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Optimal Design and Process Simulation for Additive Manufacturing

L. Schelhorn[*]*, M. Gosch*[**]*, L. Debeugny*[***]*, P. Schröter*[*]*, W. Schwarz*[*]*, S. Soller*[*]
[*] *ArianeGroup GmbH, Taufkirchen, Germany*
lidia.schelhorn@ariane.group
[**] *ArianeGroup GmbH, Bremen, Germany*
marco.gosch@ariane.group
[***] *ArianeGroup SAS, Vernon, France*
loic.debeugny@ariane.group

Abstract

Additive manufacturing is an innovative technology that opens new opportunities where traditional manufacturing technologies reach their limitations. Unconventional and structurally optimized designs can be generated with the help of topological optimization, taking into account manufacturing constraints like the maximum overhang angle. In order to avoid a costly trial and error process during the development phase of a new component, a layer-by-layer manufacturing process simulation can help to predict the part's behaviour during the build-up process and thus to anticipate potential risks such as part failure due to thermally induced stresses or collision with the recoater. This paper presents the methods and tools used for optimal design and manufacturing process simulation at ArianeGroup and demonstrates how new components benefit from it during the development phase.

Abbreviations & Acronyms

AiO	All-in-One
AM	Additive Manufacturing
CAD	Computer-Aided Design
CT	Computed Tomography
DLR	German Aerospace Center
DP	Dye Penetrant
ESA	European Space Agency
ETID	Expander-Cycle Technology Integrated Demonstrator
FEA	Finite Element Analysis
GOM	Gesellschaft für Optische Meßtechnik
HIP	Hot Isostatic Pressing
NDI	Non-Destructive Inspection
NURB	Non-Uniform Rational B-Spline
SIMP	Solid Isotropic Material with Penalization

1. Introduction

Industrial applications of the new additive manufacturing (AM) technology have been developed at ArianeGroup for several years. In order to ensure a proper introduction of this manufacturing technology and to enable industrialization of the developed products, a comprehensive approach was pursued covering all relevant aspects of the entire additive manufacturing process chain. Figure 1 gives a rough overview of the wide range of activities that need to be addressed during each step of the process chain. Starting from design of the part including other engineering topics like material characterization or build job preparation, especially post-processing and quality control after manufacturing play a significant role besides the manufacturing process itself.

The main focus of this paper is the pre-manufacturing step "design & engineering", more precisely structural optimization and manufacturing process simulation that help to design and manufacture high-quality components. In the first part of the paper, the topology optimization process including reconstruction of the optimized geometry is presented and the importance of manufacturing constraints like the maximum overhang angle is emphasized. The second part addresses the manufacturing process simulation as an important contribution to the development of a new additive manufacturing component. In addition, ArianeGroup application cases are presented for both topics.

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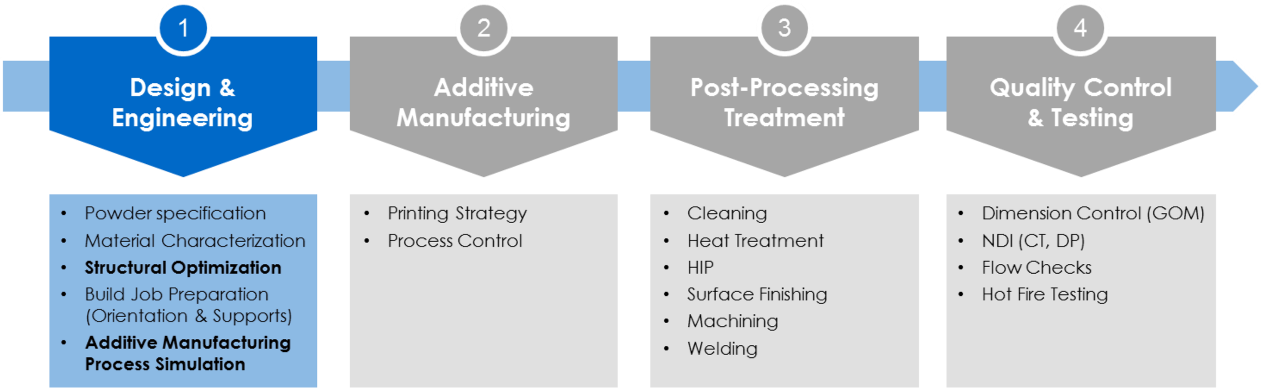

Figure 1: Additive manufacturing process chain at ArianeGroup

2. Optimal Design for Additive Manufacturing

Apart from many other benefits, additive manufacturing offers a high level of design freedom and thus significant advantages in terms of mass reduction and improvement of the structural performance. As many other aerospace companies, ArianeGroup takes advantage of this innovative technology in order to develop high-performance light weight structures. In this context, topology optimization can be applied in the design process in order to find the optimal geometry under specified boundary conditions while respecting the inherent constraints of the additive manufacturing process. Figure 2 shows an overview of the main steps during the optimal design process. Besides topology optimization and validation analysis of the optimal design, both taking place inside a finite element analysis (FEA) software, the optimization process involves two important steps that need to be performed in the computer-aided design (CAD) environment: preparation of the design space and reconstruction of the optimized design.

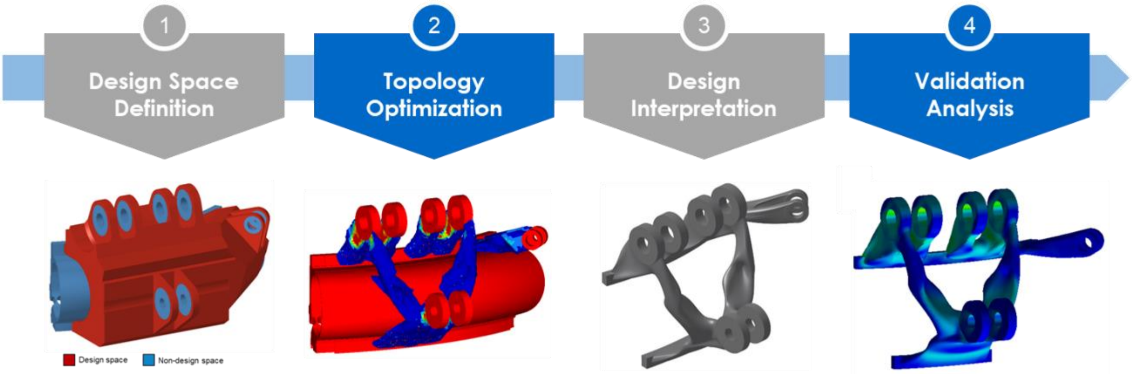

Figure 2: Optimal design process chain

In the following sections, the individual steps of the optimal design process chain are addressed in more detail, followed by a presentation of selected industrial applications from ArianeGroup.

