ALM ISCAR - Additive Layer Manufacturing of a redesigned ARIANE Bracket - Overview and Status

Svenja PESTOTNIK[1], Sebastian KÉBREAU[2], André DRÖSE[2], Pascal VERMEER[2], Freerk SYASSEN[3], Matthias RADNY[3], Jérôme BRETEAU[4]

[1]Airbus Safran Launchers GmbH, Germany
[2]Airbus DS GmbH, Germany
[3]Airbus Operations GmbH, Germany
[4]European Space Agency Headquarters, France

Abstract

Being among the most promising manufacturing processes to date, additive layer manufacturing is predestined to secure the competiveness of next generation European launchers. Within ESA Future Launchers Preparatory Programme, the ALM ISCAR was set up as a maturation project to prepare the implementation of additively manufactured parts into the launcher environment. In this frame, various technical fields such as topology optimisation, ALM process and post treatment definition, mechanical property characterisation and non-destructive testing are being matured. The paper gives an overview on the project and its technical logic and tasks.

1 Introduction

Additive Layer Manufacturing (ALM) is "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1]. The history of ALM traces back to the early 1980s, when it was originally conceived as a way to make prototypes. Today ALM has evolved to the extent that it is increasingly applied to produce final products. Unlike traditional manufacturing processes involving subtraction (e.g. milling) and forming (e.g. stamping, bending and molding), additive manufacturing joins materials together to build products. This way, it reduces raw material usage, lead times for part production and manufacturing costs while maintaining or improving the performance of the end product.
After working mostly with plastics (Airbus for example has manufactured and is flying a high number of different types of plastic brackets, clips and other parts holding cables, wires and hoses in place, using additive manufacturing [2]), the application of metals is now in the focus.

1.1 Benefits of ALM

Additive Layer Manufacturing enables a design-driven manufacturing process which allows highly complex structures, and still being extremely light and stable. The more complex the structures are, the more pronounced the cost and time advantages of ALM compared to conventional manufacturing processes are. ALM allows further pushing of the mass performance as manufacturing constraints are further reduced. Furthermore, structures that were previously not manufacturable by other techniques now become possible.
Another benefit is the increased material efficiency through reduction of waste because only the needed material is used. This is especially beneficial for relatively expensive aerospace materials such as titanium. While conventional machining can entail a scrap rate as high as 80–90 percent of the raw material, ALM can bring the scrap rate down to 10–20 percent, given the basic distinction between subtractive and additive methods of manufacturing. [3] A research of Oak Ridge National Laboratory (ORNL) and Lockheed Martin on their Bleed Air Leak Detect (BALD) bracket shows that the buy-to-fly ratio (i.e. ratio of raw material weight divided by weight of the finished part) can be reduced from 33:1 to 1:1 for the aforementioned bracket by using electron beam melting (EBM). In terms of cost comparison, even though the titanium alloy (Ti-6Al-4V) powder used in the ALM process costs more than the wrought Ti-6Al-4V used in the traditional process, 50 percent of the cost of a bracket can still be eliminated without compromising its mechanical properties. [4]

1.2 Market status

Today, the additive manufacturing technology experiences an exponential growth in more or less all industrial fields (aerospace, automotive, medical, dental, …), as well as in private domains - the quote "democratisation of manufacturing" (original source unknown) brings it straight to the point - where a polymer 3D printing system with decent quality placed right next to the personal computer is becoming a standard equipment allowing prototyping and manufacturing at home for a reasonable price.

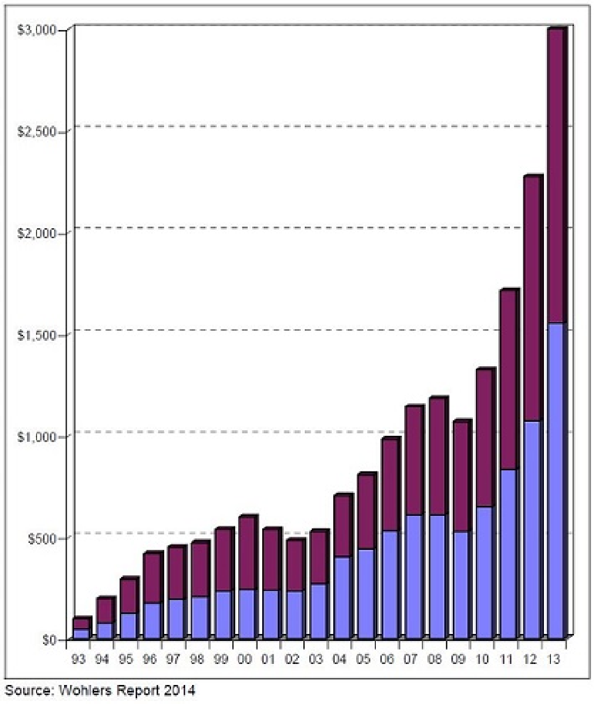

Figure 1: Worldwide revenues (in millions of dollars) for additive manufacturing products and services [5]

In this respect, the work of Terry Wohlers perhaps provides the most global overview on the market, particularly visualised through the well-known revenues chart (Figure 1). [5] As it becomes eminent, in the last 3 to 4 years, the market grew by a factor 3 for both products (lower bars) and services (upper bars). For clarification: *products* include manufacturing systems, materials and aftermarket products, whereas *services* comprise revenues generated from parts produced by service providers, training, workshops, et cetera. [5]

Nevertheless, the majority of systems in operation are polymer systems primarily used for prototyping.

