European Regional Development Fund

Deliverable 2.2.1.: Report of the results of the Industrial phase

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OUTLINE

INTRODUCTION

The Work Package 2 (WP2) of the ADDISPACE project with Title: *Demonstrative pilot project of additive manufacturing technologies transfer in SMEs of the aerospatial sector* proposed to develop and fabricate 4 pilots to transfer the AM technologies to SMEs of the aerospace sector in the SUDOE. In the Activity 2.2: *Industrial research phase,* all the partners have developed 4 pilots.

In this report all the results, conclusions and recommendations obtained in the 4 pilots are explained.

OBJECTIVE

The main objective of this document is to compile the results obtained in this Industrial research phase of the ADDISPACE project.

DESCRIPTION

During this task, 4 pilots have been developed attending to the Terms of Reference defined in the previous task. Each pilot was leaded by each different technological centre and uses different technologies and materials in order to cover different industry interests. A matching between centers and technologies was performed in order to develop interesting pilots for AM technology transfer in the WP3.

In the Table 1, the selected technologies, participants and leader of each pilot are detailed.

Table 1. Pilot, technology, leader and participants of each working group.

Pilot	1	2	3	4
Technology	**SLM**	**LMD powder/TLM**	**WAAM & LMD powder/robot**	**SLM/TLM**
Leader	**FADA CATEC**	**IPLeiria**	**ESTIA**	**LORTEK**
Participants	IPLeiria	ESTIA	LORTEK	FADA CATEC
	MICRONORMA	GNC	VLM	ADIRA
		ADIRA		

Pilot 1: SLMilling

RESULTS OF THE INDUSTRIAL PHASE

Introduction

The metallic manufacturing in aerospace sector is known for the tight tolerances usually required given the criticality of certain aspects that affect the structural behavior of aircraft. Despite the huge potential of MAM technologies in aerospace sector, nowadays this technology cannot fulfill all requirements in order to obtain a final part and conventional manufacturing processes have to be into account. Surface roughness, holes and interfaces tolerances, mechanism and assembly parts still depend on the conventional machining processes in order to full fill the requirements. This key point has to be considered in additive manufacturing value chain.

The Pilot 1, called *SLMilling,* aims to demonstrate the MAM is a valuable technology for aerospace sector and fits into the whole manufacturing value chain

The aim of this pilot is the development of a part manufactured by Selective Laser Melting, SLM, taking into account the subsequent processes that need to be undertaken to complete the whole manufacturing value chain. Down below the objective, methodology and main results are presented.

Objective

Fabricate component by MAM-SLM in Titanium 64. The component to be study is an Aerospace Fitting, see Fig. 1.

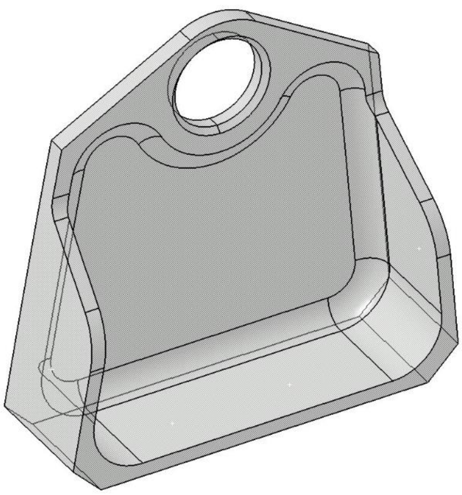


Fig. 1. Aerospace fitting.

Aspects such as the manufacturing strategy, part orientation and part geometry are focused on subsequent machining operation where the final part is obtained, meeting the strict requirements of tolerances and dimensions.

The additive manufacturing value chain will be completed with the inspection and verification of the final part by means of different Non Destructive Techniques.

Methods and evolution

The component under study has a large percentage of critical surfaces (interfaces) in terms of tolerances and dimensional requirements. Those surfaces are marked in green in the image shown below, Fig. 2. In addition to them, the central hole (colored in orange) and the rivets, that join the component to the structure, have tight tolerances.

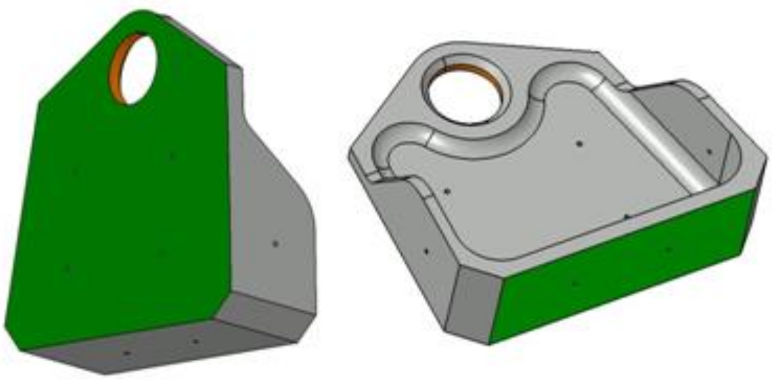


Fig. 2. Aerospace fitting: Interfaces.

According to the structural behavior of the component, which is defined by the end user, the final assembly follows a back-to-back strategy, as it is shown in the picture below (Fig. 3). This strategy compromised the failure mode of the structure in case it is necessary.

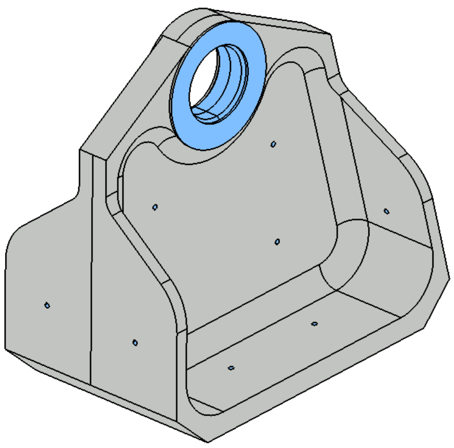


Fig. 3. Aerospace fitting: back to back strategy.

Regarding the manufacturing strategy, it has followed the back-to-back positioning solution for the structural behavior: back-to-back fitting parts have been joined in the CAD model as shown in Fig. 4.

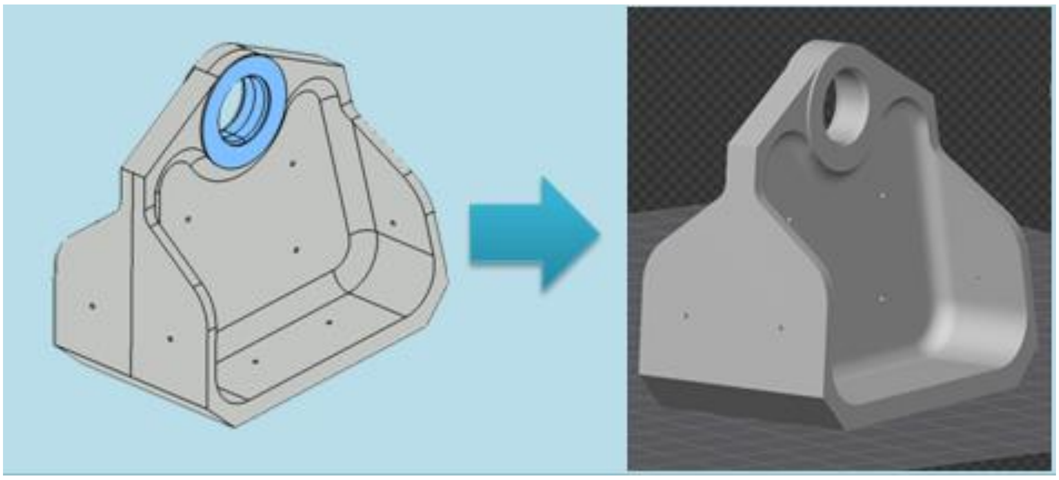


Fig. 4. Aerospace fitting: union of two parts in one CAD file.

As it has been explained above, a strategy to have both part obtained from the same CAD is presented. The parts are adjoined to the manufacturing substrate so this substrate is used as tooling for CNC operations in a 5-axis machining system. Once the holes and rivets have been drilled, the wire cutting technique is applied. Operations by means of wire cutting are represented schematically in the following figure (Fig. 5).

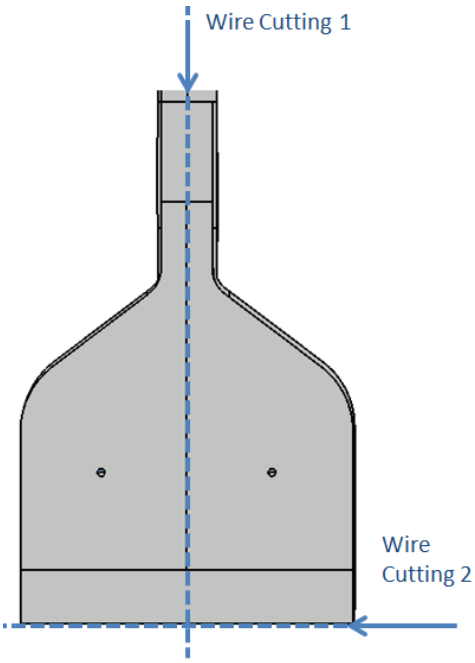


Fig. 5. Aerospace fitting: wire cutting operation.

Wire cutting operation No. 1 separates both fittings after drilling operations. Wire cutting No. 2 separates both parts from the substrate. With these operations, the final tolerances and dimensions for critical surface (Fig. 2) are achieved.

Results

Once the additive manufacturing and machining strategies have been theoretically described, the results are presented down below.

The components have been manufactured in titanium TiAl6V4 by SLM. The following picture (Fig. 6) shows the result after the part manufacturing.

