ALABAMA

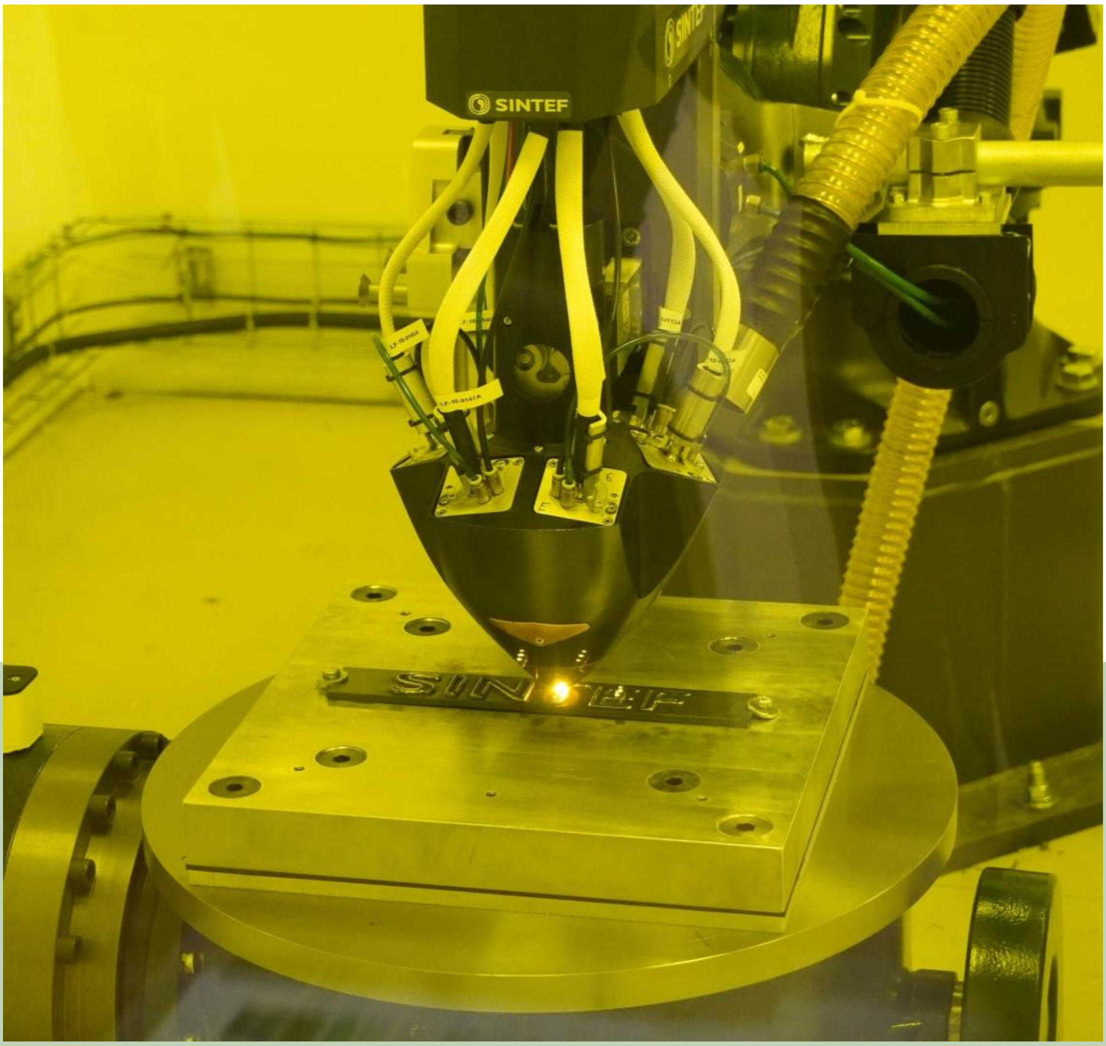
Deliverable 1.2:

Standards & Interfaces

Evaluation of all standards related to data & information exchange. Definition of data interfaces, semantic concepts, data collections.

Published date: 2024-12-19

Public, version 1.0



Co-funded by
the European Union

This project has received funding from the European Union under the Horizon Europe Grant № 101138842. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Project

Project title	Acronym	Grant agreement nr.	Project start	Project end
Adaptive Laser Beam for Additive Manufacturing	ALABAMA	101138842	01.01.2024	01.01.2028

Deliverable

Name of deliverable	Deliverable nr.	Work Package
Standards & Interfaces	1.2	WP1

Dates & Partners

Due date	Submission date	Main authors	Contributing partners	Reviewers
31.12.2024	19.12.2024	FhG SCAI	ALL	SINTEF

Abstract

This document summarizes the data workflow for all the three use cases, namely aerospace, maritime and automotive, while providing information about the various data formats that are employed in each step. The material, CAx, manufacturing and testing domains for each use case are described, regarding standardised methods and data interfaces planned for the ALABAMA project. In addition, standards and industrial practices that are to be employed for each use case are introduced, with the overarching goal of creating a model-centred ecosystem based on these and identifying requirements for material characterization.

A particular emphasis is placed on the ISO/ASTM standards and structured frameworks that aim at organizing information (ontologies) in the domain of additive manufacturing (AM). This document highlights the challenges incurred across working with multiple use cases and the huge amount of data transfer required for a streamlined workflow. To meet this challenge in additive manufacturing the new Interface Standard for Integrated Virtual Material Modelling in Manufacturing Industry (VMAP) will be further developed in the ALABAMA project.

Keywords

LASER, DED, Standards, VMAP, Ontology, Digital Product Passport

Revisions

Version	Submission date	Comments	Author
v0.1	08.11.2024	Basic structure of the document	Fraunhofer SCAI
v0.2	26.11.2024	Contributions to Chapter 3	NAM
v0.3	26.11.2024	Contributed to Chapter 4	CRF
v0.4	29.11.2024	Contributions to Chapter 2	GKN
V0.5	01.12.2024	Contributed to Chapter 2	SINTEF/EURECAT
V0.6	03.12.2024	Reviewed	SINTEF
V0.7	04.12.2024	Contributions to Chapter 2,3,4	Aerobase
V0.8	10.12.2024	Contributed to Chapter 3	IWS
V0.8	10.12.2024	Contributed to Chapter 4	IRIS
V0.8	10.12.2024	Contributed to Chapter 2,3,4	FPS
V0.9	11.12.2024	Contributed to Chapter 5	SINTEF
V0.9	11.12.2024	Merged all the changes and contributed to Chapter 6 & 8	SCAI
V0.9	11.12.2024	Review and updates	ALL
V0.9	11.12.2024	Reviewed	SINTEF
V1.0	18.12.2024	Final Review and update of workflows and cleaning the text.	SINTEF

Disclaimer

This document is provided with no warranties whatsoever, including any warranty of merchantability, non-infringement, fitness for any particular purpose, or any other warranty with respect to any information, result, proposal, specification or sample contained or referred to herein. Any liability, including liability for infringement of any proprietary rights, regarding the use of this document or any information contained herein is disclaimed. No license, express or implied, by estoppel or otherwise, to any intellectual property rights is granted by or in connection with this document. This document is subject to change without notice. ALABAMA has been financed with support from the European Commission. This document reflects only the view of the author(s) and the European Commission cannot be held responsible for any use which may be made of the information contained.

Acronyms and definitions

Acronym	**Meaning**
ALABAMA	Adaptive Laser Beam for Additive Manufacturing
AM	Additive Manufacturing
ISO	International Organization for Standardization
ASTM	American Society for Testing and Materials
AVFF	Adding-Value Functional Feature
BPQ	Build Process Qualification
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CBC	Coherent Beam Combining
CCD	Charge-Coupled Device
CET	Columnar to Equiaxed Transition
CFD	Computational Fluid Dynamics
COG	Centre of Gravity
CNC	Computer Numerical Control
CTE	Coefficient of Thermal Expansion
DED	Directed Energy Deposition
DED-LB/M	Laser beam Direct Energy Deposition using Metals
DED-LB/P	Laser beam Direct Energy Deposition using Powder
DoE	Design of Experiments
DPP	Digital Product Passport
DSS	Duplex Stainless Steels
FWHM	full Width at Half Maximum
GA	Genetic Algorithms
HDF	Hierarchical Data Format
HPC	High-Pressure Compressor
LVI	Liquid-Vapor Interface
NDE	Non-Destructive Evaluation
SEM	Scanning Electron Microscope
TTB	Time-phase Transformation Block
SMC	Sheet Moulding Compound
SAMM	Semantic Aspect Meta Model
STEP	Standard for the Exchange of Product Model Data

About the ALABAMA project

The ALABAMA project aims to develop and mature adaptive laser technologies for AM. The objective is to decrease the porosity and to tailor the microstructure of the deposited material by shaping the laser beam, both temporally and spatially, during the AM process.

The key innovations in the project are to develop multiscale physics-based models to enable optimization of the AM process. These process parameters will be tested and matured for multi-beam control, laser beam shaping optics and high-speed scanning. To ensure the quality of the process, advanced online process monitoring, and closed loop control will be performed using multi spectral imaging and thermography to control the melt pool behaviour coupled with wire-current and high-speed imaging to control the process.

To verify that the built material fulfils the requirements, advanced characterization will be conducted on coupons and on use-cases. The matured technology will be tested on three use-cases: aviation, maritime and automotive. These three industrial sectors span a broad part of the manufacturing volumes: from low numbers with high added value, to high numbers with relatively low cost. However, all these sectors struggle with distortions, stresses, and material quality.

The ALABAMA use-case demonstrators will improve the compensation for distortions during the AM process, reduce the build failures due to residual stresses, reduce porosity and improve tailoring of the microstructure. Overall, this will contribute to up to 100% increase in process productivity, 50% less defects, 33% cost reduction due to increased productivity and energy savings, a reduction of 15% in greenhouse gases and enable first time-right manufacturing thanks to simulation, process monitoring and adaptive control.

The end users will insert the technologies while the sub-technologies developed in the work packages will be commercialized. This will increase the autonomy for a resilient European industry.

Contents

1. Introduction

D1.2 “Standards & Interfaces” aims to achieve the main objectives of WP1:

- Evaluation of current standards, need for extensions and identification of standardization bodies.
- Increased flexibility and interoperability of engineering workflows by using established data and interface standards.

With this deliverable we will be able to see:

- The set of ‘standardized’ interfaces for a seamless exchange of data
- Implementation of available standards for describing simulation workflows and material characterization.

1.1. Document Structure

The document contains the following chapters:

“Use Case Compressor”: This chapter will present the data workflow chart for the Compressor use case and provide details about each step along with the relevant data files. See Figure 2 for the workflow chart of the compressor use-case.

“Use Case Impeller”: This chapter will present the data workflow chart for the Impeller use case and provide details about each step along with the relevant data files. See Figure 14 for the workflow chart of the impeller use-case.

“Use Case Automotive”: This chapter will present the data workflow chart for the Automotive use case and provide details about each step along with the relevant data files. See Figure 28 for the workflow chart of the automotive use-case.

Each domain within the workflow processes, as further described in section 1.2, have included additional figures for enhanced readability.

“Open Ontologies in the Additive Manufacturing Domain”: This chapter will largely focus on the available ontologies in the additive manufacturing domain and how these can be used by the project. Ontologies are structured frameworks used to organize information, enabling the representation of knowledge within a particular domain in a formal, machine-readable way.

“Semantic Data for Digital Product Passport”: Details about the data required for the digital passport and the full semantic data integration process.

“Conclusion”: The summary and the conclusion for this deliverable, along with the future steps for the project will be detailed in this chapter.

1.2. Workflow process for each use-case

The **workflow process** is segregated into four domains: Material, CAX, Manufacturing & Testing.

The **material domain** largely focusses on acquiring the material properties either via supplier data sheets or via testing and then using these data sets to build the Material Models in MSC Marc.

The **CAX domain** covers the whole process chain from the CAD to the CAM. The local melt pool and laser absorption simulations are performed with input from 'bead on plate specimens.' The results are then used for thermomechanical simulations of more process test geometry to guide deposition, path planning and process simulation and testing. A similar chain of steps is followed for the component geometry provided by the end-user.

The **manufacturing domain** requires machine preparation with powder nozzle characterization and calibration of fixtures, deposition head, sensors, and auxiliary set-up. Once the machine set-up is complete, the deposition process starts and is evaluated with sensors, camera etc. until a desired level of quality is achieved. This component is then subjected to stress relief treatment, dimensional check and 3D scanning.

The **testing domain** carries out the various required tests on the process test geometry or the component geometry to evaluate the material and the design for final approval.

This workflow defines the responsibilities of all use case partners and provides clarity for engineers regarding the types of data and file formats required or exchanged at each step. Once this information is organized within the workflow, engineers can determine which formats can be seamlessly converted to a standard format, such as VMAP, and which require more effort.

The goal is to first catalogue all file formats associated with a specific use case and then systematically determine how they can be translated into a standard format. While managing multiple formats within a single use case may be straightforward, working across multiple use cases and partners necessitates a unified format. Adopting a standard format not only streamlines the workflow but also significantly reduces the time spent on file translation per tool and engineer.

2. Use Case Compressor

2.1. Introduction

The use case for the compressor casing (Figure 1) is a notional geometry of a high-pressure compressor casing (HPC-case) for an aeroengine. The proposed design in a final machined condition has a weight close to 20 kg. The HPC-case is a load carrying structure in the core of the aeroengine. The component is subject to high temperature and pressure loads. However, the most critical design feature for the compressor is the capability to contain a blade off event. These events are rare, but it is very important that the engine can contain such failures to assure that no one is hurt or injured during the flight. For the HPC-case to be able to withstand these events the material needs to be both strong and ductile to maximize its ability to absorb the energy from the impact of the blade. After such a failure is contained, the engine will stop producing power and the natural airflow through the engine core will cause the compressor to rotate (windmilling). During this condition there will be a high unbalanced load in the engine which will result in vibrational loads in the component. Therefore, the component needs to be able to withstand these vibrations which requires sufficient low and high cycle fatigue resistance.

Figure 1: Compressor Casing

This component is a strategic component for GKN in its journey with additive manufacturing. Today HPC-cases usually are cast, however; there are significant supply chain issues for these components. Therefore, it is of interest to develop an alternative solution for components such as the HPC-case.

The material in the finished additive manufacturing case should:

- Compensate deformations to enable a near net-shape as-built component.
- Gain near isotropic properties, by tailoring an equiaxed microstructure.
- Defects < 100 µm to ensure the material integrity will satisfy the requirements in the aerospace industry.

2.2. Workflow Process

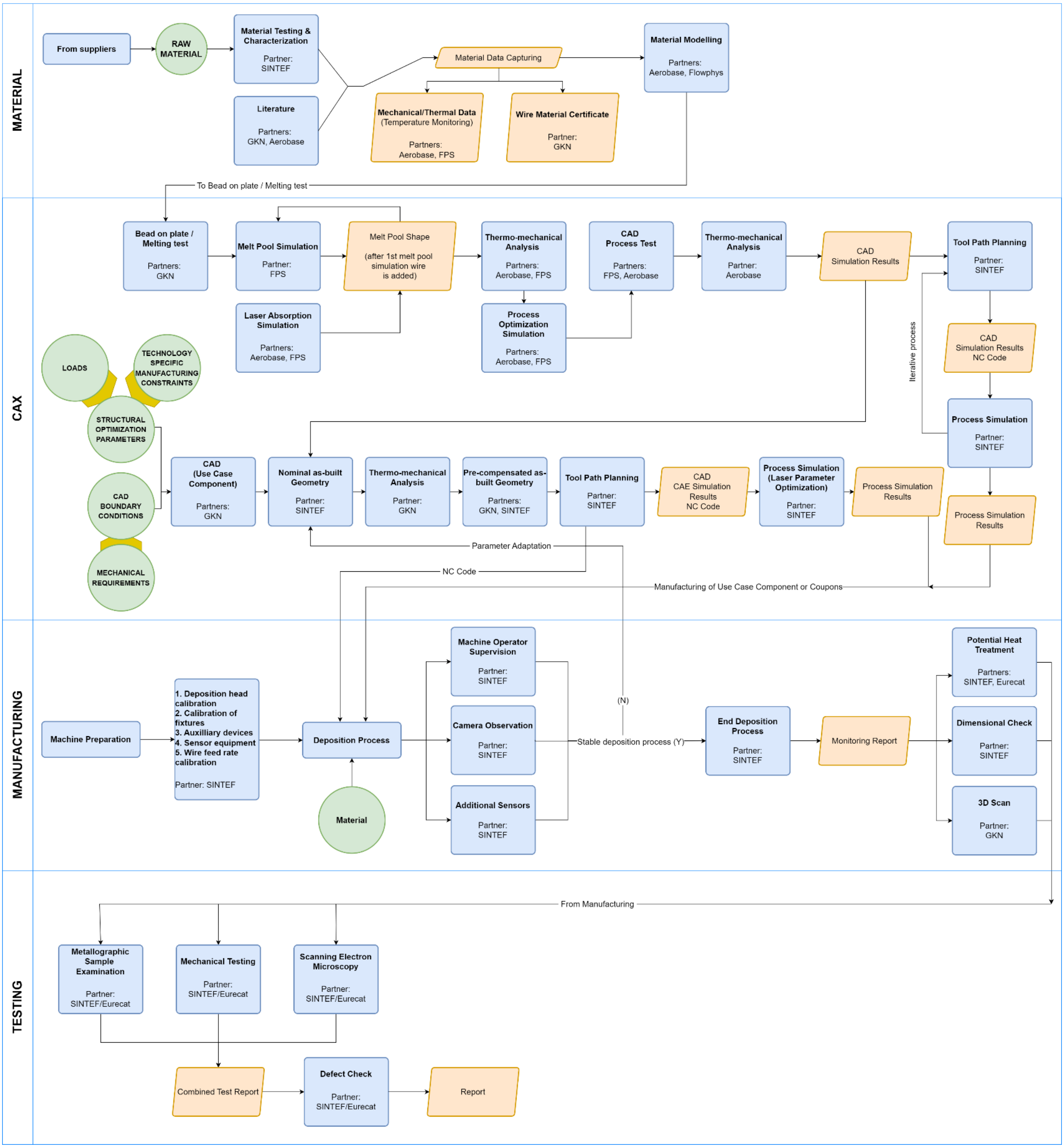


Figure 2: Compressor Workflow Chart (Readable text available for individual domains)

2.2.1. Material Domain

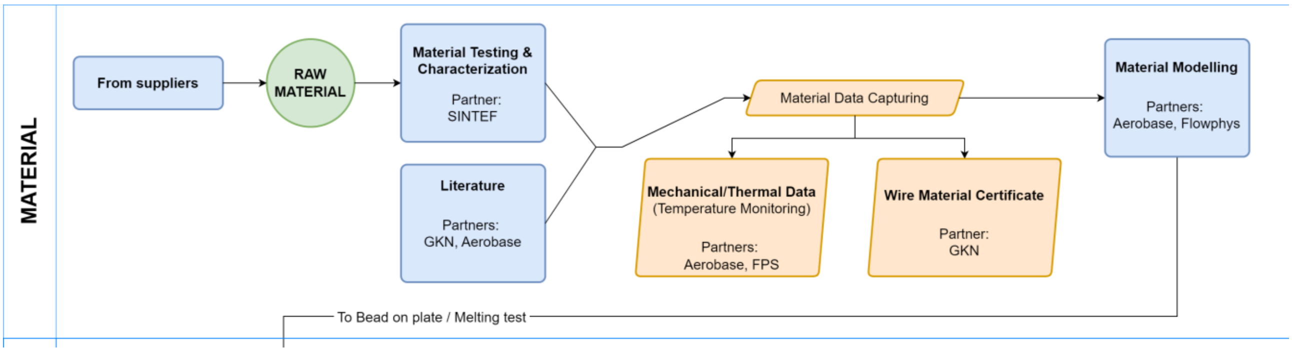


Figure 3: Material Domain Overview for Compressor Use Case

The feedstock material is received from the supplier along with the data sheet. The material testing and characterization will be carried out by SINTEF and the results will be provided to Aerobase & Flowphys for material modelling. The wire material certificate will be delivered by GKN suppliers.