In launcher industry, most applications are loaded metallic parts - structural and/or functional - and there is still a way to go to reach a maturity level which allows application in serial production. One step for industry and aerospace authorities is to put the appropriate set of standards in place. In addition, the processes and machines need further improvement on robustness and quality control. In contrast to classical manufacturing technologies, a much stronger collaboration between technology system providers and the aerospace industry is required to master these challenges.

2 ALM within Airbus DS and Airbus Safran Launchers

The development of the new ARIANE 6 launcher, aiming on the global market forecast for competitive launch services with optimized performance and cost efficiency, invites new manufacturing technologies for consideration to realise these objectives.
Within this context, the industrialization of additive manufacturing as an independent manufacturing process in launcher serial production is the key for this development, and will be enabled through the implementation of the bracket developed within the presented project in ARIANE 5 upper stages.

The maturation and qualification of the ALM process will be extended within the Airbus Group to fulfil specific space requirements such as cryogenic environments and dedicated design philosophies. The main steps until ARIANE baseline implementation are shown in Figure 2.

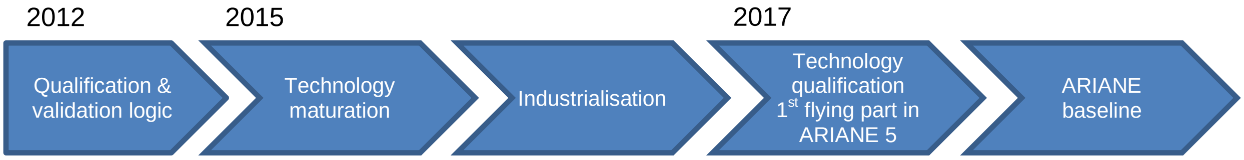

Figure 2: Global technology application timeline at AIRBUS DS and Airbus Safran Launchers

3 ALM ISCAR

3.1 Overview

Additive Layer Manufacturing has been called "The Third Industrial Revolution" [6] and the entry of ALM into the aerospace industry is eminent. By employing ALM, complex, integral, topology optimised structures can be realised which would not be manufacturable with subtractive manufacturing techniques. Due to the speed and efficiency with which additive manufacturing can produce parts, the technology is most beneficial for products that require high customisation, have complex designs and are made in small quantities [7], which corresponds to products in the aerospace industry. This offers significant mass savings while production lead times and manufacturing costs can be lower compared to conventional techniques.
Introduction of ALM into the ARIANE launcher serial production offers a competitive edge for the European launcher industry on an international market that is subjected to steadily increasing competitive pressure.

A major enabler for the ALM ISCAR project was the German national technology programme PREPARE with DLR, which focuses amongst other technologies also on ALM. As part of the PREPARE programme a definition of a launcher vehicle specific qualification and validation logic for additively manufactured structures has been established, and in addition, a systematic screening of the ARIANE 5 upper stage was conducted to identify a potential application for ALM for secondary structures. Based on criteria such as mass saving, cost saving, integration of sub-assemblies or dimensioning load type, the Inner Attitude and Roll Control System (ISCAR) bracket was identified as promising and a typical representative.

As part of an ARIANE upper stage design refinement, a set of thrusters of the ISCAR became obsolete and was removed. The bracket formerly supporting this thruster set - hence the name "ISCAR bracket", see Figure 3 and Figure 4 - has the potential for a redesign and associated mass gain, while fulfilling the remaining function, i.e. the support of the critical feed line for the Outer SCAR and the Vent line.
This represents a unique opportunity: redesign of the ISCAR bracket by employing topology optimisation and additive manufacturing, and thus the implementation of additively manufactured hardware in an operational space vehicle serial production.

Following this preliminary phase, the ALM ISCAR project was established in the frame of ESA's Future Launchers Preparatory Programme (FLPP) for final technology maturation prior to qualification.

Its objective is to increase the maturity of ALM with respect to space specific requirements such that a subsequent qualification programme can follow. As result of the ALM ISCAR project, the demonstration of a prototype in a relevant environment [8] is envisaged. Based on the advanced maturity level within the AIRBUS GROUP, Ti-6Al-4V in combination with SLM powder bed is considered for the ALM ISCAR project.
In order to reach the objective, ALM ISCAR was set up to answer the needs with respect to technical fields such as topology optimisation, ALM process and post treatment definition, mechanical property characterisation and non-destructive testing.

The project started beginning of 2015 and is foreseen to be completed mid of 2016.

The European Space Agency (ESA) is the major customer of this work. The internal customers are the ARIANE upper stage production programme as well as the ARIANE 6 development programme.