2.1 Topology Optimization

The main task of topology optimization is to generate an optimal material layout within a prescribed design space under given constraints. Starting from a general optimization problem, it can be stated mathematically as follows:

$$\begin{array}{lll} \text{minimize}_{x}\, f(\boldsymbol{x}) & & \\ \text{subject to} & g_j(\boldsymbol{x}) \leq 0, & j = 1, \dots, k \\ & h_j(\boldsymbol{x}) = 0, & j = 1, \dots, l \\ & \underline{x_i} \leq x_i \leq \overline{x_i}, & i = 1, \dots, n \end{array} \tag{1}$$

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In equation (1), f is the objective function, g_j the inequality and h_j the equality constraints. They are called response functions and are in general dependent on the n design variables x_i arranged in the vector $\boldsymbol{x}$. As a special type of constraints, $\underline{x_i}$ and $\overline{x_i}$ represent the lower and upper bound of the design variables.

The most commonly used topology optimization method in commercial optimization tools like OptiStruct is the so-called density method, also known as the Solid Isotropic Material with Penalization (SIMP) approach. The design variables are defined as pseudo-densities of the finite elements inside the design space, varying between 0 (void) and 1 (solid) and continuously modifying the elemental stiffness. By removing elements in regions that do not require material, the method predicts an optimal material distribution within the given design space. In order to avoid large areas of intermediate densities and drive the design towards a discrete representation of either 0 or 1 for each element, a power law penalization method is applied:

$$\widetilde{\boldsymbol{K}}(\rho) = \rho^p \boldsymbol{K} \tag{2}$$

In equation (2), $\widetilde{\boldsymbol{K}}$ is the penalized and $\boldsymbol{K}$ the real stiffness matrix, ρ is the density and p the penalization factor greater than 1. The most commonly used objective functions are mass and compliance, which need to be minimized under specified constraints like maximum deflection or minimum natural frequency of the structure. In the context of additive manufacturing, taking into account manufacturing constraints such as the maximum overhang angle or a minimum wall thickness play a significant role. If limitations of the additive manufacturing process are not addressed early in the optimal design process, many benefits of this new technology will be wasted due to a high amount of required support structures or costly post-processing steps for support structures' removal and surface treatment of the printed part. The handling of these manufacturing constraints is discussed in the next section.

2.2 Design Interpretation

The result of the topology optimization is the most efficient material distribution for the corresponding load definition. As these results often take the form of complex shapes, they can no longer be effectively modelled by using the commonly used design approaches which were developed for the generation of components by conventional manufacturing processes (e.g. milling and turning).

For additive manufacturing structures, it is preferred to use instead NURB (Non-Uniform Rational B-spline) surfaces to generate the design. These surfaces are generated by splines defined by several control points. Alteration of the control points results in a change of the surface. These splines are defined with curvature tangency providing the advantage of reducing stresses in sharp edges and also automatically generate a smoother transition in surface area change which is preferred in additive manufacturing.

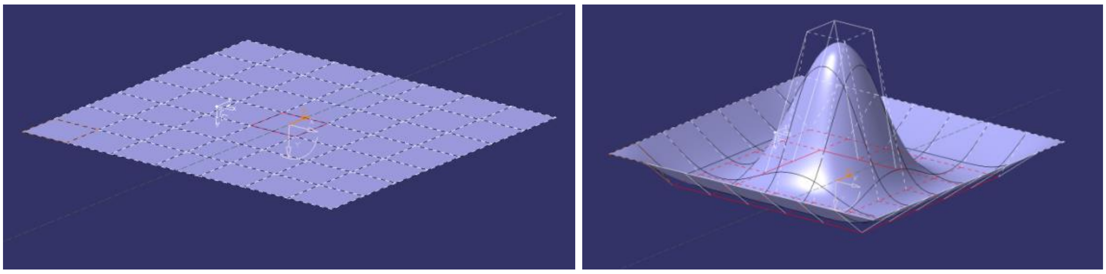

Figure 3: NURB surface before and after drag and drop of several control points

Another advantage is the change of the shape by movement of the control points. This approach enables the generation of an AM design much easier and faster. Furthermore, the control points can simply be shaped around the resulting geometry of the topology optimization. In addition, it is no longer necessary to define exact numerical values for dimensions like the cross-section of branches, therefore eliminating the need for generation of sketches with exact diameter definitions which are in addition no longer required for the additive manufacturing process. Instead, the cross-section can be adapted by dragging the shape until it fits the results from topology optimization.

2.2.1 Manufacturing Constraints and Impact on Design

An important advantage of the NURB shape is that the mathematical formulation automatically implements recommendations of the additive manufacturing process. The mathematical NURB formulation does not create sharp edges, thus resulting in smooth transitions between surfaces which are favorable from the manufacturing process but also from structural perspective, as the smoother transition will lead to reduced stresses in the grooves. Additionally, material at outer, unloaded edges is automatically removed reducing the overall mass of the component.

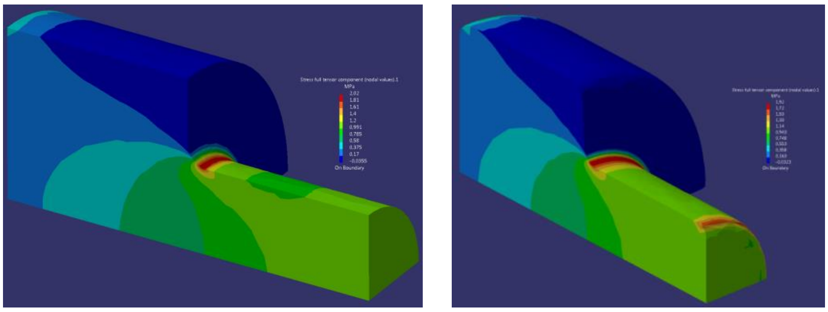

Figure 4: Shaft generated with conventional part design (left) vs NURB surface modelling (right) and the resulting principal stresses in the groove

Another advantage is the smoother change of cross-sections which is favorable during the printing process. A smoother gradient over the change of the surface geometry generates a more steady cooling process and therefore reduces the residual stresses and distortion left in the part after the printing process.

