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# Additive Manufacturing (AM). Status in Airbus Defence and Space (Spain)

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## Abstract

The Additive Layer Manufacturing (AM) is a manufacturing technology that helps to obtain optimum and complex designs which can be produced fasterand leading to weight reduction, costs savings and lead time reduction. Airbus plans to introduce elements using AM.
Alongside AM, optimization techniques have been used for many years and have gained more relevance with AM for two reasons: Its capability to produce complex geometries and its use to reduce cost and lead time. Airbus is progressing with different Authorities to certificate structures manufactured with this technology. A stepped approach is being agreed and some examples are herein presented.

## 1. Introduction

The Additive Layer Manufacturing (AM) is a new technique that helps the industry to obtain more optimized and complex designed structures which can also be produced with higher speed leading to weight reduction and costs savings. In this line, Airbus has a plan to introduce in the aircraft new or better designed elements to be produced using AM. It is also an objective and obligation of Airbus to investigate the properties and characteristics of the possible material to be used with this new technology.

Due to their inherent flexibility, AM processes are being considered for a variety of application domains that span new parts, part repairs and the aftermarket. At the same time, there are a number of implementation challenges identified by multiple researchers and organizations, including the complexity of manufacturing process, the applicability of conventional NDI inspection methods, the lack of industry standards and design allowables, etc. AM processes have complex physics, and usually involve millions of highly localized (on the order of 20–50 lm) melting and re-solidification cycles. The resulting microstructures may be anisotropic and/or location-specific and, in general, differ from cast or wrought microstructures for the same alloy; various types of material anomalies may be introduced, such as porosity or lack of fusion. Complex near-net or final part shapes, combined with AM microstructural attributes, may challenge conventional NDI capabilities, as compared to wrought or cast material

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systems. These technical challenges are further exacerbated by the current lack of field experience with AM components as well as limited full-scale production experience, at least in commercial aviation applications.
As the main responsibility of Airbus is the safety, for the implementation of AM, as for any new material or manufacturing technology, a set of calculations and tests must be carried out. Several case studies have been set to select the best parts to start introducing this new manufacturing technology. Some of them are presented in this article which is centred in the advances accomplished by Airbus Defence and Space in Spain taking into account both, plastic and metallic materials.

Within the metallic materials the Titanium development is mainly performed by Airbus Operations while Aluminium alloys are leaded by Airbus Defence and Space. The manufacturing technology, used for metallic materials, is powder bed fusion (PBF) based on the fusion of metallic powder using laser or electron beam as source of energy. Plastic materials are developed following two different techniques: Filament Layer Manufacturing (FLM) and Selective Laser Sintering (SLS) working with Polyetherimide and Polyamide respectively.

All new designs have been studied and developed in a process of concurrent engineering with different departments: design, structural analysis (stress and fatigue & damage tolerance), structural testing, loads, AAR system, acoustics and vibration…

The objective of this article is to briefly introduce the advances carried out by Airbus Defence and Space in AM implementation containing also a short introduction to the optimization process in AM and to the way for certification of this manufacturing process as well as a description of some of the parts selected for AM implementation

## 2. Optimization Driven Design Process

As presented during the introduction AM capabilities allow the engineers to design new shapes which resulted very difficult to obtain or even impossible by traditional manufacturing technologies. To exploit the full potential of AM technology, optimization techniques must be used for two main reasons: first, weight reduction which may bring benefits to aircraft industry but are essential for space sector and second, cost reduction for AM parts. Current technology maturity makes the AM cost for aerospace applications a challenge that the industry must face. In AM technology, unlike subtractive traditional technologies, the less material printed the lower cost of the final part is achieved. In order to make profitable the AM in the aerospace sector engineers must use all resources in their hands to make cheaper the AM design.

Optimization techniques are well known by the Aerospace industry since they have been used for decades with different materials (CFRP, metal alloys…) and traditional manufacturing technologies. Two main optimization techniques may be applied during the design process.

1. Topology optimization. This optimization technique attempts to find an optimal material distribution for a given set of load cases (loads and boundary conditions applied to the structure). Therefore the engineer can locate the material where is actually is needed removing it from the areas where the material is not effectively working. This optimization technique usually generates shapes commonly known in the literature as "organic" or "bionic" that can be more easily reproduced by AM. However, even if AM is capable to reproduce the topology optimization output shapes, the engineer must understand the topology optimization result as a guide to propose a new design supported by the combination of the mentioned topology result plus engineering experience. For this reason, topology optimization techniques are frequently used, independently of the manufacturing technique, during a conceptual design phase.

2. Parametric optimization. Once a preliminary concept (based or not on a topology optimization result) is defined, parametric optimization techniques may be used to get the optimal dimensions of this preliminary concept. These techniques, commonly known as size & shape optimization techniques in the optimization community, are able to modify the structure dimensions or attributes to minimize/maximize the objective function (mass minimization, stiffness maximization…) respecting a set of constraints defined by the engineer (maximum stress or displacement allowed, frequency range for natural frequencies…).

Although the benefits of applying structure optimization in the design cycle are clear, its use for traditional material and manufacturing technologies has been limited in the past only for cases in which the improved structure

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performance justified the engineering investment (mainly time) to achieve it. The optimization application alters the traditional design process applied in the industry. Figure 1 shows the traditional design process versus the more complex optimization driven design process.