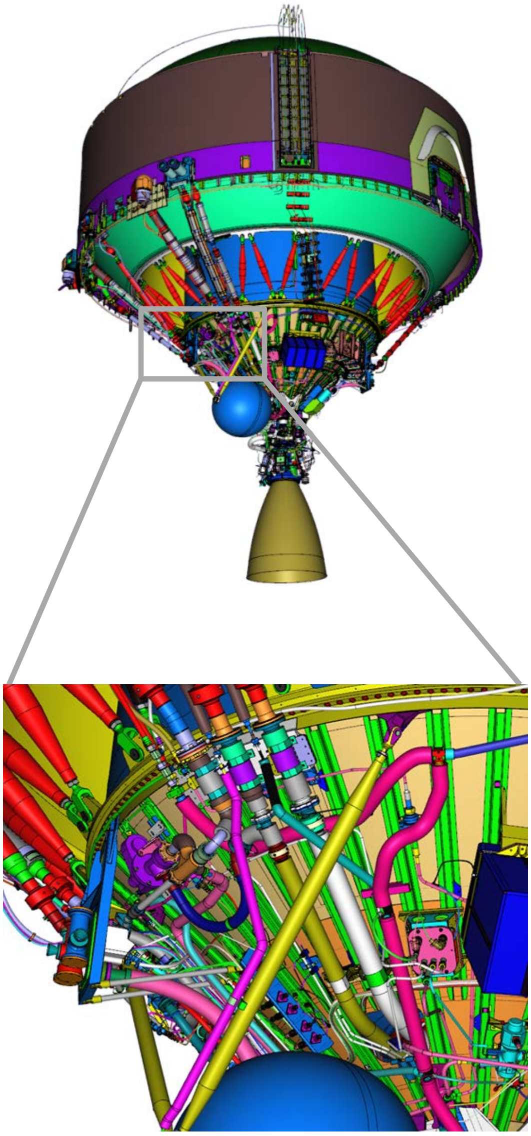

Figure 3: ISCAR bracket with thruster cluster on ARIANE upper stage, overview (top) and detail (bottom)

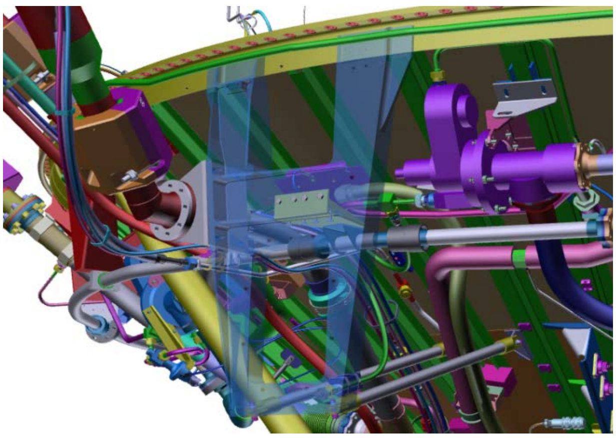

Figure 4: ISCAR bracket after thruster removal for ARIANE upper stage

3.2 Technical logic

The flow chart in Figure 5 shows the overall technical logic and main dependencies within the ALM ISCAR project. The main fields of technical activities are explained hereafter and according to the project status, dedicated activities are presented in more detail in this paper.

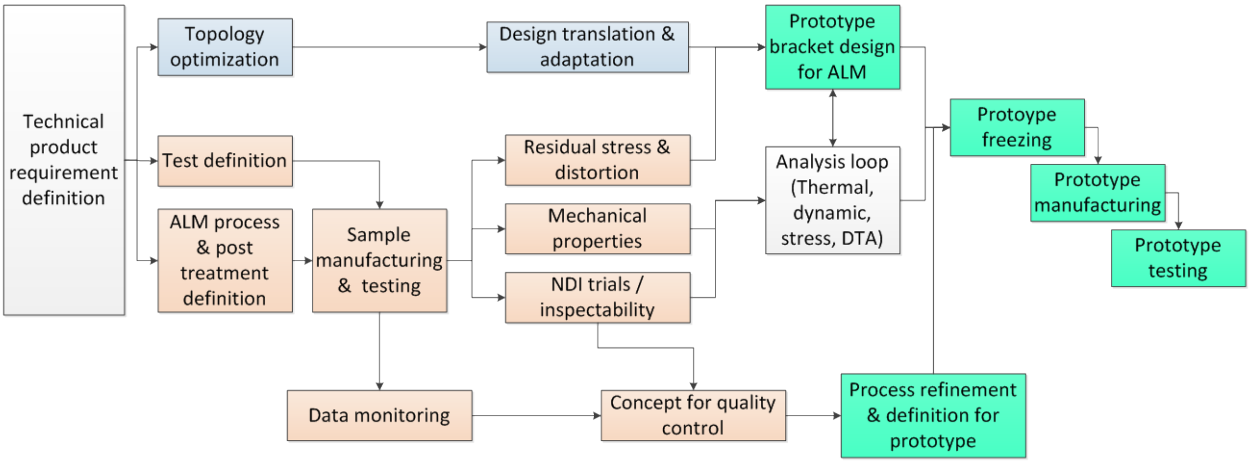

Figure 5: Overall technical logic and main dependencies within the ALM ISCAR project

Starting from the definition of technical requirements, two main branches are triggered. The upper branch (blue) deals with the identification of an optimised design, based on a topology optimisation and followed by the design interpretation, translation and local adaptation. The lower branch (red) deals with the definition of needed sample tests in order to properly characterise the ALM process and material. Furthermore, the manufacturing and sample testing is part of this lower branch, completed with a process data monitoring and its usage for a quality control concept. The test results leading to information on residual stress & distortion, mechanical properties and information on non-destructive inspectability will then enable the analysis of the prototype design with respect to the applicable structural failure modes. The prototype definition and manufacturing process can then be set-up (green part of the flow chart), based on the consolidation of the sample manufacturing process. The prototype manufacturing and testing complete the activities of the maturation project.