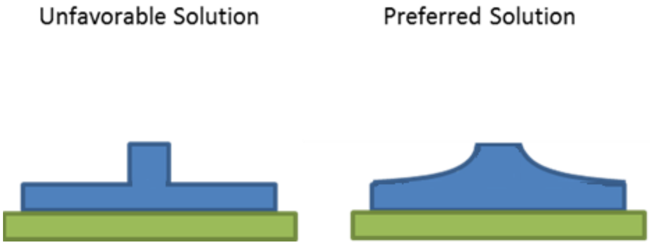

Figure 5: Manufacturing recommendations implemented with NURB – steady change in cross-sections

The usage of NURB surfaces for the generation of component design is completely different from the conventional part design process, resulting in the fact that the designer needs to invest some time in learning the usage of NURBs. This learning time can be reduced by the usage of standard shapes, which can be extracted from a library.

2.2.2 Standard Shape Generation for Interfaces

For the first additive manufacturing parts, a considerable amount of time was consumed by the generation of the design of local interfaces based on the NURBS approach. As this process is repetitive for every part, a standard library for these interfaces was created. In this library, different types of force introductions are characterized and, depending on their typical machined design approach, transferred into a NURB based approach.

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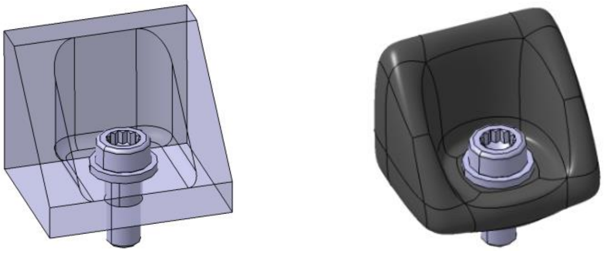

Figure 6: "Bathtub" force introduction for a bolted connection with a machined approach (left) and the corresponding design using the NURB approach (right)

The shapes from the library can be copied and inserted in the part. The reconstruction process then follows the following principle:

1. Generation of the local interface design based on the standard shape library
2. Generation of connection points (points in topology where two or more load paths meet)
3. Merging of the local interfaces and the connection points
4. Sizing of the cross sections of the NURB surfaces according to the structural limitations
5. Implementation of machined operations, e.g. holes and threads

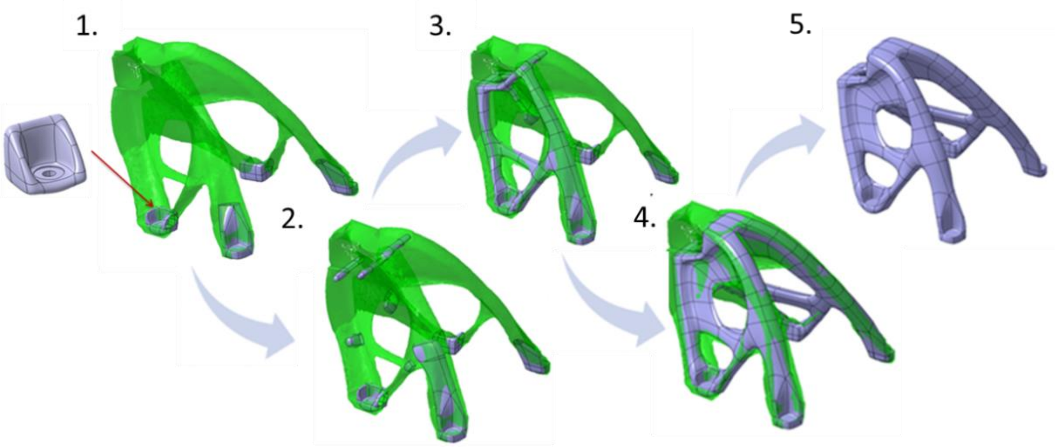

Figure 7: Design steps for the reconstruction of a topology optimization result

2.2.3 Avoiding Support Structures in the Design Process

In general, support structures are recommended whenever the angle φ between a corresponding surface and the building plane xy is lower than a given value, see Figure 8.

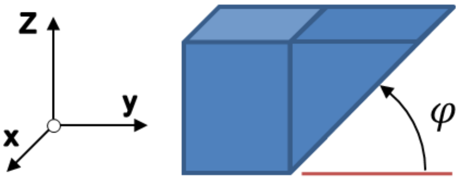

Figure 8: Angle definition for support structures

Support structures can be seen as waste in the manufacturing process. They consume powder and energy, additionally increasing the build time and therefore the cost of the part. The removal process usually involves manual work or machining and requires access to the areas with support structures, which is often not possible such as for hollow parts or internal channels.

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In order to reduce the amount of support structures, it is recommended to keep the corresponding surface angles of the part during the reconstruction above the process requirement. Surfaces which would require support structures can be easily identified by a draft angle analysis and potentially modified to create self-supporting structures, see Figure 9.

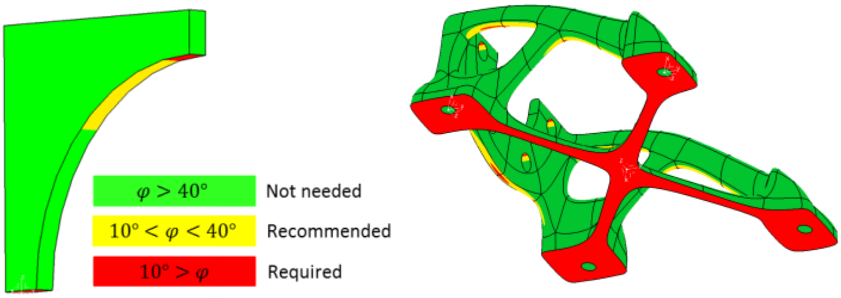

Figure 9: Draft angle analysis in CAD used to identify areas for support structures (red/yellow)

In Figure 10, two examples for the generation of self-supporting structures can be seen. As the draft angle analysis has been configured to mark areas for supports with yellow color, it is easy for the designer to alter the angles in order to minimize the amount of required support structures.