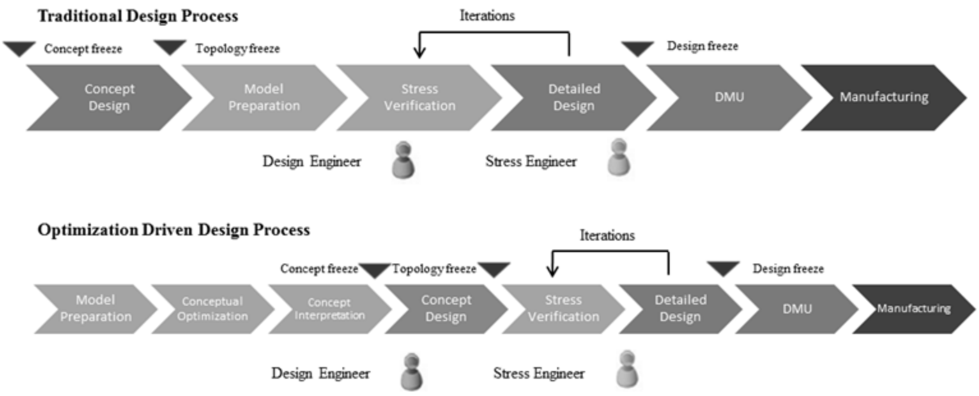


Figure 1: Traditional Design Process versus Optimization Driven Design Process

In previous processes Topology optimization technique supports the conceptual optimization step whereas parametric optimization techniques may support the iterations needed during the detail design definition.

For AM Parts, especially at early technology implementation phases where the costs remain still high, the decision about the application of this more complex design process becomes trivial as the design process must be cost reduction driven. Figure 2 shows the optimization driven design process to be applied for an AM part. In this case, manufacturing preparation activities (for example: orientation within the printing chamber) must be taken into account before the final design is frozen.

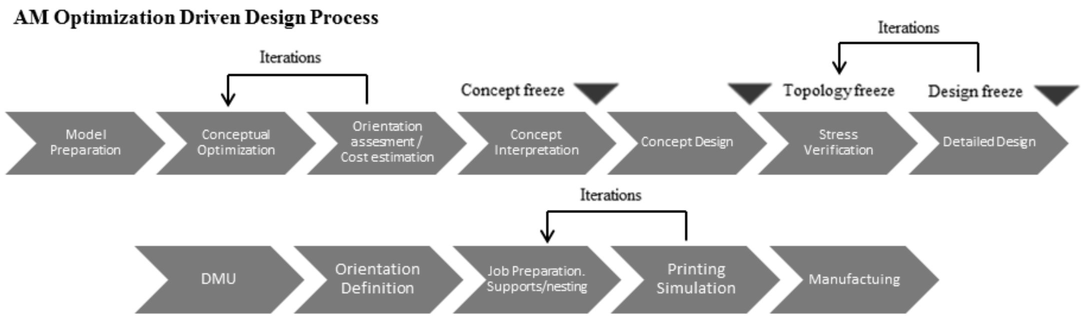


Figure 2: Optimization Driven Design Process for an AM Part

## 3. Manufacturing Engineering

When a new technology bounds into the existing ecosystem of available technologies, it is necessary a new balance after a competition; ending up in a reorder of the individual sharing. Also, this competition would eventually force to stretch the capabilities of the existing technologies, fighting to reduce the loss of its own sharing (this could be the case of employing optimization techniques for the design of parts to be manufactured by traditional technologies, decoupling optimization and additive manufacturing). All this implies a benefit in terms of cost reduction and/or an improvement of the suitability of the designs (the larger the list of available manufacturing technologies, with their own pros and cons, the more likely a part will be manufactured by the most appropriate technology).

The manufacturing process itself will impact the cost of the part, but also to its suitability to the different applications through the features that the process provides to the part. So let us consider a generic manufacturing process and check how the proper selection of operations and acceptance criteria can impact on cost and this features of the part.

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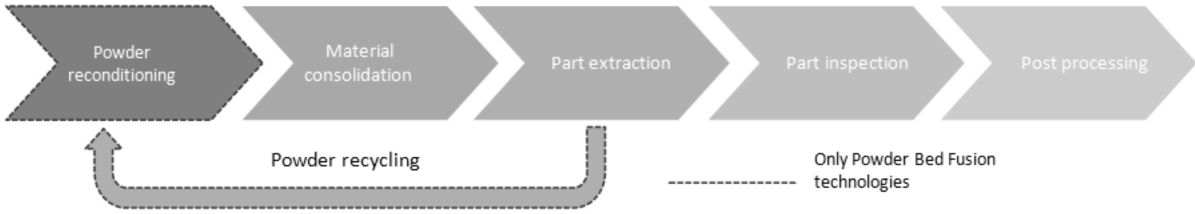


Figure 3: Schematic manufacturing process

1. Powder reconditioning:

In case of Powder Bed Fusion (PBF) technologies, the raw material is provided in powder format, with a particle size distribution being part of the material specifications with the same importance as the chemical composition. PBF requires large amount of powder to operate, since the chamber is filled at its maximum height although only a small fraction of this powder is molten to integrate the part. Even if the powder has been far from the hot dot of the energy beam (laser or electrons), it can be affected by either the high temperature reaches in the chamber (that would lead to partial sinterisation of powder) or splashes from the melting pool blown with the shielding gas flux.

Thus, we have on one hand a large amount of unmolten powder and on the other the certainty that it could include larger particles[1], so a process to ensure that the powder remains within the specified parameters (in terms of grain size distribution) is required. This process can include drying of powder to remove moisture, "sieving" and/or maximum number of sieves (reuses). This latter condition comes from the need to ensure that chemical composition remains also stable due to the reactivity of some alloys (as aluminum) and the high temperatures reached in the chamber that favors chemical reactions that could alter the composition[2].