3.3 Detailed tasks and first results

3.3.1 Technical requirements definition

The primary input and starting point for the ALM ISCAR activities are the technical product requirements. These requirements are mainly higher level requirements, constraints and needs which are imposed from the environment into which the ALM produced component shall be implemented. In the present case, this environment is defined by the ARIANE launcher and upper stage requirements and comprises among others:

- the design space in which the new bracket can be located and the volume that can be filled without interfering with present subsystems on the engine thrust frame
- interface requirements & constraints, defined by the allowables of the supporting structures
- the acceptable or preferred type of material (e.g. Ti-6Al-4V in the present case)
- the loads that must be sustained by a bracket at the dedicated location and in the dedicated function (e.g. supporting the lines)
- project requirements, defining e.g. the margin policy to be applied but also the failure modes to be verified for structural components and the applicable rules in order to be compliant from safety and reliability point of view (e.g. statistical basis for material properties)
- quality requirements.

3.3.2 Topology Optimisation

Topology optimization is the process of determination of connectivity, shape and location of voids inside a given design domain.

Applied in an early stage of the conceptual and preliminary design stage where design changes have a large impact on the performance of the final structure, topology optimisation has significant implications. Due to the high freedom of design it has an essential impact onto the overall structural behavior.
In order to fully exploit the freedom regarding shape and complexity additive manufacturing offers, for the ALM ISCAR project, several topology study loops with different targets are performed.

In the following paragraphs, the optimisation workflow (Figure 6) applied in the project is described.

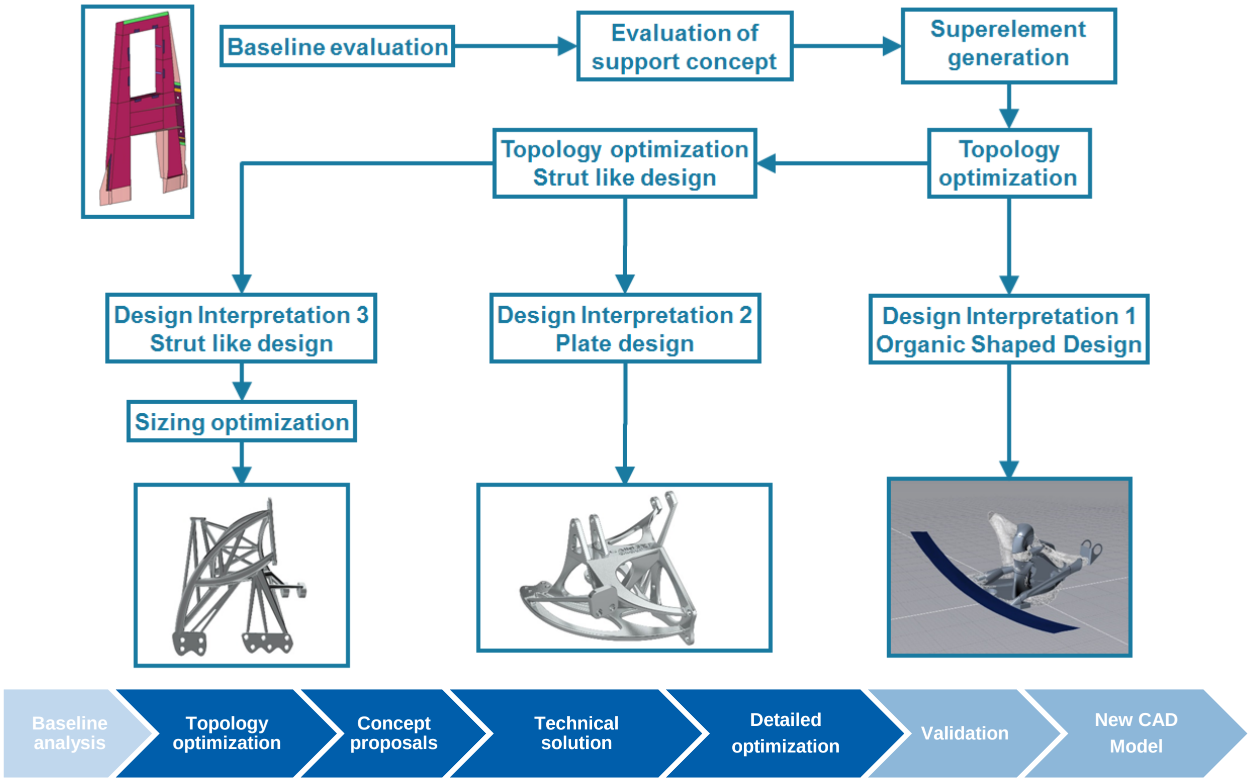

Figure 6: Optimisation workflow

In the **first phase** of the optimisation, all relevant information and data need to be captured and specified. It is of high importance not to miss any requirements or restrictions, which can influence the results or make these infeasible in a later stage.

Taking all input data into account, a baseline analysis is performed in order to assess the basic behaviour of the surrounding structure and the structure to be optimised, as well as the interface loads and the influence of local stiffness and stability.

Basic design drivers can be directly addressed:

- strength
- stress
- stability
- basic manufacturing constraints (e.g. thickness ratio and drops).

More advanced design drivers, such as natural or responding frequencies, temperature dependent material effects, thermal and fluid flow requirements, need to be specified in detail to find customised setup solutions.