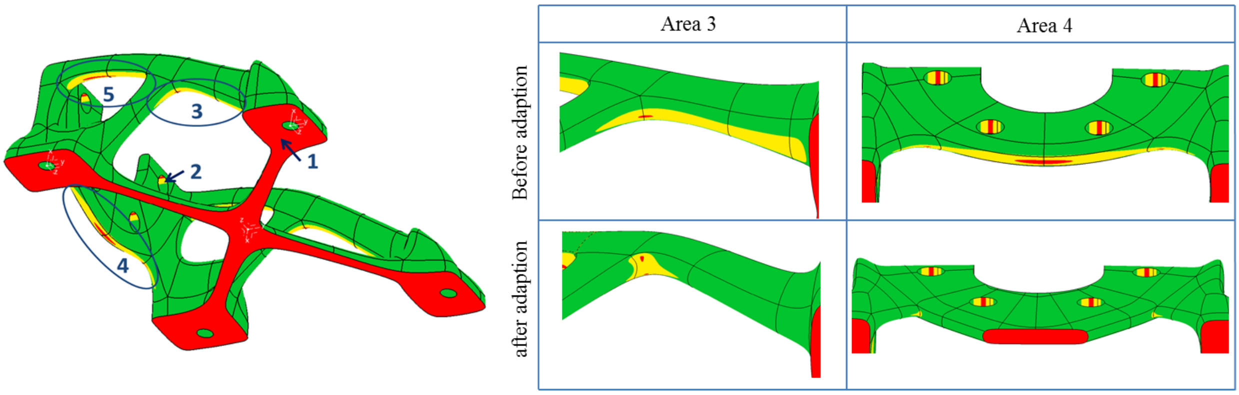

Figure 10: Generation of self-supporting structures based on the draft angle analysis results

For area 3: The branch connection would need support over the complete length. After modification of the surfaces via drag and drop, the amount of required support structure can be minimized up to a point where it is only needed at the joint of the two branches.

For area 4: In this case, the start of the interface is moved downward to the first layer of the building plane. With this approach, it is possible to introduce two surfaces with angles of higher than 40°. However, the modification comes at the cost of additional mass and therefore also additional material consumption. In this case, the gain is that the support structure does not need to be removed manually.

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2.3 Application Cases

Figure 11 illustrates some application cases created with the additive development workflow described above. These range from smaller parts and components to large structure feasibility studies, such as:

1) Valve bracket, approx. 100 mm bounding box
2) Distributor block
3) Electrical connector bracket
4) Engine actuator bracket
5) Avionic compartment, approx. 2 m height

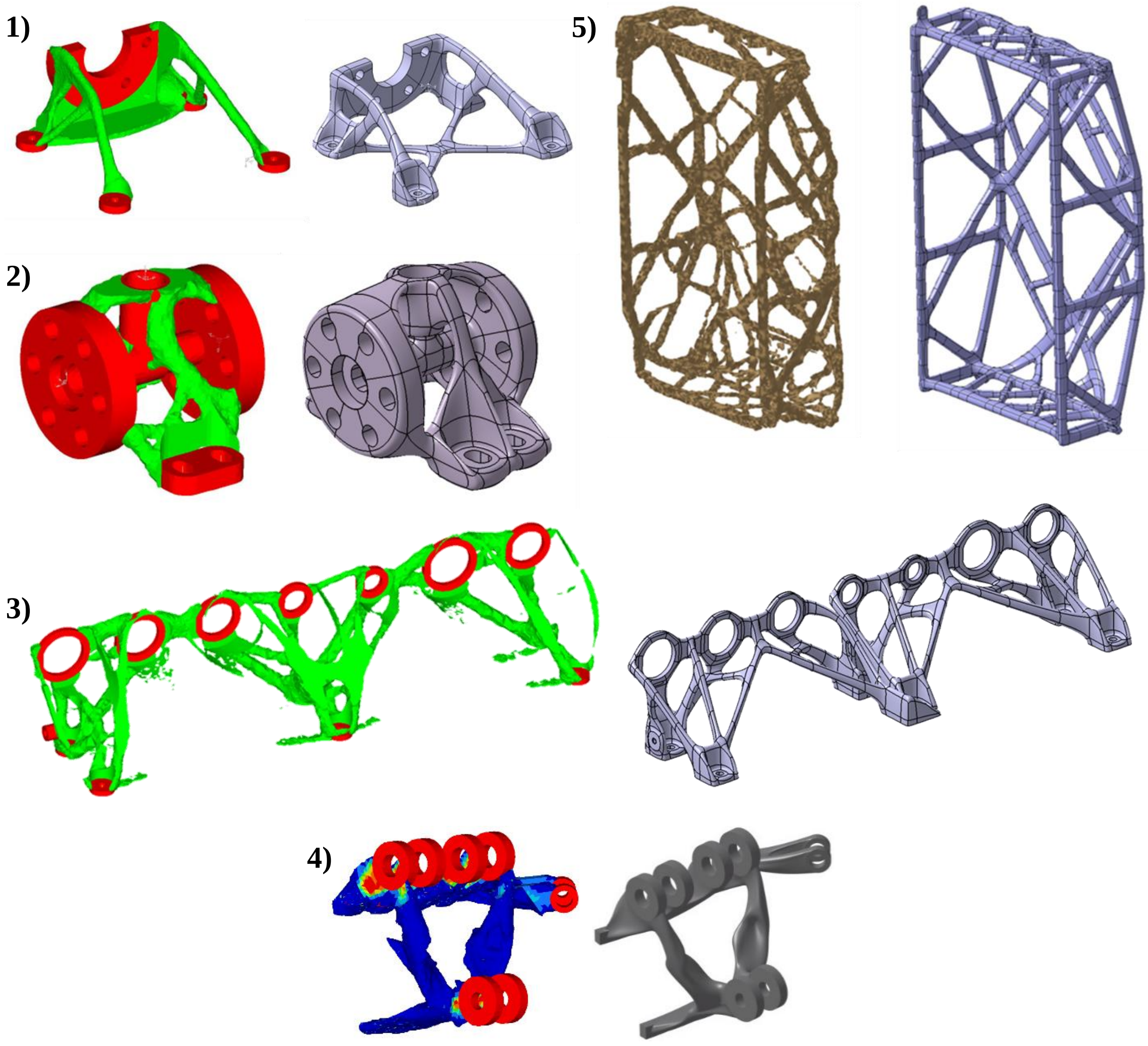

Figure 11: Comparison of topology optimization result and final design of different structural parts and components developed by ArianeGroup

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3. Process Simulation of Powder Bed Additive Manufacturing

The main challenges in powder bed additive manufacturing are build job abortions due to high part distortions leading to collision with the recoater, failure of support structures or even cracking of the produced part due to excessive residual stresses induced by the printing process. These manufacturing problems usually require an iterative trial and error process until the part design and process parameters are well adjusted. In order to avoid this costly trial and error approach, ArianeGroup integrated manufacturing process simulation into the overall additive manufacturing process chain, as illustrated in Figure 12.