VMAP Standard offers the possibility to store material models and the material testing data for archiving or for transferring it to other partners.

2.2.1.1 Material Characterization

The feedstock wire used in the project is Ti-6Al-4V grade 5 and will be used to manufacture specimens for material characterisation and to generate validation data for the directed energy deposition (DED) simulations. The material characterisation will focus on the material properties that are important to simulate and predict the DED process behaviour. Material characterisation will initially focus on microstructure in the material produced with the DED process as a function of laser formations, before moving on to characterise properties that are not well defined in literature. Features in the microstructure such as α/β phase ratio, lath size and columnar β grain structure will be evaluated as a function of DED process parameters.

2.2.1.2 Material Data Capturing

1. Thermophysical Properties

The thermophysical properties of the Ti-6Al-4V alloy include various characteristics that depend on temperature, making it essential for applications such as AM. According to Mills (2002), the alloy's density of 4.43 g/cm^3 at room temperature changes slightly with temperature due to thermal expansion, reflected in its coefficient of thermal expansion (CTE) $(9–10\times10^{-6}\,{}^{\circ}C^{-1})$. Young's modulus decreases with temperature, following the Wachtman model, while Poisson's ratio exhibits a linear temperature dependence. The specific heat capacity, measured using DSC, shows latent heat transformations occurring between 935°C and 1000°C, with a fusion heat of approximately 290 kJ/kg. Thermal conductivity, affected by the Wiedemann–Franz law, varies due to phase changes and is crucial for heat transfer modelling. Moreover, the diffusion mechanisms in the α and β phases significantly impact alloy behaviour during AM processes. These properties and a rule of mixtures approach help predict the alloy's thermal and mechanical behaviour under various processing conditions.

In addition to the thermophysical properties of the solid state, the melt pool analyses require properties for liquid and potentially also gas phases. For the liquid phase, relevant properties are density, thermal conductivity, specific heat capacity, viscosity, surface tension, thermal expansion, absorptivity, and emissivity. These properties are dependent on temperature, and in addition the viscosity may also be dependent on shear rate (non-Newtonian fluid). The Wiedermann-Franz law provides the conductivity also for the liquid phase. Models based on curve fitting to data from the literature, e.g. Boivineau et al (2006), Wunderlich (2008), will be used for the simulations.

2. Feedstock Wire Material Certificate

Ti-6Al-4V grade 5 feedstock wire will be used for testing. In the preliminary tests, classification of the wire will not be necessary since the focus will be on optimizing the microstructure. In mechanical testing, however, AMS4954 is to be used for part deposition to ensure correct chemical composition and quality.

2.2.1.3 Material Modelling

Material modelling of **Ti-6Al-4V**, a dual-phase titanium alloy, is essential for predicting its behaviour during processes such as AM and other thermo-mechanical treatments. This modelling involves several key areas.

1. Microstructure evolution

The alloy undergoes phase transformations between the α and β phases, which are influenced by temperature, cooling rates, and alloying elements. During additive manufacturing, thermal gradients and cooling rates drive a transition from columnar to equiaxed grains. This Columnar-to-Equiaxed Transition (CET) significantly affects the mechanical properties, as equiaxed grains provide more isotropic strength than columnar structures.

2. Thermo-physical properties

Accurate modelling must consider temperature-dependent properties such as density, thermal conductivity, specific heat capacity, and the thermal expansion coefficient (CTE). These properties are crucial for understanding melt pool behaviour, heat transfer, and thermal distortion.

3. Flow Stress Behaviour

Flow stress is modelled as a temperature, strain rate, and phase composition function. This modelling includes long-range interactions (a thermal stress) and short-range lattice resistance (thermal stress), essential for predicting deformation and stress distributions.

4. Time-Temperature Block (TTB) Approach

The TTB approach simplifies complex thermal histories encountered during additive manufacturing by dividing them into manageable blocks. Each block corresponds to distinct thermal cycles, such as heating, cooling, or isothermal annealing, along with their associated phase transformations. This method allows for accurate simulation of phase evolution, including martensitic transformations, lamellar α/β formation, and grain refinement. It also captures the effects of heating and cooling rates. TTB also facilitates integration with machine learning models for real-time process control.

5. Phase Transformation Kinetics

Models like the Kirkaldy-type equation describe the transformation rates between the α and β phases, considering thermodynamic driving forces, nucleation, and diffusion mechanisms. Understanding these kinetics is vital for simulating non-equilibrium phase evolution during rapid thermal cycles.

6. Residual Stress and Distortion

Coupled thermo-mechanical models can predict stress accumulation during thermal cycling, reducing defects such as warping or cracking during manufacturing. By integrating these aspects, material modelling for Ti-6Al-4V enables precise manufacturing process optimization, ensuring tailored microstructures and mechanical properties for aerospace, medical, and industrial applications.

7. Liquid state fluid properties

As discussed in the material data capturing section, most of the fluid properties of the molten state will be modelled as linear or curve fitting to experimental data from the literature. The Carman-Kozeny relation will be used in the mushy region. In addition, non-Newtonian fluid models may also be evaluated (Herschel-Bulkley and Carreau-Yasuda), as they are already implemented in the Flowphys software. Surface tension and the modelling of the Liquid-Vapor Interface (LVI) is very important, because surface tension gradients cause Marangoni flows which often dominates the fluid flow in a melt pool. The LVI is modelled such as to allow for varying surface tension both in space and time.

2.2.2. CAx Domain

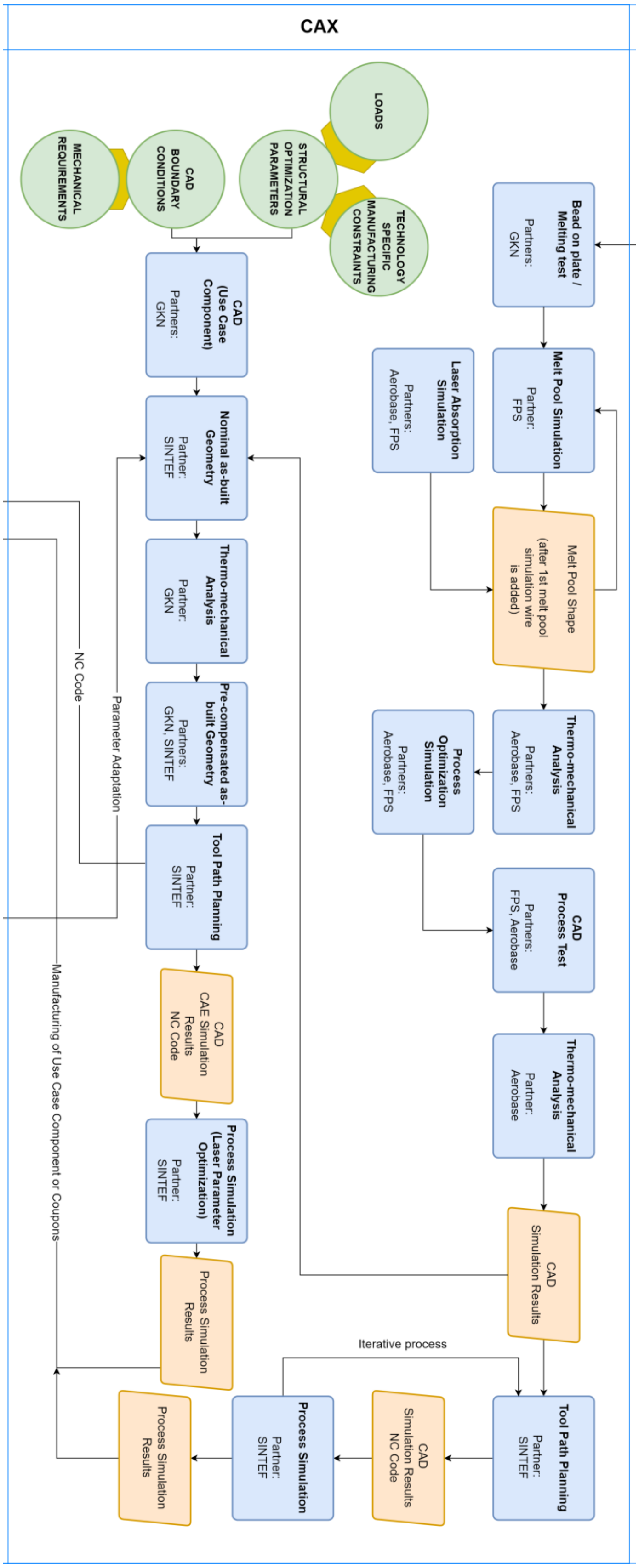


Figure 4: CAX Domain Overview for Compressor Use Case

This section has been organized based on the components instead of the processes because the lifecycle of the components is the focus area for this domain. A **'bead on plate/melting test'** has been developed by LTU and accepted by all the partners. This model will be used by all the use cases. This coupon is subjected to melt pool and laser absorption simulation, followed by thermomechanical and process optimization simulation.

The knowledge gathered about the melt pool and laser absorption for the particular material using the bead on plate/melting test coupons is then used to calibrate and validate the process model before performing a '**process test**' where a simple geometry is deposited. The process test geometry will be developed by Aerobase and Flowphys to carry out thermomechanical simulations, tool path planning and process simulations. Tool path planning will take the physical process and the simulation results into account and generate NC Code for building the geometry. The process simulation will use the CAD & simulation results along with NC Code to optimize the laser parameters.

Finally, GKN will provide a **'component geometry'**, that SINTEF uses to create a nominal as-built geometry. This geometry is again pre-compensated based on the thermomechanical simulation results. SINTEF will then generate the tool path and carry out the process simulation before the deposition process starts.

The CAD geometries will be stored in STEP format only. However, for the simulation data coming from various solvers, VMAP Standard would be the ideal format. The data can be easily translated to the solver specific format for evaluation and translated again to the VMAP format for storage and analysis. All the partners can look at the simulation results using 3D viewers like Paraview or HDF5 viewer to look at the data structure.

2.2.2.1 Bead on Plate/Melting Test

1. Specimen Geometry

The bead on plate/melting test coupon geometry is a rectangular flat bar substrate measuring 100x50x8 mm. It is provided as a STEP file.

2. Melt Pool & Laser Absorption Simulations

Surface tension and the modelling of the Liquid-Vapor Interface (LVI) is very important. Surface tension is temperature dependent, and the strong temperature gradient caused by the laser will therefore result in strong surface tension gradient along the LVI, which in turn will generate Marangoni flows. This is typically the dominant flow mechanism in a melt pool and therefore needs to be modelled in detail. FPS has developed a novel method for simulation of the melt pool and the LVI which includes surface tension effects for both normal ("curvature") and tangential ("Marangoni") forces, buoyancy, and free surface motion. It is based on a stressed-state finite element structural shell that can handle large deformations through a variationally consistent co-rotational formulation and

Computational Fluid Dynamics (CFD) Navier-Stokes with Arbitrary Lagrangian-Eulerian (ALE) and advanced mesh movement and smoothing algorithms. The structural and CFD simulations are two-way coupled, and the sharp interface provides accurate description of the melt pool free surface shape as well as accurate fluid flow boundary-layer shear stresses on the LVI. This method allows for temperature and composition/concentration gradients of the surface tension and provides high accuracy. The liquid in the melt pool can be simulated with an incompressible approximation. However, this can create numerical divergence related to difficulties to fulfil the incompressibility condition inside the melt pool. Therefore, we will use a weakly compressible formulation for the flow inside the melt pool. A key novelty in ALABAMA is to investigate and optimize different laser beam shapes. To model the laser absorption, data-driven models based on experimental literature data (e.g. curve fitting or Kriging meta-model, which we often use in the Flowphys software) and the Beer-Lambert law will be used. Because the metal is reflective, the penetration depth is small, which can make the application of Beer-Lambert difficult. Therefore, models based on boundary heat flux surface absorption will also be tested. The shape of the laser beam, e.g. Gaussian, or ring (“doughnut”), etc. will be modelled as a geometric distribution of the laser intensity.

3. Thermomechanical Simulations

Calibrating the melt pool in AM requires meticulous measurements derived from a bead-on-plate melting experiment to enhance the accuracy of the melt pool and laser absorption models. Utilizing high-resolution infrared thermography alongside cross-sectional analysis of the melt pool provides essential data regarding its dimensions, peak temperatures, and cooling rates. This information is critical for fine-tuning laser absorption efficiency and adjusting the heat source parameters, ensuring that the melt pool behaviour is accurately represented in simulations. Integrating this calibrated melt pool model into a comprehensive thermo-mechanical-metallurgical framework can significantly improve predictive capabilities regarding temperature distributions, phase transformations, and residual stresses. This integration enhances simulation reliability.

4. Process Optimization Simulation

Process optimization in AM utilizes thermo-mechanical-metallurgical simulations that integrate advanced digital tools to predict and improve manufacturing outcomes. By combining models for heat transfer, mechanical stress analysis, and metallurgical transformations, these simulations provide valuable insights into defect formation, residual stresses, and microstructure evolution. Techniques such as the Time-Temperature Block approach enhance phase transformation analysis even while using a lumped approach. At the same time, Columnar-to-Equiaxed Transition models help ensure grain refinement and improved mechanical properties. Optimization involves calibrating laser intensity profiles, scanning paths, and thermal management strategies to reduce defects, customize microstructures, and enhance part performance. These simulations allow optimal process parameters beforehand. This ensures that manufacturing is accurate from the first attempt and aligns with the desired quality and functionality of the final product.

In addition, FPS will use its software tool chain to perform data-driven process parameter optimization. The parameter optimization consists of the following workflow: 1) create an initial test matrix through a DoE analysis based on Latin Hypercube Sampling (LHS); 2) perform simulations with parameter values from the DoE test matrix followed by processing the simulation results; 3) create a meta-model based on the simulation results (e.g. Kriging); 4) Perform global optimization with Genetic Algorithm; 5) Perform new simulations with the newly optimized parameters. If the objective function has converged, then stop; otherwise, add the new simulation to the meta-model and repeat steps 3 to 5. The process is summarized in Figure 5.

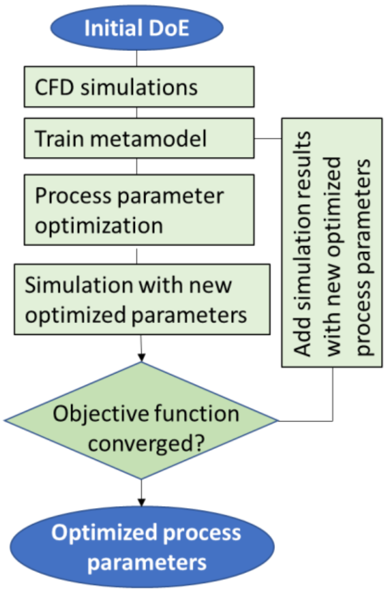


Figure 5: Summary of the process parameters optimization procedure

2.2.2.2 Process Test (Calibration & Validation Model)

1. Specimen Geometry & Process Parameters

The geometry of the component that will be used for validating the fluid flow and thermo-mechanical models has been defined and can be seen in Figure 6. The size of the substrate is 100x50x8 mm, and the AM-built material (called the wall) has a size of 60x25x6 mm. The STEP file format will be used for the CAD geometry.

Table 1: Initial Process Parameters for Compressor Use Case

Process Parameters	Values / Ranges
Laser Formations	2-5
Traverse speed	7.5-15 mm/s
Laser Power	1056-1500 W
Wire feed	0.1-0.5 kg/h

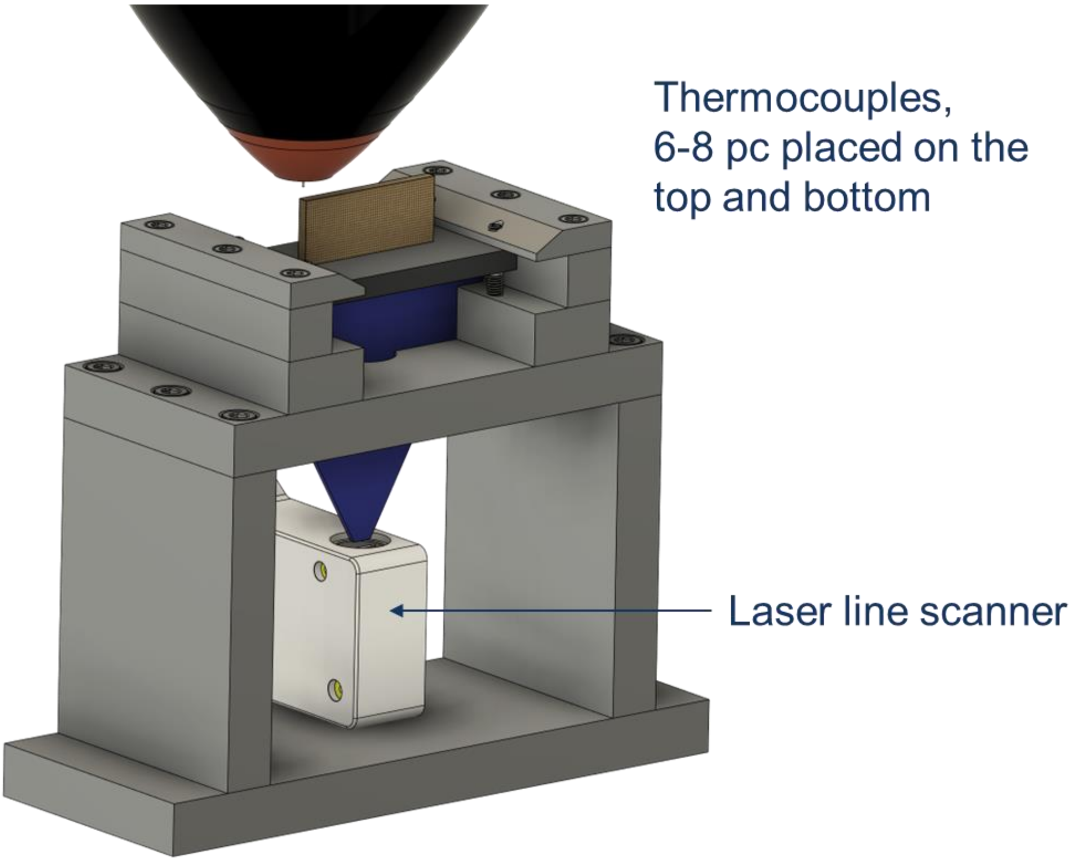


Figure 6: Experimental setup for process test to validate the computational models.