In the **second phase**, a concept optimisation is performed.
After defining the optimisation objectives (minimise mass, maximise stiffness, etc.) in subject to the given requirements and restrictions and a defined loads set, the conceptual optimisation (i.e. Topology-, Levelset- or Free Size Optimisation) is carried out.

For classical topology optimisation, typically two approaches can be followed:

- stiffest concept in subject to a weight target
  The stiffest concept approach allows understanding of the load transfer within the given design space with a minimum of information input, and gives a good indication for setting up more advanced conceptual optimisation studies. Figure 7 exemplarily explains this approach.
- lightest concept in subject to stiffness constraints (or advanced)
  The lightest concept approach allows a detailed view into the minimum needed distribution of material to fulfil the predefined restrictions. Dependent on the mesh size, very fine structure solutions can be observed.

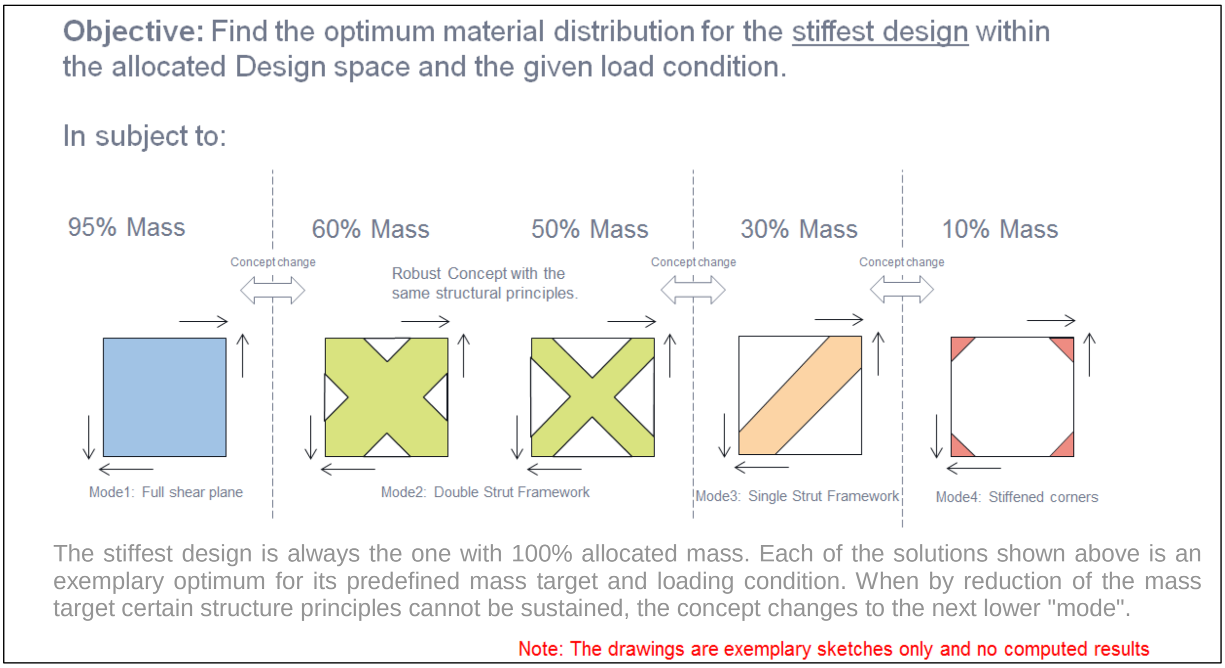

Figure 7: Material distribution within allocated design space

For a better interpretation of influencing parameters during the concept phase, the optimisation setup evolves from a simplistic approach (e.g. stiffest concept) to the final setup which could be programmed to be efficient (as detailed as needed, as simple as possible), or a full setup covering complex methods fed in by external routines.
To keep the concept phase as efficient as possible after each loop, it needs to be clarified whether the found proposal is sufficient to enter into the interpretation phase, or further studies are needed in order to get closer to the optimum.

For the ISCAR bracket, a topology result based on the stiffness approach and a defined mass target is shown in Figure 8.

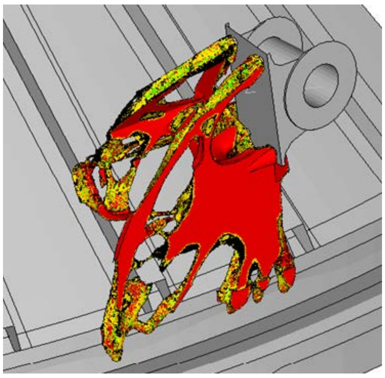

Figure 8: Preliminary result of topology optimisation of the ISCAR bracket

Based on the topology proposals in the **third phase** (concept interpretation), different variants are created taking basic structure- and design principles into account:

- recognition of structure-function principles
- abstraction into quick design concepts following the principles
- assessment and trade-off for weight / performance / cost
- concept validation.

In order to verify the structural principles of the preliminary interpretations and to provide a first estimation on weight-to-performance, a preliminary finite element analysis is performed.

The most suitable concept (weight to cost to performance) is identified and agreed in a design review.

In **phase four** (concept design), the technical design interpretations will be performed taking into account:

- derived structure-function principles
- detailed design principles
- available manufacturing technologies and constraints (subtractive, additive, casting, etc.).