After completion of the part's CAD design and print job preparation, a process simulation is performed in order to predict distortions and residual stresses in the printed part. If no potential manufacturing issues are identified by the simulation, the component is passed to the next step of the process chain and thus can be manufactured with confidence. In the case that potential risks are identified during the build job, the process simulation provides valuable inputs for possible design modifications or adjustments of the print job set-up until the predicted manufacturing risks are iteratively eliminated.

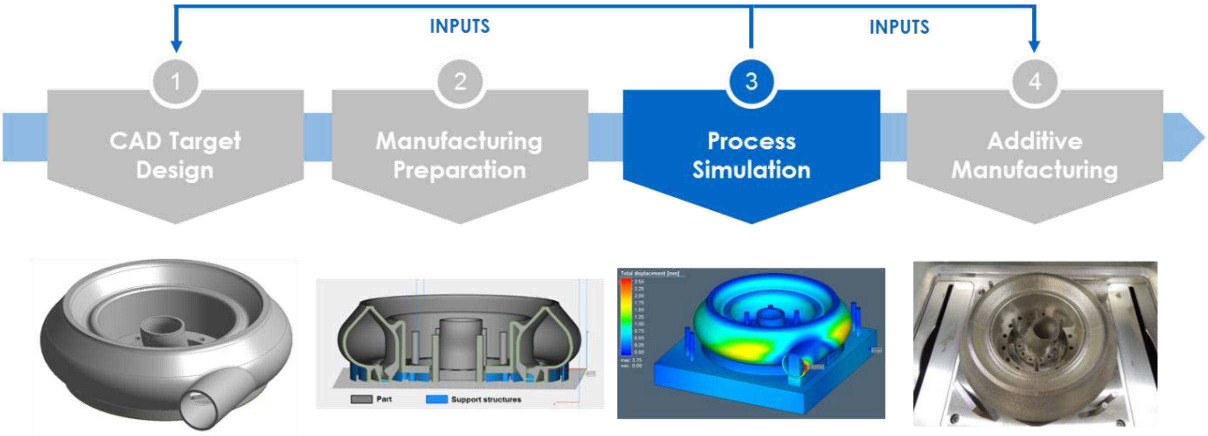

Figure 12: Process simulation as part of the additive manufacturing process chain

Following sections present two different macro scale simulation approaches used in ArianeGroup, which in contrast to the local microscopic simulation methods are able to predict the whole part's behavior during the build-up process.

3.1 Inherent Strains Method

The so-called inherent strains are strains caused by thermal gradients that occur during the additive manufacturing process. They consist of thermal strains, plastic strains and strains induced by phase transformations, and are dependent on material properties and process parameters:

$$\varepsilon^{inherent} = \varepsilon^{th} + \varepsilon^{pl} + \varepsilon^{ph} \tag{3}$$

Under the assumption of a comparable thermo-mechanical history of each welding seam, which is significantly smaller than the additively manufactured part, the inherent strains are calibrated based on simple cantilever specimens shown in Figure 13. For the calibration procedure, cantilever specimens with predefined geometry are printed in different orientations using exactly the same process parameter set and metal powder that is used later to print the parts. After cutting the specimens from the build plate, the resulting max. z-distortion of the cantilever tip is measured and used as reference for the calibration process of the inherent strains, during which the difference between the measured distortion and the simulated distortion using the inherent strains is minimized.

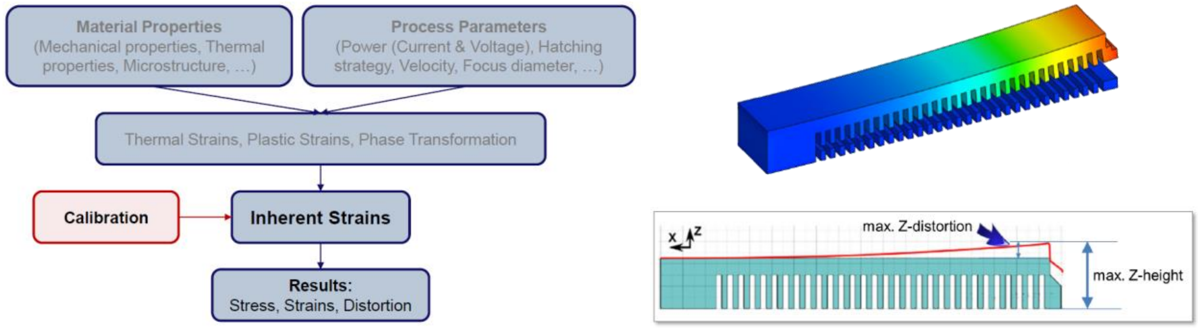

Figure 13: Calibration of inherent strains [3]

Once the inherent strains are calibrated for a specific material, machine and process parameter set, they can be used in order to simulate the distortions of real components. It is noted that the inherent strains method is a purely mechanical approach since the thermal history is included in the calibrated inherent strains. Therefore, it is an extremely fast and efficient simulation method compared to conventional thermo-mechanical analysis methods.

3.2 Thermo-Mechanical Approach

A thermo-mechanical approach for additive manufacturing process simulation was developed by ArianeGroup and implemented in a standard FEA software, before commercial tools for process simulation were available on the market.

The simulation model is prepared according to the steps depicted in Figure 14. First, the part geometry is sliced into horizontal layers and positioned on the build plate. Subsequently, the part and the build plate are meshed via conformal meshing and the part's elements are deactivated. After that, the model is ready for the thermo-mechanical simulation.

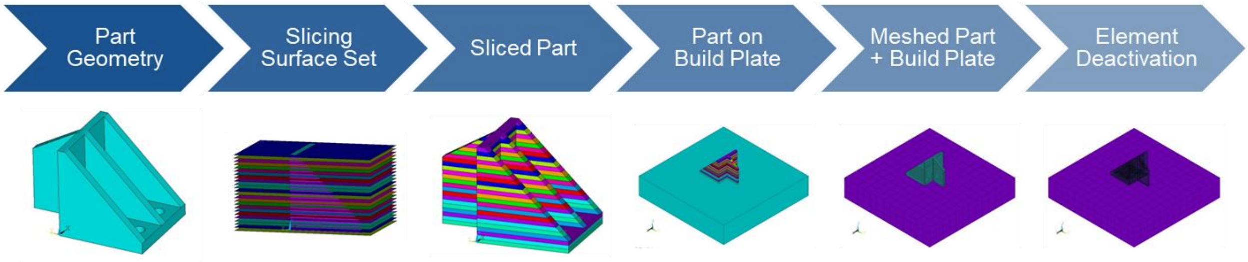

Figure 14: Model preparation for thermo-mechanical process simulation

The coupled thermo-mechanical process simulation consists of two main analysis steps and is sketched in Figure 15.