2. Thermomechanical Simulations

A systematic methodology that amalgamates experimental data with numerical forecasts is essential to calibrate and validate AM simulation models effectively. The process begins by capturing in-situ measurements, which may include temperature distributions and distortions occurring throughout the AM process. For instance, strategically positioned thermocouples on the substrate allow for precise monitoring of thermal cycles. In addition, displacement sensors diligently track distortions in the component layer-by-layer. These empirical measurements are critical benchmarks for adjusting various model parameters, including heat source efficiency, material properties, and boundary conditions.

Validation of the model entails a rigorous comparison of simulated results—such as phase fraction changes and stress distributions—with the corresponding experimental data in the coupon scale. This ensures the accuracy and reliability of the material and process model's predictions. The entire calibration process is iterative, allowing for continuous refinement and enhancement of simulation fidelity. By optimizing AM process parameters through this rigorous approach, we significantly improve the ability to predict the final performance of components produced via AM.

3. Tool Path Planning

The process test coupons will be hard-programmed in the KUKA robot system using KRL-code, and the robot controller will control the sub systems. In this way, the effects of each process parameter can be directly observed on the quality of the produced geometry.

4. Process Simulation

In hard programming, the process is not simulated. When using a CAM-software, the process will be simulated to avoid crashes or unwanted behaviour. This is described in Section 2.2.2.3.

2.2.2.3 Component Geometry

1. CAD Geometry

The aerospace use-case represents a simplified notional compressor casing. This casing consists of a drum with varying thickness, three flanges and different types of bosses on the casing. The maximum diameter of the casing is 586 mm while the smallest is 466 mm. The height of the drum is 190 mm. The geometry is shown in Figure 1.

2. Thermomechanical Simulations

Thermomechanical simulation of the deposition of the simplified component will be performed to predict the deformation and temperature distribution in the part. These results will allow to design near-net shape deposition process that minimizes material usage and reduces post-processing costs. In addition, strategies for pre-compensation of the deformation will be proposed to ensure that the final deposited part meets the specifications with minimal adjustment.

3. Tool Path Planning

For complex geometries, SKM DCAM will be used to generate deposition paths. The Meltio and the robot system will be controlled through socket programming, where the code is interpreted by a Linux main control computer that run the sub-controls, like the robot-controller, Meltio laser/wire-feed/hot-wire/gas and sensor systems.

4. Process Simulation

For complex shapes, process simulation is important for crash avoidance. Using SKM DCAM software the movement of the robot and DED head relative to the cell and compressor geometry for full deposition is simulated, ensuring the build will complete without error. Figure 7 shows an example of an augmented reality simulation on a cell phone. Such a simulation can be forwarded to partners and seen locally.

Figure 7: Simulation with AR applying SKM DCAM. This can be forwarded to all partners and seen locally. The screenshot displays the process working on top of a real office desk.

5. Thermomechanical Simulations

Thermomechanical-metallurgical simulations, which combine heat transfer, mechanical deformation, and metallurgical transformations, are crucial in understanding the AM process. These simulations provide insights into material behaviour during the AM process and capture the intricate dynamics of rapid heating and cooling cycles that lead to complex phase changes and residual stresses.

Heat transfer models focus on temperature gradients, thermal conductivity, and latent heat effects in these simulations to accurately represent the thermal environment. Mechanical simulations evaluate distortions, stresses, and strains from thermal expansion and contraction throughout manufacturing. The metallurgical component of the models forecasts critical changes such as phase evolution, shifts in grain morphology (including transitions from columnar to equiaxed structures), and microstructure refinement.

Coupled simulations optimize key process parameters by integrating various aspects, such as laser power and scanning speed. This optimization aims to reduce defects, enhance microstructure control, and achieve specific mechanical properties in AM components. This approach is valuable for materials like Ti-6Al-4V, SAF 2507, AlSi7Mg, and other specialized alloys, where tailored performance is essential for advanced applications.

2.2.3. Manufacturing Domain

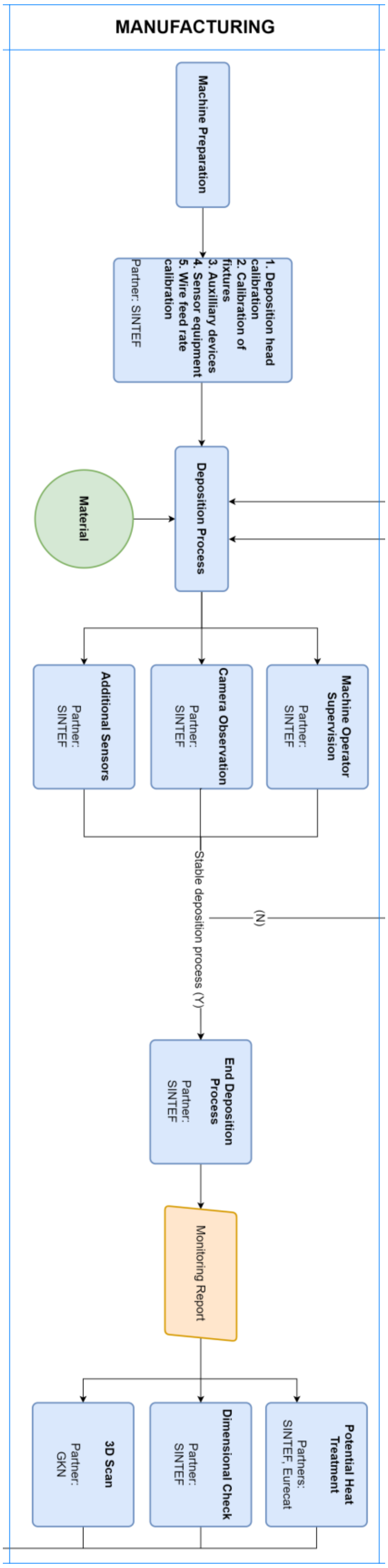


Figure 8: Manufacturing Domain Overview for Compressor Use Case

The machine preparation, carried out at SINTEF, is the very first step in manufacturing and it can be performed in parallel with the other processes. This requires calibration of deposition head, manufacturing set up and calibration of fixtures, set up of auxiliary devices (Cooling, heating), set up of additional sensor equipment and wire feed rate calibration.

The deposition process receives the NC Code from the tool path planning step and feedback from the process simulation of the laser parameter optimization. The machine then carries out the deposition process while the machine operator physically supervises the process along with cameras and sensors. Operator observations and sensor data are fed back to the CAX domain to improve the component design, deposition path planning and process parameters until a stable deposition is achieved.

When an acceptable part geometry is achieved, a monitoring report is generated and evaluated. The component geometry is then sent for stress relief and dimensional verification. The 3D scanning task is performed by GKN, while the other steps are carried out by SINTEF.

VMAP Standard allows for the storage of sensor data and images. The specific sensor data formats may have to be incorporated into the VMAP Standard but the base structure to store timesteps and measured values is already available within the Standard.

The end deposition process report can be stored as a link to the VMAP Files which will store the measurement data.

2.2.3.1 Machine Preparation

Before starting the deposition process the operator needs to be go through steps to ensure correct and repeatable operation of the machine for building Ti-6Al-4V. These include physical steps of changing the wire to the correct type (Ti-6Al-4V), setting and calibrating lasers, cleaning the nozzle and calibrating the system to include build plate (this is done with a three-point method using a probing nozzle to set origin, X-axis and XY-plane of the build coordinate system). Further control steps are needed to input deposition parameters in the control software and check the path planning of the build. Furthermore, the required oxygen level of below 20 ppm for Ti-6Al-4V needs to be met, this requires flooding an inert protective enclosure with Argon gas (99.9999 % purity) until measurements from the Ntron Microx oxygen analyser (detailed in deliverable 4.1) reach this level. To note, local shielding gas directly from the nozzle further contributes to the deposition protection.

2.2.3.2 Deposition Process

During the DED-LB/M process 6 coaxial lasers mounted on the DED head melt substrate material to create a melt pool into which the wire is fed and melted. Feeding wire into the melt pool produces a bead as the deposition head is moved relative to the build surface. This allows the part to be produced layer-by-layer. At the end of the deposition the system will automatically stop the robot motion, lasers, and wire feed.

2.2.3.3 Part Evaluation

Two thermal cameras in different positions provide feedback and monitoring of the melt pool and surrounding material (Infratec VarioCam HD 800 & Optris PI 08M). The output from these cameras are temperature readings which can be used to monitor process instabilities and determine critical areas where defects may form, and where higher or lower energy inputs could affect the microstructure. Furthermore, the data acquired from the thermal cameras will be used to guide simulation and modelling activities. Secondly, the part could be evaluated with continuity measurements to detect if the wire loses contact with the melt pool. This measurement has the capability to find local anomalies, problems with programmed layer height and locate instabilities with the process. Investigations are necessary to fully understand the use of these measurements. It is also possible within SINTEF to use a high-speed camera to obtain data for simulation and modelling, the necessity of this will be discussed during the progress of the project.

1. Heat Treatment

Residual tensile and compressive stresses form due to rapid cooling during the deposition process. These will be resolved through stress relieving of the component in a suitably sized furnace with either an atmosphere of air (if surface machining is still to be done) or inert argon (final surface condition). The stress relieving will be conducted in the range of 550 – 650 °C for 1- 8 hours to reduce these remaining internal stresses without significantly changing the microstructure. One of the goals of the ALABAMA project aims at creating an equiaxed microstructure with isotropic properties in the as-built condition. Process parameter optimization can achieve this by providing suitable conditions for CET. In addition, annealing can be used to improve the microstructure by removing martensite in the as-built microstructure, which is required to satisfy the standards used for DED-LB of Ti-6Al-4V components at GKN, with reference to AMS4999.

2. 3D Scanning

SINTEF will use a line scanner with the same robot system as the build head to scan the geometry of the part. This can detect defects or geometric deviations. However, the system is less accurate than the structured light system at GKN. Together we will compare in-process solution to the special machine solution. 3D scanning of the final component will be done at GKN in Trollhättan with a NADCAP approved method AC7130 Measurement & Inspection Three Dimensional Structured Light Systems 3DSL.

Figure 9: In the picture, a small version of the VC nano 3D Z that is used to evaluate depositions from the ALABAMA project. Mounting the scanner to a robot, SINTEF has made a software to extract and utilise the scan data.

2.2.4. Testing Domain

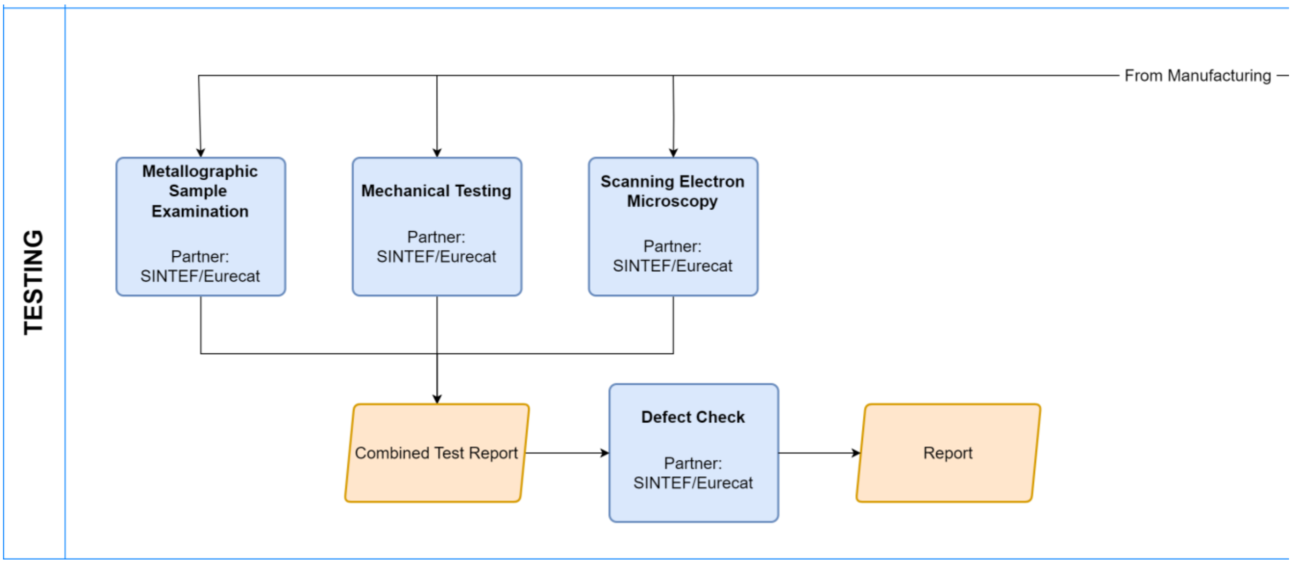


Figure 10: Testing Domain Overview for Compressor Use Case

The material testing will be performed in stages, starting with simple microstructural investigations for initial process development, before proceeding with mechanical testing and more advanced analysis once the deposition process has been optimized.

2.2.4.1 Metallographic check

Characterisation of the underlying microstructure is important for understanding deposition strategies. The preparation process follows ASTM E3, the recommendations from the material preparation equipment suppliers (Buehler and Struers), and internal SINTEF procedures for etching/ heat-tinting to reveal the characteristic microstructures. Light optical microscopy will then be used to examine the microstructure in relation to the deposition strategy employed.

2.2.4.2 Mechanical Testing

Mechanical testing will be performed in accordance with the standards listed in 2.3.2. These specify specimen geometries, loading conditions and measurement procedures to ensure valid mechanical properties are obtained from the material. With output values of yield and ultimate tensile strength, elongation at failure, fracture toughness and fatigue resistance needed to validate the component material.

2.2.4.3 Scanning Electron Microscopy (SEM)

Electron microscope analysis enables characterising microstructure at higher magnifications and resolutions than light optical microscopy. Combined with electron back scatter diffraction and energy-dispersive X-ray spectroscopy this will provide information in the form of grain shape and size distributions, crystallographic texture, and phase distributions. Preparation of the metallographic specimens are detailed in ASTM E3, while ASTM E407 outlines procedures for microetching. The two standards will alongside the application notes from Struers provide a good framework for sample preparation to achieve reliable characterisation through SEM.

2.2.4.4 Defect Check

The key requirement of defects < 100 μm in the component will be analysed using initial visual inspections, lights optical microscopy and x-ray computed tomography (XCT). This inspection path will conform to the guidelines in ASTM E3166 which deals with non-destructive evaluation of aerospace parts produced through additive manufacturing.

2.3. Standards employed for the Use Case

2.3.1. Process Qualification Standards

It is common to apply a qualification standard to test and qualify an AM production route. Examples of such standards are DNV-ST-B203 and API 20S, which are relevant for the impeller case described in Section 3.3.1. These standards describe test extent and sampling to ensure that an AM process produces acceptable material with regards to process-specific weaknesses. For the compressor use-case AMS 7010A is a relevant standard to provide requirements for DED-produced aerospace parts, but it does not specify requirements for process qualification.

2.3.2. Material Testing Standards

The mechanical properties will be evaluated using ASTM and ISO specified testing methodologies and geometries, these are summarized in Table 2. Tensile behaviour testing will follow ISO 6892-1/ASTM E8M for ambient conditions and ISO 6892-2/ASTM E21 for elevated temperatures. Linear elastic plane strain fracture toughness values will be determined through ISO 12135/ASTM E399. Fatigue properties generated from the proposed new rapid testing methodology according to CWA 18107-2 will be benchmarked against conventional fatigue tests as per ISO 1099 or ASTM E466.

Table 2. Summary of standards for materials testing.

Tensile tests	Fracture toughness	Impact test (Charpy)	Fatigue
EN ISO 6891-1		EN ISO 148-1	EN ISO 1099
ASTM E8M / ASTM E21	ASTM E399		ASTM E466
			CWA 18107-2

For the storage of material data and material models VMAP Standard Format can be employed. See Section 2.3.4 for more details on the VMAP Standard.

2.3.3. CAD Model

For all the CAD models, STEP standard from ISO is the most popular and widely used standard by all CAD software. STEP, the **St**andard for the **E**xchange of **P**roduct Model Data, is a comprehensive ISO standard (ISO 10303) that describes how to represent and exchange digital product information.[1]

2.3.4. CAE (Computer Aided Engineering) & Measurement Data

The VMAP Standard[2] focusses on gaining a common understanding and interoperable definitions for the modelling of materials and manufacturing processes and generating universal concepts and open software interface specifications for the exchange of simulation results information in CAE workflows. It is an interface standard for integrating multi-disciplinary and multi-software simulation processes in the manufacturing industry along with I/O routines, which can be integrated in any CAE Software. VMAP is a vendor-neutral standard for CAE data storage and transfer to enhance interoperability in virtual engineering workflows. The VMAP interface and transfer file relies on the HDF5 technology. The Hierarchical Data Format (HDF) implements a model for managing and storing data.

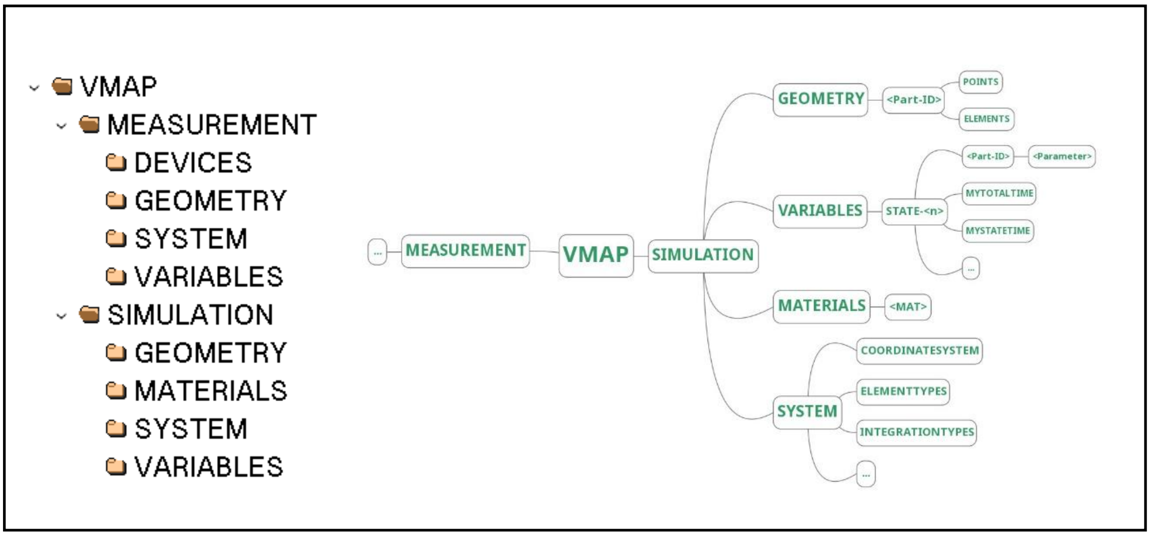


Figure 11: Overview of the VMAP Storage Structure – Simulation Group.

