

DEVELOPMENT AND TEST OF A THREE AND AN HALF SPACE APPLICATIONS USING ADDITIVE MANUFACTURING TECHNOLOGIES

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ABSTRACT

In the frame of the GSTP activity entitled “Development and test of Additive Manufactured Space Hardware” a Consortium having CSL as prime contractor is proposed to start from a blank sheet of paper developing different space hardware including a spectrometer of small dimension, a complex helium distribution system for launchers, a multifunctional bracket of large dimension and an advanced casing for electronic cards with improved thermal management. Demonstrators for the three first items will be manufactured and tested to reach TRL 5. The design of the casing for electronic card will only be matured through multi-objective topological optimisation. The members of the Consortium (CSL, Lambda-X, Thales Alenia Space France, Thales Alenia Space Belgium, 3D system Layerwise, Safran AB with the support of LISI Aerospace Additive Manufacturing, KU Leuven and Open Engineering) have been working closely together to take on board the challenges related to such development. The paper presents the study cases status showing the pros and cons of the selected concepts.

1 BACKGROUND

Back in 2011, the European Space Agency granted two parallel TRP activities entitled “Advanced Manufacturing Methods for Systems-of-Microsystems Nanospacecraft”. The aim was to redesign, manufacture and test demonstrators with increased levels of complexity i.e. Level 1: item (part) design individually optimised, Level 2: item design driven by the application requirements and Level 3: item design driven by the subsystem to which it belongs. The Prime Contractors of the selected consortia were TNO and CSL. Those studies were the first attempts to place in perspective the broad range of Advanced Manufacturing Technologies to develop advanced space hardware. Those studies showed that Additive Manufacturing is an important contributor to the Advanced Manufacturing technologies; always complemented by others processes. Since then, several activities initiated by the Agency aimed at placing in a system perspective the production of parts. This “Development and test of

Additive Manufactured Space Hardware” activity is part of this strategic developments. One of the expected outputs is a better understanding of the interactions across the different entities involved in the procurement chain.

2 WORK ORGANISATION

The work on this project is divided in different successive tasks. Four case studies are running in parallel and going through these tasks.

Task 1 objective was the definition of detailed parts requirement. Care is also been taken to list all the additional functions that could take advantage of the additive manufacturing.

Task 2 was to perform a preliminary design and ensure through samples and prototypes that there was no showstopper in the principle of the manufacturing, integration and validation of the concept.

Task 3 goes into the detailed design of the parts. At the end of this task, the manufacturing drawing, plan and the test plan shall be fully ready and secured.

Final task (4) is the manufacturing of the parts and test in representative environment to demonstrate TRL5. Only the last case study (advanced casing for electronic cards) will not go through this task.

In the next sections, each case study is described.

3 OPTICAL SPECTROMETER

3.1 Description

The goal of the Lambda-X optical spectrometer study is to investigate the use of additive manufacturing (AM) in an integrated optical application. This includes the mechanical structure, brackets for optical components, specific optical parts like mirrors, baffles, light traps for stray light reduction but also the optical alignment features with the addition of well-controlled degree of freedom adjustments.

The test case selected is the spectrometer of the UV-visible channel of the NOMAD instrument, part of the Exomars mission. It is a Czerny-Turner configuration illustrated in Fig. 1.

In this case, additive manufacturing is exploited in order to reduce the overall mass, simplify the alignment

procedure and reduce the overall number of parts.

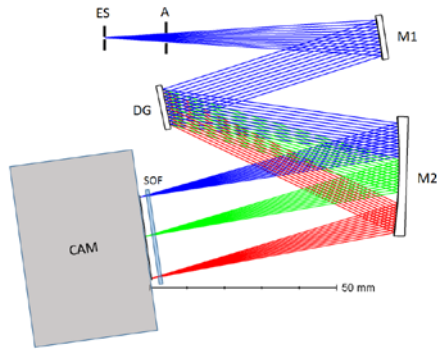


Figure 1. Optical layout of the spectrometer

In this activity, CSL is also developing a surface treatment process to reduce the surface micro-roughness of components made by additive manufacturing in order to make them suitable for optical imaging applications. The proposed method comprises the following steps

- Deposition of a roughness buffing layer
- Shape correction of the component surface through figuring of the previous layer
- Deposition of an optical functional coating

The buffing layer is actually a harden film coated over the surface in a liquid precursor form that allows filling-up surface anfractuosités and therefore reducing the micro and nano-roughness. However, as a drawback, the buffing layer introduces surface wave-front errors that need to be corrected by figuring/polishing for applications such as an optical telescope.

