Manufacturing of 3D Printed Metal Components for Helicopter Drive System

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INTRODUCTION

This paper unveils the manufacturing processes and entailed challenges related to the 3D printing of metal parts for aerospace purposes, presenting two distinct case studies. The first case study examines the design and fabrication of lightweight components of the input module of a tilt-rotor drive system (Next Generation Civil Tilt-Rotor – NGCTR – Technology Demonstrator), representing a pioneering application of Additive Manufacturing technologies in aeronautics. Besides these functional components which comprise auxiliary lubrication tanks and pump cases, metal Additive Manufacturing has also been adopted to realize a scaled model of the whole gearbox of the tilt rotor, for dissemination purposes, proving the accuracy, flexibility and short lead times that such digital manufacturing process can offer. By analyzing this second case study, we aim to demonstrate the advantages and challenges associated with different AM technologies in aerospace applications, providing insights into their potential for future advancements.

BACKGROUND

Metal Additive Manufacturing (AM), and particularly Selective Laser Melting (SLM), is emerging as a transformative technology with exciting potential for the aerospace sector. Its ability to reduce component weight, optimize geometries, and enable the production of complex parts has garnered increasing interest among aerospace Original Equipment Manufacturers (OEMs). However, the widespread adoption of AM in critical aerospace applications poses substantial challenges.

A primary challenge is the need for rigorous quality control to ensure the structural integrity of AM-produced components. Defects, such as porosity and cracks, can negatively impact component performance and reliability, especially in the extreme operating environments typical of aerospace. Therefore, mastering advanced defect monitoring and material characterization techniques is essential must-to-have to succeed.

Furthermore, the complexity of introducing 3D-printed parts into critical systems, like oil-wetted helicopter drive systems, requires a multidisciplinary approach: Ref. 2 provides an intriguing example of the different factors to be tackled.

Despite these challenges, the potential applications of AM in aerospace are vast. Beyond weight reduction and topology optimization, AM can be further exploited for the repair of existing components, extending their lifespan and reducing maintenance costs.

The case studies presented in this paper underscore the transformative potential of additive manufacturing in the aerospace sector.

CASE STUDY NR. 1 – FUNCTIONAL COMPONENTS

A specific case study involves the development of experimental components for a tilt-rotor drive system using AlSi10Mg aluminum alloy and SLM technology. The components are pairs of Auxiliary Tanks and Pump Cases, wherein one pair is installed on the left nacelle and the other on the right nacelle. This project aims to establish a standardized production process, including heat treatments, surface treatments, material characterization and Non-Destructive Testing (NDT) techniques, to ensure the quality, repeatability and reliability of AM-produced components.

The case study demonstrates the industry's commitment, from Prime to contractors, to develop standardized AM production processes for critical aerospace applications, ranging from design phase to execution and testing.

The design phase of the components, for which Leonardo Helicopters was accountable, is described in in Ref. 1. and can be summarized as follows, for the two component types:

- **Auxiliary tanks** provide backup lubrication, requiring compact, vertically-oriented designs due to their installation close to the nacelle structure. Their hydraulic circuits include filling, overflow, and dripping ducts with metering elements for oil control. Limited space and high-speed engine rotation necessitate robust, cantilevered designs with high stiffness to avoid dynamic issues due to resonance excitation. Additive manufacturing enables optimized shapes, allowing for a geometry following the shape of the nacelle structure, targeted at maximum oil retention and structural integrity; features like "T-shaped" ribs and thin walls of 1 mm thickness with stiffeners are exploited to cope to the aforementioned dynamic requirement. Figure 1 shows the auxiliary tanks inserted in the digital mock-up of the aircraft, highlighting the great challenge in optimizing the available room.

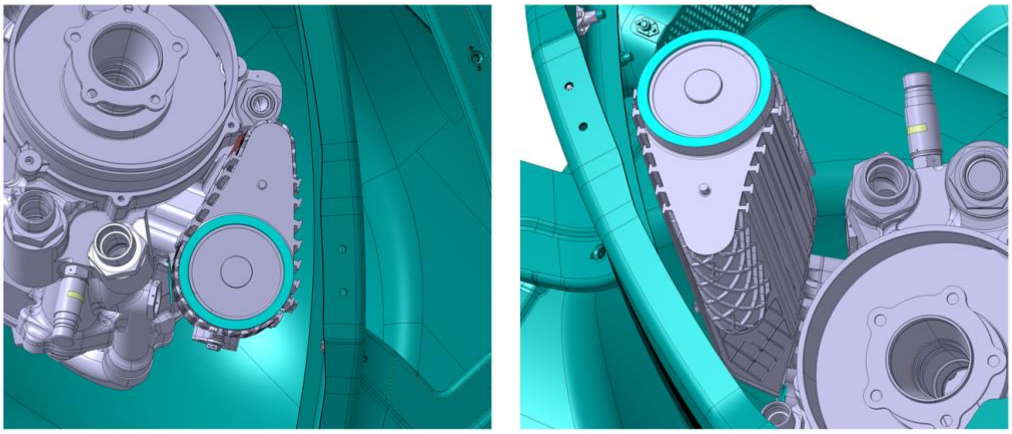

Figure 1 – Auxiliary tank installed on aircraft digital mock-up.

- **Oil pump cases**, designed for AM, enable complex internal geometries and substantial weight reduction through optimized wall thickness and strategic structural elements. Design challenges include support-free internal oil ducts, integrating legacy components, and managing roller bearing loads. Localized areas featuring a thicker wall and stiffeners address structural demands, while a careful design of internal ducts and external geometries avoid unremovable supports. Drop-like internal channel profiles and permanent supports facilitate manufacturing. This approach achieves a 30% weight reduction compared to conventional methods, demonstrating the benefits of AM in complex mechanical components.