Many of the commonly used CAE tools can already store data in VMAP Standard format. For MSC Marc there is already an existing wrapper developed by the software vendor. This can be

---

[1] https://steptools.com/stds/step/

[2] https://vmap-standard.org/Specifications/

further extended based on the project requirements. ParaView is a commonly used visualization software which can be used to view VMAP data.

Since, VMAP supports data storage for measurement process, the data can be transferred from the CAE domain to the manufacturing domain in this format.

VMAP Standard format has been developed for storing measurement data including, sensor data, raw images etc. Hence, the testing data can be successfully stored in the VMAP format, which can then be used for mapping purposes or validation purposes.

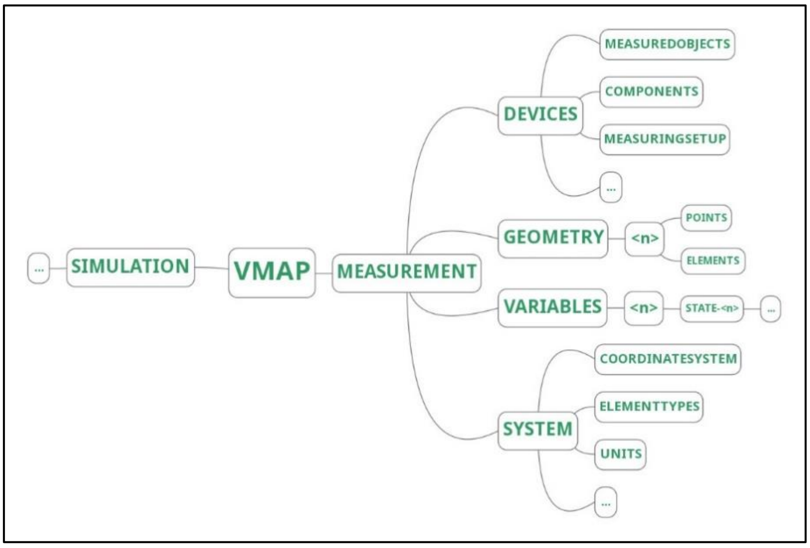


Figure 12: Overview of the VMAP Storage Structure – Measurement Group.

2.3.5. Standards that define acceptance criteria for material properties

Deliverable 1.1 suggests that the DED-LB manufactured parts should have properties that are similar or better than castings. AMS 4999 sets requirements for DED-LB manufactured Ti-6Al-4V, while AMS 4991G and AMS4992 set requirements for annealed and hot isostatically pressed (HIP) Ti-6Al-4V, respectively.

A comparative analysis between these standards would be valuable when defining material acceptance criteria or allowables. DED-LB produces microstructural features that are different from cast materials, particularly with regards to the anisotropy/texture and martensitic phase formation. Therefore, AMS 4992 may not sufficiently cover the unique characteristics of a microstructure deposited with DED-LB, e.g. detection of detrimental phases and subsequent need for heat treatment. In addition, the in-house experience held by GKN, as well as the joint experience and knowledge of the consortium, will be invaluable when setting supplementary requirements. A compressor that is subjected to high loads and temperatures may undergo various forms of metallurgical failure. These include but may not be limited to fatigue, fracture, and creep. Standards that are applicable to tests of such failure modes are outlined in the previous Section 2.3.2.

3. Use Case Impeller

3.1. Introduction

The impeller use case will employ powder-based DED with 2507 Super Duplex Steel powder, and a laser energy source. Duplex stainless steels (DSS) are the preferred material for many engineering applications in the petroleum and refining industry, combining characteristics of both ferritic and austenitic stainless steels provided correct build parameters and post build heat treatment. If not correct, the potential to form detrimental intermetallic phases increases drastically, which could lead to unwanted material properties.

Sigma phase is a chromium rich phase, and it grows into chromium rich ferrite following the nucleation at the grain boundaries. Sigma phase can be formed by either of the following mechanisms:

- Nucleation and growth from ferrite
- Eutectoid transformation of ferrite into secondary austenite and sigma
- Growth from austenite after total consumption of ferrite.

Figure 13: Reference Impeller Design

Applying shaped beams for DED can lead to numerous questions regarding quality of the product and solidity of the process. Due to this, the development phase needs to be a mix of experimental and simulation phases. Firstly, data need to be collected through testing, so that process knowledge and behaviour is understood. This knowledge will be used to build confidence in the simulation models, through experimental validation. Once the simulation models have been validated, they will be used to optimize the process to reach the highest quality possible.

3.2. Workflow Process

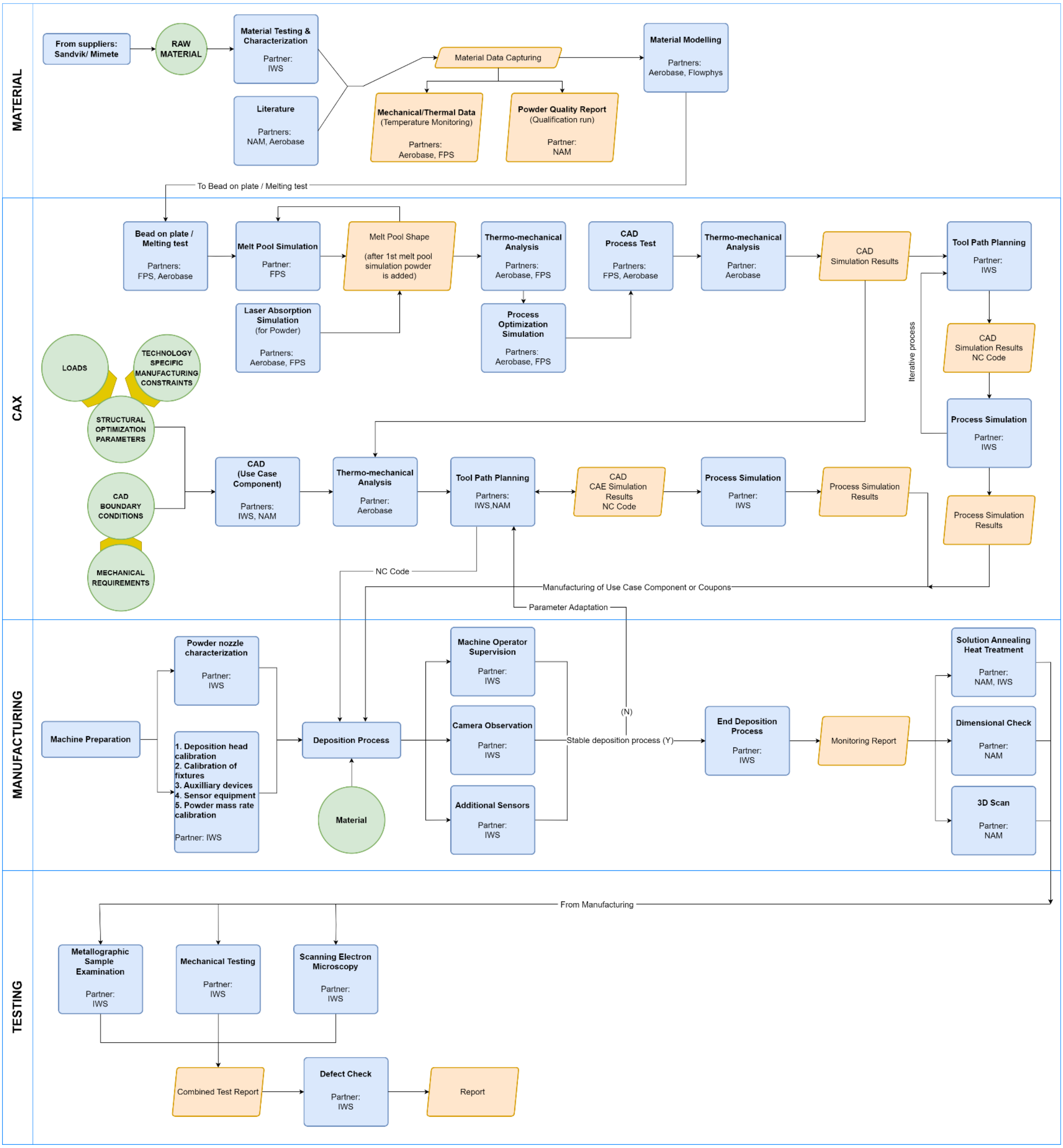


Figure 14: Impeller Workflow Chart

3.2.1. Material Domain

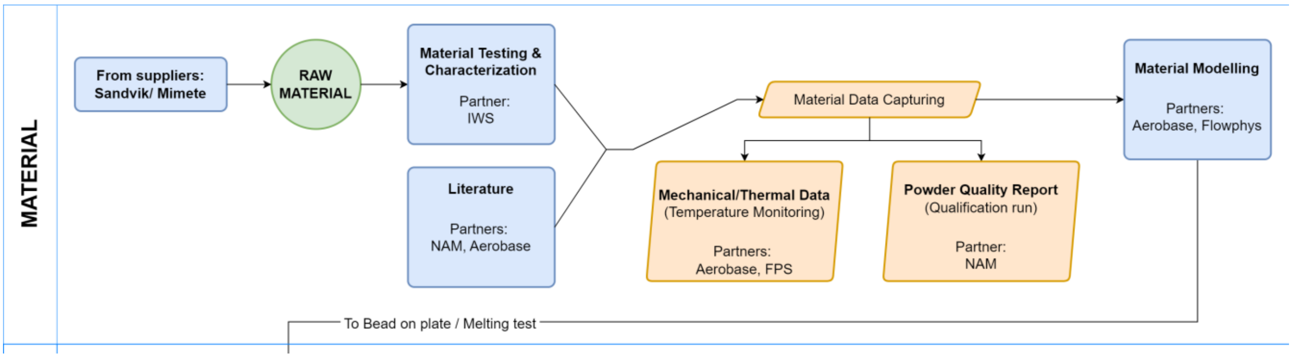


Figure 15: Material Domain Overview for Impeller Use Case

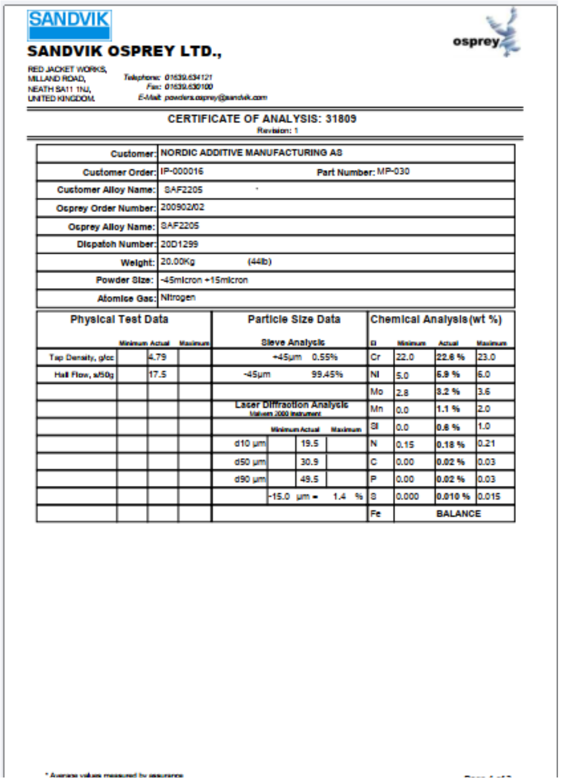
The feedstock material is received from the supplier along with the data sheet certificate. The powder quality report will be provided by NAM suppliers. The material testing and characterization after the DED-LB/P process will be carried out by IWS after definition of the used system and processing conditions and it will be provided to Aerobase & Flowphys for material modelling.

VMAP Standard offers the possibility to store material models and the material testing data for archiving or for transferring it to other partners.

3.2.1.1 Material Characterization

Material for this case will be delivered by Sandvik. The material is delivered with a certificate that states several characteristics for the material. A request to include oxygen content is also made, since high oxygen levels is critical for the impact toughness of the part. Certificate is received as PDF file. Key characteristics are:

- Chemical Composition
- Powder size distribution
- Target Flowability
- Oxygen Content



SANDVIK

osprey

SANDVIK OSPREY LTD.,

RED JACKET WORKS,
MILLAND ROAD,
NEATH SA11 1NJ,
UNITED KINGDOM.

Telephone: 01639.634121
Fax: 01639.630100
E-Mail: powders.osprey@sandvik.com

CERTIFICATE OF ANALYSIS: 31809
Revision: 1

Customer:	NORDIC ADDITIVE MANUFACTURING AS
Customer Order:	IP-000016 **Part Number:** MP-030
Customer Alloy Name:	SAF2205
Osprey Order Number:	200902/02
Osprey Alloy Name:	SAF2205
Dispatch Number:	20D1299
Weight:	20.00Kg (44lb)
Powder Size:	-45micron +15micron
Atomise Gas:	Nitrogen

Physical Test Data

	Minimum	Actual	Maximum
Tap Density, g/cc		4.79	
Hall Flow, s/50g		17.5	

Particle Size Data

Sieve Analysis

+45µm	0.55%
-45µm	99.45%

Laser Diffraction Analysis
Malvern 2000 Instrument

	Minimum	Actual	Maximum
d10 µm		19.5	
d50 µm		30.9	
d90 µm		49.5	
-15.0 µm =		1.4 %	

Chemical Analysis (wt %)

El	Minimum	Actual	Maximum
Cr	22.0	22.6 %	23.0
Ni	5.0	5.9 %	6.0
Mo	2.8	3.2 %	3.6
Mn	0.0	1.1 %	2.0
Si	0.0	0.6 %	1.0
N	0.15	0.18 %	0.21
C	0.00	0.02 %	0.03
P	0.00	0.02 %	0.03
S	0.000	0.010 %	0.015
Fe		BALANCE	

Figure 16: An example of how the certificate looks like from Sandvik.

3.2.1.2 Material Data Capturing

1. Thermophysical Properties

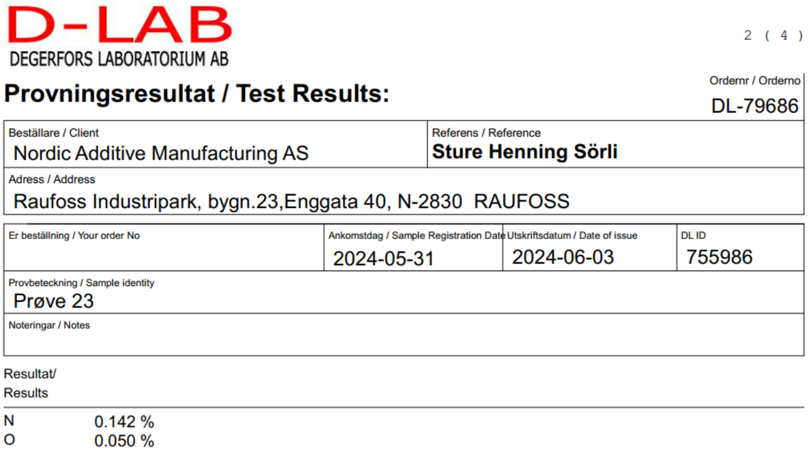
SAF 2507, a super duplex stainless steel, is pivotal in engineering applications where strength and corrosion resistance are key. These properties exhibit significant temperature dependence, influencing performance and behaviour during processing.

Starting with density, this material exhibits a decrease in density as the temperature rises. At 293 K, the density is 7809 $\mathrm{kg/m^3}$, decreasing to 7402 $\mathrm{kg/m^3}$ at 1373 K. Another significant characteristic that varies across different material phases is the coefficient of thermal expansion (CTE). For example, the CTE is approximately $10 \times 10^{-6}\ ^{\circ}\mathrm{C}^{-1}$ for ferrite, $16 \times 10^{-6}\ ^{\circ}\mathrm{C}^{-1}$ for austenite, and $13 \times 10^{-6}\ ^{\circ}\mathrm{C}^{-1}$ for the Sigma phase. Heat capacity is another key property that increases linearly with temperature. However, it's important to note that this increase does not account for latent heat contributions from phase transformations. The latent heat associated with specific phase changes, such as the transformation from ferrite to austenite or the formation of the Sigma phase, is relatively minimal compared to the significant latent heat of fusion, estimated at around 300 kJ/kg. Additionally, thermal conductivity shows a notable improvement, increasing from 12.2 W/m·K at 293 K to 30.7 W/m·K at 1373 K.

Regarding thermophysical properties in the molten state, the thermophysical properties will be determined with a similar approach as for use case 1, see 2.2.1.2, subsection 1.

2. Powder Quality Report

The powder quality report will be the manufacturers certificate for the powder material as shown and described above. We will also have a test report for the oxygen content that will look like the picture below.



D-LAB
DEGERFORS LABORATORIUM AB

2 (4)

Provningsresultat / Test Results:

Ordernr / Orderno
DL-79686

Beställare / Client Nordic Additive Manufacturing AS	Referens / Reference **Sture Henning Sörli**
Adress / Address Raufoss Industripark, bygn.23,Enggata 40, N-2830 RAUFOSS	

Er beställning / Your order No	Ankomstdag / Sample Registration Date 2024-05-31	Utskriftsdatum / Date of issue 2024-06-03	DL ID 755986
Provbeteckning / Sample identity Prøve 23			
Noteringar / Notes			

Resultat/
Results

N	0.142 %
O	0.050 %

Figure 17: A sample report from test of Oxygen and Nitrogen

3.2.1.3 Material Modelling

Material modelling of SAF 2507, a super duplex stainless steel, emphasizes the need to accurately capture its microstructural evolution, thermophysical properties, and phase transformations under various thermal and mechanical conditions. The alloy’s intricate dual-phase microstructure—comprising ferrite, austenite, and the sigma phase at elevated temperatures—contributes to its complex behaviour, essential for precise process simulation.

1. Microstructural evolution

A vital aspect of this modelling is the transition from columnar to equiaxed grains, known as the Columnar to Equiaxed Transition (CET). This transition is particularly significant during welding and additive manufacturing (AM). The CET is significantly affected by cooling rates and thermal gradients during processing. Equiaxed grains typically yield superior mechanical properties than over columnar structures, making this transition crucial for enhanced material performance.