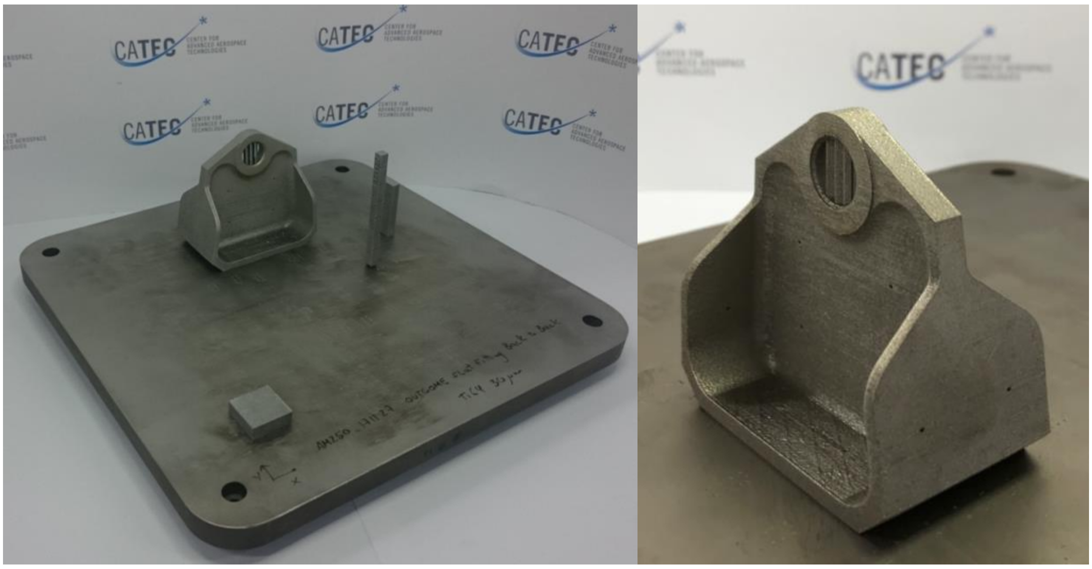


Fig. 6. Aerospace fitting: manufacturing results.

Once the manufacturing is carried out, the substrate goes to machining operation as laid down below. The following picture (Fig. 7) shows both final parts.

Fig. 7. Aerospace fitting: machining results.

Non Destructive Testing

In order to validate the final parts, some different testing has been performing over the part. The test and inspection which has been performed are:

- **Surface roughness analysis**

The analyzed surfaces are presented in Fig. 8 and measurements in Table 2

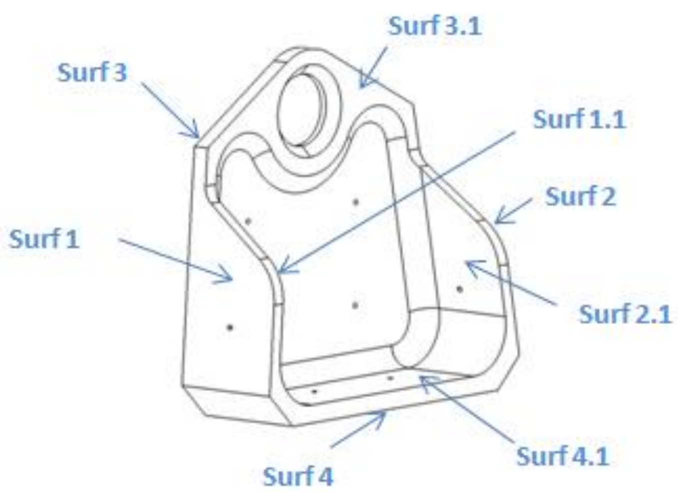


Fig. 8. Aerospace fitting: Surface ID.

Surface ID	Ra - [µm] As Built PART	Ra - [µm] Sand-Blasted PART
Surf 1	8.9	8.4
Surf 1.1	8.2	8.3
Surf 2	13.4	8.8
Surf 2.1	8.0	8.3
Surf 3*	2.8	2.3
Surf 5.1	8.1	7.3
Surf 4	3.6	1.8
Surf 4.1	5.4	3.8

Table 2. Average surface roughness values.

- **XCT- X Ray Computed Tomography**

A dimensional analysis has been carried out by means of nominal to actual comparison by X-Ray Computed Tomography (XCT). This method allows fitting the XCT data set into the nominal CAD model determining over/undersize among the entire part surface. The obtained results are represented in Fig. 9 and Fig. 10 where the data set under examination has been color-coded according to deviations vs. nominal CAD.

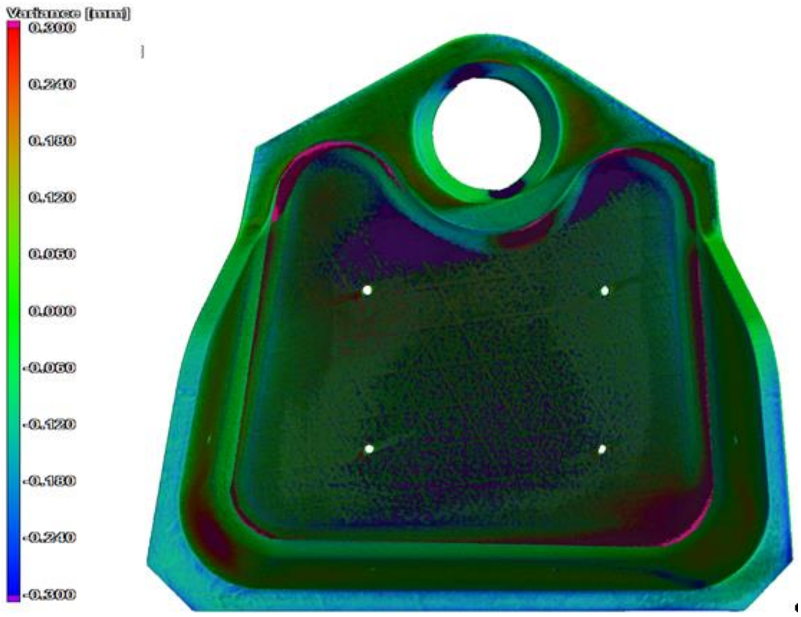


Fig. 9. Aerospace fitting: Dimensional verification by XCT (front view).

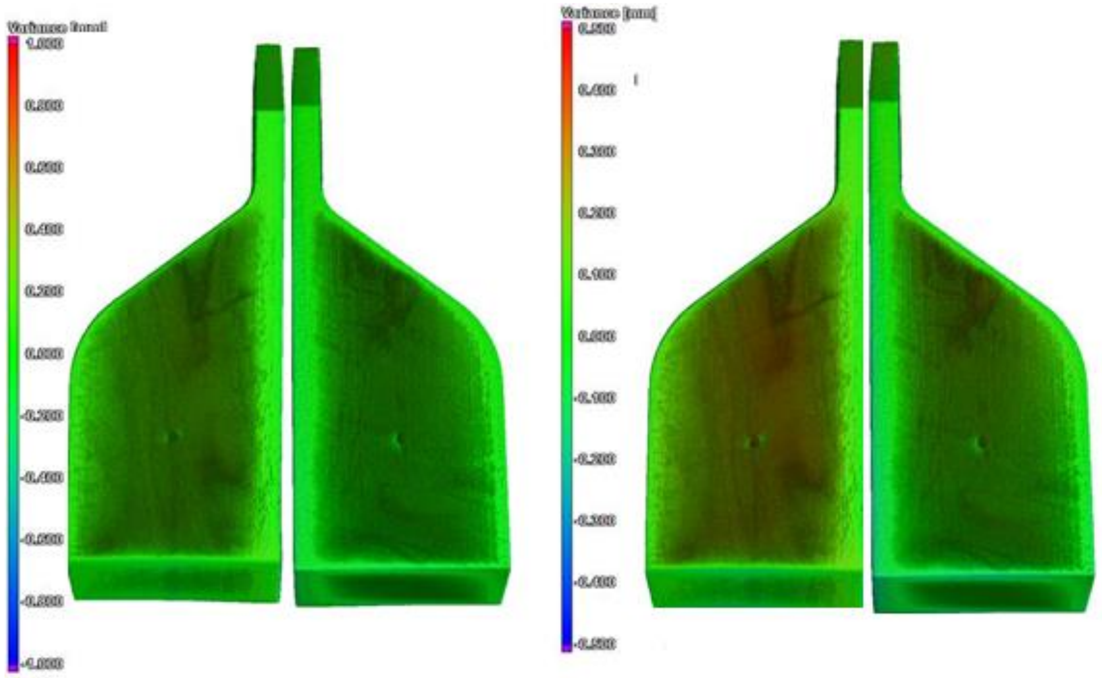


Fig. 10. Aerospace fitting: Dimensional verification by XCT (lateral views).

PROPOSAL OF ADAPTATION AND RECOMMENDATIONS

Design

When MAM technology is considered for a part manufacturing, certain geometrical flexibility is desired in order to adapt the part design to the manufacturing technology. This has been a key point to address and solve some manufacturability drawbacks and distortions proper of manufacturing in Titanium. In spite of these issues and thanks to the experience in the MAM technology, especially in SLM where different problematics have been overcome, the result has been satisfactory.

Equipment

The equipment used has satisfied all the key points to which the development of this pilot 1 has been exposed.

Control and monitoring

The presence of non-destructive testing is crucial to verify and assure the quality with which a component is manufactured by SLM. The valuable alternative is the X-Ray Computed Tomography, which in addition to providing three-dimensional information of the manufactured component, through nominal to actual comparison, provides information regarding void contents and internal defects that are not available on the surface.

Pilot 2: LMD powder/TLM

RESULTS OF THE INDUSTRIAL PHASE

Introduction

Metallic Additive Manufacturing is still not very present in the aerospace industry. Indeed, even if the market is growing significantly, there are few examples of parts made in Metallic Additive Manufacturing. However, the LMD/P process allows a lot of features such as reloading, adding function on complex surfaces and even a complete parts manufacturing.

Currently, manufacturers prefer to use conventional processes rather than Metallic Additive Manufacturing since the youth of the process.

However, in some cases, conventional methods require many manual operations, such as welding, riveting, etc.