So, a more detailed powder reconditioning task would consist of:


Figure 4: Task at reconditioning of powder

Drying can be done by mean of industrial desiccant bags, and sieving shall be carried out in controlled atmosphere (in order to avoid reaction with air); both operations are mandatory at least for aluminium alloys and the latter for any material (including polyamides).

The maximum number of sieves allowed has a huge impact on the cost of part, since this criterion can convert an "in principle" valid material in scrap quite rapidly. A rationalisation based on proven behaviour of the powder during a complete cycle (being part of a fabrication, being recycled, dried and then bottled for reuse) is required to increase raw material use as much as possible. In case that there is no evidence of properties degradation of the powder along the uses, it can be relaxed including the more costly inspection that the chemical composition represents.

So the key aspects in case of reconditioning of powder would be:

- Use industrial solutions for drying and sieving (in controlled atmosphere).
- Increase as much as possible the maximum number of recycles by testing how the grain size distribution and chemical composition evolves with the reuses.

[1]Indeed, it was noticed in analyzed samples of used aluminum powder the presence of particles around 1mm of larger dimension with a combined weight that represented 10%÷12% of the weight of the sample inspected

[2] For instance, traces of oxygen in the chamber atmosphere or from the evaporated moisture present in the powder could become alumina on the powder surface

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- Avoid the chemical composition tests for every single reuse of powder and consider to maintain this only in quite large number of recycles and to determine the maximum number of recycles itself.

2. Material consolidation:

This operation tackles the transformation of the raw material (normally wire or powder) in a solid through the addition of energy (heat, laser beam of electron beam) and represents the most costly step in the manufacturing of a part. The material consolidation is governed by a large number of parameters, much of them related to the scanning strategy. Selected parameters determine the building time (that directly impact on cost) and other aspects that can affect to the process in a more subtle way.

The cost of this operation is mainly driven by its duration, and we can do the simplification of considering this is as a function of the volume of the part (through the time required to melt the powder) and the time to spread the powder for every single layer. The former can be described as $t_m = \eta \cdot \frac{C \cdot V \cdot \Delta T}{P}$, and the latter as $t_s = t_r \cdot \frac{H}{thk}$.

| | |
|---|---|
| $\eta$ | is the efficiency of the heat absorption of the process, and would include the influence of the vast number of parameters |
| $C$ | is the Specific heat capacity of the alloy (in $J/mm^3 \cdot ºC$) |
| $V$ | is the volume of the built |
| $\Delta T$ | is the required temperature increase to melting point |
| $P$ | is the power of the machine |
| $t_r$ | is the time that requires the recoater to spread the powder in one layer |
| $H$ | is the maximum height in chamber of the built |
| $thk$ | is the layer thickness |

Considering an aluminum alloy, increasing the power of the laser together with an increase of the thickness of the layers would end up in a reduction of the building time, but it impact in the quality of slicing (the larger the layer thickness, the lower the resolution of the geometry we can obtain), and also could degrade the powder more intensively and favors the appearance of flaws in the part. Also, the proper selection of the scanning pattern could promote the high cooling rate of the melting pool, and then, achieve a refined microstructure, that will impact on mechanical properties. Finally, the proper combination of layer thickness and other parameters of the face-down surfaces could end up in better surface quality just right after the built. This is of special importance since it could ease subsequent operations (for instance, by avoiding chemical milling of aluminum alloys that are requested for dye penetrant inspections).

So the parameters selection for the material consolidation has to consider not only the manufacturing time, but also how it would impact the powder, the internal defects, the mechanical properties and the need for surface enhancing operations. As a general rule, increasing the power and layer thickness to their maximum compatible with the requested quality would be the best approach for a cost reduction. Beyond that point, in which this increase deteriorates other features, it shall be consider inside the end2end process.

3. Part extraction:

This operation has a bigger impact in case of metal PBF processes than for FLM, for which the part is normally accompanied with a supporting structure built from a secondary extruder made of a dissolvable material; withdrawing the part from the base plate (that is just stuck by adhesion) and from the surrounding supports is relatively easy. Also in case of SLS, since the part requires no support to be fabricated (although it is important providing opening for the powder to go out from closed volumes).

It is in PBF, and especially in Selective Laser Melting (SLM), where it has to be considered this point with a bit more of attention. Unlike Electron Beam Melting (EBM), supports do reach the base plate and stiff the part to avoid distortions due to residual stresses during cooling down (the supports are welded to the upper surface of the baseplate, while for EBM, these supports are intended to drain the heat and just are embedded in the sintered powder cake). If it is not properly designed, this support structure can act as confining walls that avoid the powder to be withdrawn after the build, what represent a health & safety risk (for the powder to be present during the sawing of the supports) and an over cost that this lost powder represents. Figure 5 shows the view of an elbow from the Air-to-Air refueling (AAR) system of MRTT family made from AlSi10Mg alloy where can be seen how supports are not directly attached to the baseplate in order to ease aspiration of powder after built.