2. TTB Approach

The TTB method effectively models SAF 2507 thermal cycles. This approach breaks down temperature history into distinct phases: heating, isothermal holding, and cooling. Each segment corresponds to specific phase transformations, such as ferrite to austenite, ferrite to sigma, and austenite to sigma. By accounting for these dynamic changes in phase fractions, the TTB method significantly improves simulation accuracy. It also helps predict the alloy's thermal and mechanical behaviour throughout processing.

3. Phase Transformation Kinetics

Phase transformation kinetics are meticulously modelled, considering chemical composition, grain size, and thermal history. Key empirical equations, including the chromium and nickel equivalents (Cr_{eq} and Ni_{eq}), provide insights into phase stability and the likelihood of transformations occurring. The transformations between ferrite and austenite are modelled through rate equations calibrated against dilatometry test results.

4. Thermophysical properties

Temperature-dependent thermophysical properties are integral to the modelling process. Density, thermal conductivity, heat capacity, and CTE significantly influence heat transfer, phase stability, and material deformation during processing.

5. Liquid state fluid properties

The molten state fluid properties will be modelled with a similar approach as for use case 1, see Section 2.2.1.3, subsection 7.

3.2.2. CAx Domain

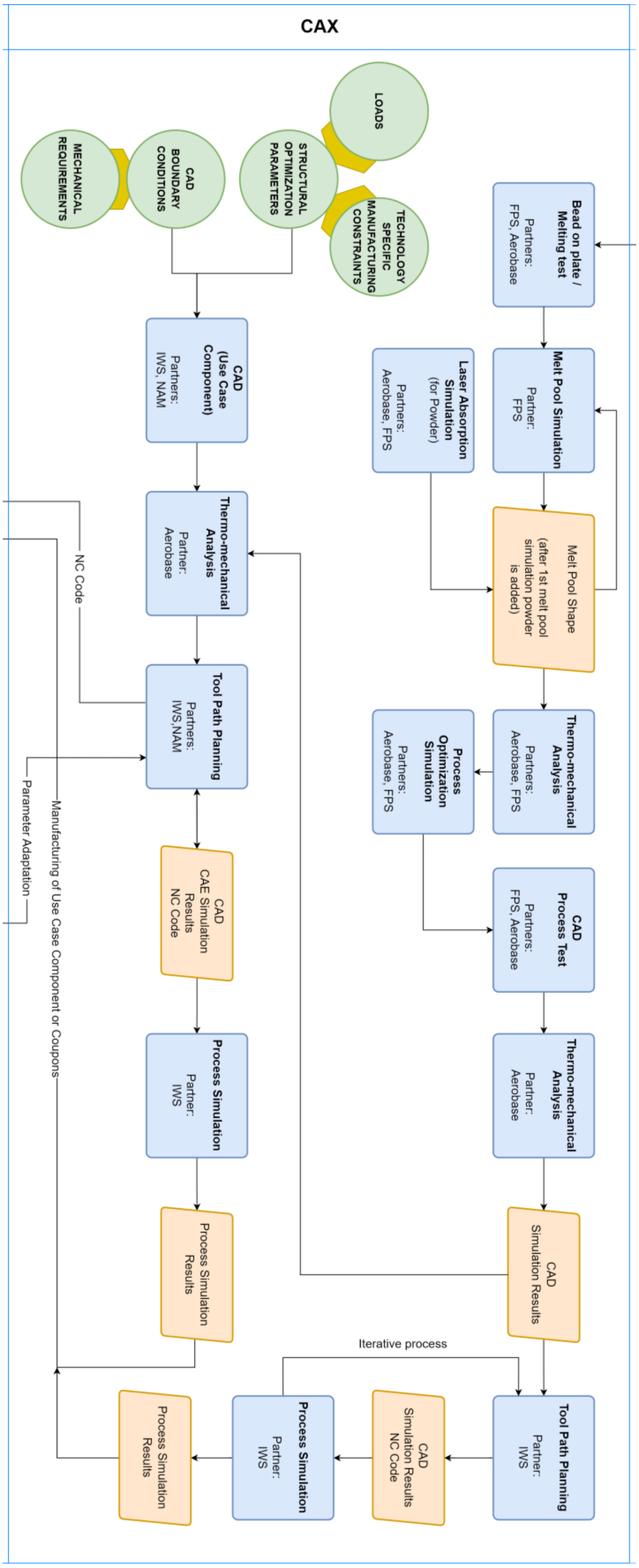


Figure 18: CAX Domain Overview for Impeller Use Case

This section has been organized based on the components instead of the processes because the lifecycle of the components is the focus area for this domain. The CAD model of the clamping and measuring system for the initial **´bead on plate/melting test´** has been developed by LTU and agreed by all the partners. This tests on a simple substrate will be used by all the use cases in a similar way to gather and compare the process characteristics as well as the results with the simulations. This bead on plate specimens is subjected to melt pool and laser absorption simulation, followed by thermomechanical and process optimization simulation.

The knowledge gathered about the melt pool and laser absorption for the used material using the bead on plate/melting test is then used with the **'process test'**, which is exclusively developed for calibration and validation of the processes. The process test geometry design will be developed by Aerobase and Flowphys to carry out thermomechanical simulations, tool path planning and process simulations. Tool path planning will take the physical process and the simulation results into account and generate NC Code for building the geometry. The process simulation will use the CAD & simulation results along with NC Code to optimize the laser parameters.

Finally, NAM will provide a **'component geometry'**, which will be subjected to thermomechanical Analysis at Aerobase. IWS will then generate the tool path and carry out the process simulation before the deposition process starts.

The CAD geometries will be stored in STEP format only. However, for the simulation data coming from various solvers, VMAP Standard would be the ideal format. The data can be easily translated to the solver specific format for evaluation and translated again to the VMAP format for storage and analysis. All the partners can look at the simulation results using 3d viewer like Paraview or HDF5 viewer to look at the data structure.

3.2.2.1 Bead on plate / Melting test

1. Specimen Geometry

Initial tests with the laser beam shaping source will be carried out on steel flat substrates and monitored with the use of high-speed cameras. These simple experiments will be necessary to identify the correlation between laser beam shape and melt pool characteristics when manufacturing single tracks, areas with tracks next to one another and volumes of material. The data gathered during these steps and the results of the metallographic analysis obtained will be used to train the melt pool and laser absorption simulation model.

Initial melting tests have been performed with a CBC laser source in 2024 that can generate any "apparent" laser beam shape by pulsing 32 different lasers around a focal area. These experiments, shown in Figure 19 allowed to identify in ring shapes the ideal laser beam shaping solution for DED-LB/P when considering the restriction of directionally independent characteristics.

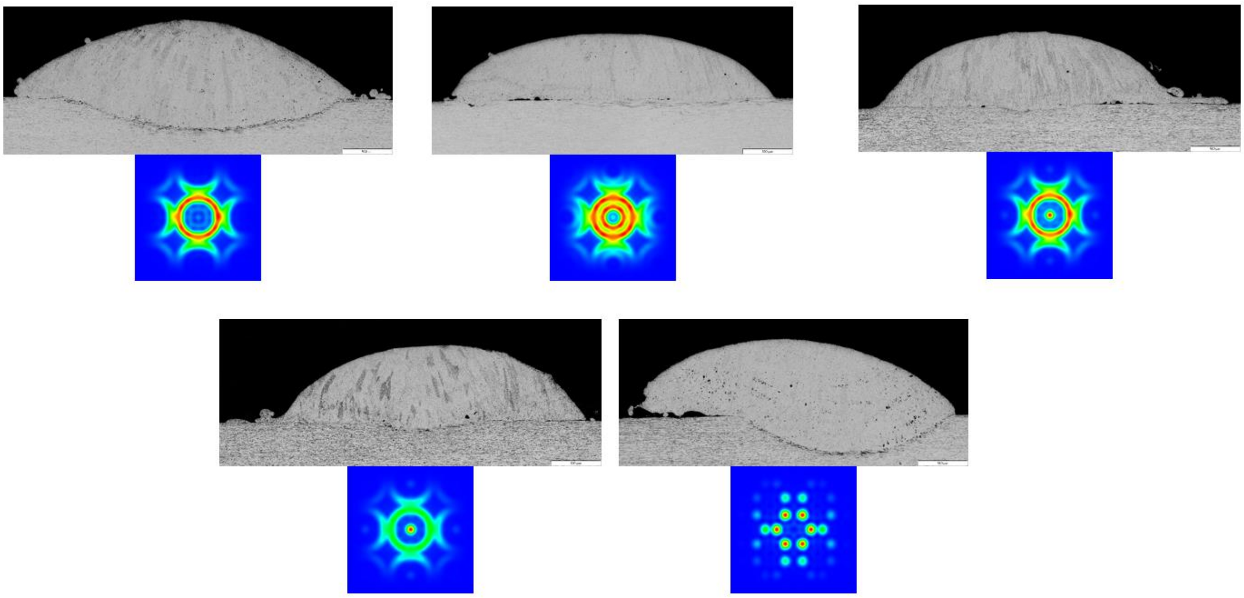


Figure 19: Cross section of beads on plate performed with a CBC laser source and identification of the most promising shapes

2. Melt Pool & Laser Absorption Simulations

For the melt pool & laser absorption simulations, an approach similar to use case 1, see Section 2.2.2.1, subsection 2, will be used.

3. Thermomechanical Simulations

The thermo-mechanical simulation of coupons is very similar to use case 1 (Section 2.2.2.1 subsection 3) except for the process parameters for DED-LB and material.

4. Process Optimization Simulation

The process optimization simulation is very similar as use case 1 (Section 2.2.2.1 subsection 44) except for the process parameters for DED-LB and material.

3.2.2.2 Process test (Calibration & Validation Model)

1. Specimen Geometry & Process Parameters

The geometry of the component that will be used for validating the fluid flow and thermo-mechanical models has been defined and can be seen in Figure 6. The size of the substrate is 100x50x8 mm, and the AM-built material (called the wall) has a size of 60x25x6 mm. The STEP file format will be used for the CAD geometry. Different process parameters sets will be used depending on the results obtained with the initial tests with ring shaped fibre lasers.

Table 3: Initial Process Parameters for Impeller Use Case

Process Parameters	Values / Ranges
Laser Formations	Single and double ring both with and without centre point
Laser velocity	500 – 1500 mm/min
Laser Power	Max. 3 kW
Built rate	Up to 20 g/min

2. Thermomechanical Simulations

The thermo-mechanical simulation of the complex geometry for calibration and validation is very similar as use case 1 (Section 2.2.2.2 subsection 2) except for the process parameters for DED-LB and material.

3. Tool Path Planning

The tool path planning for the process test wall with dimensions 60x25x6 mm is a function of the results obtained during the bead on plate tests where the dimension of each bead will be measured. According to these results, a tool path planning will be programmed with Siemens NC and post-processed in an NC program (g-code) readable by a CNC machine.

4. Process Simulation

The CNC machine will be integrated into the CAM software itself to simulate the machine movement prior to the NC code generation and verify the feasibility of such movements according to speed and possible collisions.

3.2.2.3 Component Geometry

The use case involves a circular impeller for pumps, featuring variable material thickness and geometry. The original maximum diameter is Ø600mm, with a height of 194mm and a total weight of nearly 120kg. To reduce build time, the part can be scaled. The unique internal waterways necessitate advanced CNC programming.

The deposition process will use the same parameters as the simplified specimens shown below. A CAD model of the use case can be seen in Figure 20.

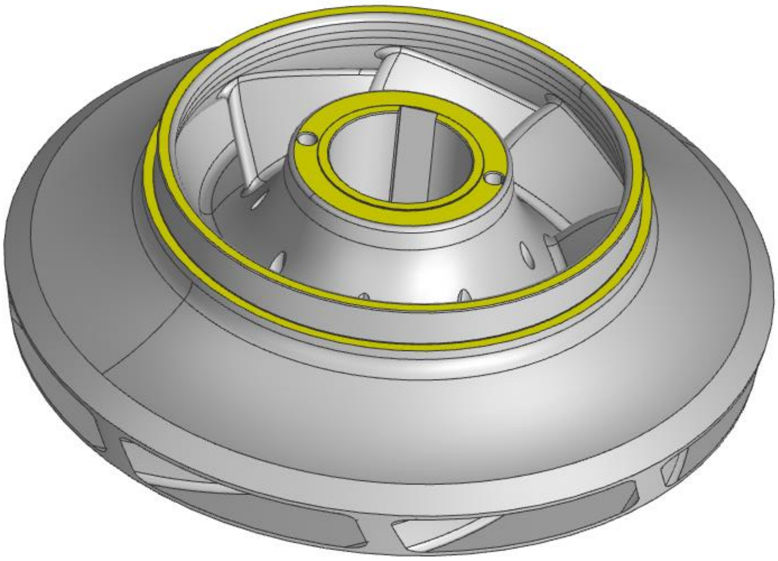


Figure 20 - A CAD model of the reference geometry

3.2.2.3.1 CAD Geometry

NAM have made a test specimen for the test to be conducted at Aerobase for temperature curve. The sample is made with 25Cr Super Duplex and built with the same parameters as we would use for production. Main parameters are:

- Laser Power: 1200W
- Powder: 20g/min
- Shielding gas: 6,5 l/min
- Carrier gas: 5 l/min
- Spot size: 2mm

Figure 21: Test specimen

1. Thermomechanical Simulations

The thermo-mechanical simulation of the component for optimization is very similar as use case 1 (Section 2.2.2.3 subsection 55) except for the process parameters for DED-LB and material.

2. Tool Path Planning

The tool path planning for the component geometry is a function of the results obtained during the bead on plate tests where the dimension of each bead will be measured. According to these results, a tool path planning will be programmed with Siemens NC and post-processed in an NC program (g-code) readable by a CNC machine.

3. Process Simulation

The CNC machine will be integrated into the CAM software itself to simulate the machine movement prior to the NC code generation and verify the feasibility of such movements according to speed and possible collisions.

3.2.3. Manufacturing Domain

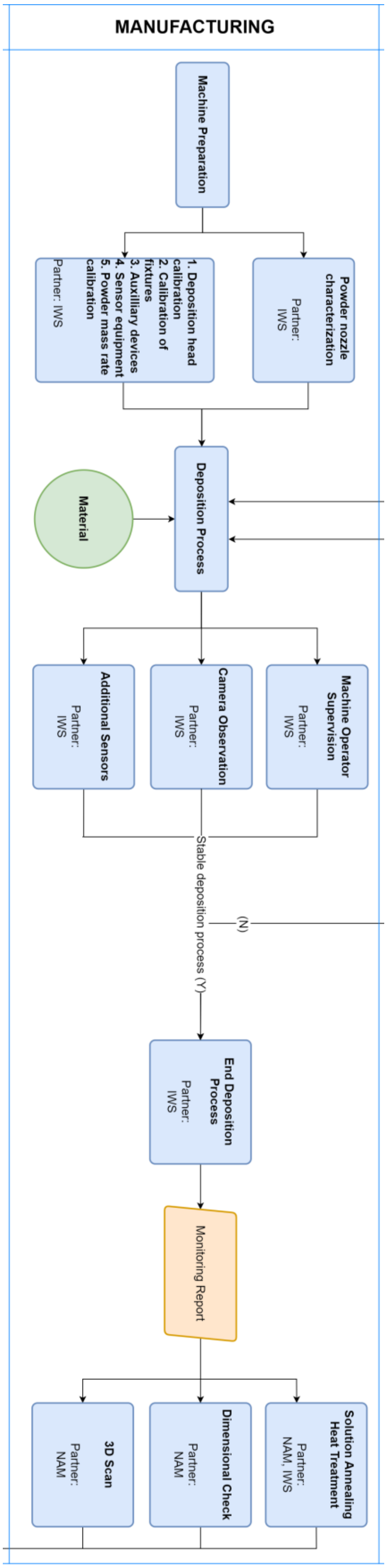


Figure 22: Manufacturing Domain Overview for Impeller Use Case

The machine preparation, carried out at IWS, is the very first step in manufacturing and it can happen parallel to the other process. This requires powder nozzle characterization and calibration of deposition head calibration database, manufacturing set up and calibration of fixtures, set up of auxiliary devices (cooling, heating), set up of additional sensor equipment and powder mass rate calibration.

The deposition process receives the NC Code from the tool path planning step and feedback from the process simulation of the laser parameter optimization. The machine then carries out the deposition process while the machine operator physically supervises the process along with cameras and sensors. Operator observations and sensor data are fed back to the CAX domain to improve the component design, deposition path planning and process parameters until a stable deposition is achieved.

Once the end deposition process is completed, the monitoring report is sent to for evaluation along with the process test geometry or the component for stress relief analysis, dimensional check and 3D scanning to NAM.

VMAP Standard allows for the storage of sensor data and images. The specific sensor data formats may have to incorporated into the VMAP Standard but the base structure to store timesteps and measured values is already available within the Standard.

The end deposition process report can be stored as a link to the VMAP Files which will store the measurement data.

3.2.3.1 Machine Preparation

The main steps required for preparing a DED-LB/P machine include:

- Clamping of the impeller core in machine environment
- Alignment of the component via machine specific routines
- Definition of zero point
- Check of laser and machine related system for process validation
- Test of the program without laser and powder for collision avoidance
- Control of powder delivery system and calibration
- Cleaning of the welding area

3.2.3.2 Deposition Process

The main steps required during and after the DED-LB/P process include:

- Execution of the laser metal deposition as well as milling machine programs
- Process supervision and data gathering from available sensors
- Unclamping of the impeller
- Removal of excess powder
- Manual removal of metal spatter along inlet edge of the blades

- Process documentation

All sensors are installed and checked before the start of the process and include cameras, thermos-cameras in-line with the laser optics and powder flow sensors.

3.2.3.3 Part Evaluation

1. Stress Relief Treatment

The stress relief treatment is carried out at a local company called "Norsk Herdesenter", which specialises in heat treatment.

The heat treatment is based on the ASTM A182M standard for forged 2507 material, which is in accordance with requirements from NORSOK M-630. There is however a difference here since we are cooling with Nitrogen instead of quenching in water; we have done tests to verify cooling rates that are very similar to the water quenching, so we know that we get the same results as called for in the standards.

Report from the heat treatment is normally in PDF format, but CSV format is also possible to export directly from the furnace software.

Figure 23: Ipsen Heat Treatment Furnace

Figure 24: Example of part in the furnace

2. Dimensional Check

After final machining, some key dimensions are measured in CMM. Key dimensions are chosen by the end customer for the part. Normally 3 – 8 critical dimensions are important for assembly of the part. Only machined features will be measured to show they are within tolerance.

3. 3D Scanning

Once we get the part here at NAM we will scan the part with 3D laser scan to verify the geometry against the nominal CAD model. The 3D scanner uses proprietary software and the file format .stl up until export to a selection of CAD formats. We have the data exported to Parasolid (.X_T) file format to be able to use this in our CAD system (Siemens NX).