That is why the partners of the ADDISPACE project have agreed to improve the maturity of the LMD / P technology by analysing all the value chain of this technology, from design to testing through all the steps necessary for manufacturing:

- Allow complex shape
- Reduce considerably the material costs (less waste)
- Reduce considerably operation costs (less machining)
- Reduce considerably the Buy to Fly ratio
- Prove that MAM technologies can be an interesting alternative in many cases

Objective

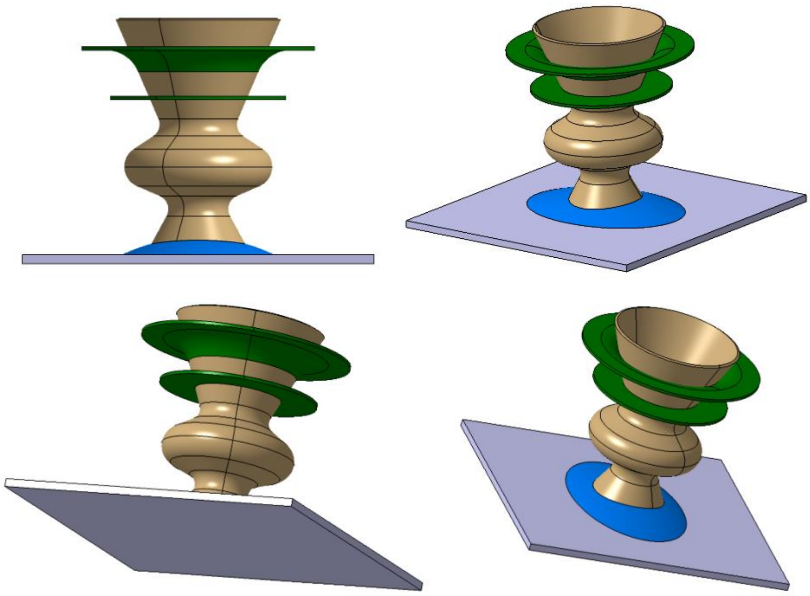
The pilot 2 has several objectives to improve the technology and to gain the trust of futures users:

- Analysis of the value chain for manufacturing in LMD/Powder technology
- Design for LMD/P
- Programming the best trajectories
- Manufacturing of the part using different technologies (5 axis machine, robot deposition, etc.)
- Quality inspection, Dimensional control, NDT
- Comparison between different LMD/P processes

All the pilot 2 partners think this work will have some territorial impacts through the development of the knowhow on MAM and the technological transfer to SUDOE region. Also, the partners want to prove the benefits of MAM in comparison with conventional processes.

Methods and evolution

To achieve the objective, a showroom aeronautic part was proposed by the LAUAK Group, an aerospace Tiers 1 supplier:



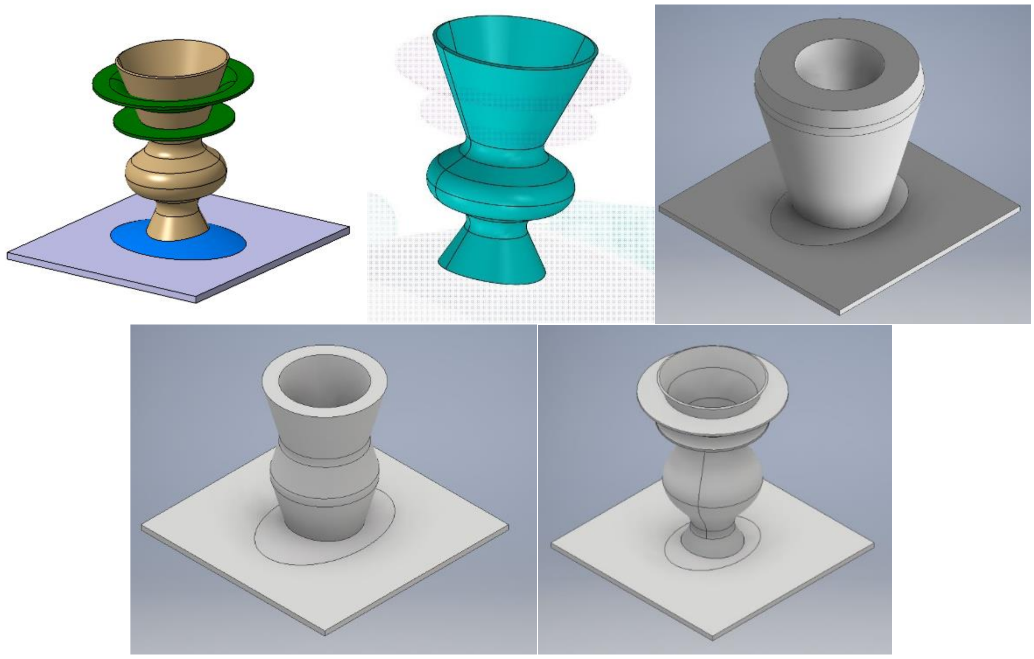
This part highlights actual limitations of conventional manufacturing (welded tubes, fitting tube, change of diameter, different types of collars, the difficulty to adding functions and to reloading material on a complex shape, etc.). The following sequence was defined:

- Study the specific design principles and adaptations for LMD/P technologies
- Generate the best trajectory for different processes
- Manufacturing the part using LMD/P 5 axis machine, 3 axis machine and robot.
- Perform quality Inspection, dimensional control, NDT and visual surface inspection.
- Comparison between the 3 different LMD process (Time study, redesign time, setup time, manufacturing time, material and machine costs, etc.).

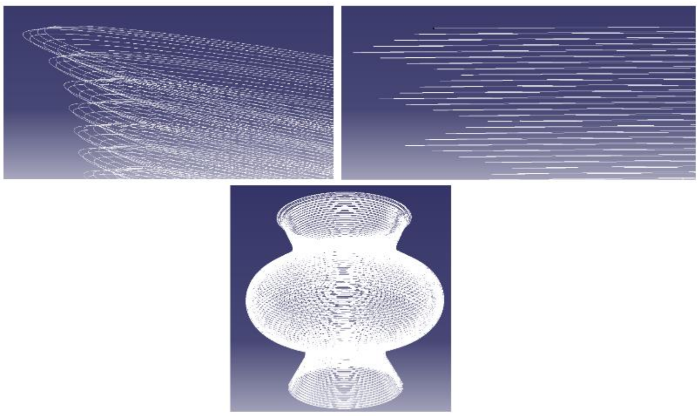
Results

ADDIMADOUR Manufacturing method:

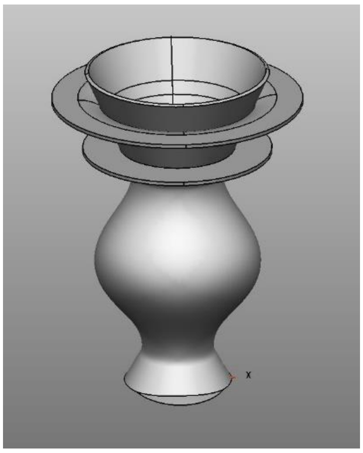
- Redesign the part for the 3 processes: LMD/P 5 axis machine (ADDIMADOUR technology), LMD/P 6 axis robot (GNC Laser technology) and LMD/P 3 axis machine (ADIRA technology)



- Programming of different strategies:
  - Triple evolutive spiral with the 10Vx Nozzle in 3 weld beads in width: Continuous strategy which could allow a faster deposition. Problematic: Difficulty to maintain the distance Nozzle/Part



  - Simple evolutive spiral with the 24Vx Nozzle in 1 weld bead in width: Continuous strategy which could allow a faster deposition. Problematic: Too much power for the little dimension of the part, impossibility to manufacture.
  - 1 weld bead with the 24Vx Nozzle with sequences: No continuous strategy, too much power even if some sequences are applied.
  - 3 weld beads with the 10Vx Nozzle: No continuous strategy but the deposition is possible. Problematic: Very long deposition and the angle are too important, it was necessary to redesign the part to avoid collision between the part and the nozzle.



- Manufacturing with 3 circular weld beads in 5 axis machine with the 10Vx Nozzle

ADDIMADOUR Equipment:

- LMD/P: BeAM 800 5 axis machine
- Deported clamping system

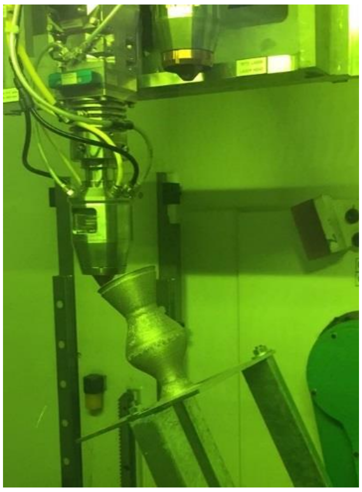
ADDIMADOUR Raw Material:

- 10 substrates 316L Stainless Steel 200 x 200 x 5mm
- 10 kg of Powder Stainless Steel 316L
- ½ rack of Argon bottles (1 rack: 16 bottles each at 200 bars, for the distribution of the powder in the nozzle. 1 rack: 168 m^3, 1 bottle: 10.5m^3)

ADDIMADOUR Results:

- Difficulties on programming a such little complex geometry
- Difficulties on manufacturing with the 24Vx Nozzle
- Difficulties on manufacturing with the too big original angles
- Necessity to redesign the part to avoid the high risk of collision.
- Manufacturing on a complex surface was a success
- Adding collar was a success.
- Necessity to develop a software to prevent collision between Part and Nozzle. (Collision during manufacturing on the adding of the second collar non-visible on the simulation).
- No necessity to have a heat treatment
- Necessity to machine the collar if a functional surface is required.