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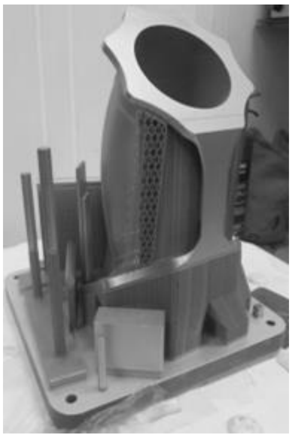


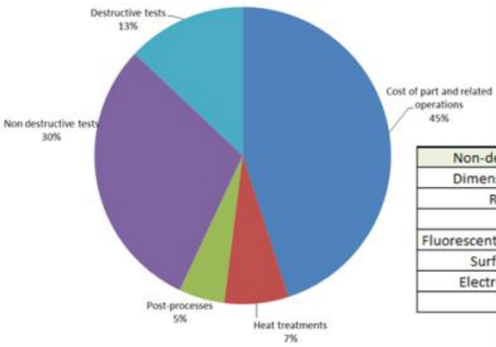
Figure 5: Opening in support structure to ease powder aspiration in AAR System of MRTT aircraft

Design can also affect the ease with which the supports can be removed. In case of plane surfaces, it is possible placing this surface against the baseplate to avoid supports. Performing the removal by Electrical Discharge Machining (EDM) provides a ready surface taking advantage of this required operation.

So the part extraction can be improved (and thus the cost of this operation) by the design of supports (to not to entrap powder and to ease its removal) or by welding the part directly to the baseplate through a plane surface and making use of EDM to detach from it.

4. Part inspection:

The combined cost of part inspections (including destructive and non-destructive testing) can reach almost as much as the part manufacturing and its associated costs in case of metallic parts. In the next figure it is shown the qualitative cost break-down for an aluminum alloy.




| Non-destructive testing | Destructive testing |
|---|---|
| Dimensional inspection | Macrography |
| Radiography | Micrography |
| CT Scan | Chemical composition |
| Fluorescent penetrant inspection | Tensile test on accompanying samples |
| Surface roughness | |
| Electrical conductivity | |
| Hardness | |

Figure 6: Cost break-down of the manufacturing of an aluminum part by SLM

The process modifies so deeply the nature of the material from the supplied raw format to the final usage that it is not possible relying on the acceptance at supplying to ensure that the consolidated material is acceptable. For loaded parts (mainly metallic) is currently mandatory some kind of inner volume and chemical composition checks. Unlike chemical composition that appears to have to be maintained for metals with no foreseen alternative, inner volume inspection presents different possibilities. It is accepted that the most precise flaws detection for metallic materials is Computed Tomography (CT), but its high cost and the low number of qualified suppliers discourage its employ, and specifically, maintaining this inspection together with X-Rays[3].

[3]It tends to be maintained both inspection but just as a preliminary stage to set up the X-Ray inspection, for it to be able to achieve the same level of certainty in the flaws detection for certain part and with the intention to remove CT from the process for that part

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On the other hand, surface roughness limits and geometrical description are present in the drawings and/or models, so they are mandatory. Fluorescent Penetrant Inspection (FPI) is maintained as the simplest way to discard superficial damage caused by residual stresses during fabrication. Only Hardness and Electrical conductivity appear to be redundant[4].

Destructive tests have to be maintained due to the inherent complexity of the consolidation process to ensure that the final material complies with specification, till the influence of the different parameters is fully understood and the process can be defined by the individual values of the key parameters. Therefore, the rationalisation of the inspections comes from the selection of the inner volume inspection method (X-Ray or a very-few-projections CT), the withdrawal of hardness and electrical conductivity tests and the reduction to the minimum of destructive testing (what will be possible once gained enough confidence with the stability of the process).

5. Post processing

Post-processes bring the part right from the heat treatment to the condition to be installed. We will find operations such a surface enhancing, boring/reaming, chemical etching, machining, anodizing and painting. It was depicted when treating the consolidation of material and inspection of parts that it is possible affecting the post-processing by the proper selection of parameters, for instance, by enhancing the surface quality to make unnecessary the chemical milling prior to FPI. Figure 7 shows the quality of one elbow from the AAR System of MRTT family and a zoomed view of its surface.

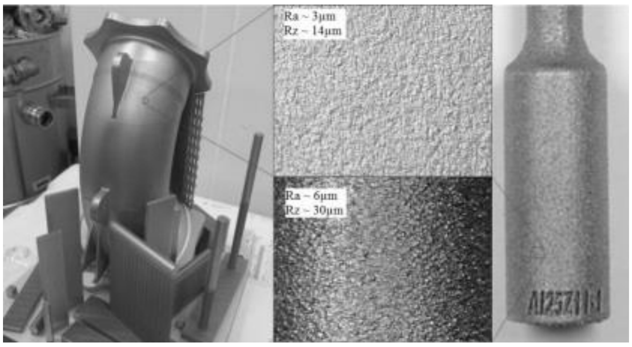


Figure 7: Surface condition of AAR System elbow compared with a regular surface condition of a tension sample from the same material

As a rule, the less material that must be removed and the less required tooling, the better. That means:

- The holes should be printed at a preliminary diameter in case of large diameters, or at least determined their position for small diameters (to avoid the employ of drilling patterns), at least in case of holes with large position tolerance.
- The addition of material in mating surfaces (to be machined) shall be the less compatible with the uncertainty of the final shape after heat treatment
- Chemical etching prior to FPI has to be considered as part of the post-processes, since it modifies its condition.
- It can be tuned the parameters set so that achieving a surface quality compatible with FPI; the ability of the part to be inspected through FPI imposes additional requirement that sometimes exceed the roughness requirements specified in drawings and/or models.
- Chemical milling can be withdrawn from the process for aluminum alloys if the required roughness and the ability to be inspected through RPI is achieved just through parameters set tuning and etching prior to FPI.
- Anodizing and painting is specified in the drawings and/or models, so they have to be maintained.

