DOI: 10.13009/EUCASS2019-606

8TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Steps for Flying Additive Manufacturing Hardware in Space

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Abstract
The qualification of new technologies and new materials in the space sector is always subjected to a high number of qualification tests and maturity steps to go thru. Additive manufacturing technology opens a new opportunity to create new products with better performances than the ones limited to traditional manufacturing technologies, but at the same time the level of risk of implementation is higher due to the lack of maturity of the technology.
To push the use of additive manufacturing technology it is needed to work on these identified risks and mitigate them step by step in the different phases: from requirements identification to material qualification, AM definition of the part and justification, inspection and validation by test.
The opportunities that give us this technology is linked to the topology optimized new parts, looking for mass saving opportunity larger than 40%. Additive Manufacturing (and particularly Powder Bed Laser Fusion) is the technology able to manufacture the geometry output of the optimization process. Additionally, this novel design approach gives the opportunity of reducing the number of parts comparing with the traditional design, and keeping the same functionality.
The aim of this paper is to describe how these steps are covered in two different applications. This use cases are CHEOPS AM Solar Array Brackets in Titanium and Scalmalloy and Umbilical connector bracket in Scalmalloy.

1. Introduction

The qualification of a new technology such as additive manufacturing is one of the most important challenges that the aerospace industry faces nowadays. Additive Manufacturing shows a wide range of new products where performances can be improved or that couldn't exist without this new technology. But AM cannot compete today with traditional manufacturing process with well known behaviour and qualified process. There is a step to walk forward.

The technology is well established in the non flight products. The process to make flight hardware involves setting up the right testing, inspection and process control. This paper is focused in metallic additive manufactured products using selective laser melting (SLM) process. It is shown how all this process is implemented in the product development and definition. This process is followed in to different parts: CHEOPS titanium brackets for solar panels and LAUNCHERS umbilical connector bracket.

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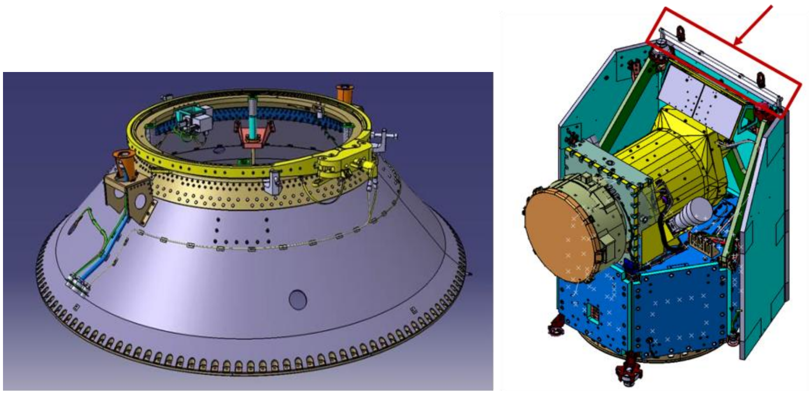

Figure 1: Cheops Solar Array Brackets and Umbilical connector

It will be described the end to end process for the definition, manufacturing, inspection and qualification of the part, with special focus on the importance of the requirements set-up. AM pieces are not covered by traditional design rules. The influence of out of the traditional design cycle variables from different sources (thermal, manufacturing, assembly…) deeply influence the final result and have to be taken into account in the optimization loop.

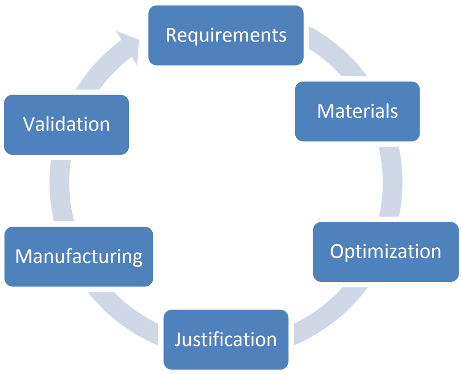

Figure 2: Additive Manufacturing development cycle

2. Requirements

2.1 Product Requirements

The most important step in the product development is the requirements set up. Usually this phase is inherent to the product specification, but in additive manufacturing products it can be found that the lack of design rules that help to cover manufacturing process, needs additional requirements to be set up. These requirements will come from manufacturing, post processing, assembly, inspection and verification phases.