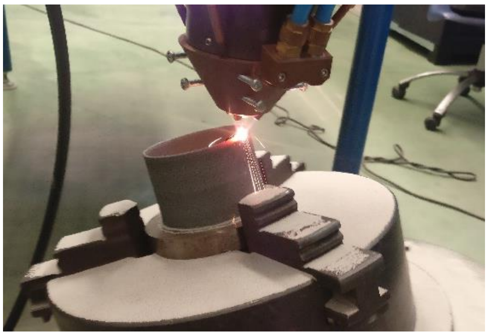




GNC LASER Equipment:

Own integrated robotic laser cell, which its main elements are:

- Rofin FL040 laser
- Robot Fanuc M-710 and tilt and rotate positioner (Fanuc A05B)
- Precitec YW52 laser cladding head

GNC Laser has bought a 3D tool path software, Tebis laser cladding pack. But it is less developed than we expected (a beta version because real pack commercialization has been delayed close to one year), having to work with a teaching manual programming, impossible to manufacture pilot 2 part.

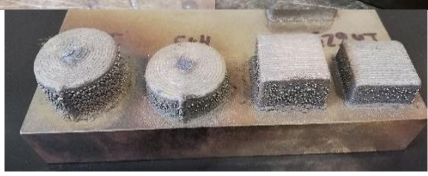
GNC LASER Raw Material:

- Powder: 2’5kg of AISI 316 stainless steel.

GNC LASER Results:

GNC Laser has been unable to manufacture pilot 2 part, and without suitable tool path software we only can work in basic geometries:





PROPOSAL OF ADAPTATION AND RECOMMENDATIONS

Design

According to the design, we can recommend some propositions:

- For a 5-axis machine, be careful of the different angles to avoid collision between the part and the nozzle. For example, to manufacture a vase with 50mm diameter, the angle of manufacturing must be inferior to 50°.

- If necessary, in 3 axes, a tolerance on the angle manufacturing could be possible but cannot extend 15°. Any wall whose inclination is greater than 15 ° with respect to the growth direction of the part shall be manufactured using the 5-axis system. If this angle is exceeded, the laser will not impact the material on the part and the welding will not be acceptable.

- The Beam 800 machine is dedicated to large part size, it is recommended to have a part which the dimensions are superior to 100mm.

- It is necessary to consider that contrary to LBM process, LMD/P doesn't require any support to manufacture the part. A study of feasibility has to be done to add different functions (5-axis accessibility, collisions, angle of deposition, possibility of manufacturing a geometry, etc.)

Equipment

- In terms of equipment, if we don't consider the reloading on a complex shape, the LMD/P 5 axis machine was not very appropriate to manufacture the original geometry. Even if the part is manufactured, it was necessary to redesign the part to allow the manufacturing. With the original geometry and considering the dimension, LBM process could be preferable.

- If we consider the reloading and the adding of functions, LMD/P 5-axis machine is very relevant. The collars have been manufactured easily as the manufacturing of the vase on the curve surface.

- To manufacture such a component in a 3-axis machine is totally unsuitable. All the part has to be machined after the manufacturing in order to obtain the collars.

ADIRA and GNC Laser were unable to deliver a manufactured part. An alternative has been found to replace one of the technologies (Trumpf has been contacted and has accepted to manufacture the part using their 5 axis machine), enabling a comparison between 2 machines. This is not an ideal situation, but we believe it to be an acceptable solution.

Raw material

In term of raw material for manufacturing this kind of part, we can preconize:

- 2 substrates for a parametric study (Metallographic inspection)
- 8 substrates to test different strategies of manufacturing (test phases)
- 1 substrate for the final part
- Powder of material
- Argon bottles for the distribution

Control and monitoring

- Development of a software which could facilitate the spiral strategies
- Development of an anti-collision system (on the machine or a simulation software)
- Control of the distance Nozzle / part (With an optical telemeter or other system) to guarantee the best distance. This system must be automatic to simplify the programming of the part.
- Metallography laboratory (Analyse the microstructure) with cutting and polishing systems and microscopy analysis.
- Control in Process (adapt the deposition, the parameters, etc. according to the previous layer)
- Software for monitorisation of the process (Saving of all the datas, parameters, etc.)
- Laser pyrometer to control the temperature of deposition, temperature of the substrate, etc. This can be done also with some thermocouple on the substrate.

Pilot 3: Large Titanium part CMT & LMD/P

RESULTS OF THE INDUSTRIAL PHASE

Introduction

Currently, we find very few examples of the use of Metal Additive Manufacturing to build large Aerospace components and particularly in Titanium. Indeed, most of the manufacturers continue to build parts with conventional technologies, technologies they are confident with and since MAM technologies are relatively new, it can give a sense of an immature technology.

However, with conventional technologies, manufacture these kind of parts (large parts in titanium) requires a very high cost and a very long Lead Time Manufacturing (Between 50 and 75 weeks). Also, in addition to the points mentioned above, these parts originally forged require huge losses after machining.

That is why, partners of the pilot 3 want to develop and improve the way of manufacturing using MAM Technologies to:

- Reduce considerably the Lead Time Manufacturing (50-75 weeks to less than 10 weeks)
- Reduce considerably the material costs (less waste)
- Reduce considerably operation costs (less machining)
- Reduce considerably the Buy to Fly ratio
- Prove that MAM technologies can be an interesting alternative in many cases

Objective

The pilot 3 have several objectives to improve the technology and to gain the trust of future users:

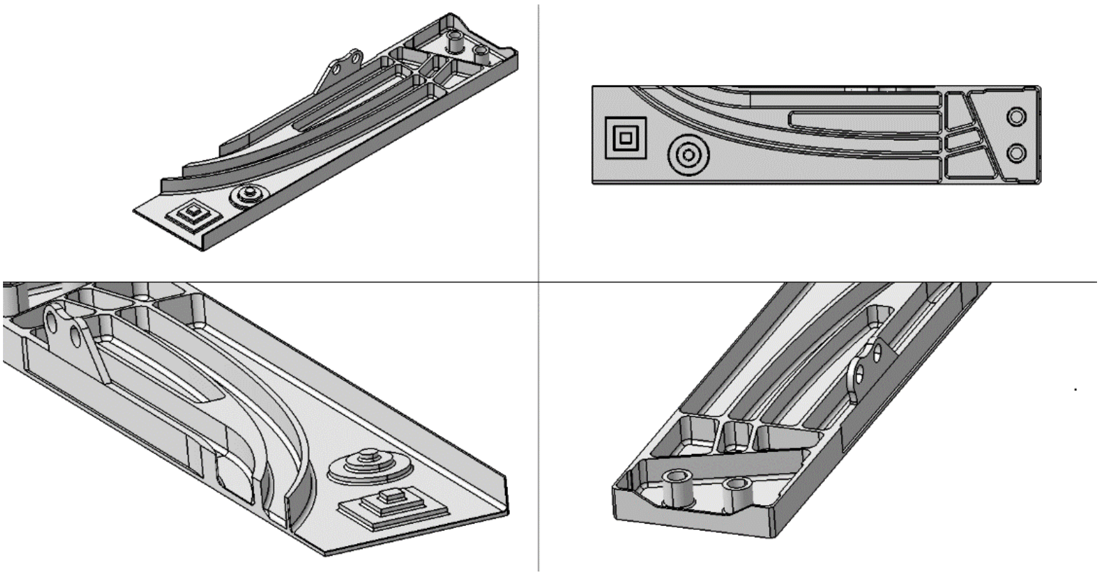
- Manufacturing of a big Titanium structural aeronautic part by Wire Deposition
- Manufacturing this part with robotic cells
- Make a hybridization with CMT (WAAM deposition) and LMD/Powder Technology
- Demonstration of control in process during MAM deposition with a sample of the part (Geometrical inspection in the same time of the manufacturing to control and adapt the deposition in real time)
- Machining a Ti6Al4V (grade 5) part with a robotic arm to compare it with the machining by 5 axis machine.

The manufacturing of this big titanium part (with crosses, variable thicknesses, lot of dilatation, etc.), the development of inert gas chamber, the development of the control in process, the machining of Ti6Al4V with a robotic arm, the hybridization of 2 technologies and the big reduction of the Buy to Fly ratio will have a lot of territorial impacts.

Indeed, this will participate to the development of the knowhow on MAM technological transfer to SUDOE region and prove the real benefits of MAM in comparison with other conventional technologies. The pilot 3 partners, through these developments, want to open minded lot of manufacturers to use MAM technologies in a near future.

Methods and evolution

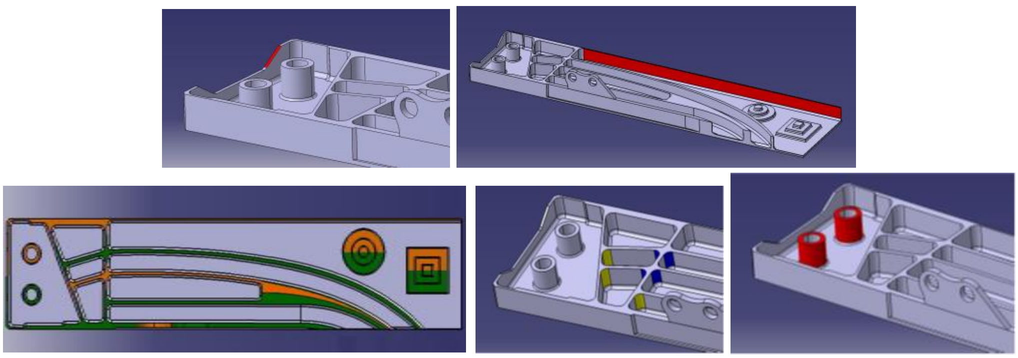
The LAUAK group, aerospace Tiers 1 supplier, has proposed a geometry to the ADDISPACE consortium:



This showroom part, which can be disseminated, have been designed for ADDISPACE but which is very similar to many structural parts of an aircraft. Generally, this kind of part are original machined part from a forged titanium block and which have a very high Buy to Fly ratio.

The dimensions are the following: **800 x 175 x 70 mm.**

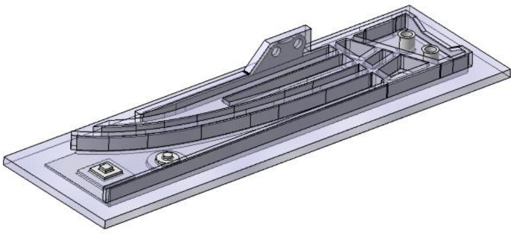
This part is very challenging with several functions, like progressive walls, long and thin walls, variables thicknesses, multisection crosses, fuctions added, etc.