The outcome of this creative phase is a feasible technical solution ready for validation.

Phase five of a detailed size and shape optimisation takes detailed restrictions and constraints into account, locally optimising the concept design, i.e. thickness, radii, shape (Figure 9).
The outcome of the detailed optimisation phase is a well-balanced set of parameters fulfilling all structural requirements.

Figure 9: Technical solution of the ISCAR bracket

In the last step of the optimisation driven design process, a final stress validation (Figure 10) is performed to ensure the feasibility of the new structure.

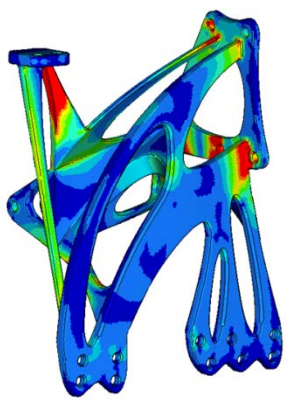

Figure 10: Stress analysis on technical solution of the ISCAR bracket

3.3.3 Residual stresses

In order to predict the residual stresses and distortions from nominal geometry during additive manufacturing, a first quick simulation of the design has been run at the Institute for Integrative Simulation and Engineering of Materials and Processes (ISEMP) at the University of Bremen. The concept design, positioned on a virtual build platform and generically supported, has been translated into a pure mechanical simulation model in which the thermo-mechanically induced plastic strain is introduced as mechanical load (Inherent Strain Method). This enables fast computation times. The figures below show a schematic representation of the build orientation plus supports (Figure 11) and preliminary results for strain (Figure 12), distortion (Figure 13) and residual stress (Figure 14).

A proposed orientation of the bracket design is shown in Figure 11. The support structures are based on general design for manufacturing guidelines, e.g. recommending supports for areas with >45° overhang, holes larger than 6mm etc.

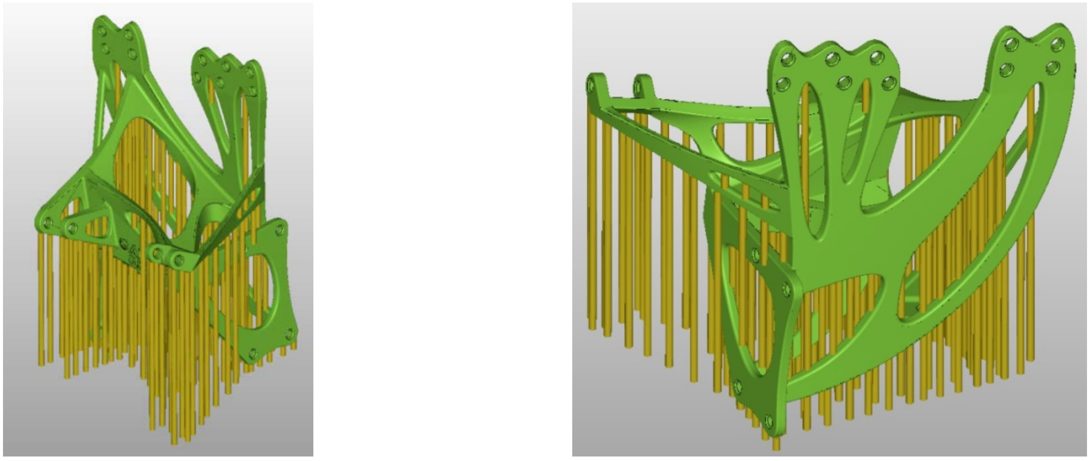

Figure 11: Proposed orientation with visualisation of necessary supports

The predicted level of plastic strain for the as-built, non-heat treated product is shown in Figure 12. Generally, the stiffer members face a higher strain with some hot-spots for potential cracking.
It has to be noted that these results are preliminary results in frame of preparation of the detailed computation.

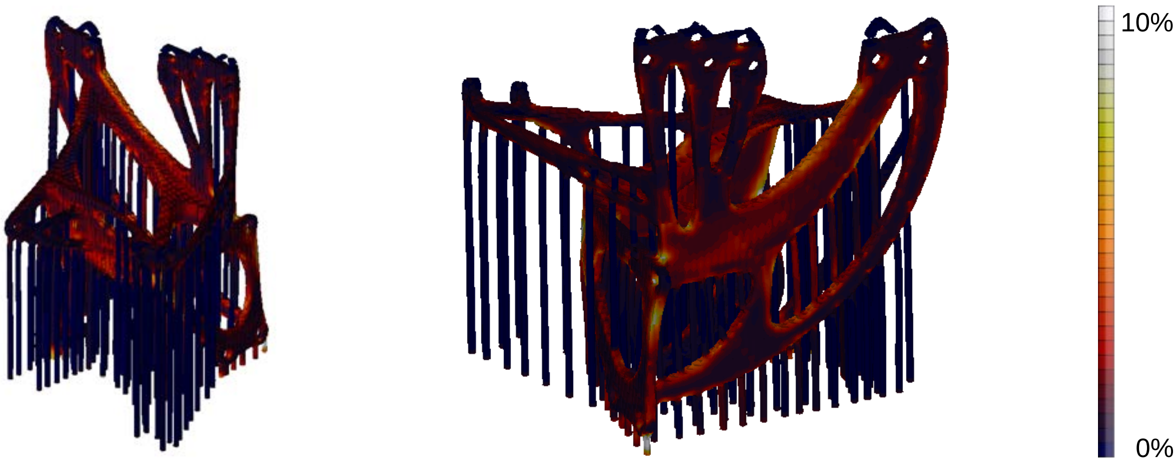

Figure 12: Plot of predicted plastic strain of the ISCAR bracket during manufacturing

The predicted deviation from the nominal geometry is visualised in Figure 13. It has to be noted that these results are preliminary results in frame of preparation of the detailed computation.