[4]These inspections were performed usually to confirm the nature of the material and temper, that are proven by destructive tests

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## 4. AM Way of Certification

As described in previous chapters in AM, the material is consolidated during the printing process. Subsequently, the material properties are highly dependent on the printing parameters, and also on the post process treatments (like HIP or surface finish). Different levels of qualification are considered to demonstrate that the material, part or process complies with the expected requirements, in a robust and reproducible way.

1. Material qualification:

   Within material qualification, the powder characteristics (chemical composition, form, size, density…) that a powder has to ensure to obtain the expected final properties after part manufacturing, are stablished.

2. Part qualification:

   The part qualification demonstrates the accuracy of the part to its requirements. It regards to the material properties and also the functionality of the part, which is normally validated by tests. It is not necessary to use a qualified material, but it has to be demonstrated that the material properties obtained for the part are the required ones to attain its functionality.

3. Process qualification:

   The process qualification evidences the capability to produce, within determined parameters, different parts with the accurate material properties, geometry and surface finish. Additionally to a process specification with the key parameters frozen, it is required to have a qualified powder and material specification.

Part and process qualifications are always obtained for a unique machine and site. Any change on the parameters specified on the qualification reports involves a delta in the qualification. With the qualification it is demonstrated the fulfillment of specific requirements, but it is not evidenced the safety for flight. This is part of the certification process. Only parts to be installed on an aircraft are certified, not the raw material powder or the process. Most of the data obtained during qualification is reused as certification evidence. The main certification concerns with AM technology are related with the material properties, process robustness and repeatability. That means the following paragraphs of CS 25 must be fulfilled:

1. CS25.603 – Materials:

   *All materials used to produce structural elements whose failure would have a negative impact on safety must:*
   - *Be established on the basis of experience or test*
   - *Conform to approved specifications that ensure having strength & other properties assumed in the design data*
   - *Take into account effects of environmental conditions*

   These conditions are covered by tests at coupons level performed during material, part or process qualification.

2. CS25.605 – Fabrication Methods:

   *All manufacturing processes must:*
   - *Produce a consistently sound structure*
   - *If a fabrication process (e.g. gluing, spot welding, heat treating) requires close control, the process must be performed under an approved process specification*
   - *Be substantiated by a test programme*

   The robustness and repeatability of a specific process with the frozen parameters is substantiated by the part or process qualification tests.

3. CS25.613 – Material Strength Properties & Material Design Values:

   *Strength and Design values used to design structure must:*
   - *Be based on testing of materials meeting approved specifications to establish design values on a statistical basis*

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Design values are obtained on a statistical basis from coupon tests obtained during material, part and/or process qualification. Moreover, knockdown factors can be applied to cover uncertainties, to be always on the conservative approach.

4. Specific domain requirements:

   Strength and deformation, fatigue and damage tolerance, flammability, toxicity, leakage, conductivity, … To be proved by specific analysis or tests

Due to the continuous development of the technology to improve the material knowledge, a step by step approach regarding the criticality of the parts is considered.


Figure 8: Step by step approach for criticality

The level of criticality achievable for each part depends on the acceptance of a variety of defects inherent to this technology (lack of fusion, porosity, inclusions, distortion, roughness…) and the available inspections to screen them. AM technology is evolving along with the experience to minimize defects, effectiveness of the inspections and improvement of the final result. Thus the criticality of the parts is progressing from the non loaded parts to statically sized, with a deeper awareness of the static material properties. Now the challenge is to deepen in fatigue and crack growth behavior to develop the next criticality level.

## 5. AM Parts Developed in Airbus Defence and Space

### 5.1 Scalmalloy Prototypes

To verify the process and the technology, prototype applications are carried on using a stepped approach on the complexity of the part coordinated with the certification approach. The sequence covered is the following:

1. ISO Design
2. Integrated Part
3. Topologically Optimized Design

### 5.1.1 Cover

The first prototype corresponds with an ISO design part. The part selected is an external cover used in the MAW System installed in the C-295 (light and medium aircraft). The decision to use this application for an AM prototype is due to the current high lead time as a spare part.

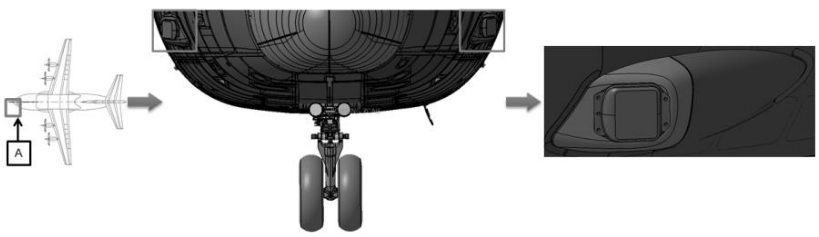


Figure 9: External cover of MAW system

Small changes are needed to change the current design to one more appropriate for AM technology. The use of some available software are used to select the best orientation, and with this input, the more relevant features to design the new AM part are in the inner surface (small changes must be done to avoid surfaces below 45º respect to printing direction) and the external surface which must keep its original geometry due to aerodynamics requirements.

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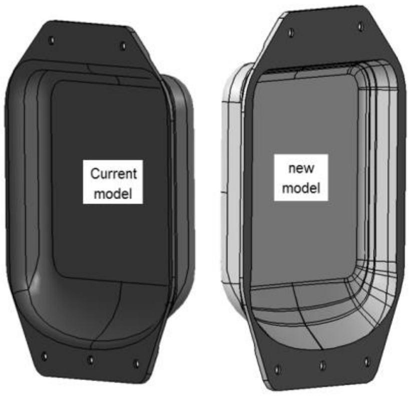


Figure 10: Current versus ALM design of the cover

Simulating a real qualification process, inspections were performed and witness samples were printed in the same batch than parts. Figure 11 shows the nesting definition and the qualification batch.