The introduction of this new manufacturing/design process has itself new requirements not covered by the traditional design rules. Design rules will be then part of the qualification of this new technology.

The typical and most important specific part requirements are listed below. There are geometrical limitations: no go volumes allocation, functionality of the part and part adjustability, assembly process, interface points, accessibility,... And also the important functionality requirements such as stiffness and strength of the part will be specified as in a traditional product.

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For example, even if the technology allows reducing the number of parts simplifying the assembly, and even improving the cost, there could be part adjustability requirements that constrain thedesign, and are very important not to forget if we want to do real products.

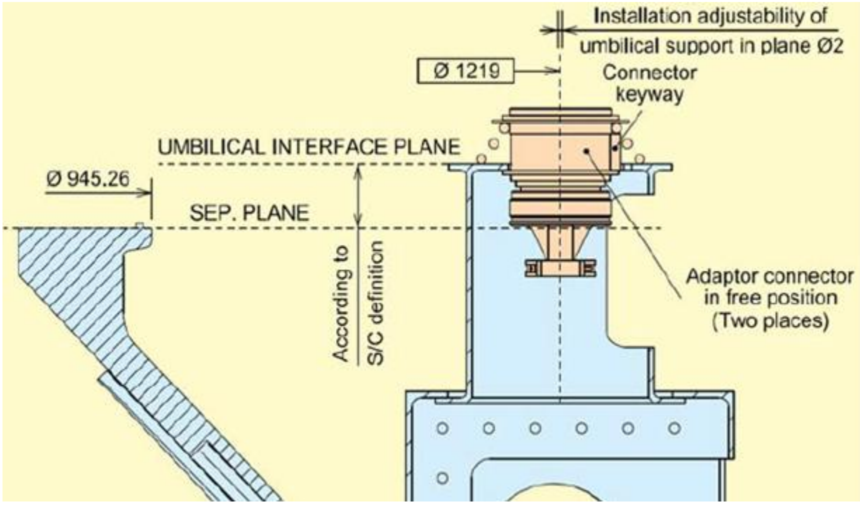

Figure 3: Umbilical adjustability requirement

All these traditional requirements are adapted to the maturity of the technology. For example: minimum margin of safety for flight loads is required to be higher than 3.0 in AM parts in order to ensure the viability of the bracket covering possible changes or uncertainties in loads, geometry and maturity of the technology. When a bracket is fully optimized, it is only sized for the load cases considered in the analysis, the probability to cover other load cases is very low, and in such a case, it means that the bracket is not fully optimized.

Global buckling analysis of the bracket shall also be performed and a knock down factor of 0,5 is considered conservatively in this analysis. This value has been taken as conservative one due to the absence of specific methodology for ALM bionic shapes. A study of imperfections in these shapes could be done, but in this case buckling is not usually a sizing criteria, as the minimum size of the structural elements is also limited by inspection methodology.

2.2 Process requirements

On top of the specific part requirements, process requirements should be collected from the full life cycle of the part. Manufacturing needs to support parts of the structure if the angles are not self-portable. The objective is to minimize the additional supports, even if these kind of elements have additional functions (ie. heat dissipation). Geometrical tolerances are also influenced by the growth direction.

To cover all manipulation and transport land load cases abuse loads of 100N at the edges of the bracket (legs) are considered in the sizing. These are called handling and transport loads, and margin of safety of MoS>0 is required for these loads.

But this is only one example of the different requirements that are collected going thru all cycle of the product: definition, manufacturing, postprocesing, verification, inspection… It is shown in next chapters how different limitations are converted into requirements feeding the development cycle. This process is key in the part definition due to the optimization process: once the requirements are established, the part will be created only to cover those scenarios. If a requirement or loading scenario is forgotten, it is difficult that shall be covered with the design; that will mean that the part has not been optimized adequately.

2. Materials

Additive Manufacturing new materials are fully characterized by the material manufactured, but material properties are closely linked to process parameters in the different machines. Then in any case, for sizing and justification

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purpose, an additional reduction of 10% for strength allowable has been applied to cover the influence of the manufacturing parameters and the kind of SLM machine involved.

When a material is selected usually it is taken into account: density, stiffness, strength, thermoelastic behaviour, electrical and thermal conductivity. The study cases of CHEOPS and UMBILICAL CONNECTOR are a good example of how material qualification is very important into the selection of the material, and the main factor even over the behaviour needed.