Results

ADDIMADOUR Manufacturing method:

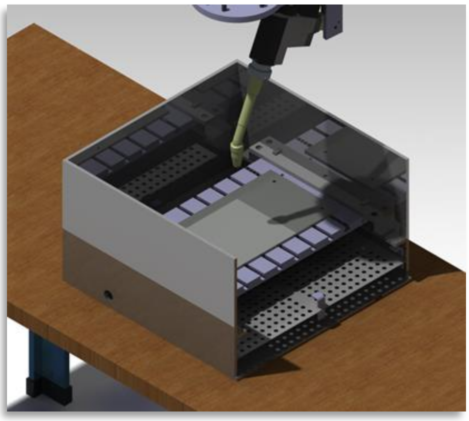
- Redesign of the part with over thicknesses (5mm on each side of walls)
- Make some trials on different titanium part to test different strategies
- Programming the part with oscillations (Zig/Zag strategy)
- Manufacture the part with CMT technology on a thin substrate: 900 x 275 x 16mm
- Add functions with LMD/P 5 axis machine (2 cylinders, 1 pyramid and 1 cylindrical pyramid)
- Heat treatment (840°C – 4Hours in Controlled atmosphere)
- Scan 3D of the part for programming the machining
- Machining the part



ADDIMADOUR Equipment:

- CMT Synergic Transpuls 3200 Fronius
- KUKA KR100 6 axis robot
- LMD/P – 5 axis machine BeAM Magic 800
- Little protective chamber (300 x 300 x 230mm) for tests phases
- Big protective chamber to avoid oxidation on titanium deposition (1500 x 750 x 600mm)
- Clamping system (8 big flanges and 2 fixing rails)

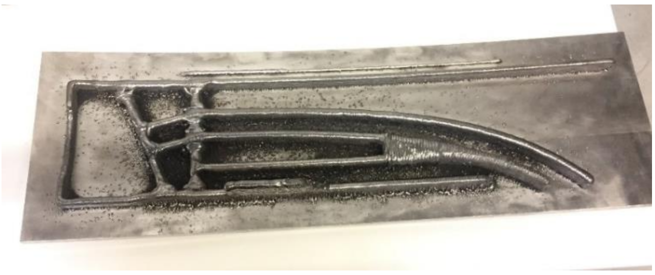
  

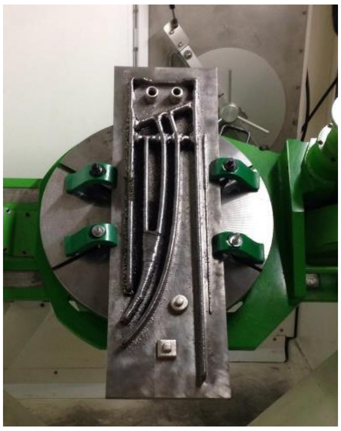
ADDIMADOUR Raw material:

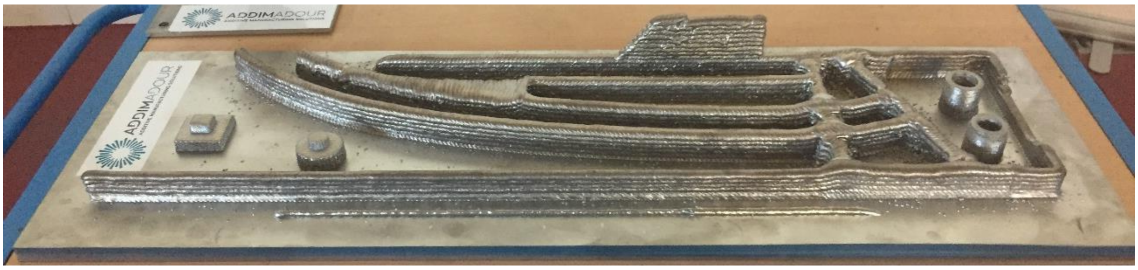
- 1 Titanium Substrate of 900 x 275 x 16mm
- 1 Titanium Substrate of 450 x 125 x 16mm (for tests phases)
- 8 Titanium Substrate of 200 x 200 x 200mm (for tests phases)
- 3 kg of Powder Titanium
- 2 Coils of 10kg each of Titanium wire, D1.2mm
- 2 rack of Argon bottles (1 rack: 16 bottles each at 200 bars, for the inert gas chamber as well as for the distribution at the end of the torch. 1 rack: 168 m^3, 1 bottle: $10.5m^3$

ADDIMADOUR Results:

- Lot of deformation on CMT Manufacturing: About 27mm on each side of the part. Residual stresses very important which requires an important system for clamping the part during the manufacturing.
- Lot of projections during manufacturing.
- No oxidation on the part, either on CMT manufacturing of LMD/P deposition. The inert gas chamber works well (<50ppm O2).
- Programming with oscillations strategy is relevant despite an important energy deposition.
- Adding functions with a LMD/P 5 axis machine was a success.
- Heat treatment was necessary to relax and straighten the part. The result is convincing. (840°C during 4 hours with controlled atmosphere, and 150 of pressure on the part for straightening).
- No porosity on CMT Manufacturing and less than 0.1% for LMD/P deposition.
- Scan 3D of the part is not mandatory but very useful for programming the machining.
- Machine the Titanium part is a complex task because lot of projections and irregularity of surfaces.







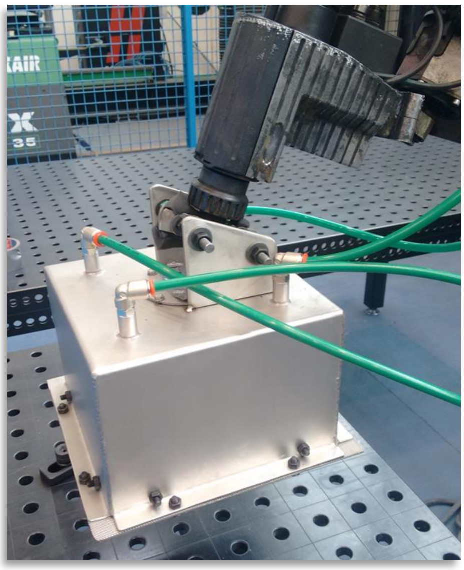
LORTEK Manufacturing method:

- Redesign of the part with over thicknesses (7 mm on each side of walls) taking into account the surface that has to be removed by machining
- Make some simulations to define the thickness of the substrate in order to reduce the distortions
- Make some small parts with stainless steel and titanium to define the best strategies and assure sound walls with mechanical properties similar to cast or forging
- Programming the part with oscillations (Zig/Zag strategy)
- Pre-machining the substrate
- Manufacture the part with CMT technology on a thick substrate: 840 x 215 x 40 mm on Stainless Steel

- Manufacture the part with CMT technology on a thick substrate: 860 x 235 x 65 mm on Ti6Al4V. the manufacturing of the part has to be protected with a trailing in order to avoid the oxidation of the material
- Stress relieve heat treatment in protective atmosphere

LORTEK Equipment:

- CMT Synergic Transpuls 4000 Fronius
- KUKA KR16 6 axis robot
- Little protective chamber (250 x 150 x 150mm) for tests phases
- Trailing system for inerting to avoid oxidation on titanium deposition and enable the local protection for big part manufacturing

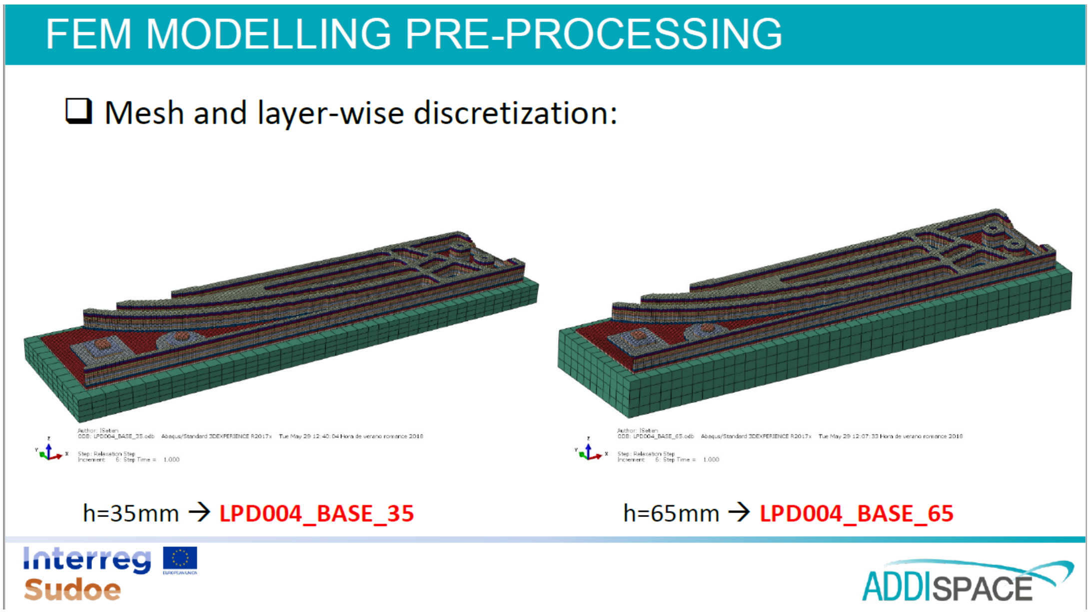


LORTEK Raw material:

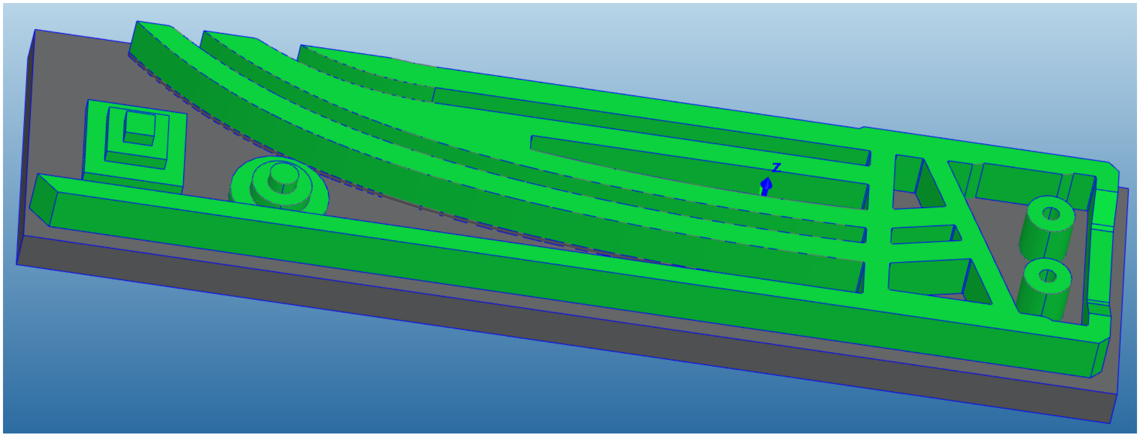
- 1 Stainless steel Substrate of 840 x 235 x 40mm
- 16 Stainless steel substrates of 150 x 150 x 10mm (for tests phases)
- 6 Coils of 10 kg each of Stainless steel wire, D1 mm
- 1 Titanium Substrate of 860 x 135 x 65mm
- 16 Titanium Substrate of 150 x 150 x 10mm (for tests phases)
- 9 Coils of 10kg each of Titanium wire, D1.2mm

LORTEK Results:

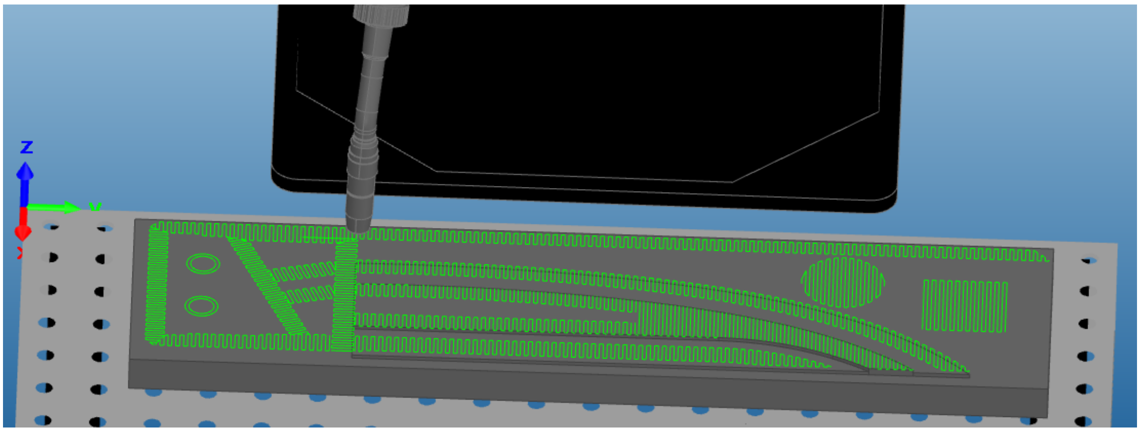
- From the simulation it was decided to use a thickness of plate of 65 mm in order to have the minim distortion



- The redesign for WAAM manufacturing was obtained

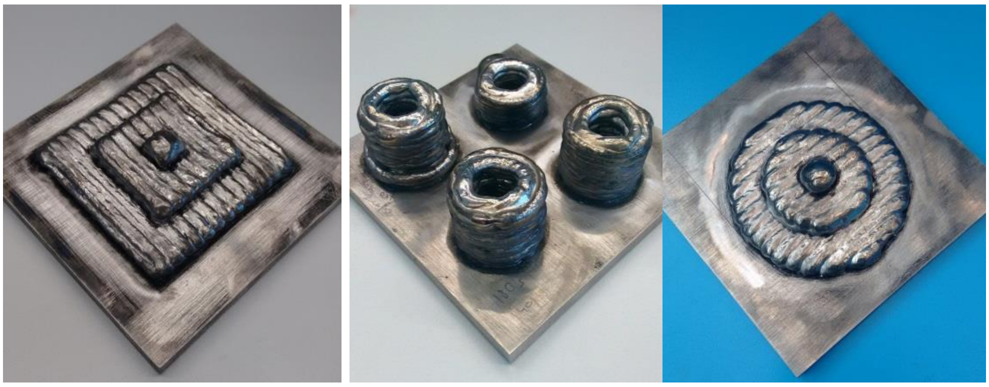


- From this redesign the definition of the trajectories for the robot were stablished.

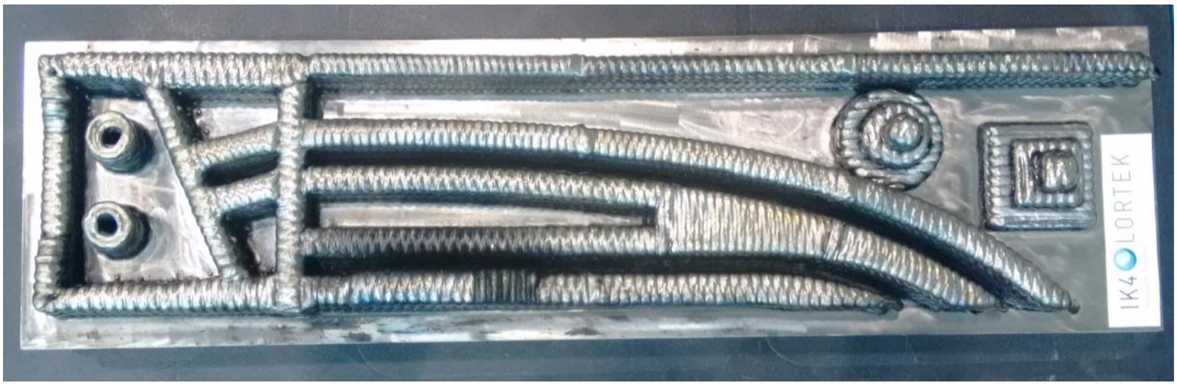


- The first trial in stainless steel was obtained

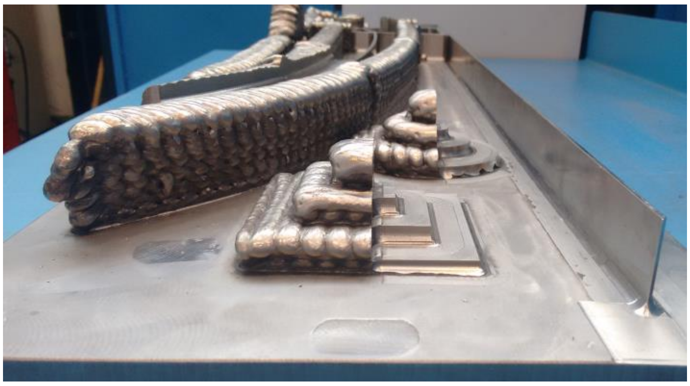
- Parts in Ti64 were obtained in order to obtain the best electrical parameters and define the appropriate strategies for the manufacturing of the whole part.

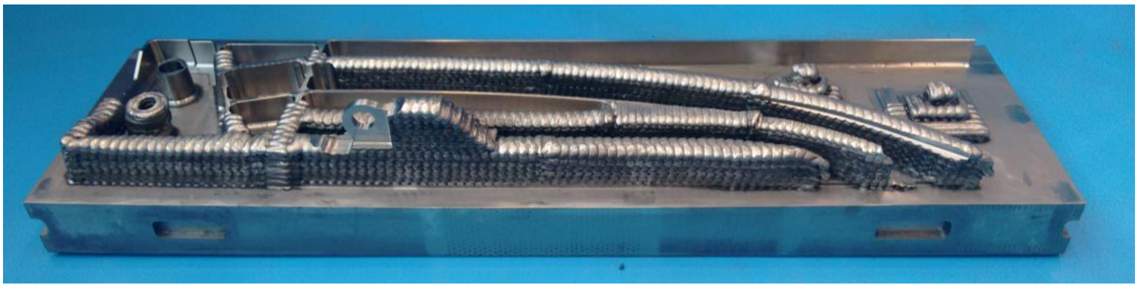


- Finally the part in Ti-6Al-4V was manufactured.



After the machining the final result of the demonstrator presented the following aspect:





VLM Robotics method:

- CMT Advance 4000R Fronius
- KUKA KR360 Agilus
- Process control robotic technology
- Machining robotic cell

Raw material

ADDIMADOUR Raw material:

- 1 Titanium Substrate of 900 x 275 x 16mm
- 1 Titanium Substrate of 450 x 125 x 16mm (for tests phases)
- 8 Titanium Substrate of 200 x 200 x 200mm (for tests phases)
- 2 Coils of 10kg each of Titanium wire, D1.2mm
- 2 rack of Argon bottles (16 bottles each at 200 bars, for the inerting gas chamber as well as for the distribution at the end of the torch. 1 rack: 168 m^3, 1 bottle: $10.5m^3$.