We import the Parasolid (.X_T) file into Siemens NX as a sheet model. If necessary, we can continue to work on the sheet model to close it fully and have a 3D solid model.

We will then send the part to PWHT and re-scan the part when it is heat treated to verify that we have not had any distortion during the heat treatment.

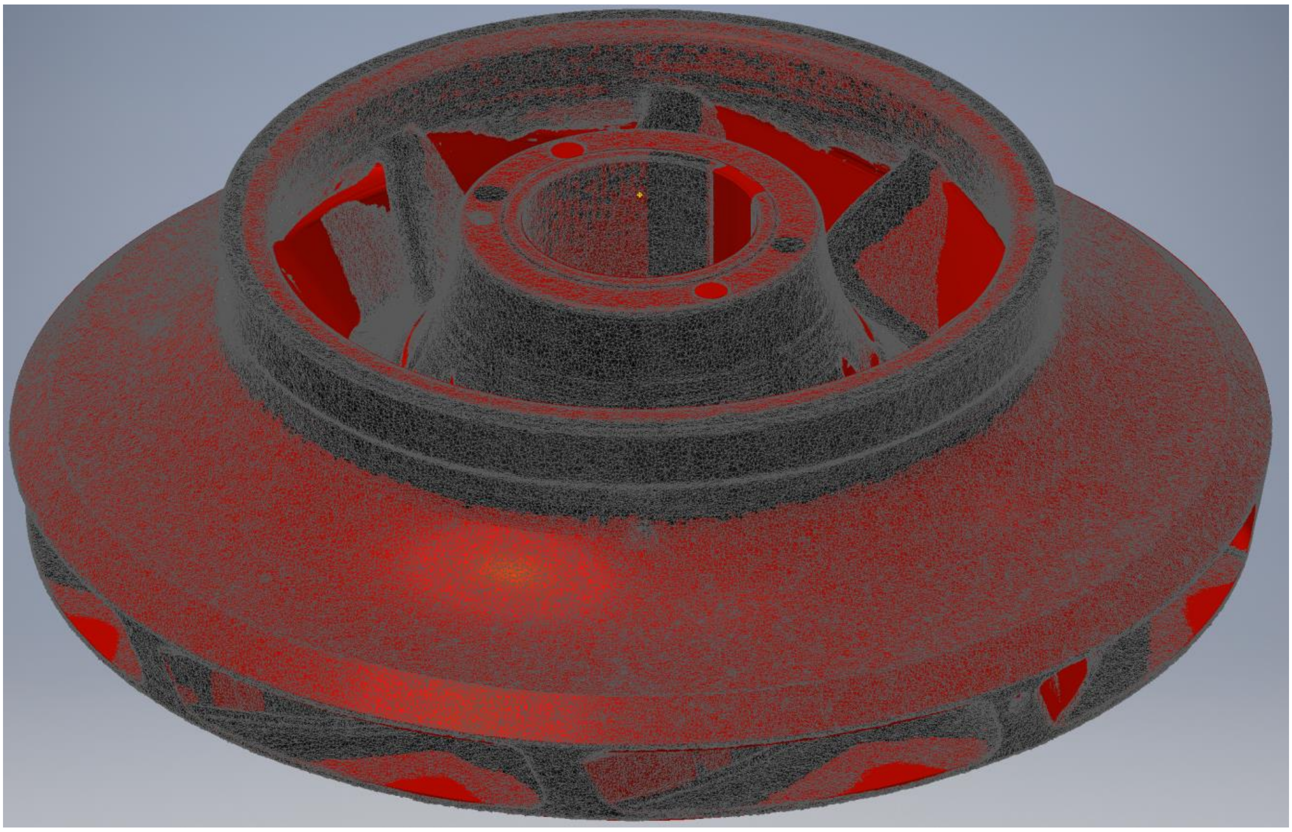


Figure 25: Sample 3D Scanned Part[3]

---

[3] https://www.creaform3d.com/en/portable-3d-scanner-handyscan-3d

3.2.4. Testing Domain

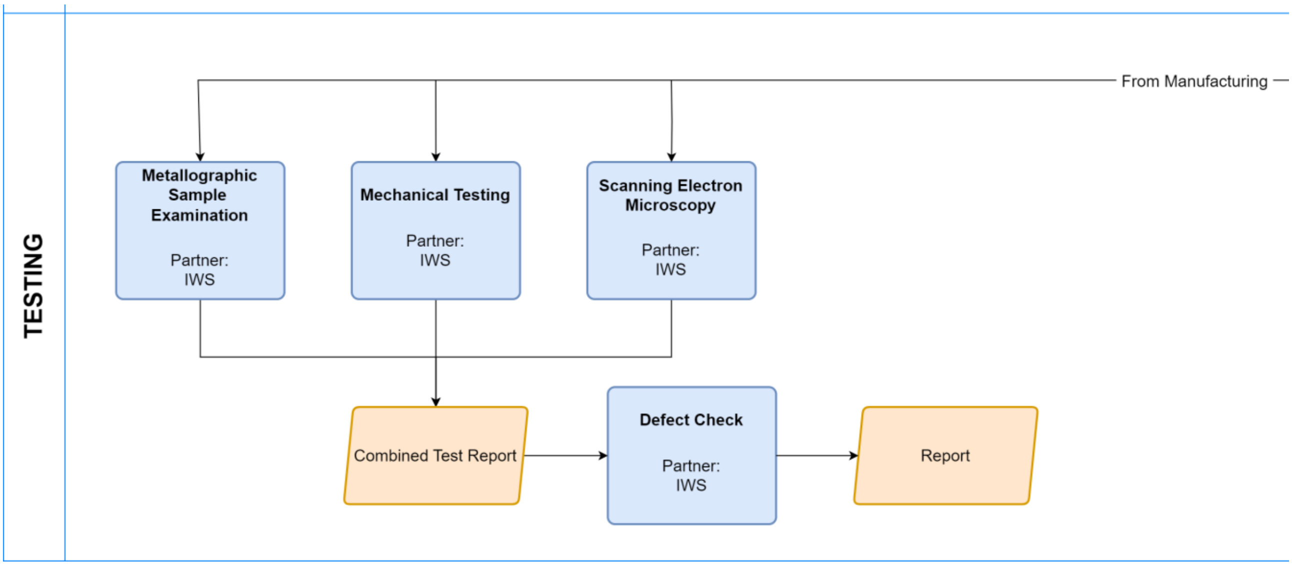


Figure 26: Testing Domain Overview for Impeller Use Case

The material testing will be performed in stages, starting with simple microstructural investigations for initial process development, before proceeding with mechanical testing and more advanced analysis once the deposition process has been optimized.

3.2.4.1 Metallographic check

Characterisation of the underlying microstructure is important for understanding deposition strategies. The preparation process follows the recommendations from the material preparation equipment suppliers and internal Fraunhofer IWS procedures for sample preparation and etching to reveal the characteristic microstructures. Light optical microscopy will then be used to examine the microstructure in relation to the deposition strategy employed. Metallographic check will also be performed at the end on machined samples out of the final demonstrator. The ferrite content in the super duplex 2507 steel will also be checked to verify that it matched with the defined requirement and the tested material for mechanical testing. Characterization of detrimental phases will also typically be done during the metallographic check.

3.2.4.2 Mechanical Testing and corrosion testing

Mechanical testing will be performed in accordance with the standards listed in Table 4. These specify specimen geometries, loading conditions and measurement procedures to ensure valid mechanical properties are obtained from the material. They are complemented by DNV-ST-B203, which specify the methodology required for process qualification. The tests will give output values of yield and ultimate tensile strength, elongation at failure, fracture toughness and fatigue resistance needed to validate the component material.

3.2.4.3 Scanning Electron Microscopy

Electron microscope analysis enables characterising microstructure at higher magnifications and resolutions than light optical microscopy. Combined with electron back scatter diffraction and energy-dispersive X-ray spectroscopy this will provide information in the form of grain shape and size distributions, crystallographic texture, and phase distributions. Preparation of the metallographic specimens are detailed in ASTM E3, while ASTM E407 outlines procedures for microetching. The two standards will alongside the application notes from Struers provide a good framework for sample preparation to achieve reliable characterisation through SEM.

3.2.4.4 Defect Check

The requirement to defects in the component will be analysed using initial visual inspections, light optical microscopy and x-ray computed tomography (XCT).

3.3. Standards employed for the Use Case

3.3.1. Material Testing Standards

The BPQ (Build process qualification) tests are carried out according to DNV ST-B203 for our qualified materials. Acceptance criteria for these tests are based on ASTM A182 and some additions through NORSOK M-630. For super duplex the impact test is done at -46 °C according to NORSOK instead of -18 °C as specified in ASTM A182.

Usually, the feedstock composition is not measured to verify the composition given by the certificate. However, we suggest checking the oxygen content of the feedstock powder to verify the oxygen content with the same method as we will use on the final part. The method used is combustion refractor according to ASTM E 1019. This method uses high temperature combustion of a small material sample, and then analyses the exhaust for oxygen content.

Table 4: Overview of all the Material Tests[4]

Testing activities	Standard
Tensile testing	ISO 6892-1:2009, MOD)
Impact testing	ISO 148-1:2016 (Metallic materials — Charpy Pendulum-Impact test —Part 1: Test method) Temp: -46 Celsius
Macrostructure assessment	ASTM E3-11(2017) (Standard Guide for Preparation of Metallographic Specimens)
Microstructure assessment	ASTM E3-11(2017) (Standard Guide for Preparation of Metallographic Specimens)
Hardness measurement	ISO 6507-1:2018 (Metallic materials — Vickers hardness test — Part 1: Test method)
G48 corrosion test	ASTM G48 ISO 17781
Chemical analysis	Niton XL3t XRF Analyzer
Penetrate testing	ISO 3452-1:2013 (Non-destructive testing — Penetrant testing — Part 1: General principles)
Ferrite content	Feritscope DIN EN ISO 2178 / ASTM D7091

---

[4] https://www.dnv.com/energy/standards-guidelines/dnv-st-b203-additive-manufacturing-of-metallic-parts/

Fatigue testing	EN ISO 1099, ASTM E466 or CWA 18107 - 2

For the storage of material data and material models VMAP Standard Format can be employed. See Section 2.3.4 for more details on the VMAP Standard.

3.3.2. CAD Model

For all the CAD models, STEP standard from ISO is the most popular and widely used standard by all CAD software. STEP, the **S**tandard for the **E**xchange of **P**roduct Model Data, is a comprehensive ISO standard (ISO 10303) that describes how to represent and exchange digital product information.

3.3.3. CAE & Measurement Data

Since, the process is the same as use case 1, the standard application will also remain the same. VMAP Standard can be used to store both CAE & Measurement/Testing data. Please refer to Section 2.3.4.

3.3.4. Testing Standards

Some standards related to qualification of metal components manufactured by additive manufacturing exist, such as DNV-ST-B203 and API 20S, which are relevant for the impeller case described in Section 3.3.1. These standards describe test extent and sampling to ensure that an AM process produces acceptable material with regards to process-specific weaknesses.

4. Use Case Automotive

4.1. Introduction

As consumer preferences evolve, product upgrades can extend their lifespan, introduce technological innovations, and ensure advanced environmental performance.

Manufacturers must prioritize sustainable practices by focusing on remanufacturing, upgrading, and maintaining components. To remain resilient to technological advancements, products designed for upgrades must incorporate features that enhance their durability. For in-stance, a high-pressure die-cast part (red component in the Figure below) will undergo extraction and augmentation using DED-LB/M technology, incorporating unique enhancements.

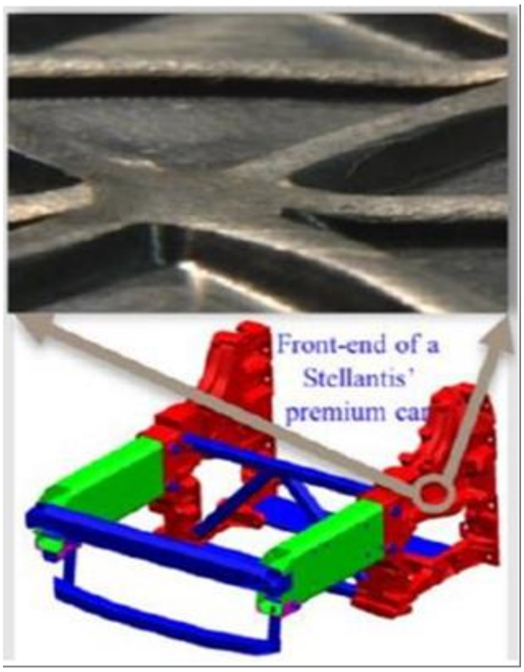


Figure 27: Automotive Component

HPDC component must fulfil several requirements to guarantee good filling, solidification, and sound quality. When it comes to part extraction from the mould draft angles have to be considered accordingly to the wall depth and ejector positioned in a uniform lay-out. Geometry wise, basic guidelines given are to keep a uniform wall thickness, avoiding sharp corners and massive-to-thin sections.

Despite its critical importance and high demand, the lightweight redesign of this component will contribute to improved sustainability and shorter lead times.

4.2. Workflow Process

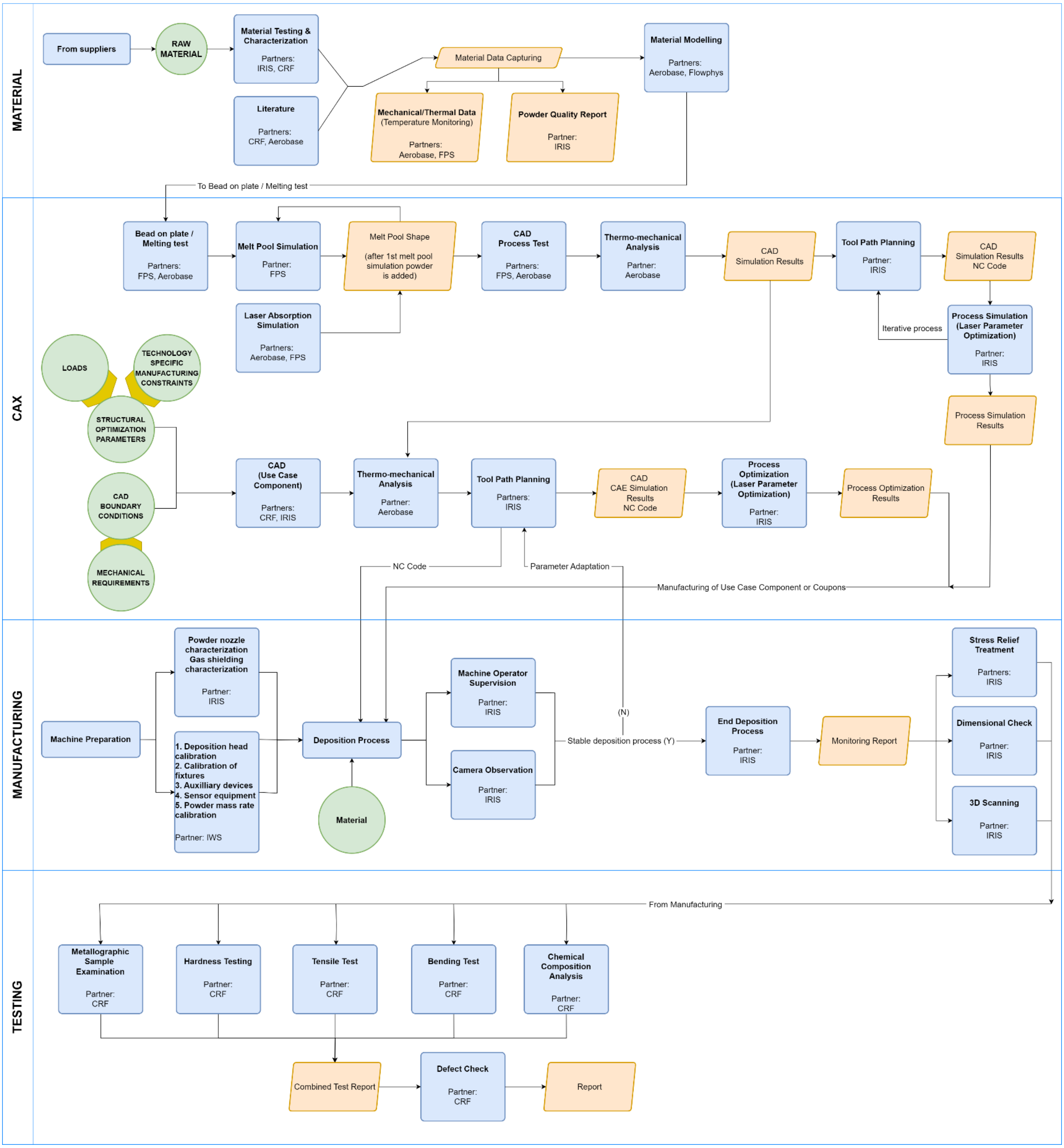


Figure 28: Automotive Workflow Chart

4.2.1. Material Domain

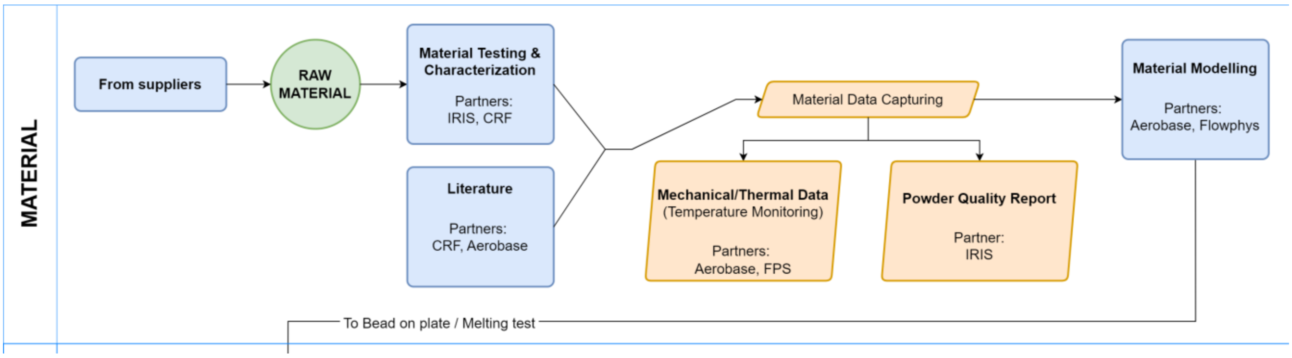


Figure 29: Material Domain Overview for Automotive Use Case

The feedstock material is received from the supplier along with the data sheet. The material testing and characterization will be carried out by IRIS and provided to Aerobase & Flowphys for material modelling. The powder quality report will be provided by CRF suppliers.

VMAP Standard offers the possibility to store material models and the material testing data for archiving or for transferring it to other partners.