In case of CHEOPS SA brackets, the best material for the technical needs is the Scalmalloy®, but in this case the flight part was done in titanium as the process for this material was already qualified. Anyway, a Scalmalloy® part was designed, manufactured and verified, opening the possibility for future use.

UMBILICAL CONNECTOR bracket was developed in Scalmalloy® thanks to the steps forward taken in the previous project. This decision made possible to optimize the part in terms of mass and cost. The maximum mass saving can be ensured by using aluminium instead of titanium and the cost is also reduced by, avoiding the need of HIP in the aluminium.

Scalmalloy® aluminum is a high strength aluminium, material data sheet for both materials Titanium, AM conventional aluminium and Scalmalloy® mechanical properties are shown below:

	AlSi10Mg	Scalmalloy	Ti6Al4V
0.2% Offset Strength (Mpa)	230	470	1020
Tensile Strength (Mpa)	350	520	1070
Specific Strength	131	195	243
Enlongation at Break (%)	6	13	14
Vickers Hardness HVO,3	119	180	320
Density (g/cm^3)	2.67	2.67	4.41

Table 1: Material properties

2. Optimization and Justification

As it has been already mentioned, the main strength of AM parts is that almost all potential of the current optimization tools can be surrogated to the consecution of a part with less manufacturing constraints than the traditional machined ones. The optimization process can be divided into different steps, being the optimization constraints and goals at the core of the process. These constraints and goals will arise from the requirements already collected, connecting the different phases of the design.

Requirements are the baseline of the optimization loop and help to define the different steps: volume allocation, constrains and objectives and manufacturing orientation.

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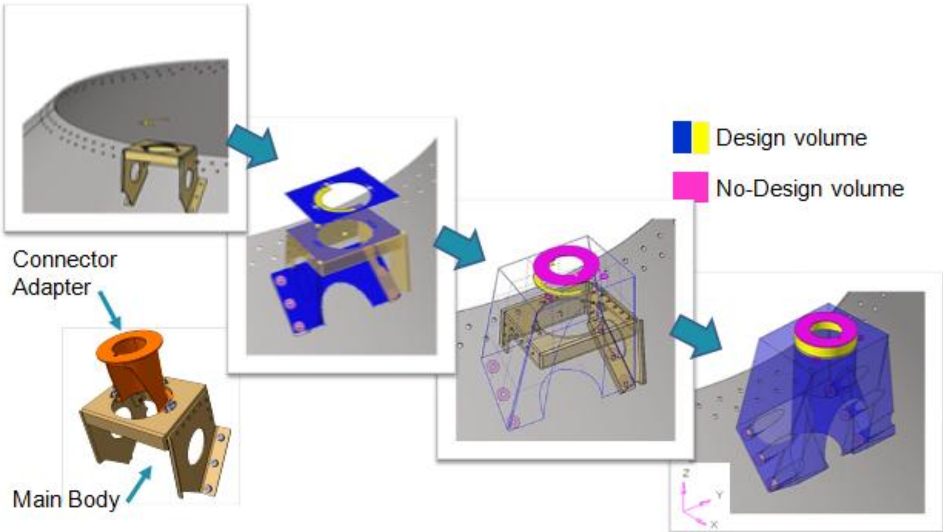

Figure 4: Optimization process: allowable volumes

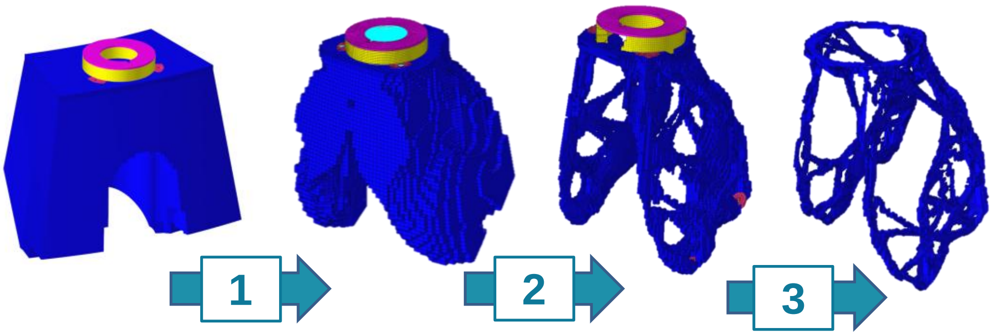

Figure 5: Optimization process: goals

Allowed volumen as defined in functional specification is key to define the design volume but assembly constraints (such as tightening tools or accessibility) should also be taken into account.