VLM ROBOTICS Raw Material:

- AL Wire Diam 1.6mm, ALMG5 Technosou

Control and monitoring

ADDIMADOUR Control and Monitoring:

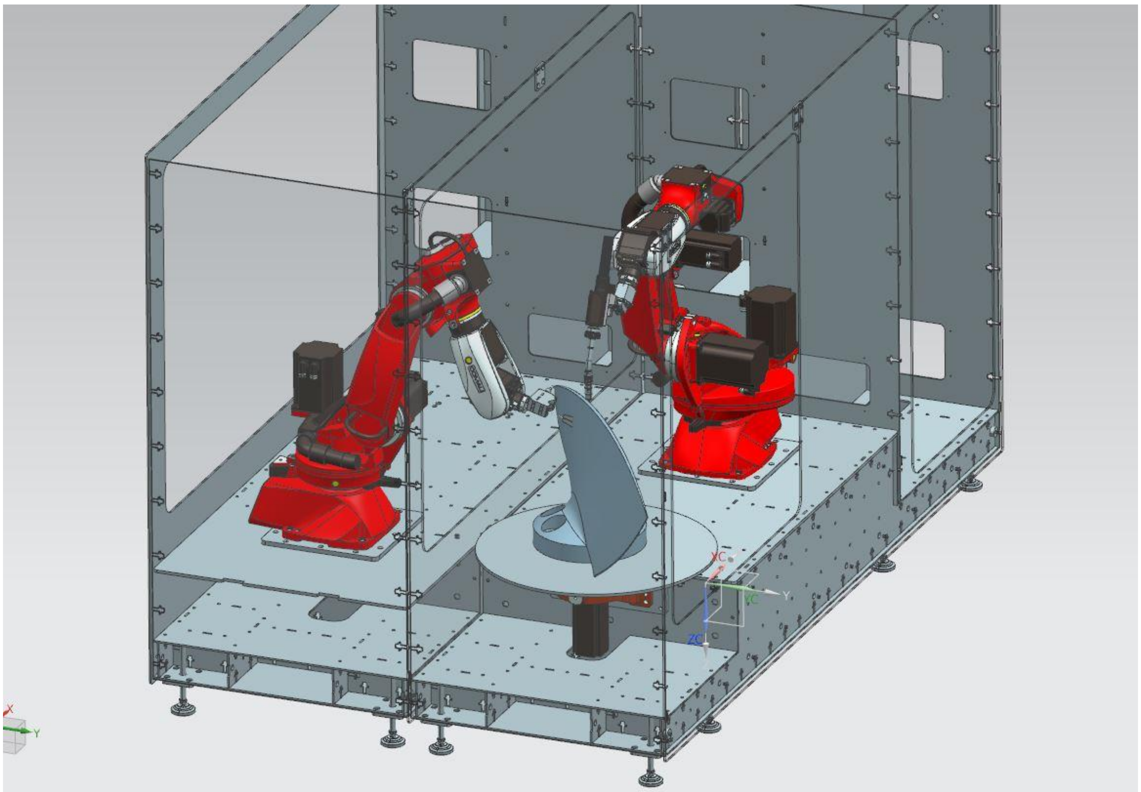
- Laser pyrometer
- Control of O2 in BeAM machine and in the Inert gas chamber
- Laser telemeter
- Synergical law by Fronius: NIBAS – Fronius Controller
- Controller KUKA KRC2
- Metallography laboratory

VLM ROBOTICS Control and Monitoring:

The demonstration consisted in producing a sample of the aluminum showroom part (for which the inerting is simpler) by carrying out thanks to a 2nd robot of the control in process on geometry of deposit.

For that, VLM Robotics used its Compa@qt® robotic additive manufacturing cell, its new machine which was launched commercially at the Toulouse industry fair (end of last October).

To this first cell was joined another robotized profilometric laser control cell intervening downstream of the depot.



The originality is to use the numerical control to operate these 2 coordinated cells to allow feedback in closed loop.

The demonstration showed the ability to accurately measure (100 µm) the X, Y and Z profile, especially to validate compliance with CAD tolerances.

Tomorrow, this configuration will correct the deposit based on the observed failure.

In a very close future, no additive manufacturing will be done without the integration of control in the process. It is indeed mandatory to secure the deposit to open the market for the manufacture of additive parts.

Dimensional control sensors and CNDs still need to be developed or adapted to be integrated

- Machining Titanium trials from LORTEK and ADDIMADOUR with robotic arm
- Control in Process development using 2 robots (1 one deposition and 1 for control)

VLM Robotics Equipment:

- CMT Advance 4000R Fronius
- KUKA KR360 Agilus
- Process control robotic technology
- Machining robotic cell

PROPOSAL OF ADAPTATION AND RECOMMENDATIONS

Design

According to the design for WAAM, we can recommend two propositions:

- **Symmetrical bi-faces component**: Indeed, to avoid the important deformation of the part during manufacturing, deposition only on one side of the part implies a lot of deformation. If the deposition is nearly symmetrical on both faces, deformations can be compensated. The Bi-faces deposition implies <u>to have a tilt table</u> to allow the deposition on each side of the substrate.
- **Redesign totally the part:** Additive Manufacturing allows us a great freedom of design, so we must think and design differently. The component proposed by LAUAK is an original part forged and machined. If we know the environment of the part, with the entire load cases, the other parts in interaction with this one, we can design this part especially for Additive Manufacturing processes. We can go even further in improving the part.

In all cases, it is necessary to put over thicknesses on the CAD part to allow the machining after the manufacturing.

Equipment

Deposition Technology

- In terms of equipment, those used by the ADDISPACE pilot 3 partners are relevant and seem appropriate.
- Other technologies exist like LMD/W or TIG Plasma but are more expensive and slower. TIG Plasma for example requires a continuous orientation of the torch in order to have the wire properly oriented.
- The CMT Process is relevant because it is the less expensive, the control is relatively easy, the fastest and which implies the less deformation (Cold Metal Transfer).

Inerting system:

2 different systems to allow the deposition of Titanium material have been tested and approved:

- Big inert gas chamber
- Ad-hoc symmetric trailing system

The 2 systems are very different and have each their advantages and their limit:

	Advantages	**Limits**
Big inert chamber	- Allow Titanium deposition - Control of atmosphere possible (%O2) - No need to control the orientation of the torch - All geometries possible	- Large size (> 1500 x 750 x 600mm) - Necessity to put the tilt table on the inert chamber
Trailing system	- No oxidation of Titanium parts - No limit of part dimensions - Light device - No need to control the orientation of the torch - All geometries possible	- The design has to assure an appropriate gas flow without turbulences - Risk of collision if the building strategy is not optimised

Other equipment:

- Necessity to have a tilt table to allow a Bi-faces component.

- Necessity to have a good system of clamping (fixation of the part during the manufacturing). The clamping system must be considered at the beginning of the CAD design. We preconize to set at least 50mm at each sides of the part for the clamping system.

Raw material

In term of raw material for manufacturing this kind of part, we can preconize:

- 1 Titanium Substrate for the real part
- 1 Titanium Substrate for tests phases
- Some little Titanium Substrates to study the parameters and find the good strategy
- Powder Titanium in the case of reloading
- Some coils of Titanium wire for tests phases and the real part
- Rack of Argon bottles for deposition and inerting the part during manufacturing (Inert gas chamber as well as trailing system)

Control and monitoring

- Control of O2 is very important (%02 < 50ppm to manufacture Titanium)
- Control of the stick-out (With an optical telemeter or other system) to guarantee the best distance between the torch and the part. This system must be automatic to simplify the programming of the different layers
- Metallography laboratory (Analyse the microstructure) with cutting and polishing systems and microscopy analysis.
- Control in Process (adapt the deposition, the parameters, etc. according to the previous layer)
- Software for monitorisation of the process (Saving of all the datas, parameters, etc.)
- Laser pyrometer to control the temperature of deposition, temperature of the substrate, etc. This can be done also with some thermocouple on the substrate.
- AVC control to adapt the height taking into account the voltage.

Post Processing

- Heat Treatment 840°C – 4 hours in controlled atmosphere for Titanium in order to stress relief the part and make easier the machining
- Scan 3D
- XCT, X-ray computed tomography in order to verify the absence of pores.
- Machining of the surface. It is important to find the best parameters in order to remove the minimal quantity of material and be as close as possible to a BTF of 1.

Pilot 4: SLM Opti-lattice

RESULTS OF THE INDUSTRIAL PHASE

Introduction

One of the goals of AM is to maximize the reduction of weight of components and number of pieces among others. As a model, bionic structures are the most optimized ones. They support all the strengths required reducing the quantity of material. Also they can play other different roles by increasing the surface area. Biomimetics transfer these natural designs to the design of components that needs to reduce weight maximizing the surface area, responding to Multiphysics issues. In this way, this pilot wants to show different options of making topology optimization and searching limits of design and simulation tools, and AM equipment and their processor software.

Objective

To show a different topology optimization option, searching limits of current design and simulation tools, AM equipment and processor software.

Methods and evolution

Simulation tools used were various: INSPIRE, HyperWorks, Catia V5 and nTopology. The simulation tools INSPIRE and HyperWorks act similar. They can design, define design spaces, calculate the stresses, displacement and optimize parts trough FEM until all the requirements are met. For design and redesign the parts and finally include lattice structures, delimiting zones of lattice and bulk material, INSPIRE, Catia V5 and nTopology has been used.

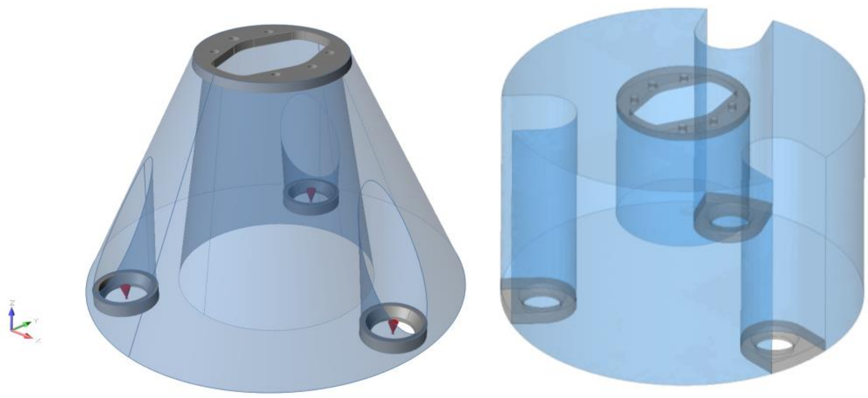


Figure 1. Different design spaces used for the topological optimisation.

Each partner used their own equipment and software in order to see differences in results and strategies. AM equipment used were SLM Solutions and RENISHAW (Figure 2). Both commercial brands based on powder bed fusion. The processor software used was Magics and QuantAM.