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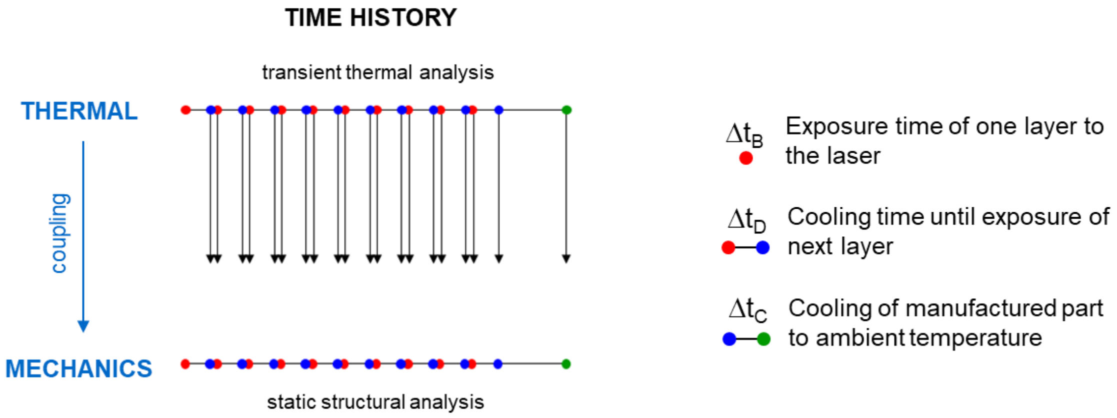

Figure 15: Coupled thermo-mechanical process simulation approach

1. **Transient thermal analysis**
   During the transient thermal analysis, the elements of the part's first layer are activated and subjected to the used material's melting temperature for a defined exposure time (Δt_B). The transient temperature distribution during a short cooling period (Δt_D) is calculated, until the next layer is activated and exposed to the melting temperature. This procedure is repeated until all element layers of the simulated part are activated. At the end of the process, the part is cooled down to ambient temperature (Δt_C).

2. **Nonlinear static structural analysis**
   The simulated thermal history of the manufacturing process is used as a thermal load input in the subsequent non-linear static structural analysis. Activating the elements layer-by-layer, the elasto-plastic stresses and strains are computed for each time step, allowing for identification of potentially critical areas in the part with high plastic strains. The stress relocation after cutting the printed part from the build plate is included in the simulation by deactivation of the contact elements at the end of the process.

The element layer of a simulated part can be either activated as a whole, or discretized according to a scanning strategy as illustrated in Figure 16. In general, it can be stated that with increasing resolution of the process zone, the energy input becomes more continuous and the deformations smaller. However, in view of computational time limitations, it is important to find the necessary discretization level of a simulation model that enables a sufficient prediction quality. In this context, the required mesh size refinement is also an important question. For this purpose, a convergence study was performed on test specimens, showing a reasonable convergence of the deformation for an element size of 0.6 mm in case of complete element layers activation. [2]

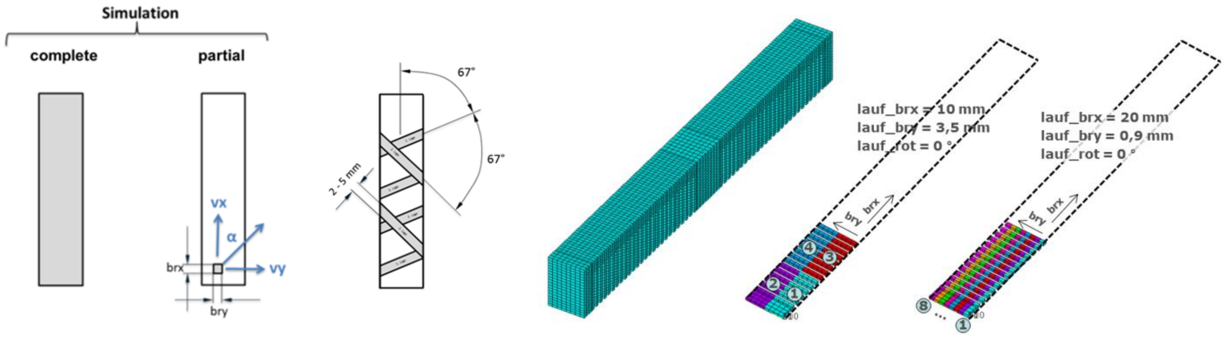

Figure 16: Element layer discretization and possible scanning parameter variations [2]

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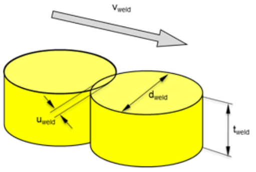
In order to compute the cooling period Δt_D between the activation of consecutive element layers, a volumetric laser speed is defined according to the sketch in Figure 17. Hence, the parameter Δt_D is determined by dividing the activated elements' volume by the volumetric laser speed.



v_{weld} = Laser speed 1200 mm/sec
d_{weld} = Laser diameter 0.1 mm
t_{weld} = Laser depth 0.1 mm
u_{weld} = Scan overlap 0.01 mm

$$\boxed{vol_{weld} = v_{weld} \cdot (d_{weld} - u_{weld}) \cdot t_{weld} = 10.8\ \frac{mm^3}{s}}$$

Figure 17: Definition of the volumetric laser speed [2]

Various input parameters are involved in the thermo-mechanical process simulation. In order to investigate the influence of different input parameters on the simulation results, a workflow for sensitivity studies and model calibration was established with the parametric optimization software OptiSLang, see Figure 18. Based on the performed sensitivity study results, the relevant input parameters were optimized in order to match the test specimen's measured deformation values and thus to provide a better overall prognosis quality.