4.2.1.1 Material Characterization

The material characterization will be performed with:

- Chemical analysis: Optical Emission Spectrometer.
    - Output: pdf report
- Hardness analysis: Vickers and Brinell hardness indentation.
    - Output: pdf report
- Microstructure investigation: Optical microscopy on metallographic samples.
    - Output: pdf report
- Tensile test: Proportional specimen on Universal tensile machine.
    - Output: pdf/excel report

4.2.1.2 Material Data Capturing

1. Thermophysical Properties

The thermophysical properties of AlSi7Mg and AlSi10Mg are similar when performing AM processes. AlSi10Mg density decreases slightly with increasing temperature, and its CTE averages 23.5 ppm/°C up to 350°C. Measurements of specific heat capacity (C_p) reveals peaks corresponding to fusion, with a latent heat of fusion of approximately 425 J/g. Thermal conductivity varies depending on the alloy and direction; pure Al has higher conductivity while alloying elements like Si and Mg reduce it. As a result, AlSi10Mg exhibits lower thermal conductivity. . Regarding thermophysical properties in the molten state, the thermophysical properties will be determined with a similar approach as for use case 1, see 2.2.1.2, subsection 1.

2. Powder Quality Report

The Powder Quality will be investigated in term of water and contaminant contest as long as granulometry.

- Output: pdf report

4.2.1.3 Material Modelling

Material modelling of **AlSi7Mg** and its closely related alloy, **AlSi10Mg**, focuses on understanding the effects of thermal cycles, rapid solidification, and phase transformations characteristic of AM. This modelling framework provides insights into AlSi7Mg response during AM processes, allowing for thermal management and microstructural property optimization for high-performance applications. The primary aspects of modelling include:

1. Microstructure evolution

AlSi7Mg solidifies into a dendritic α-Al matrix, followed by Al-Si eutectic structures at the grain boundaries. AM cooling results in fine microstructures, including a supersaturated solid solution of Mg and Si within the α-Al phase. Aging or heat treatments promote Mg2Si precipitation, which enhances material strength.

2. Thermophysical properties

Accurate modelling includes temperature-dependent properties such as density, thermal conductivity, specific heat capacity (Cp), and CTE. For example, AlSi10Mg has a latent heat of fusion of approximately 425 J/g and a CTE of 23.5 ppm/°C. Solute scattering affects its thermal conductivity, reducing its heat dissipation efficiency compared to pure Al.

3. Thermal and residual stress management

During AM, thermal gradients and rapid solidification rates lead to residual stresses and distortions. Material models capture these stresses and their effects on microstructural stability.

4. Temperature and Strain Rate-Dependent Flow Behaviour

Engineering stress-strain curves show strength decreases and ductility increases at higher temperatures, particularly above 200°C. These models help predict deformation under thermal and mechanical loading conditions.

5. Liquid state fluid properties

The molten state fluid properties will be modelled with a similar approach as for use case 1, see Section 2.2.1.3, subsection 7.

4.2.2. CAx Domain

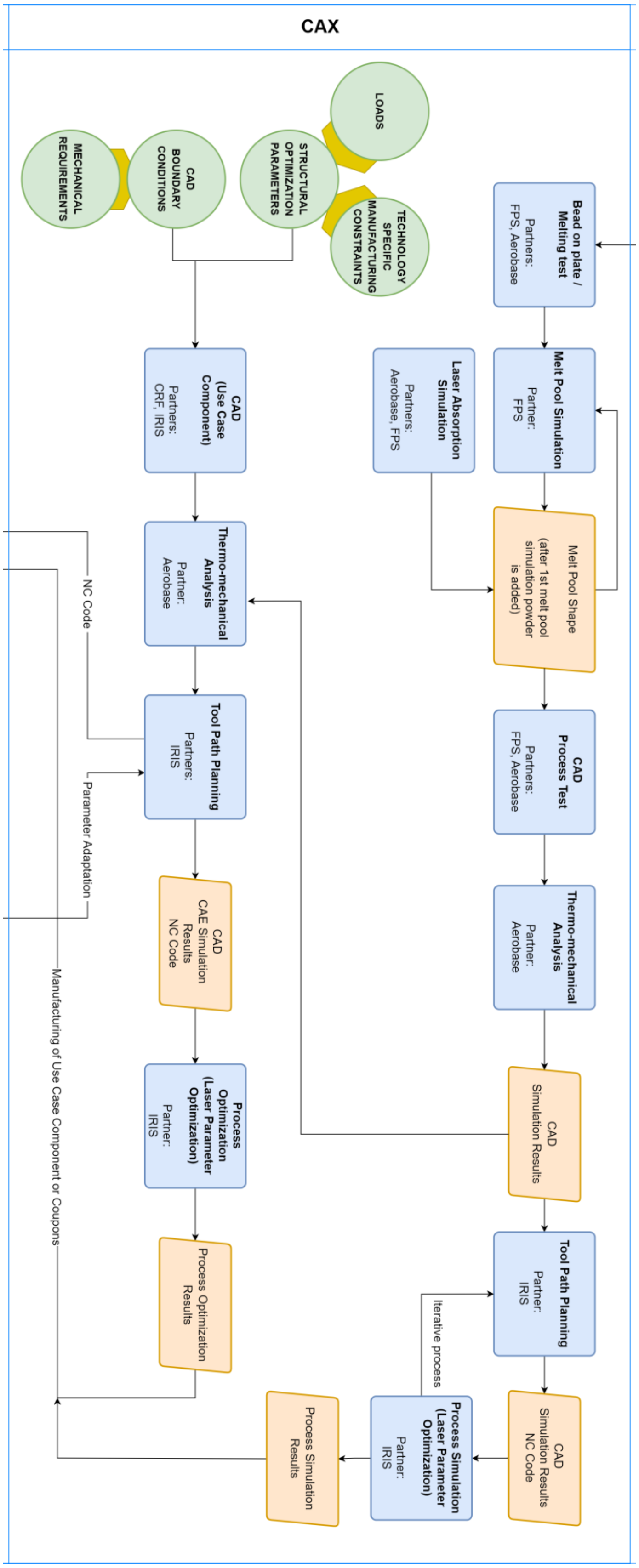


Figure 30: CAX Domain Overview for Automotive Use Case

This section has been organized based on the components instead of the process because the lifecycle of the components is the focus area for this domain. The CAD model of the substrate called the **'bead on plate specimen'** has been developed by LTU and agreed by all the partners. This model will be used by all the use cases. This coupon is subjected to melt pool and laser absorption simulation, followed by thermomechanical and process optimization simulation.

The knowledge gathered about the melt pool and laser absorption for the particular material from the bead on plate specimens is then used by the **'process test specimen'**, which is exclusively developed for calibration and validation of the processes. The complex geometry design will be developed by Aerobase and Flowphys to carry out thermomechanical simulations, tool path planning and process simulations. Tool path planning will take the physical process and the simulation results into account and generate NC Code for building the geometry. The process simulation will use the CAD & simulation results along with NC Code to optimize the laser parameters.

Finally, CRF will provide a **'component geometry'**, which will be subjected to thermomechanical Analysis at Aerobase. IRIS will then generate the tool path and carry out the process simulation before the deposition process starts.

The CAD geometries will be stored in STEP format only. However, for the simulation data coming from various solvers, VMAP Standard would be the ideal format. The data can be easily translated to the solver specific format for evaluation and translated again to the VMAP format for storage and analysis. All the partners can look at the simulation results using 3d viewer like Paraview or HDF5 viewer to look at the data structure.

4.2.2.1 Bead on Plate/Melting Test of Substrate Material

1. Specimen Geometry

There are several specimen geometries that will be used to check the mechanical properties of the printed samples. This is due to the different thermal load that specimen undergoes depending not only on the process parameters but also on the specimen shape and the associated thermal load and cooling speed. The specimen will be 12x110x12↑ body, 2x110x12↑ wall and 2x110x0,5↑ single track.

2. Melt Pool & Laser Absorption Simulations

For the melt pool & laser absorption simulations, an approach like use case 1, see Section 2.2.2.1, subsection 2, will be used.

3. Thermomechanical Simulations

The thermo-mechanical simulation of coupons is very similar as use case 1 (Section 2.2.2.1 subsection 3) except for the process parameters for DED-LB and material.

4. Process Optimization Simulation

The process optimization of coupons is very similar as use case 1 (Section 2.2.2.1 subsection 44) except for the process parameters for DED-LB and material.

4.2.2.2 Process Test (Calibration & Validation Model)

1. CAD Geometry & Process Parameters

The geometry of the component that will be used for validating the fluid flow and thermo-mechanical models has been defined and can be seen in Figure 6. The size of the substrate is 100x50x8 mm, and the AM-built material (called the wall) has a size of 60x25x6 mm. The STEP file format will be used for the CAD geometry.

Table 5: Initial Process Parameters for Automotive Use Case

Process Parameters	Values / Ranges
Laser oscillation pattern	Defocused beam (about 500 µm height) scanned around a circular path of about 1.5 mm radius
Laser velocity	Linear translation ad 900 mm/min, scanning frequency 200-300 Hz
Laser power	1200 W
Build rate	Up to 15 gr/min
Scanning pattern	Sinusoidal single line or dual line walls.

2. Thermomechanical Simulations

The thermo-mechanical simulation of the complex geometry for calibration and validation is very similar as use case 1 (Section 2.2.2.2 subsection 22) except for the process parameters for DED-LB and material.

3. Tool Path Planning

The tool path for the thermo-mechanical simulation test will be generated by Mastercam and available in G-Code standard.

4. Process Optimization

The process optimization will be carried out on plates of the same specimen material with similar dimensions, thickness, and clamping. The process will optimize porosity, shape, substrate distortion and productivity.

4.2.2.3 Component Geometry

1. CAD Geometry

The CAD files will be shared in an appropriate standard format (e.g. .stl), according to the request by the partners.

2. Thermomechanical Simulations

The thermo-mechanical simulation of the component for optimization is very similar to use case 1 (Section 2.2.2.3 subsection 55) except for the process parameters for DED-LB and material.

3. Tool Path Planning

The tool path planning program will be shared in G-Code and upon request in Abb robot studio programming Languages.

4. Process Simulation

The process simulation will be carried out by RoboDK post-processing on G-Code generated by Mastercam to verify path accessibility (robot arm length) and clearance. The simulation will validate the process or highlight the need for reprogramming and splitting the printing process.

4.2.3. Manufacturing Domain

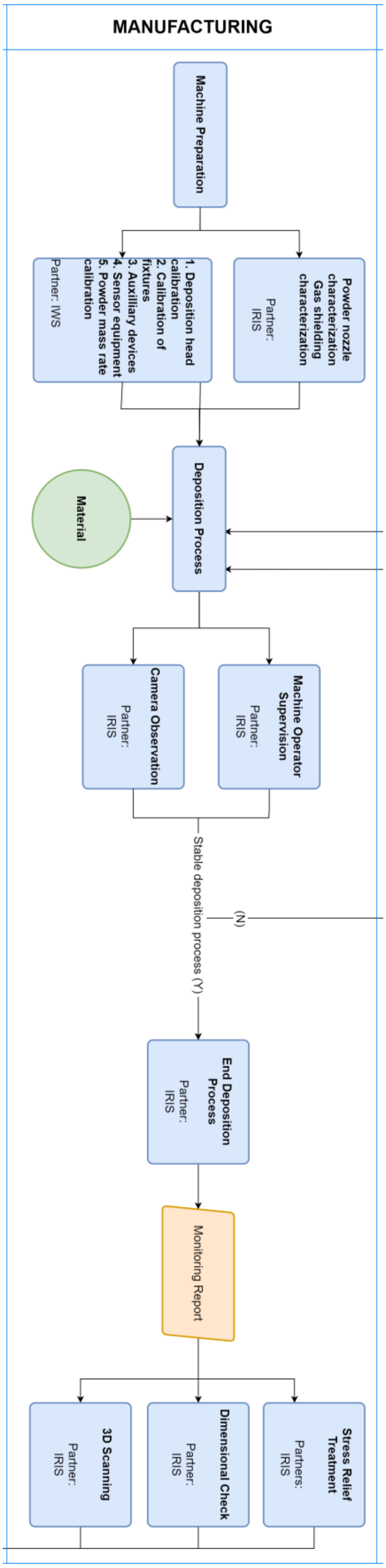


Figure 31: Manufacturing Domain Overview for Automotive Use Case

The machine preparation, carried out at IRIS, is the very first step in manufacturing and it can happen parallel to the other process. This requires powder nozzle characterization and gas shielding characterization. The calibration of deposition head, manufacturing set up and calibration of fixtures, set up of auxiliary devices (Cooling, heating), set up of additional sensor equipment and powder mass rate calibration.

The deposition process receives the NC Code from the tool path planning step and feedback from the process simulation of the laser parameter optimization. The machine then carries out the deposition process while the machine operator physically supervises the process along with cameras and sensors. Operator observations and sensor data are fed back to the CAX domain to improve the component design, deposition path planning and process parameters until a stable deposition is achieved.

Once the end deposition process is completed, the monitoring report is sent to for evaluation along with the process test geometry or the component for stress relief analysis, dimensional check and 3D scanning to IRIS.

VMAP standard allows for the storage of sensor data and images. The specific sensor data formats may have to incorporated into the VMAP standard but the base structure to store timesteps and measured values is already available within the standard.

The end deposition process report can be stored as a link to the VMAP files which will store the measurement data.

4.2.3.1 Machine Preparation

1. Laser Power

Laser power will be characterized by means of a calibrated power meter. The calibration will be done at different laser power robot commanding value.

2. Laser Focus

The focus position will be checked with a focus monitor.

3. Powder Nozzle Feeding Ratio

The feeding rate will be characterized by weighting the amount of powder, which is feed in a fixed amount of time, the powder being collected and then weighted by a precision balance.

4. Powder Nozzle Focusing

The focusing of the powder will be qualitatively characterized by means of a CCD camera and high-power white source which provide, by means of scattered light, an image of the powder under the powder nozzle. Laser line illumination will be tested.

5. CCD CAMERA

CCD camera magnification will be calibrated by means of calibrated optical target allowing the precise determination of the pixel/mm ratio.

6. GAS FLOW RATE

Every gas flow rate will be controlled by means of flow meters.

7. GAS SHIELDING

Gas shielding efficiency will be checked with a O2 sensor.

4.2.3.2 Deposition Process

The Directed Energy Deposition (DED) additive manufacturing process using a laser and powder nozzle is a precise and versatile method for fabricating, repairing, and enhancing metallic components. Here's an overview of the process, emphasizing the use of a CCD camera for observing the melting pool.

1. Process Description

- **Energy Source and Material Deposition**
  i. A high-power **laser** serves as the energy source, delivering focused energy to a specific spot on the workpiece. This laser generates a small molten pool on the substrate material. The laser power for the Alabama process will be in the range of 1200 W to 1500 W. The laser head is a high scanning laser head. The wait path along the robot path will be circular (ensuring isotropy) with a controlled amplitude and frequency.
  ii. A **powder nozzle** is used to deliver metallic powder (feedstock) directly into the laser-induced molten pool. The powder melts upon contact with the pool, bonding to the substrate and solidifying rapidly as the laser moves away. The used powder nozzle is a circular coaxial nozzle integrated with a slow flow gas shielding device.

- **Layer-by-Layer Building**
  i. The laser and nozzle system will be mounted on an anthropomorphic robot, allowing precise control of material deposition in three dimensions. The toolpath will be programmed using Mastercam which will generate a G-Code for the path followed by roboCAD post processing for the ABB robot studio programming language.
  ii. The process builds the component layer by layer, adding material to existing parts (the use case component) for adding stiffening walls.

- **Monitoring and Feedback**

i. A CCD (Charge-Coupled Device) camera is positioned to observe the melting pool in real-time. This camera captures high-resolution images and videos of the dynamic interaction between the laser, powder, and substrate.
ii. The captured data is used to monitor critical parameters, like melting pool size and shape. Consistent pool dimensions are crucial for ensuring uniform material deposition and mechanical properties.

- **Feedback Control**

i. The CCD camera data is often integrated into a feedback loop with the process controller. This setup allows for real-time adjustments of laser power and scanning head frequency and amplitude to maintain optimal deposition conditions.

- **Cooling and Solidification**

i. As the laser moves along the programmed path, the molten pool rapidly cools and solidifies, forming a metallurgical bond with the substrate. The process repeats to form successive layers or repair specific areas.

2. Advantages of CCD Camera Integration

- **Quality Assurance**: Continuous observation ensures defects, such as porosity or cracking, are minimized during the build.
- **Process Optimization**: Real-time monitoring enables fine-tuning of parameters for improved build quality and efficiency.
- **Enhanced Automation**: Automated systems use CCD data to dynamically adjust for fluctuations in environmental or material conditions.

4.2.3.3 Part Evaluation

1. Stress Relief Treatment

Stress relief treatment of an aluminium component produced by a Directed Energy Deposition (DED) laser additive manufacturing process is a critical step to reduce residual stresses induced during fabrication. The process typically involves controlled thermal cycles to enhance the dimensional stability and mechanical properties of the component. Here's an overview of the stress relief treatment:

- **Purpose of Stress Relief**

i. Reduce Residual Stresses: The rapid thermal cycling inherent in the DED process—caused by localized laser heating and rapid cooling—creates significant residual stresses. These stresses can lead to distortions, cracking, or reduced fatigue life of the component.

ii. Enhance Dimensional Stability: Relieving internal stresses minimizes the risk of deformation during subsequent machining or in-service operations.
iii. Improve Mechanical Properties: Uniform stress distribution contributes to better fatigue performance and overall reliability.

- **Steps in Stress Relief Treatment**

i. Preparation

Cleaning: The component is thoroughly cleaned to remove any contaminants, such as oxidation, powder residues, or grease, that could interfere with the heat treatment process.

ii. Heat Treatment Process

Controlled Heating

- The aluminium component is placed in a furnace with a controlled atmosphere (e.g., inert gas or vacuum) to prevent oxidation.
- It is heated to a specific temperature, typically ranging from 300°C to 400°C (572°F to 752°F), depending on the aluminium alloy used.

Cooling: Controlled cooling, either in the furnace (furnace cooling) or in still air, is performed to avoid introducing new thermal stresses.

- **Benefits of Stress Relief Treatment**

i. Improved Structural Integrity: Reduced likelihood of cracking or failure during service.
ii. Enhanced Process Compatibility: Better compatibility with subsequent machining or finishing processes.
iii. Increased Reliability: Prolonged lifespan and consistent performance in demanding applications.

Stress relief treatment is an essential post-processing step to ensure the success and durability of aluminium components produced by the DED laser additive manufacturing process.

2. Dimensional Check

The dimensional check will be performed by means of conventional metrological tool and will be aimed mainly to check the stiffener height and width on the component. The measure will be carried by means of a dedicated digital calliper or linear variable differential transducer.