Figure 2. Powder Bed Fusion machines used in order to manufacture the demonstrators.

Two materials were used in this pilot: Scalmalloy® and AlSi10Mg obtained by gas atomized powder. Both were characterized in order to verify their quality to be used in the machines.

Results

An evolution of the optimization process is shown for different materials: AlSi10Mg and Scalmalloy®.

In the case of the results obtained for AlSi10Mg, in Table 3 and Table 4, all the evolution of optimization can be observed with the properties of the different designs.

The **original design** commonly fabricated by machining, uses the material Al 7050 T7452. This material is not weldable as it is prone to hot cracking and hence, this design was reproduced in AlSi10Mg because. In this case, the factor of safety was below the limit which has to be 1.25 of the ultimate tensile strength and 1 of the yield strength of the material AlSi10Mg.

Topological optimization was performed for AlSi10Mg by defining a design space with the restrictions and loads imposed by the final user, always taking into account the factor of safety. In this way, we achieved the maximum weight reduction achieved for this material.

In the next step, different lattice designs were fabricated through small samples in order to validate them according to the fabricability (Figure 3). From the obtained results the best lattice design was applied to topological optimised design, however in order to fulfill the factor of safety, the section needed to be increased.

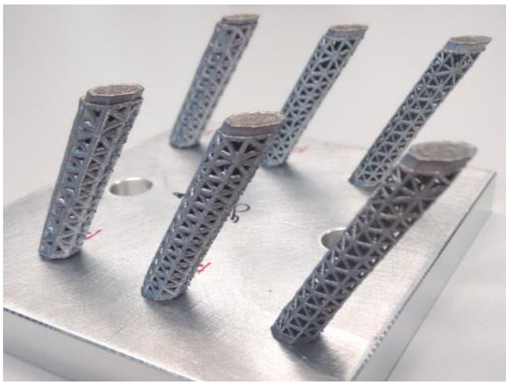


Figure 3. Trials with different lattice dimensions necessary to validate for the application on the design.

In order to obtain the objective of the pilot, the hybrid optimization, several steps were followed as shown in the schema in Figure 4. The resulting hybrid design is a combination of the lattice incorporation design and topological optimization design. The dimensions of the topological optimized one were introduced as lattice in the inner side of the lattice incorporation design. This design was tested with stress and strength simulation. Several cuts were performed in order to leave bulk material in places with higher requirements and lattice in the rest of the part.

Final hybrid design was obtained by fulfilling the factor of safety and obtaining a weight reduction similar to the one obtained by topological optimization (maximum weight reduction). This result gives an advantage in material reduction and surface maximization for specific applications.

Table 3. Original and evolution of the optimisation designs and the final manufactured parts.

Original design	Topological optimisation	Lattice incorporation	Hybrid optimisation
			
			

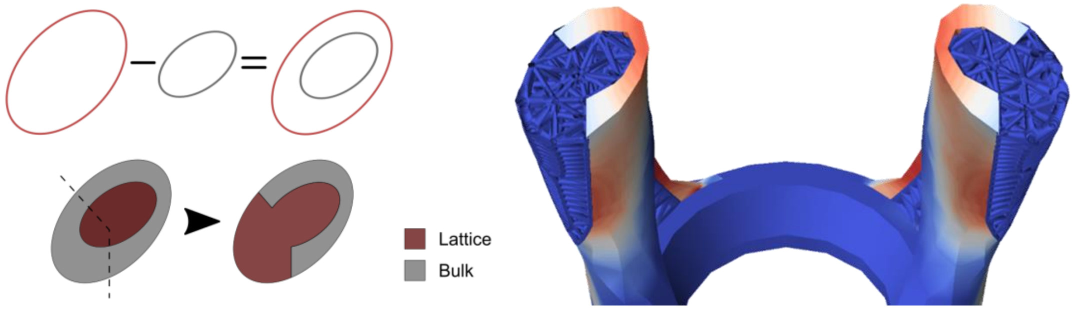


Figure 4. Followed strategy to obtain the hybrid optimised design.

Table 4. Comparison of the different properties obtained for each design.

Model	Material	Weight	Maximum Stress	Factor of safety	Maximum Displacement	%Weight
Original	Al 7050 T7452	185.30 g	360 MPa	1.15	0.45 mm	100.0%
Original	AlSi10Mg	173.29 g	360 MPa	0.59	0.47 mm	93.5%
Optimum topology	AlSi10Mg	114.10 g	168 MPa	1.26	0.29 mm	61.6%
Lattice incorporation	AlSi10Mg	138.20	169 MPa	1.25	0.33 mm	74.6%
Hybrid optimisation	AlSi10Mg	116.81	169 MPa	1.25	0.43 mm	63.0%

In the case of Scalmalloy®, the topology optimization of the part was undertaken following the requirements of the original component. A significant weight reduction was achieved by the conventional top optimization: 58 % mass reduction.

Subsequently, lattice structures incorporation was suggested and prior to overcome the lattice design and inclusion into the component, certain lattice manufacturing trials were performed. The aim of the trial campaign was to test the manufacturability limits of the SLM technology when using the selected material, Scamalloy®. The results for different sections and lengths of the lattice bars are presented in Figure 5.

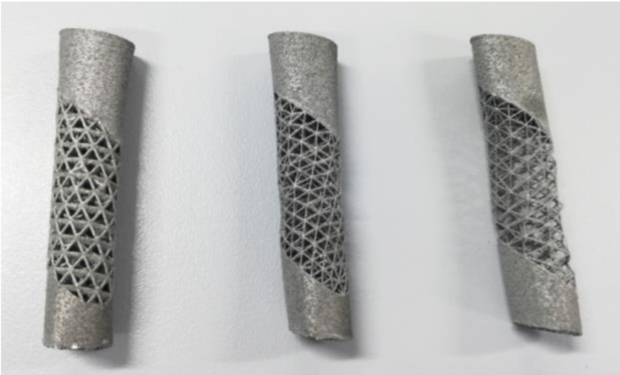


Figure 5. Manufacturing results of lattice manufacturability campaign.

Once manufacturability was proven, the part was redesigned including lattice structures regarding the manufacturing results to select the diameter and length of the bars. Moreover, the redesign process was focused in order that all compromised interfaces were connected with solid part in addition to the lattice.

The obtained results are the ones shown in Table 5 which shows original, final simple optimized and final lattice optimized designs; and Table 6 which includes the numerical results.

Table 5. Original, topology optimized and hybrid designs: CAD views (first row) and manufacturing results in Scalmalloy® (second row).

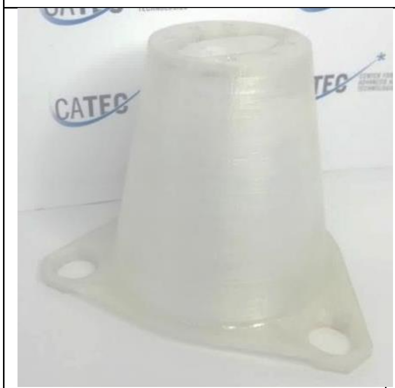
Original design	Topology optimised	Hybrid optimisation
		
		
**PLA prototype for dimensioning purposes*		

Table 6. Mass and mechanical results of original part and Scalmalloy® topology optimized designs.

Model	Material	Weight	Maximum Stress	Factor of safety	Maximum Displacement	%Weight
Original	Al 7050 T7452	189 g	360 MPa	1.15	0.45 mm	-
Optimum topology	Scalmalloy®	88 g	392 MPa	1.29	0.95 mm	47%
Optimum lattice	Scalmalloy®	80 g	-	-	-	42%

PROPOSAL OF ADAPTATION AND RECOMMENDATIONS

Design

The target component is linked with other parts using bolts. If the other parts could be redesigned, the opportunities and hence the topological optimization could be improved. The other parts can be linked together in another way or can be fused in a unique component and hence the freedom of the design space increases.

For lattice incorporation into a topological optimized design, it is often necessary to set your design requirements more conservatively than usual as the lattice incorporation will increase the displacement and strengths between 5-10 times. Hybrid optimisation gives an advantage in material reduction and surface maximization. The reduction of weight should be the same that you can obtain with the traditional optimization.

Supports need to be accurately located in order to remove them without damaging the lattice structure. A space of at least 2 mm should be left without support and none of the lattice bars should be supported.

Equipment

According to the equipment, both machines offer the same advantages for this kind of part fabrication in terms of dimensions and fabricability. This technology offers a reduction of high costly material such as AlSi10Mg and concretely Scalmalloy® highly appropriate for space applications.

Software

In the case of both used software, they offer similar options of design and redesign according to the design of bars and space between links. They offer the possibility to set up a range and hence according to the stresses the lattice applied can vary between established limits.

However, up to now, there is no software that does not need any manual design in order to have a hybrid design between lattice and bulk material. Fabrication challenges involve the transition between bulk and lattice. Also during taking into account the design of supports, lattice bars have to be accurately oriented in order to supports inside the lattice structure.

Sometimes is necessary to remove manually the lattice that the software automatically designs.

Other found limitation is that designs with lattice involve high data memory which is impossible to process in the processing software of the fabrication machine.

Raw material

Powder used for processing by SLM and focusing on the fabrication of lattice structures, the quality has to be assured in terms of particle distribution, shape and flowability. In order to fulfill the desired properties chemical composition has to be checked.

For the appropriate manufacturing of these parts in SLM is commonly recommended gas atomized powders with particle size between 20 and 63 µm.

Fabrication

Build orientation has to be accurately selected in order to avoid undesirable supports and supports in the lattice. A thin layer thickness is recommended, around 30 µm in order to avoid any failure in the bars of lattice.

Post processing

Due to the incorporation of lattice structures, powder can be entrapped between lattice cells, hence accurate cleaning of powder has to be done. Also no surface treatment is recommended in order to avoid any damage to the lattice.

In order to evaluate the quality of these AM components a X-ray computed tomography can be applied. This is normally recommended in cases of complex shapes and lattice structures in order to discard any possible pore or failure.

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