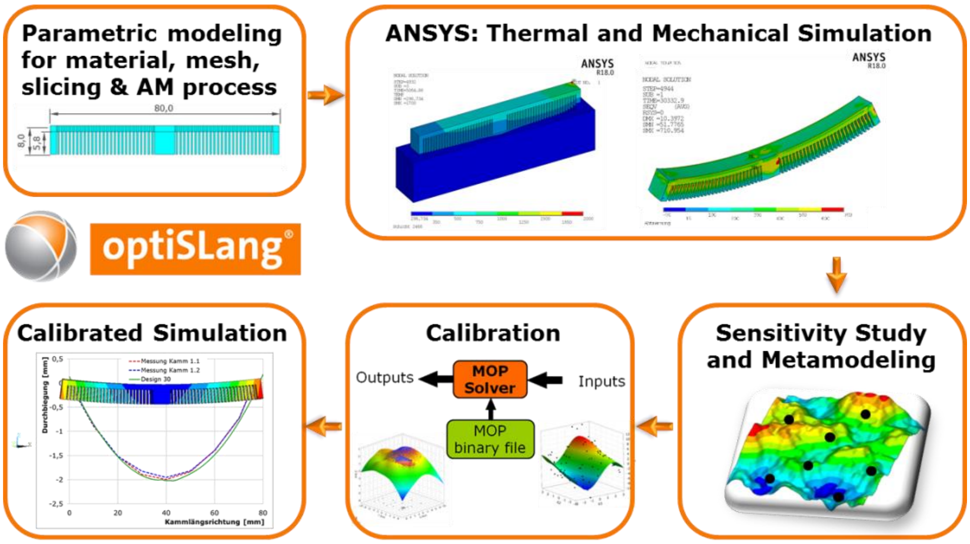


Figure 18: OptiSLang workflow for sensitivity studies and model calibration [2]

3.3 Application Cases

The two introduced process simulation methods were applied to several additively manufactured ArianeGroup products, contributing to a better understanding of the structure's behavior induced by the additive manufacturing process.

The first printed hardware simulated with the thermo-mechanical workflow was an All-in-One (AiO) injection head for the Expander Technology Integrated Demonstrator (ETID) thrust chamber assembly shown in Figure 19. Due to several cracks identified on the first printed demonstrator, the simulation of the manufacturing process was performed as part of the root cause analysis.

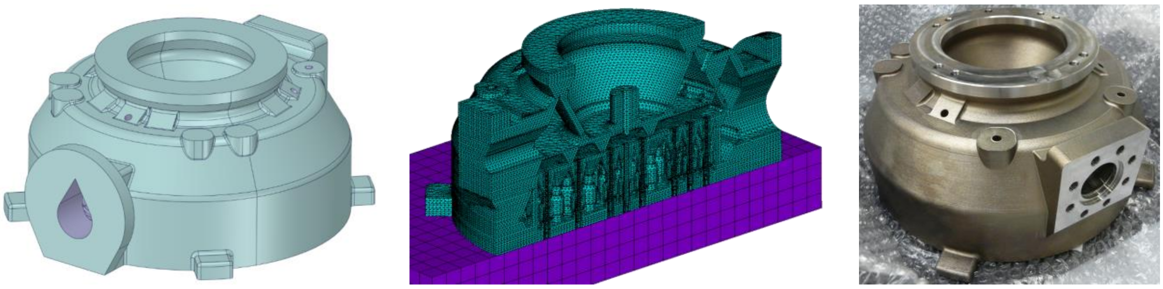


Figure 19: ETID AiO injection head: Geometry (left), simulation model (center) and printed hardware (right)

The simulated plastic strains in the AiO injection head after printing and cutting from the build plate, as well as the cracked locations identified by dye penetrant inspection, are shown in Figure 20. It can be seen that the cracked locations were reproduced by the simulation, showing high plastic strain levels in the critical areas. Other internal locations with high plastic strains, which could not be identified by dye penetrant inspection, were later confirmed as cracked areas by metallographic inspection. Based on the process simulation results, several corrective actions were defined. These measures contributed to the manufacturing of an intact second hardware which was successfully hot-fire tested on the German Aerospace Center (DLR) P3.2 test bench in Lampoldshausen [1].

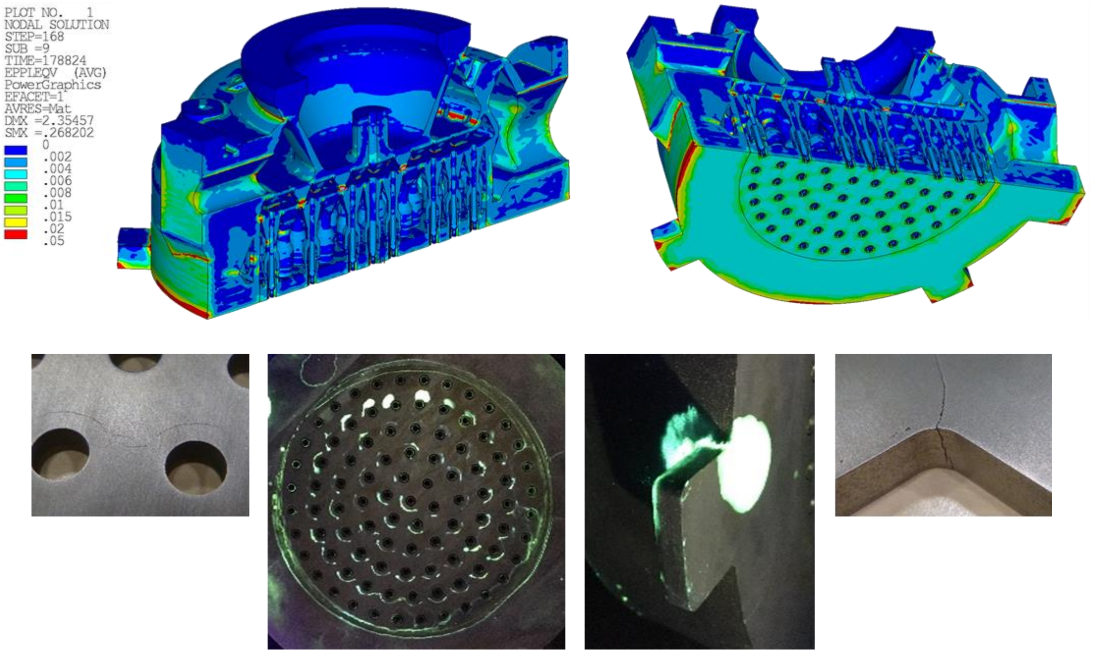


Figure 20: ETID AiO injection head: Simulated plastic strains (top) and cracks on printed hardware (bottom)

In contrast to the more time consuming thermo-mechanical process simulation, Simufact offers a possibility to quickly simulate part distortions and residual stresses which help to anticipate the risk of failure during the build-up process. Figure 21 shows an example of a gas generator head designed by ArianeGroup, where the recoater collided with the part due to excessive distortions in z-direction. The build job abortion could have been avoided by performing a process simulation in Simufact prior to the manufacturing, where the high z-layer displacement in the affected part area is accurately predicted.