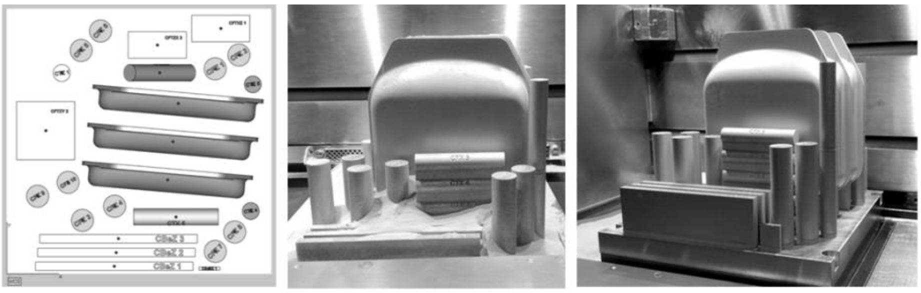

Figure 11: Nesting and production batch

### 5.1.2 Drain Mast

One of the main areas of interest for AM and where big benefits can be found is the integration of part manufactured today in different technologies and then assembled. The benefits will be among others: cost, weight and lead time. In order to demonstrate this capability different prototypes were selected. One of them is the A400M Fuel Drain Mast Assembly which has an envelope of 338,4 x 166,7 x 50 mm compatible with the machine finally selected for this application. Current design technology is welding of parts made of aluminum 3.3214. Figure 12 shows the part location into the Aircraft. Figure Y shows how the part is manufactured today

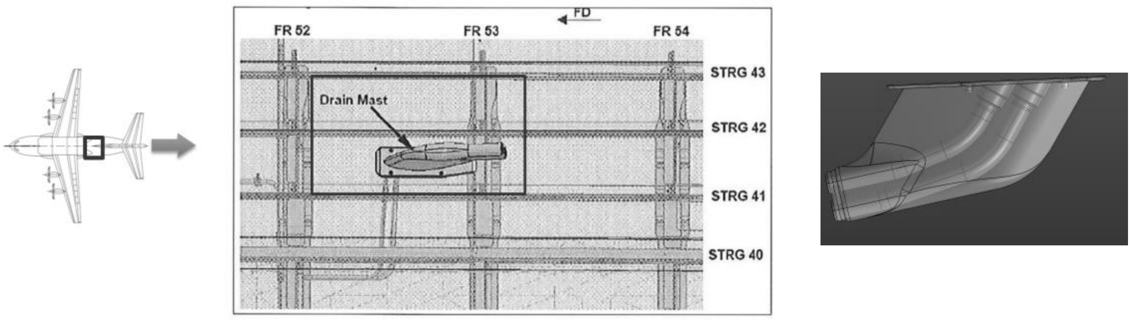


Figure 12: Drain mast location in the A400M

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The Design of the Drain Mast was done following the next steps:

1. Requirement Analysis:

   - Overall geometry and available space.
   - Bolt installation.
   - Interchangeability.
   - Inspections.
   - Maintenance/reparability.
   - System installation: if System brackets shall be installed in the part to be designed, contact surfaces, attachment points, etc. will be identified in the model in order to provide the appropriate geometry to attach the installation and to introduce the corresponding loads, if any.
   - Aerodynamic
   - Structural
   - EMC, Lightning Strike

2. Analysis of the relevant Design Features for the Redesigned AM part:

   - Attachment
   - Footprint to be respected: size, dimensions and design of interface needs to be kept
   - Interfaces (holes) to be kept.
   - Material allowance for machining of the flange to ensure an adequate surface for the sealant (2mm additional material).
   - Pad added to Interfaces (holes) to be able to mill the bearing area for an adequate fitting of the screws.

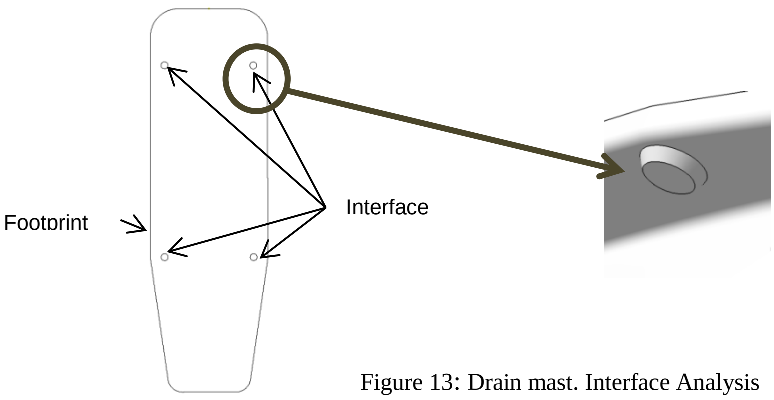


Figure 13: Drain mast. Interface Analysis

- Drainage Pipes: angle of drainage pipes needs to be kept in order to ensure that the interface pipes fit into the ALM part.