Since the optimization process is based in the mesh of the FE model, and taking into account that a compromise between mesh refinement and an affordable computational time should be adopted, the resultant geometry is quite coarse. Thus, in a next step, it is required to generate a clean geometry of the cleat by means of proper CAD software.

Even when in the previous picture the optimization process is presented as somehow linear, different inputs feed the process, mainly aiming to consider the best manufacturing approach. More detail will be provided in the manufacturing chapter.

All this process can be made with different commercial or freeware tools but, the final justification is performed by means of qualified software, accepted as reliable for the final customer.

2. Definition for Manufacturing

One of the key factors for success is to design for manufacturing which means that manufacturing constraints are continuously feeding the design process. One of the main drivers of the design is the manufacturing direction as it is going to impact the feasibility of the part. Choosing a wrong manufacturing direction impacts the mechanical properties as well as the geometry accuracy and eventually the cost. Whenever only one direction is feasible the design of the part is adapted to optimize the support structure.

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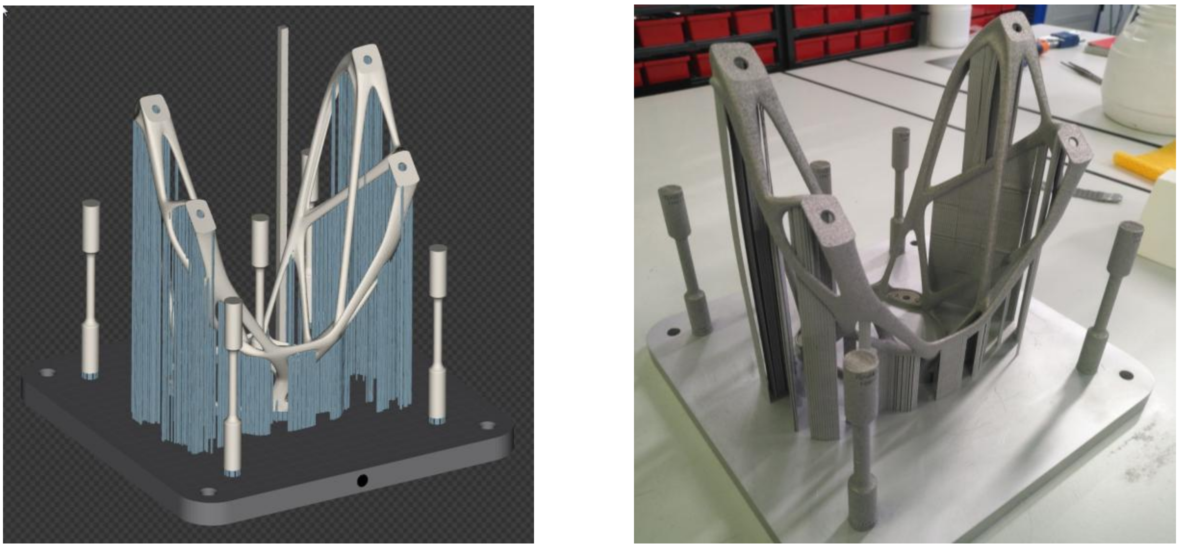

Figure 6: Umbilical Bracket manufacturing position and supports strategy

This support structure has different aims, from providing support to the geometry that is being built to ease heat dissipation and even to withstand forces derived from machining or post processing operations. As a general rule it is important to minimize the support material because the buy to flight ratio is increased (less waste), the building time is reduced and the surface finishing of the part is better with minimum post-process operations. Nevertheless supporting structure has to be analysed in detail depending on the role played during manufacturing. In Titanium parts that will be subjected to a HIP cycle, supporting structure is part of the strategy to minimize deformations during this thermal treatment. The same way, supports can be used as machining aids whenever they are designed with this purpose.