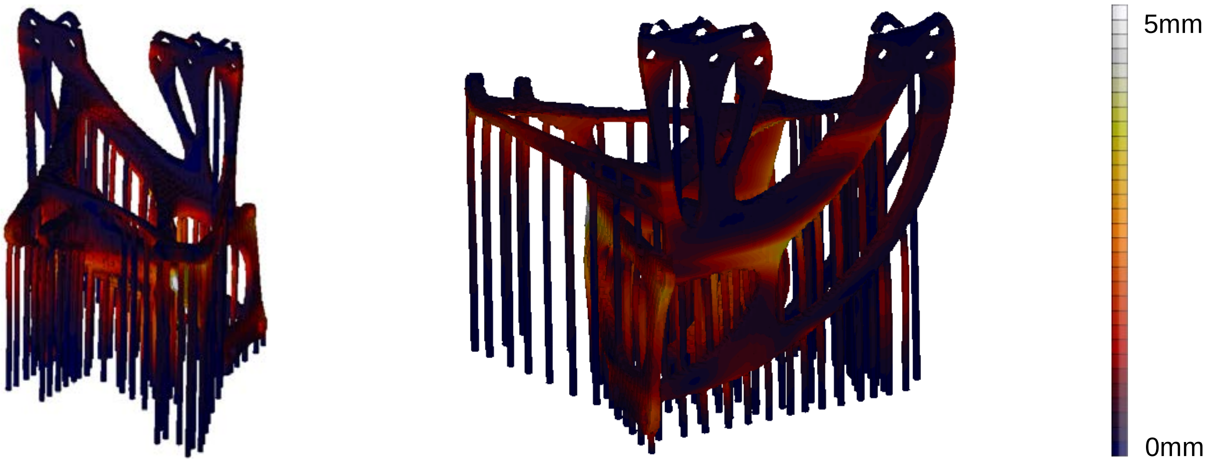

Figure 13: Plot of predicted geometrical distortion of the ISCAR bracket during manufacturing (mm)

The predicted residual stress level (Von Mises) is shown in Figure 14. Generally a relatively high stress level (up to yield stress) is expected for the as-build, non-heat treated product. An adequate heat treatment will significantly reduce the residual stress level in the part.

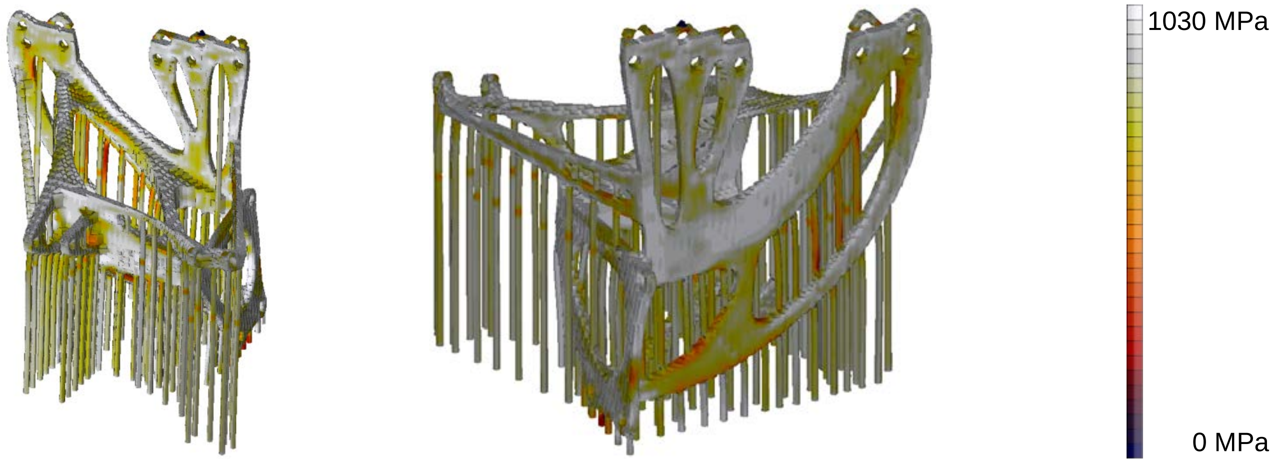

Figure 14: Plot of predicted residual stresses in the ISCAR bracket during manufacturing (Von Mises)

In frame of the project, a more detailed investigation will be performed in which the final geometry is simulated with a correlated model and the results are iterated with the mechanical verification of the structural integrity.

3.3.4 ALM Process and Post treatment

The whole process chain of additive manufacturing has to be reviewed regarding the maturity and industrialisation status of the individual steps. They are shown in the flow chart below.