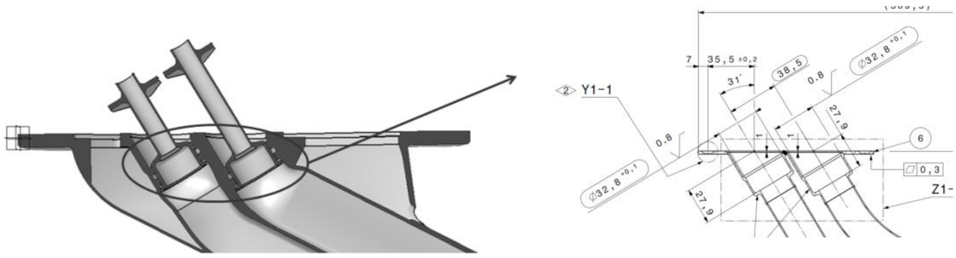


Figure 14: Drain mast. Angle of drainage piping

- Aerodynamic surface: aerodynamic performance generated by the AM design must guarantee equal or better performance than the original part.
- Angle “α“ in-between flange surface and outlet should not be changed

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3. Generation of the Design envelop:

   This envelope defines the volume that can be used for the Design of the part and shall consider the 3D printing Machine Capabilities (chamber dimensions that cannot be exceeded), other structural or systems installation or equipment in the surroundings that can limit the volume of the part. This conceptual geometry captures the functional and mechanical requirements of the component, in particular case the space for bolt connection and tooling access.

4. Design of the integrated AM part

   One of the initial goals for the redesign for AM was to keep the outer shape as it was defined considering flight physics requirements difficult to modify without deep analyses. When analyzing first potential design keeping original shapes it was finally discarded as it was not possible to be inspected by NDI techniques.

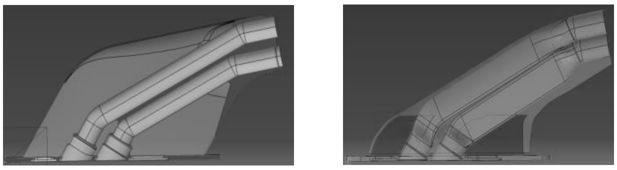

Figure 15: AM Drain mast. Preliminary designs

Then a second option was developed with an optimized aerodynamic shape and new inner duct surface for which manufacturing feasibility study came to the conclusion that despite the inspection capability was solved and due to the technology constrains it was impossible to manufacture because of the circular shape at the exhaust area. Finally, keeping the optimized aerodynamic shape, different alternatives were analyzed to solve the issue at the exhaust area.

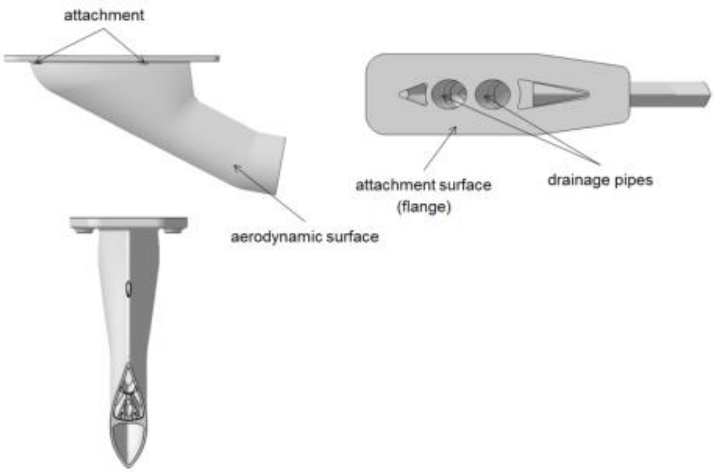


Figure 16: AM Drain mast. Final design

Once final design is performed, concurrency engineering between Design, Manufacturing and the supplier is performed to define the blank, that is, the item to be printed. The blank must contain extra thickness for areas to be milled but also may content additional structures to allow the milling operations (clamping to the milling machined, reinforcements to avoid part damage due to vibration….). During this concurrency the following approach was discussed. Additionally, final part orientation and support strategy must be defined.

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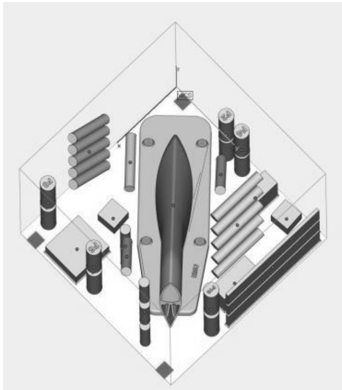

Figure 17: Drain mast. Batch Configuration

### 5.1.3 Fuel Pipe Bracket

The last Scalmalloy prototype corresponds with a topology optimized part. In this case a bracket of the MRTT (Multi Role Tanker Transport) Boom fuel line was selected due to the potential weight reduction identified and its possible positive business case as consequence of the original high buy to fly ratio (volume ratio between the raw material needed for manufacturing and the final part).

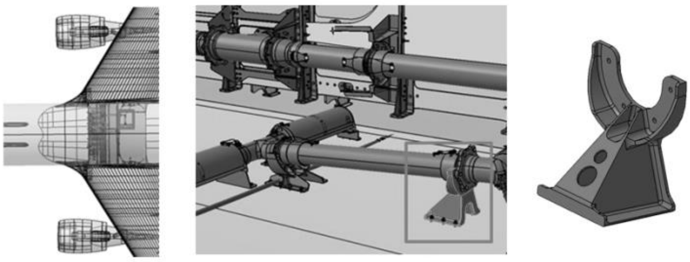

Figure 18: Fuel Pipe Bracket. Candidate selected for Scalmalloy Topology Optimized Prototype

The main challenge for this prototype was the application of the optimization driven design process explained in chapter 2.0. The advantages of applying topology optimization were already presented, however its application should be always performed by engineers with experience in this type of analyses. Ultimately, the topology optimization is a mathematical model which must be carefully used. A bad model set up can drive the optimization to nonsense structural concepts which must be automatically discarded by the engineer. In these cases the engineer must wonder about the analysis set up reviewing in the FEM the loads applied, boundary conditions, optimization responses… Moreover a robust optimized concept is often the result of a battery of topology optimizations. It is not a good optimization practice to blindly rely on the first topology optimization result. Therefore the engineer should configure a topology optimization strategy to obtain the most optimum and robust design for the new AM part. Figure 19 shows the concept evolution arisen for this AM part based on a specific topology optimization strategy.