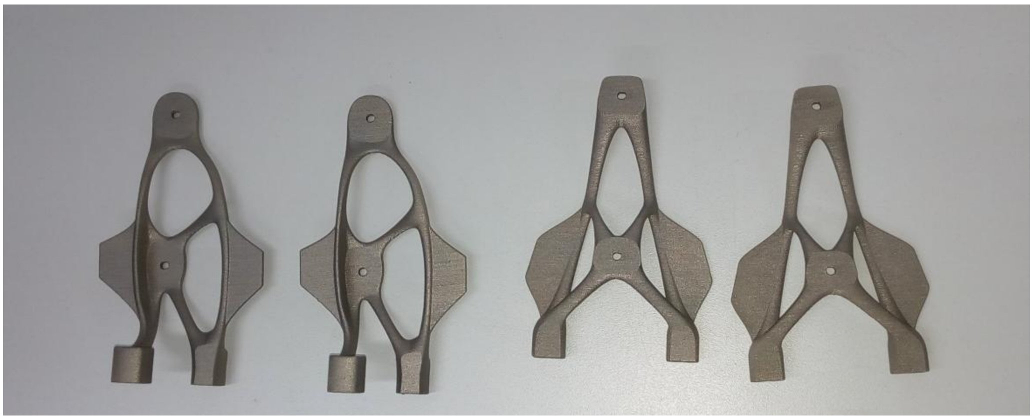

Figure 7: CHEOPS SA Brackets built with manufacturing aids for machining

Some applications require really stringent tolerances that cannot be assured by SLM processes. The direct approach is to foresee provisions in the built part mainly in form of overthickness so the gap between the built part and the theoretical part can be filled by means of the machining of the part. This building strategy also accounts for extra-material surrounding the interfaces and avoids building the part with interface holes. The quantity of material to be added deals with the accuracy of the process, the geometry of the part, the machining capabilities and the requirements in terms of assembly, tolerancing… The building strategy has to be defined for each single part (one strategy per design).

The non direct approach is to analyse in detail the building process, considering all the building parameters, optimizing the supports and correcting the stl file to be sent to the building machine so manufacturing deviations are minimized in the produced part. The applicability of the direct or non direct approach depends on the number of units, the calibration of the prediction with the process and of course on the final tolerances to be reached.

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1.1 Postprocesing

The aim of post processing operations is to fill the gap between the built part and the final part. These processes include thermal treatment, machining operations and surface treatments. All of them are necessary to get a flight part.

The group of thermal treatments is highly dependent on the material to be used; while for Titanium HIP is nowadays required in order to modify the micro-structure of the material, aluminium parts (including Scalmalloy® parts) are usually subjected to annealing processes limited to residual stress relief. The deformation risk associated to HIP is very high while it is almost negligible in the case of annealing.

As it has been previously introduced, machining operations are necessary not only to remove the supports necessary to build the part but also to move the part to its final geometry according to specification. The overthickness foreseen in the manufacturing strategy can be removed or not depending on the manufacturing results. This is also the step when interface holes and threads are manufactured as nowadays, accuracy provided by CNC machines is much higher than by SLM processes. Machining operations are inducing loads in the parts. These loads have to be taken into account during the design phase and included as an additional requirement. It is possible to reduce the machining loads impact in the design of the part by including manufacturing aids in the part extracted from the SLM machine. These manufacturing aids are usually additional surfaces that can be used for tooling fixation during machining. This tooling reduces stress and vibrations during machining operations. The machining aids are removed in the final part and, as already mentioned in the previous chapter, are part of the building strategy of the part.

The last group of post-process operations are the surface treatments. These processes aim to change the appearance or properties of the surfaces and are usually deemed to improve durability and avoid corrosion. In general, roughness got by AM building is around 15 microns and is very different from the roughness obtained by extractive methods. It is necessary to reduce roughness in certain surfaces not only because it could be required by the functional specification (for example to assure a good thermal contact) but also because other processes (such as gluing different attachments) are not qualified for surfaces obtained by additive and it is easier to machine or polish them rather than qualify the process in a new substrate.

2. Validation

In order to be able to flight parts, the process has to guarantee repeatability along the different manufacturing batches and the provision of the raw material has to be made from qualified providers. Same approach applies to all the processes surrounding the manufacturing: annealing, supports removal, surface finishing…

Regarding the manufacturing process, different parameters of the laser and chamber are monitored all along the process and archived in a log file delivered with each batch. These parameters have to be maintained within the thresholds defined for a successful manufacturing.

1.2 Test coupons

The quality is also assured by accompanying each batch of pieces with additional samples for Quality Assurance control. These test coupons provide information about the manufacturing process in the analysed batch and is useful to detect anomalies or lack of quality in a certain manufacturing event.

