing is several tens of million Euros. Investment in material modelling is a small part of it. It includes training of in-house staff in collaboration with external development partners. The majority of the investment is in personnel (five full time persons), followed by software and computing hardware roughly in a ratio of 100:10:1.

5. What technical and technological benefits resulted from the project?

Detailed process understanding helps decision making in process development and testing. It is anticipated that this will soon lead to an accelerated introduction of new materials and/or manufacturing parameters. A greater depth of understanding will help to steer development of better manufacturing machines. The simulation chain will become part of the evaluation of process deviations.

In future it should be possible to achieve locally optimized material and/or part properties. Also, during serial production the simulation tools can be used for evaluation process deviations without the necessity of destructive testing.

6. What was the business impact versus the previous approach?

Simulation contributes to a faster and more assured introduction of the manufacturing process. The process by itself allows higher design flexibility and reduced manufacturing costs. Furthermore, simulation support for deviation evaluations will mean substantial cost and time saving.

As a result of these factors, a more cost and time efficient development process is anticipated, targeting a 20-30% reduction in time in the process development and sensitivity studies stages of aircraft part development (see Figure 1) and an ROI of 3:1.

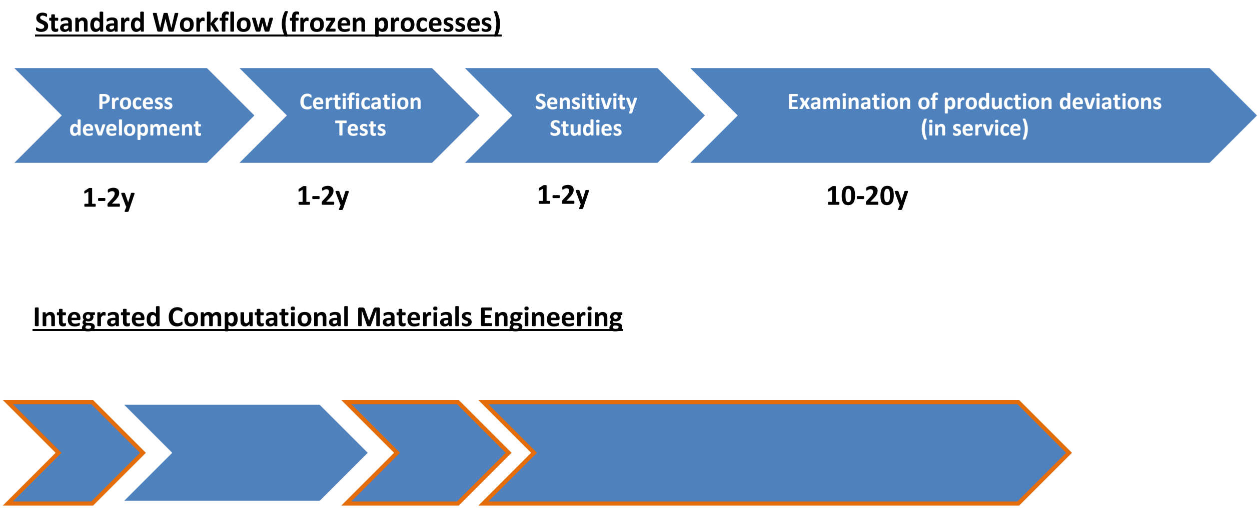

Figure 1: Materials Modelling, in the context of Integrated Computational Materials Engineering, shortens stages of the workflow and leads to optimized product properties, stable processing windows, simplified sensitivity studies, earlier product introduction and simplified deviation evaluation.

7. References:

[1] T. Maiwald-Immer, T. Göhler and A. Fischersworring-Bunk. From Melt Pool to Strength - Application of ICME Methods for the Development of Rapid Manufacturing Technologies. Proceedings of the 3rd World Congress on Integrated Computational Materials Engineering (ICME 2015), Chapter 26. DOI: 10.1002/9781119139508.ch26

[2] T. Maiwald-Immer1, T. Göhler1, A. Fischersworring-Bunk, C. Kömer, F. Osmanlic and A. Bauereiß. Application of ICME Methods for the Development of Rapid Manufacturing Technologies. 2 World Congress on Integrated Computational Materials Engineering (ICME 2013), Chapter 12. DOI: 10.1002/9781118767061.ch12