3.2 Main requirements and challenges

The main requirement is to achieve at least the same optical performances as the NOMAD instrument while benefiting from the advantages of AM, in particular for the integration of the fine adjustment in the brackets. The main challenges are twofold: the mechanical features and the optical features.

The mechanical structure is a monolithic part with covers. It includes all the mechanical aspects of the instrument: external interface, thermal expansion accommodation, optical parts mounts, and fine adjustments of relevant degrees of freedom around their nominal location. The main challenge encountered is the design of small-complicated features for the multiple adjustments like the one depicted in Fig. 3. The actual monolithic part size being 100x120x30mm, another difficulty lies in the small size of the components as shown by a typical adjustment sample shown in Fig. 4. A total of 9 adjustment split on 5 optical elements are implemented.

Concerning optics development, the main requirements coming from the UV-VIS telescope application are a surface roughness of 1nm RMS or better and a surface wave-front error better than 30 nm RMS knowing that both figures for additively manufactured components are initially of the order of several microns.

3.3 Current design and difficulties

The selected material is titanium (Ti6Al4V ELI grade 23) with reduced oxygen content. The current design is a monolithic mechanical structure with separate light traps and covers as depicted in Fig. 2. Only the light traps are black coated to absorb stray light as efficiently as possible.

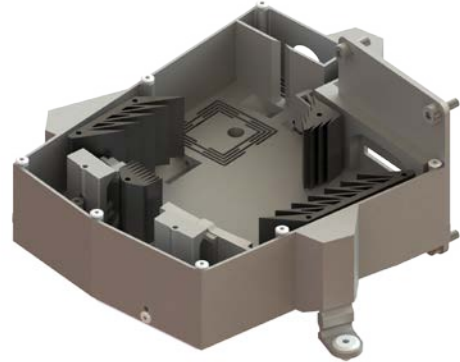


Figure 2. Monolithic structure, baffles and light traps.

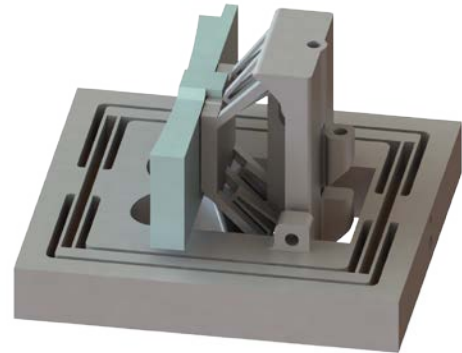


Figure 3. Fine adjustments for M2: ΘY , ΘX and distance along Z

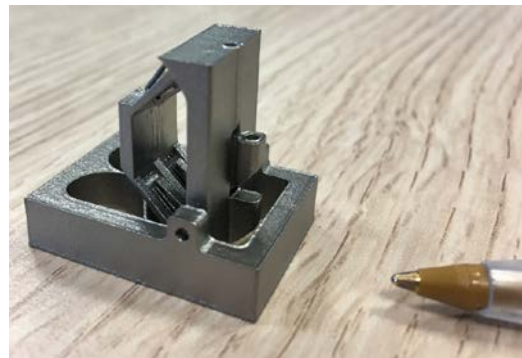


Figure 4. Example of first prototype

3.4 First prototypes and samples results

Fine adjustment features have been printed separately and tested with success: the ranges of displacement and rotation are achieved without permanent deformation of the flexures, which insures a hysteresis-free alignment method.

The first results with respect to surface roughness reduction are quite promising. Treated AM titanium slab surfaces μm -scale RMS roughness is reduced below 1

nm as one can appreciate in the following picture.

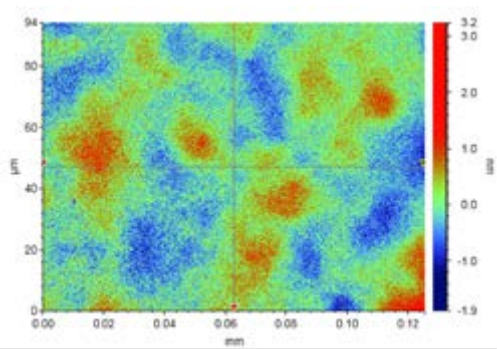


Figure 5. Surface optical profiler measurement of an AM titanium sample after treatment, $S_q=0.5$ nm.