3. 3D Scanning

The 3D scanning of the use case will be performed with The FARO 3D Laser Scanning System with a Robotic Arm. It is a high-precision measurement solution that integrates a laser scanner with a robotic arm for automated and flexible 3D data acquisition. This system is widely used in industries like automotive, aerospace, and manufacturing for quality control, reverse engineering, and digital inspection.

- **Components of the System**
  i. FARO Laser Scanner:
    - **High-Precision Scanning:** Captures millions of 3D data points per second with high accuracy, generating detailed point clouds.
    - **Non-Contact Measurement:** Ideal for fragile or complex components where physical contact might damage the surface.

  ii. Robotic Arm:
    - **Multi-Axis Movement:** Equipped with 6 or more degrees of freedom (DOF) for flexible positioning and orientation of the scanner.
    - **Automation:** Enables fully automated scanning of complex geometries and hard-to-reach areas.
    - **Precision Control:** High repeatability and smooth movement ensure accurate data capture.

  iii. Software Integration:
    - **3D Data Processing:** Software like FARO CAM2 or Geomagic is used to process and analyse the scanned data.
    - **Real-Time Feedback:** Provides instant comparison of scanned data against CAD models for inspection and verification. This is particularly relevant in the ALABAMA project because it allows to measure both the DED added stiffener and the substrate deformation due to the stiffener print.

- **Features of the FARO 3D Laser Scanning System**
  i. High Accuracy: Achieves measurement accuracies within microns, suitable for demanding quality control applications.
  ii. Versatile Scanning: Capable of scanning a wide variety of materials and finishes, including reflective, matte, or textured surfaces.
  iii. Large Working Volume: The robotic arm extends the scanning range, allowing inspection of large components or assemblies.

iv. Flexibility: The system can adapt to a variety of setups, from tabletop applications to large-scale production lines.
v. Real-Time Analysis: Instantly identifies deviations or defects by comparing the scanned data to digital models.

- **Output**

i. STL of the scanned surface: The STL file of the canner files would be
ii. False colour map: Generates accurate false colour map of the deviation between the scanned component and the nominal mathematics of the original use case and printed stiffener allowing check of the induced errors

The FARO 3D Laser Scanning System will be allowable thank to a collaboration with an IRIS partner.

4.2.4. Testing Domain

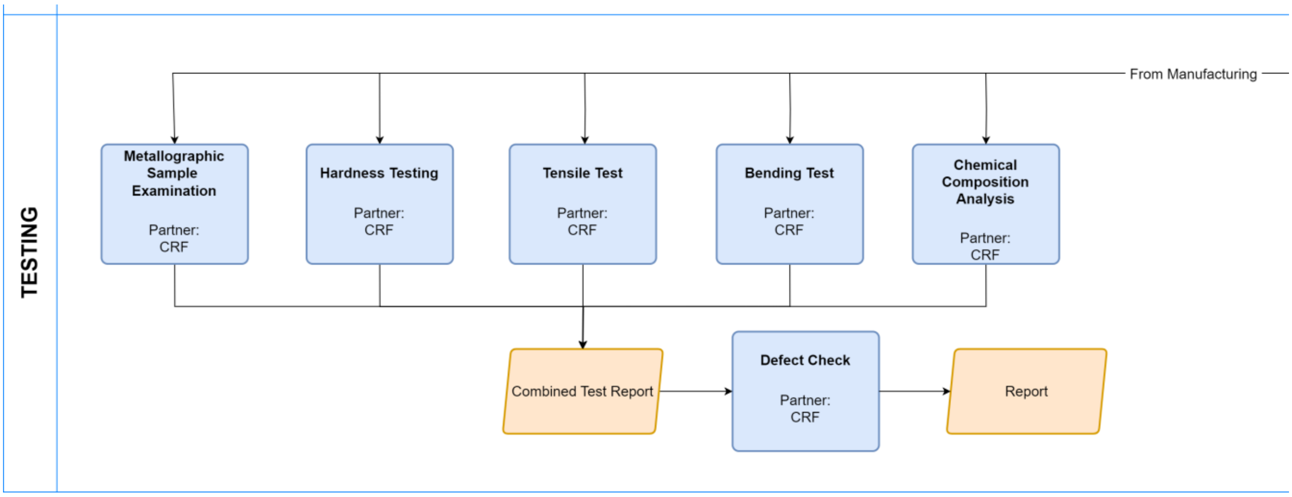


Figure 32: Testing Domain Overview for Automotive Use Case

The material testing will be performed in stages, starting with simple microstructural investigations for initial process development, before proceeding with mechanical testing and more advanced analysis once the deposition process has been optimized.

4.2.4.1 Metallographic check

ASTM E112-13 Standard test methods for determining average grain size; ASTM E407-07 Standard Practice for Micro-etching Metals and Alloys; internal Standard for evaluation.
The metallographic analysis is carried out to evaluate the compliance of the structure of the materials and to compare it with the standard raw materials.

4.2.4.2 Chemical Composition Analysis

Reference to internal standard procedure. The test is performed to check the chemical composition.

4.2.4.3 Hardness Testing

ISO 6507-1 Vickers hardness test, ISO 6506-1 Brinell hardness test. The test is performed to evaluate the hardness of the material.

4.2.4.4 Tensile Test

ISO 6892-1 metallic material-tensile testing. The test is performed to have the static properties of the material, and to evaluate if they match with the desired properties.

4.2.4.5 Bending Test

VDA 238-100 tight radius bending test. The test is performed to evaluate the bending behaviour.

4.2.4.6 Defect Check

Radiographic inspection (X-ray) and penetrant liquid will be performed to check the integrity of the component and of the sample obtained within the ALABAMA project. The ASTM E155 standard will be used for reference radiographs during inspection of Al and Mg castings. The acceptance criteria will be according to manufacturer's internal standards and cannot be disclosed.

4.3. Standards employed for the Use Case

4.3.1. Material Testing Standards

- ASTM E112-13 Standard test methods for determining average grain size;
- ASTM E407-07 Standard Practice for Micro-etching Metals and Alloys;
- ISO 6507-1 Vickers hardness test,
- ISO 6506-1 Brinell hardness test. ISO 6892-1 metallic material-tensile testing.
- VDA 238-100 tight radius bending test.
- ASTM E155 standard will be used for reference radiographs

4.3.2. CAD Model

For all the CAD models, STEP standard from ISO is the most popular and widely used standard by all CAD software. STEP, the **S**tandard for the **E**xchange of **P**roduct Model Data, is a comprehensive ISO standard (ISO 10303) that describes how to represent and exchange digital product information.

4.3.3. CAE & Measurement Data

Since, the process is the same as in use case 1, the standard application will also remain the same. VMAP Standard can be used to store both CAE & Measurement/Testing data. Please refer to Section 2.3.4.

4.3.4. Testing Standards

The Standard for components acceptance will be internal. The acceptance criteria will be according to manufacturer's internal standards and cannot be disclosed.

5. Standards for Additive Manufacturing Domain

5.1. Additive Manufacturing Terminology and Standards – ISO/ASTM

Additive Manufacturing (AM), commonly known as 3D printing is to build objects layer by layer, which contrasts with traditional manufacturing methods that often involve subtracting material from a larger piece. Being a relatively young technology, AM has been fragmented by different terminologies and lack of standardisation. This is now being addressed by both ASTM and ISO, who through ASTM Committee F42 and ISO/TC 261 collaborates on standardising terminology and requirements related to AM. A few key factors about their collaboration:

1. **Harmonization of Standards**: The primary goal is to harmonize standards across different regions and industries. This ensures that AM technologies are compatible and consistent worldwide.

2. **Unified Terminology**: By working together, ASTM F42 and ISO/TC 261 aim to create a unified set of terminologies and definitions. This helps in reducing confusion and improving communication and efficiency within the AM community. Two AM standards that aim at unifying terminology are provided below:

   - ISO/ASTM 52900: 'Additive Manufacturing – General principles – Fundamentals and vocabulary'
   - ISO/ASTM 52921: 'Standard Terminology for Additive Manufacturing – Coordinate Systems and Test Methodologies'

Several academic journals, like Additive Manufacturing, now demand that this terminology is applied in their publications. If not applied, papers will be automatically rejected.

3. **Quality and Safety**: The collaboration focuses on developing standards that ensure the quality and safety of AM processes and products. This includes guidelines for materials, operators, processes, and testing methods. Examples are provided below but the list is not exhaustive:

   - ISO/ASTM 52901 – 'Additive Manufacturing – General principles – Requirements for purchased AM parts'
   - ISO/ASTM 52931 – 'Additive manufacturing of metals – Environment, health and safety – General principles for use of metallic materials'
   - ISO/ASTM 52909 – 'Additive manufacturing of metals – Finished part properties – Orientation and location dependence of mechanical properties for metal parts'
   - ISO/ASTM 52920 – 'Additive manufacturing – Qualification principles – Requirements for industrial additive manufacturing processes and production sites'
   - ISO/ASTM 52926-1: 'Additive manufacturing of metals – Qualification principles' General qualification of operators
   - ISO/ASTM 52907: 'Additive manufacturing – Feedstock materials – Methods to characterize metal powders'

- ISO/ASTM 52954-1: ‘Additive manufacturing – Qualification principles. Part 1: Common failure modes used for risk mapping’

Standards related only to PBF-LB have been omitted.

5.2. Other standards related to AM

In addition to standards published through cooperation between ISO and ASTM, different standard organizations work on developing industry-specific standards. Examples are provided throughout this report for each use-case. For the maritime sector DNV-ST-B203 and API 20S are necessary to use for certification, while AMS standards relate to aerospace. In addition, ASME has newly incorporated a section on qualification of products produced by DED-Arc through ‘ASME BPVC Section IX-Welding, Brazing, and Fusing Qualifications’ for boiler and pressure vessels.

All standards mentioned earlier in this document are publicly accessible (some exceptions depending on geographic location for AMS standards), but the different use cases will typically be subjected to further requirements provided by the end-users, which are typically not accessible to the public. The latter point raises challenges with regards to reusing, extending or aligning a model-centred ecosystem with these standards.

The maritime case utilises the ASTM A182 and NORSOK M-630 standards, while aerospace utilises AMS 4992. These are not explicitly related to AM, but since the part is designed with a harmonised set of standards (in this case NORSOK), it is correct to apply material requirements relevant for the standards with which the part was designed. The risk with this approach is that there might be AM specific failure mechanisms that are not sufficiently investigated, leading to the part not providing satisfactory performance. A solution to this is to perform a gap analysis and introduce additional requirements from AM standards that are relevant for the specific AM technology.

6. Open Ontologies in the Additive Manufacturing Domain

Ontologies are structured frameworks used to organize information, enabling the representation of knowledge within a particular domain in a formal, machine-readable way. Some of the key concepts of ontology are entities, relationships, hierarchy, attributes, instances. Domain ontologies are generally focused on a specific area, and we see that

The DOAM[5] (Domain Ontology for Additive Manufacturing) is an ontologisation of ISO/ASTM 52900[6] which provides a standard for the general principles, fundamentals, and a vocabulary for additive manufacturing. DOAM itself comprises of two ontologies:

- astm52900[7]: A direct ontologisation of ISO/ASTM 52900 with no top-level ontology.
- doam: A domain ontology for additive manufacturing that connects astm52900 to the EMMO[8] top-level ontology and thereby provides strong ontological commitments and interoperability with other EMMO-based domain ontologies.

The project aims to repurpose and reuse these existing ontologies in the additive manufacturing domain. Obviously, this ontology might not have all the properties and finer details required within the ALABAMA Project. In this case, the project intends to extend the DOAM, keeping the new extension aligned with the current principles of the DOAM. Based on the current discussions with the ontology developers, it is possible to extend an EMMO Ontology and recommend it to the EMMC[9] Community for its addition into the EMMO.

Benefits

The domain ontologies can largely help in building the semantic web for a specific field and then assist with knowledge management by enabling data integration, sharing and retrieval across various systems and organizations. They play an integral role in achieving interoperability in the system and across the workflows. With a common language, ontology can enable logical reasoning over datasets and support a consistent data representation.

---

[5] https://github.com/emmo-repo/domain-doam

[6] https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-2:v1:en

[7] https://github.com/emmo-repo/domain-doam/blob/master/astm52900.ttl

[8] https://github.com/emmo-repo/EMMO

[9] https://emmc.eu/

Challenges

Some of the main challenges faced while building ontologies is the time it takes to understand different perspectives and achieve a common understanding through dialogue. This task itself is not only time consuming but also requires domain expertise to even start the discussion. However, the domain experts could be too narrow-minded in approach to look at the large perspective while building ontologies for the semantic web. This is why ontologies not only require domain experts but also experts from lateral domains to work together. Building ontologies is an iterative process as the domain evolves and new data, new findings are released, the ontologies must get updated and handle complex relationships. These are just a few of the challenges the project will face while identifying useful ontologies for the specific domain.

Roadmap for ALABAMA Project

Since a domain ontology for additive manufacturing already exists based on ISO/ASTM 52900, we can leverage this foundational ontology and extend it to meet our specific use cases as needed. The project's primary goal is to utilize, enhance, and learn from existing models. Additionally, we will foster collaboration with other projects and organizations engaged in similar ontology development efforts, thereby expanding our collective knowledge, and improving our approach.

7. Semantic Data for Digital Product Passport

The foundation for the Digital Product Passport (DPP) data model is the Semantic Aspect Meta Model (SAMM) developed by the Catena-X initiative. The SAMM provides a standardized ontology for representing various aspects of a product's lifecycle, supply chain, and associated data. Modelling product-related data using this SAMM ensures a consistent and standardized representation of the information required for a Digital Product Passport.

Based on the provided SAMM models, a JSON Schema can be generated to define the structure and validation rules for the DPP data. This JSON Schema will be the foundation for the DPP's data model, ensuring consistency and interoperability across all DPP instances. The JSON Schema should include all the required data.

With the JSON Schema, the DPP solution can be developed to consume and validate the data according to the Catena-X standards. The JSON Schema will serve as the blueprint for the DPP's data model, guiding the development of data storage, retrieval, and exchange mechanisms. To align with the global standard of DPP, we are trying to follow the standard provided by Catena-X. By aligning the DPP's data model with the SAMM models and the corresponding JSON Schema, it can ensure that the DPP solution is fully compatible with the Catena-X standards, enabling seamless integration and data sharing across the product's ecosystem.

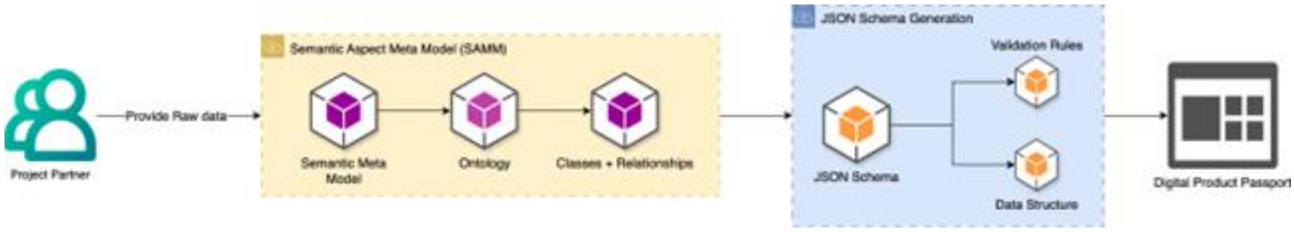


Figure 33: Semantic Data Integration Process for Digital Product Passport

Catena-X Standards

Catena-X standards[10] are a set of rules and requirements that govern how data and information are exchanged in the Catena-X data ecosystem. These standards ensure that technologies, components, and processes are developed and operated according to uniform

---

[10] https://catenax-ev.github.io/docs/standards/overview

rules. They enable interoperability between independent implementations. Catena-X standards enable a high level of transparency and comparability for all providers of services and applications. They enable data sovereignty and security for all participants in the data space.

Digital Product Passports (DPPs) and Catena-X standards

Catena-X plays a crucial role in enabling Digital Product Passports (DPPs) by providing a standardized framework and data-sharing ecosystem. The DPP concept is implemented through interoperable platforms like Catena-X, which ensure that detailed product-related information—such as (i) manufacturing data, (ii) materials and their provenance, (iii) lifecycle impacts (iv) disassembly & recycling guidelines etc. can be securely shared among stakeholders like manufacturers, suppliers, consumers, recyclers, and regulators.

For example, Catena-X supports the "Battery Passport,"[11] a specific type of DPP focusing on sustainability and traceability within the battery lifecycle. This initiative utilizes Catena-X's shared services, such as its standardized data models and secure data exchange protocols, to provide end-users with accurate and auditable product data. These passports enhance transparency and facilitate informed decisions across the product lifecycle, from design and production to recycling and reuse.

Example projects using Catena-X standards

In the BASE project, TVS is using Catena-X standards for developing DPP for batteries in automotive and marine applications and for stationary use. In RESTORE, ALABAMA & GEAR-UP projects, we will also use Catena-X standards for developing DPP for all the products in the use cases.

---

[11] https://catenax-ev.github.io/docs/standards/CX-0117-UseCaseCircularEconomySecondaryMarketplace#32-aspect-model-battery-pass

8. Conclusion

The various formats defined here for all the use cases show that there is a huge amount of data transfer which needs to take place for a streamlined workflow.

All the three use cases will follow a similar approach in terms of the additive manufacturing process, DED-LB. However, the kind of tools, and softwares which will be employed for these use cases vary significantly.

For material, CAE, and manufacturing domain, most of the data can be easily stored in the VMAP Standard format. The VMAP standard already offers clear guidelines and specifications to store the CAE simulation data. The standard has also been extended to store measurement and sensor data for specific use cases like DED-arc & Sheet Moulding Compound (SMC) processes. Within the ALABAMA project, the VMAP Standard will be extended to store measurement and monitoring data required for DED-LB process. The project will offer its use cases and the VMAP Working group for Sensor & Experimental Data will jointly assist in the further development of the standard.

VMAP offers vendor neutrality, hence, it ensures compatibility and interoperability across diverse CAE platforms. It utilizes the HDF5 file format, which is open-source and widely adopted, making data storage and exchange reliable and efficient. With the VMAP I/O, written in C++ with compatibility for other languages like Python and Java through tools like SWIG, it is easy to integrate into custom software environments. Some of the benefits of VMAP Standard include enhanced collaboration, improved efficiency, and support for emerging technologies.

Once the standard data format is implemented, the metadata can be easily identified and used to carry out basic search functions with VMAP Meta Tool. These metadata will then find their way in the respective ontologies, which will help to connect the datasets and organize the information coming from various domains and multiple steps.

Ontologies define a shared vocabulary for a specific domain. By providing consistent definitions for terms and their relationships, they ensure that datasets using the same ontology can understand each other's data. They enable datasets from different sources and formats to interact seamlessly by translating their structures and semantics into a common framework. Once the datasets are in place, querying across multiple datasets using SPARQL or other semantic query languages is possible because of the unified semantic framework.

After the ontologies have been set-up, the data properties and objects can be used to build the digital product passport.