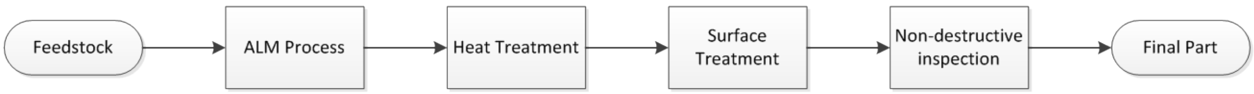

Figure 15: Principal process flow from feedstock to final part

The physical input for the ALM process is the powder in form of a feedstock. It has to be assured, that the powder is well defined and thus to have a traceable and repeatable basis for the subsequent process. Several powder properties significantly influence the manufacturing process and/or the quality of the final part. These are for example:

- chemical composition
- production process
- particle size and shape
- flow rate
- humidity
- porosity
- density
- storage, delivery and handling conditions.

For a successful definition and subsequent evaluation of the whole process chain, it is essential to control those parameters. In the definition of requirements for powder parameters, it is important to anticipate the later needs of an industrialisation, enabling a usage in machines of different manufacturers.

"As-built" material produced according to the selective laser melting process (without any post-treatment after printing) is accompanied by several drawbacks regarding the material properties, namely:

- relatively low and/or varying ductility due to the microstructure and internal flaws
- risk of significant residual stresses dependent on the part geometry
- risk of porosity (also in near surface layer) due to the melt-solidification-process and associated impact on mechanical properties, especially on fatigue resistance
- increased surface roughness due to partly melted or sintered powder particles (typical Ra>10µm), also directly linked to fatigue resistance.

To improve the material properties a heat treatment (annealing) and/or thermal pressurized process (hot isostatic pressing) is vital. The aim is to find a heat treatment set-up and sequence which fulfils the needs regarding the material characteristic. Also the industrialisation and economic aspects shall be taken into account to establish a meaningful, robust and reliable approach.

Not only are the mechanical properties negatively affected by an insufficient post treatment but also the standard non-destructive surface inspection (i.e. dye penetrant testing). Within the project, the feasibility of standard aerospace non-destructive testing processes will be evaluated to establish a baseline approach for quality assurance of additively manufactured parts. This includes the testing regarding inherent voluminous defects and surface, crack-like defects using x-ray and dye penetrant.
The challenge is, to improve the (near) surface condition by post-treatment, by adaptation of the powder specification and/or by adaptation of the manufacturing process parameters.

3.3.5 Material characterization

The characterisation of the ALM produced material is an essential part of the maturation project as it is the qualitative and quantitative way to judge the effectiveness of the established manufacturing process. The space environment requires a characterisation with respect to numerous properties, partly going beyond the needs of the aircraft requirements. In the frame of the ALM ISCAR project, the mechanical properties are in the focus of attention. They are highly sensitive to the process and are directly linked to the mass performance of the structure, especially if the investigated structure is driven by strength or damage tolerance properties. The scope of the test programme is defined by the facts that secondary structures as the ISCAR bracket:

- operate in a temperature range from cryogenic to room temperatures
- can be strength driven (requiring information on tensile, compression or shear strength)
- can be locally driven by bearing strength capability, depending on the interface design
- can be damage tolerance driven or will need at least the demonstration of damage tolerance capability, either following the safe-life philosophy in which defects of a finite starting length are not allowed to become critical during cyclic life loading or following the fail-safe philosophy in which a loss of a load path shall not cause the failure of the remaining structure under cyclic loads.

The set of mechanical test series is expanded by tests related to hardness, stress corrosion cracking, microstructure and fractography.

Further complexity in the test matrix results from the fact that properties may be dependent from the test direction compared to the ALM building direction. Lastly, a significant multiplier for the number of test samples is the need for statistical evaluation. Depending on the specification, properties must be evaluated as mean-values, on A- or on B-basis.

As stress based properties can be masked by residual stresses, the dedicated work package, presented in "3.3.3 Residual stresses", takes care of the characterisation.

3.3.6 Analysis

The objective of the analysis loop is to verify the acceptability of the topology optimised bracket design.
The analysis perimeter comprises:

- a thermal analysis in order to estimate the thermal distribution and gradients of the new bracket design in the integrated condition
- a stress analysis in order to judge the acceptability of the design in view of the mechanical properties and residual stresses identified in the material characterization and to provide input for a damage tolerance assessment
- a dynamic analysis in order to confirm the acceptability of underlying load factors and to provide frequency information as input for the damage tolerance assessment
- a damage tolerance assessment in order to judge the capability under cyclic loading.

After the successful analysis of the prototype design, the prototype structure will undergo test activities on bracket level.

4. Conclusion

It is of crucial importance to pave the way for new technologies into future launchers in order to remain competitive and successful. Proof of the technology's maturity and benefits before the launcher programme’s technology selection in terms of functionality, performance, reliability and expected cost savings determines the success of that technology. Technology maturation projects like ALM ISCAR increase the confidence level of the technology through demonstration of the technology and contribute to the specific needs of the stakeholders.
Additive Layer Manufacturing is among the most promising manufacturing processes to date. With the ALM ISCAR project, the feasibility and attractiveness of ALM for future launchers will be determined.

A subsequent qualification programme for the additively manufactured ISCAR bracket will follow the ALM ISCAR project, with the objective to implement the bracket into the ARIANE 5 serial production. The implementation logic and schedule will be established together with the ARIANE 5 upper stage production team during the next months.
The knowledge and results gained during the ALM ISCAR project will be used in a working group with ESA Technical Directorate in order to further standardise the ALM technology and prepare further industrialisation of the technique.

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