3.5 Lessons learnt and next phases

The lessons learned are mainly on the scale and design areas. The small size of the features requires an iterative design process to understand the constraints due to the AM itself but also to refine the AM parameters to accommodate the size of the components.

The few difficulties encountered during the first manufacturing tests of the optical telescope components were not so much due to the design of the part but to its very small dimensions. Indeed, if there was no problem for the 3D printing, the difficulties appeared during support removal as well as during the post-machining of some features.

The next phase will be the topological optimisation of the monolithic structure and its manufacturing as one single part.

4 HELIUM DISTRIBUTION SYSTEM FOR LAUNCHERS

4.1 Description

Safran AB case study focuses on a solenoid valves housing (SVH) controlling the distribution of gaseous helium to different subsystems of launchers engines or stages. Specifically the study concentrates on the baseplate of this SVH and on the solenoid valves (SV) bodies. Those parts are drilled with several ducts allowing the transfer of the fluid to or from the different subsystems. Fig. 6 gives an idea of how the parts currently look like.

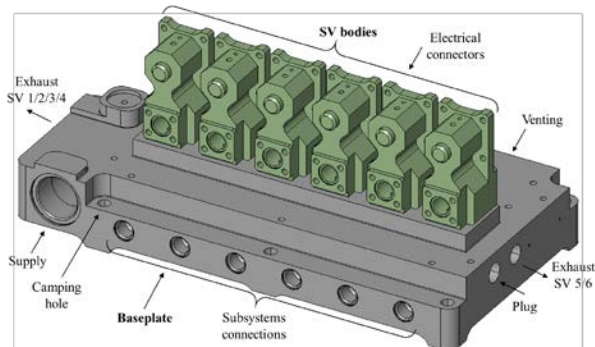


Figure 6. Baseplate and SV bodies existing design developed for ArianeGroup second stage rocket engine

The main SVH interfaces are located on the baseplate: pneumatic interfaces (supply, exhausts, users and venting) are dedicated to the transfer of the helium, electrical connectors are connected to the SV coils and clamping holes are used to fix the SVH on the launcher structure.

Due to the limitations of standard manufacturing the baseplate and the SV are currently manufactured separately before being assembled.

The main objective of this case study is to exploit the benefits of additive manufacturing (AM) in order to achieve cost and mass reduction for those parts.

4.2 Main requirements and challenges

The redesign of the SVH baseplate for AM is made taking in account the requirements applicable to the product.

First, all interfaces listed above (pneumatic, electrical and mechanical) must be retained. Consequently, several geometrical requirements are also applicable (internal ducts diameters, SV bodies geometry, etc.) However, some flexibility is allowed regarding the position and orientation of the interfaces.

Then, mechanical factors must be considered such as minimizing the mass while keeping acceptable stiffness. The part must also be able to sustain internal pressure loads and external dynamic forces (vibrations).

Moreover, environmental requirements must be taken into account. Gaseous helium is used as the internal fluid. Nevertheless, small amounts of gaseous oxygen and hydrogen are also susceptible to come back from the connected subsystems. Fluid temperature can be as low as 150 K and nominal operating pressure is 45 bars. Finally, the part must comply with severe cleanliness rules to ensure it will not contaminate the connected subsystems. Its cleaning has thus to be thought from the design phase.

Keeping in mind these requirements the main challenge of the redesign was to benefit as much as possible from the specificities of AM compared to standard manufacturing processes in order to improve the existing parts in terms of mass, cost, functionality, etc.

4.3 Current design and difficulties

Different design concepts were proposed during the preliminary redesign phase. A trade-off was carried out to select the best concept considering the strengths and weaknesses of each solution.

As shown on Fig. 7 the retained concept keeps a linear alignment of the SV (a circular disposition was also considered). However, the SV bodies are merged with the baseplate to form a single part. Their pilot and power stages are positioned perpendicularly to each other to gain compactness. Note that they were positioned in parallel and on top of each other on the original design (Fig. 6).

All required interfaces can be found on the AM design even though some of them were relocated.