There are different types of coupons: density coupons (to detect porosity or layers with lack of fusion), tensile coupons (to guarantee the material properties), fluency samples … that are used to verify that different aspects of the process are inside the qualified parameters.

1.3 Inspection

Regardless the previous considerations there are some random defects that can appear in the parts. The parts have then to be 100% inspected. This inspection has to be made by NDI methods and has to be able to detect porosity and eventual flows. RayX and tomography are the main methods used today in 100% of the parts.

The inspection is also used to verify geometrical compliance.

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1.4 Testing

Subsystems in space industry are used to be tested under acceptance or qualification loads.

Nowadays, these brackets have to be tested up to qualification levels. The number and typology of the tests will depend on the programs or application. At least the most critical environment should be covered and predicted stiffness demonstrated. In the case of CHEOPS SA hoisting brackets, only quasistatic loading was applied, while the umbilical connector was tested also under dynamic environments.

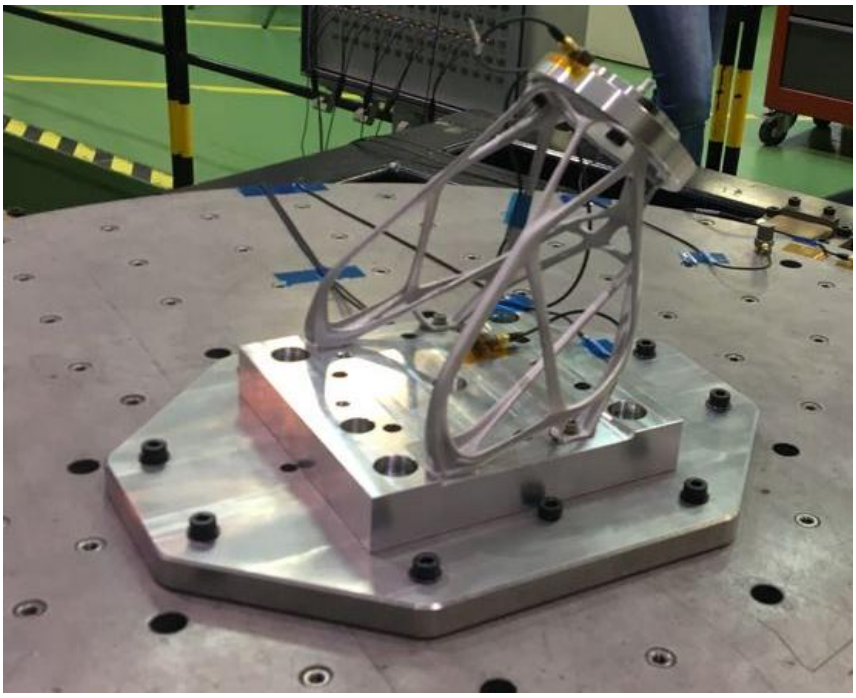

Figure 8: Umbilical connector dynamic analysis set up

There are additional difficulties associated to the testing of these brackets, as there is, in general, lack of surfaces where to implement gauges, accelerometers or any other measuring device. Special attention has to be paid at the position of the gauges and the gradients in the area. The instrumentation of the brackets has to be designed attending to the aim of the test, understanding the limitations of the brackets and tailoring the qualification strategy to the available data.

In the case of a serial of brackets, it could be accepted to qualify the design by means of one qualification test campaign and design an acceptance test policy for the others, in order to improve the production process in terms of time and cost.

2. Conclusions

Steps for flying additive manufacturing should be robust and solid not to take the new technology apart. Thanks to the verification of every part, testing under qualification loads and additional material test coupons, these parts are walking the path for flight. All this inspection and verification needs make the product more expensive, charging the part with additional cost tasks, needed for new technologies.
Once the process is qualified for a specific material, in a dedicated machine for an specific part, production can be addressed in competitive prices.
Comparing cost of the technology has to deal as well with the performances of the part, improved performances and new products can be addressed with additive manufacturing.

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[3] QUALIFICATION CHALLENGES WITH ADDITIVE MANUFACTURING IN SPACE APPLICATIONS Christo Dordlofva* & Peter Törlind* *Department of Business Administration, Technology and Social Sciences Luleå University of Technology, 971 87 Luleå, Sweden