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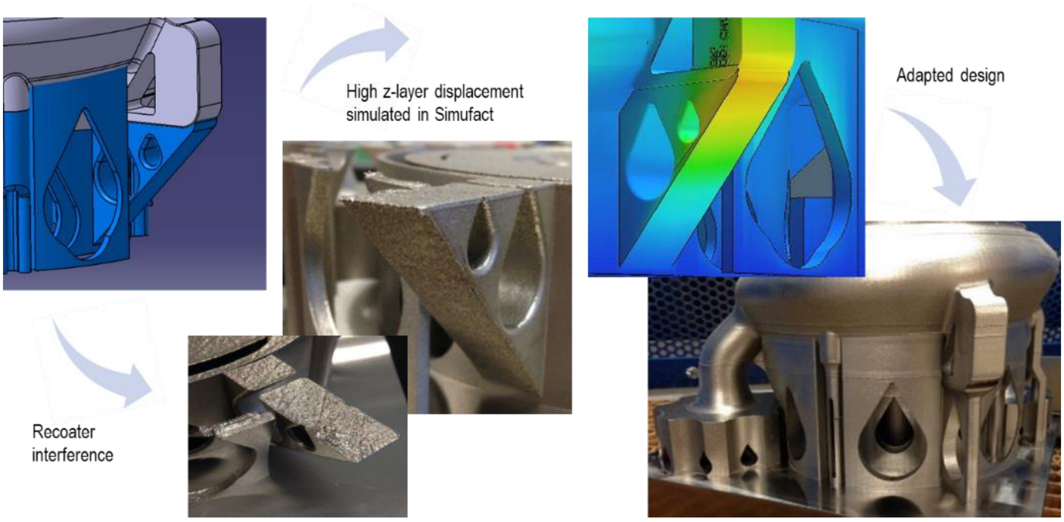

Figure 21: Recoater collision due to high z-distortions in a gas generator head predicted by Simufact

Another example for a failure predicted by Simufact is given in Figure 22. The small contact area of the printed valve casing to the build plate cracked due to high residual stresses, which can be anticipated by process simulation in Simufact based on the high level of plastic strains.

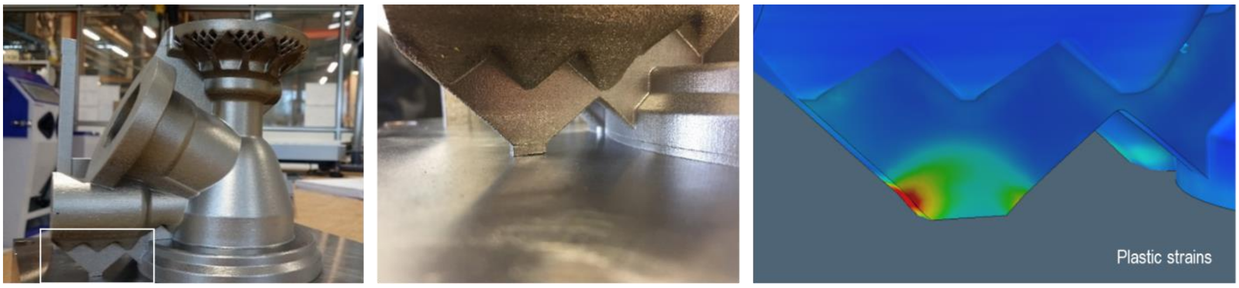

Figure 22: Cracking of a valve casing due to high residual stresses predicted by Simufact

Given that the inherent strains are properly calibrated, the distortions simulated in Simufact are generally in a very good qualitative and quantitative agreement with measurements. Figure 23 shows a comparison of the optical measurement of a heat exchanger with the simulation results, where the discrepancy is found to be 3% to max. 24%.

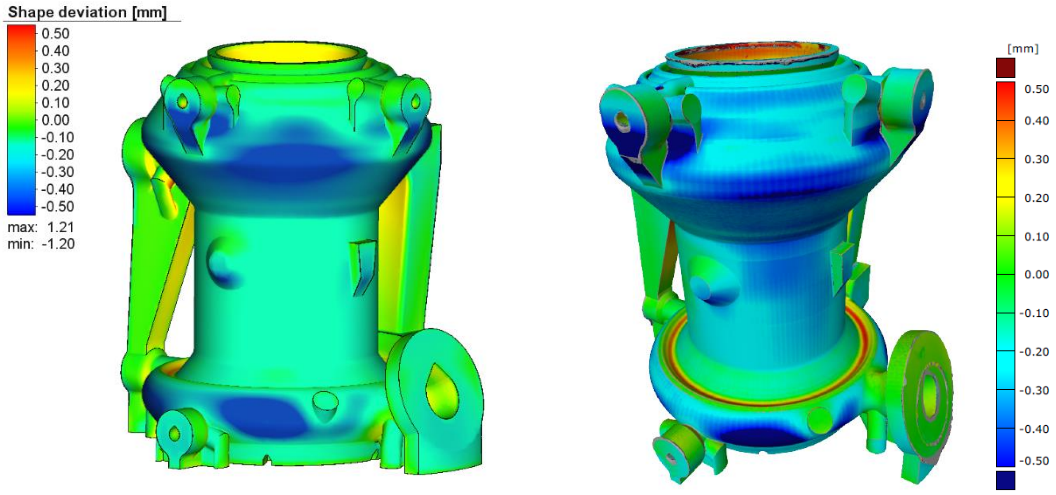

Figure 23: Comparison of simulated (left) and measured distortions (right) of a printed heat exchanger

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4. Summary

The present document presents the methods and tools used for optimal design and manufacturing process simulation at ArianeGroup. First, the optimal design process is explained with special focus on topology optimization and the subsequent design interpretation phase. Here, the advantages of using NURB surfaces for design generation after topology optimization are demonstrated, including their positive impact on additive manufacturing constraints. Presented ArianeGroup application cases for optimized structures range from launcher parts to engine brackets. Additionally, the needs and benefits of performing a simulation of the powder bed additive manufacturing process prior to manufacturing are demonstrated. Particularities of different process simulation methods are explained and ArianeGroup application cases for both simulation methods are provided.

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