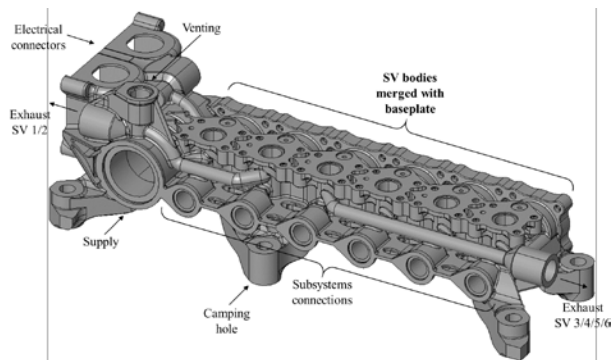


Figure 7. Baseplate current design for AM (finished)

The part displayed on Fig. 7 is a finished part having its different interfaces post-machined. But the part expected to be printed is presented on Fig. 8. This intermediate model is somewhat simplified and adapted to the limits of AM. Excess thickness was added to the functional surfaces to allow post-machining. Moreover tooling points are provided near some clamping holes to allow the balancing of the rough part before starting the post-machining. According to 3DS, few support structures will be needed to build the part. Indeed an important work was carried out to make the part self-supported and to avoid down-facing surfaces.

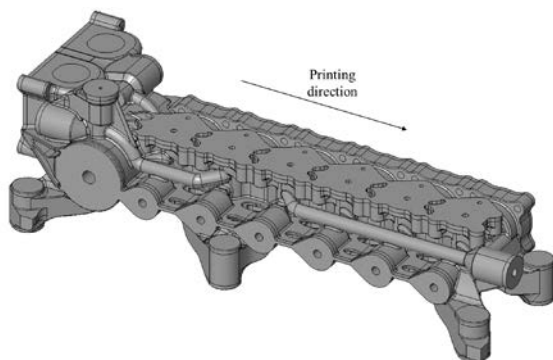


Figure 8. Baseplate current design for AM (printed).

In order to allow a first dry cleaning of the rough part after its printing all internal ducts ends are kept open. This way the non-fused powder trapped inside the part during its building can be evacuated before applying the thermal treatments.

4.4 First prototypes and samples results

Preliminary jobs are currently being carried out by 3DS in order to confirm the machine parameters to be used for the selected material (AS7G06) and to validate the different manufacturing steps.

Different samples are being manufactured to perform some tensile tests, metallographic inspections and chemical composition analysis. These samples will also be used to verify the impact of the foreseen thermal treatments (HIP + T7) on the printed rough material. Moreover, specific samples will be manufactured to validate the cleaning procedure to be applied on the demonstrator part. Others will be used to preform thermal conductivity measurements.

Finally, a first prototype will be produced to confirm the technical feasibility of the different manufacturing steps

(printing, post-machining, cleaning, etc.)

4.5 Lessons learnt and next phases

The first tasks of the project were very instructive. In particular, the redesign phase was very fruitful. Several lessons were learnt with the support of 3DS to redesign a part taking into account the specificities of AM.

The coming task will probably be even more enriching with the production of the first prototype. There is no doubt that many things will be learnt during this phase as the different manufacturing steps will be tested. The design will possibly be slightly updated considering these learnings before manufacturing the demonstrator.

The redesign of the SVH baseplate for AM has allowed reducing significantly the number of parts to be assembled: 7 parts were fused into 1 making also the economy of 18 seals, 1 plug, 12 centering pins, 12 screws, 12 washers and 12 inserts. Consequently, compared to the existing design a mass reduction of around 70% is expected for the AM version of the baseplate integrating the SV bodies. Note that the assembly time will also be reduced.

Additionally the functionality of the part was improved resulting in the deletion of 2 other parts (cover and wires support) as well as 15 screws, 15 washers and 15 inserts for the complete SVH.

5 MULTIFUNCTIONAL BRACKET OF LARGE DIMENSION

5.1 Description

The additive manufacturing with the powder bed technologies enables the realization of complex geometrical parts. The use of this technology seems particularly relevant for the realisation of structures including both mechanical and thermal functions in a single block, so deleting de facto problems of assembly and interfaces leading to thermal flux decrease.

One has been identified as particularly promising by Thales Alenia Space France, having a strong benefit from a new design and a manufacturing process change: a large multifunctional bracket for satellite Telecom platform.

5.2 Main requirements and challenges

Aluminium alloys are of course mandatory for thermal purpose applications because of their combined high thermal conductivity and weight performance. But the LBM technology maturity is lower for aluminium alloys than for titanium or steel due to both laser reflection and powder thermal behaviour in the chamber.