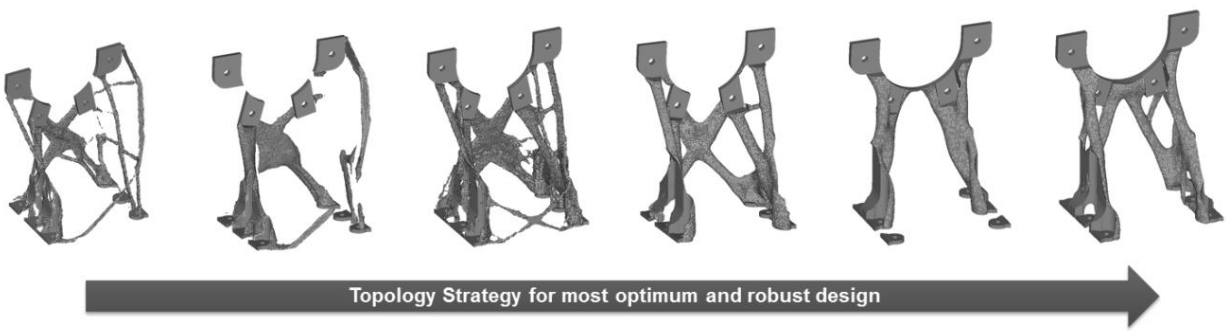


Figure 19: Fuel Pipe Bracket Topology Optimization Evolution

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Based on the last topology optimization result a new design was proposed and subsequently printed. The CAD reconstruction of the geometries arisen from the topology optimization may be a challenging process using traditional design tools. For this reason, during the last years, Design Software companies are developing specific tools to address this type of AM designs. Final design achieved a 31% of mass reduction fulfilling the same structural requirements in terms of strength and stiffness than the original design.

Figure 20: Fuel Pipe Bracket AM Design and Production Batch

## 5.2 Flying Prototypes

Inside Airbus Defence and Space there is the necessity of perform flight tests to check the aircraft performance with different configurations. Flight test campaigns should involve a few flights and the parts installed, usually, should be removed after the campaign is finished.

These parts, only one use, need to be in time and with reduced cost. Sometimes the parts are fairings or big and slender parts, this kind of parts normally need the use of tooling to be manufactured, which means additional time and cost. Additionally if during the definition phase, the external surface change, the tooling is not valid, and a new tooling is required to be designed and manufactured with extra cost and lead time. For this reason the ALM seems to be the best option of this type of parts. The technology gives the possibility of manufacture parts without tooling, in a short time, and with the flexibility to change the geometry until the last moment.

Since 2015, AM technology is used in these flying prototypes parts inside Spanish military projects. First experiences resulted not successful and could not be installed in the aircraft, one due to big deformation (during the cooling process) and other to quality issues (no procedure is followed), see Figure .

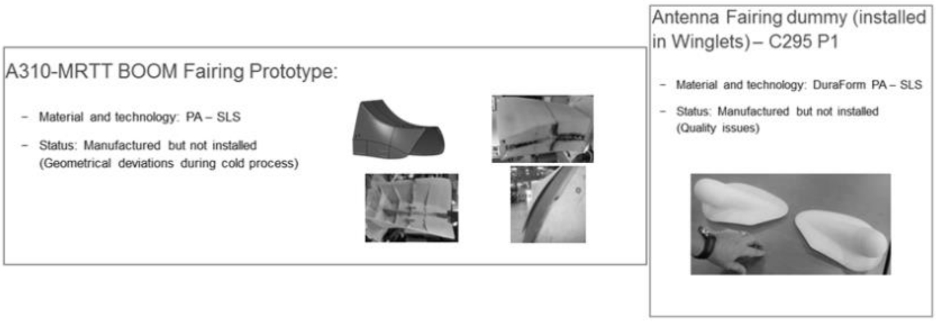


Figure 21: AM prototypes not suitable to install in aircraft

After these two first applications a third one was developed, in this case to validate the analysis performed in a drag reduction campaign. To avoid quality issues a specific procedure were launched to cover these parts. In this procedure different technology aspects are included: material, AM technique, inspections, and tests needed to control the manufacturing and the quality of the parts. These parts, see Figure 22, were manufactured, installed in the prototype aircraft and satisfactory tested during the flight test campaign.

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Figure 22: Vortex generators

During 2016 a general procedure for this types of parts were defined "Process flow for validation of ALM flying prototypes", in this document is defined the scope of the parts that could be manufactured using this technology and how will be the process to allow the installation in the aircraft. After this milestone, there are other successful applications that allow Airbus Defence and Space to reduce lead time and costs during the flying test campaigns.

Figure 23: Successful flight test applications

## 6. Conclusions

AM is a new manufacturing technology that allows a greater variety of designs compared to more traditional technologies. Nevertheless, as any new technology, there are several risks that have to be assessed and it is compulsory to understand properly its capabilities. Within A-DS, this technology is considered as a good alternative for a certain set of parts although extensive work is being done to master it before it can be massively applied. A multidisciplinary step by step approach is being followed with the aim to gather experience during the complete process using novel tools and enabling the company to move forward in the proper way with this new way of manufacturing.