The size of the targeted part (280 x 554 x 343 mm) is also a challenge because of residual stresses leading to non-acceptable distortions or health defects: the risk increases with the size of the part and the radiative surface to be printed. These risks are mitigated by the experience already acquired by both Thales Alenia Space France and LISI Aerospace Additive Manufacturing about large aluminium parts for space flight applications [2].

The main challenges for this application of AM are the

geometry accuracy for thermal control functions and mechanical interfaces (satellite and equipment interfaces), the structure sizing which is expected to resist to launching vibration solicitations and 15 years of life duration in orbit with permanent thermal solicitations. Thermal performance, including roughness and cleanliness requirements are also challenging.

5.3 Current design and difficulties

This secondary structure is supporting an equipment requiring low temperatures. It is the reason why the thermal control of the traditional manufacturing solution is sophisticated involving a liquid-vapour system and a radiative surface.

The mechanical and thermal interfaces are currently both realized by bonding which is not appropriate for a good thermal transfer and induces significant industrial constraints (surface preparation, curing time, bubbles inspection). Moreover, the assembly is done with the help of a dedicated costly tool (jig).

The supported equipment and the bracket tilt are adapted to each mission. Additive manufacturing appears as the most suitable adaptable process to handle these variations.

5.4 First prototypes and samples results

A full redesign exercise was achieved on this large aluminium structure, starting from interfaces locations and mechanical efforts for weight optimisation to reach monolithic full aluminium optimized design. The allowables for AlSi7Mg additive manufacturing alloy were determined by previous produced samples (same processing and post-processing conditions as foreseen for the large bracket). They were used as inputs according to ECSS rules to guarantee reliable sizing margins and to allow a certain robustness to further inner material defects that cannot be avoided with AM. Topological optimization was run, followed by a smoothing step. The thermal aspects were also taken into account in the design such as soft section transitions and optimized amount of material where necessary for thermal exchanges. The thermal flux is thus efficiently conducted through the structure to the radiative surfaces. The Laser Beam Manufacturing scenario was discussed with LSI Aerospace Additive Manufacturing in a co-engineering phase and further post-processing, cleaning and integration steps were anticipated in the design.

The optimized structure integrates a custom appendix to allow switching equipment with different interfaces and introducing an angle if necessary to avoid some reflections, according to the satellite accommodation.

The final weight for such a large structure in AM intends to be less than 2kg, representing a mass saving of more than 40 %.

5.5 Lessons learnt and next phases

This application case represents an additional step in space sub-systems optimization work compared to previous pure mechanical parts. Many inputs and further steps have to be included in the re-design work. Such

large and complex structures push the limits away and invite to adapt the work methodology for both design office and production engineers.

The large size multifunctional bracket is now submitted to mechanical and thermal classical modelling and analysis to validate the final design with regards to the initial requirements.

New building strategies will be experienced to build this structure, starting with preliminary trials with partial geometries. Finally, its performance will be assessed through both vibration and thermal balance testing.

6 CASING FOR ELECTRONIC CARDS

6.1 Description

This case study concerns a power converter electronic unit manufactured for satellite. One of the modules of this unit consists of an aluminium frame supporting relatively big components such as transformers and two PCBs. The dimensions of the structure are 300 mm x 150 mm x 100 mm, with an initial mass of 1400 g.

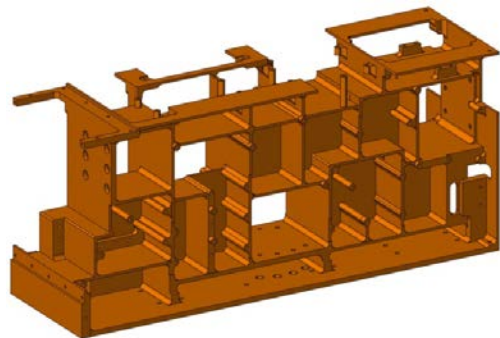


Figure 9. Metal structure to be optimised

This structure is necessary for both mechanical stiffness and for thermal behaviour as the heat generated by the electronics needs to be driven to the baseplate where a cooling by means of heat pipes is available.

The aim of this case study is to perform topological optimisation on this structure, for both mechanical and thermal aspects. Optimisation computations are performed by Open Engineering with OOFELIE::Multiphysics.

6.2 Main requirements and challenges

The design space for topology optimisation is represented in Fig. 9 including massive/dissipative components.

The sole of the structure should be kept as is in order to offer maximal contact with the baseplate for heat spreading.

Vertical walls parallel to the PCB are necessary to prevent Corona discharges (plasma) between the two PCBs – or sometimes electromagnetic pollution. They can be replaced by lattice or grid structure.

Some specified surfaces are necessary to keep the structure in contact with given components or other modules.

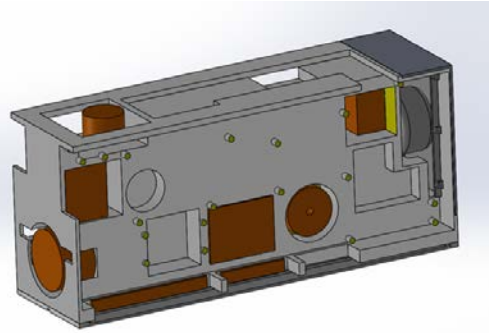


Figure 10. Design space for topology optimisation of the metal structure (in grey). Orange volumes represent big components. The 2 PCBs (not represented) are connected to the small studs.

The challenge with this case study is that a double optimisation is required, which is not widespread yet but seems to be a trend nowadays in the optimisation developments [1]. A first step is to perform each optimisation, mechanical on one side and thermal on the other side and see what results. Further optimisation can be made starting, for instance, from the mechanical optimisation to make the thermal optimisation and *vice versa*.

6.3 Current design and difficulties

The optimisation was also more complex than expected because of the dual optimisation. Computing time was very long due to the large and complex shape of the design space requiring fine mesh in order to correctly fit in the thin areas.

The application of the thermal boundary conditions on the interfaces such as PCB-structure was not easy and leading to tree-like support, so a second iteration was made by neglecting this part.

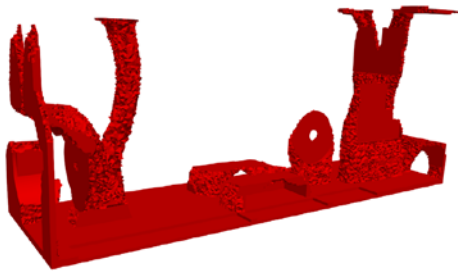


Figure 11. Thermal optimisations. 2nd iteration : heat coming from PCB has been neglected (905 g)

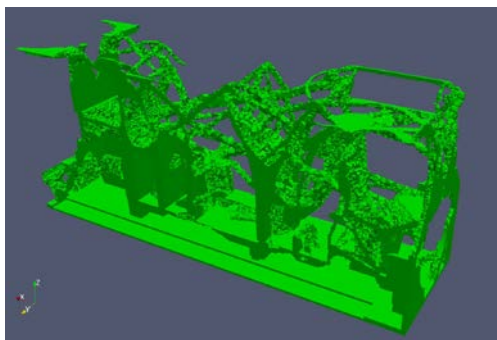


Figure 12. Mechanical optimisation over the thermally optimised structure. (1116 g).

This latter version of the thermal optimisation is used as a constraint for the mechanical optimisation, resulting in a very particular geometry which is not convenient for printing, with lots of small bars. The total mass is quite close to the initial one (1116 g vs 1400 g).

The opposite process, that is to say to add material on the result of mechanical optimisation where necessary to correctly drive heat could lead to a simpler solution.

6.4 Lessons learnt and next phases

This study leads to two big learnings. The first one is that we might have been too optimistic with the goal of dual optimisation. Even if existing software give tools to perform topology optimisation, the result may not be satisfying, particularly if the part has to be manufactured with the constraints brought by SLM technology.

The second one is that it is very complicated to redesign the structure without breaking all of the design. It is better to consider co-engineering in the architecture phase than just perform topology optimisation on an existing part and be constrained by keeping the interfaces identical.

The next step in this study is to perform the thermal optimisation over the mechanical optimisation. Then the vertical wall mentioned before have to be added with grid or lattice structure to prevent Corona discharges.

7 CONCLUSION

The project presented in this paper highlights the need to take into account additive manufacturing advantages and inconvenients from the beginning of the design, not only for the structure but also for all other functionalities. The interaction between the designers and the manufacturers is also essential, including for the post machining. Topological optimisation has proved to be efficient in some cases but developments are still needed for multi-objectives optimisations as well as for the transfer from rough output to printable design.

This project has been very fruitful and allowed all partners to further improve their competencies in design for additive manufacturing and also to establish excellent relationship between the various participants in the complete development of such parts.

8 ACKNOWLEDGMENT

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