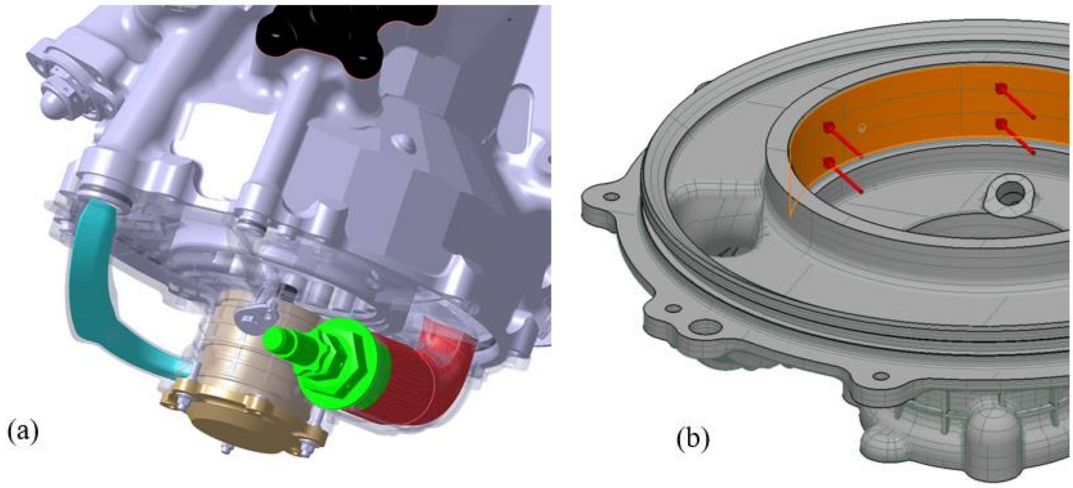

Figure 2 – Pump case.

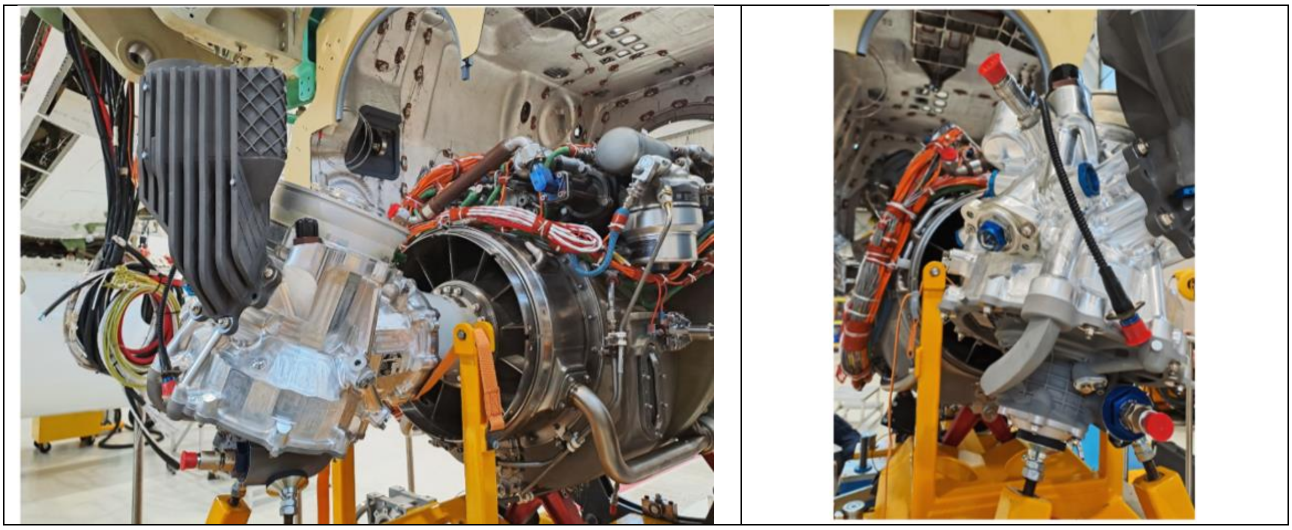

Figure 3 – ALM Components installed on A/C.

Figure 3 shows the tangible results of the cooperation between Leonardo and Aidro, a Leonardo qualified partner for Additive Manufacturing parts; with a design coming from the OEM, the supplier defined the manufacturing strategy of the components and realized them. The figure on the left shows the auxiliary tank installed on the gearbox input module, whereas the figure on the right portrays the pump case installed on the bottom of it. The following sections will investigate how it was possible to manufacture the parts starting from a Design Data Set.

Components Manufacturing Strategy

The strategies employed by Leonardo and Aidro to generate a manufacturing process compliant to stringent quality requirement typical of aerospace industry and part requirements encompasses the entire manufacturing cycle, from printing to final delivery.

The components, two auxiliary tanks and two oil pump cases, are aluminum flight ready parts categorized as “Significative” according to aeronautical standards.

The choice of adopting AM for the manufacturing of the parts, instead than other conventional techniques like CNC machining or casting, is driven by the need to minimize weight and optimize the volume occupied by the components. This last point gave the freedom to designers to experiment quite complex geometries, especially for the auxiliary tanks. In fact, those feature thin wall thicknesses reinforced by ribs, which could be obtained only by AM.

The 3D printing machine used was a EOS M290, single laser, with a printing table of approx. 250x250x300 (H) mm, located at Aidro facility in Varese area, Italy. This specific printer, with the specific single material AlSi10Mg, was previously object of qualification by Leonardo Helicopters, according to its specification for AM special process. The qualification process of the printer comprised the buildup of an initial set of coupons, heat treated T6 and then tested (tensile, density, microstructure), in order to gather an initial set of data compliant, in terms of static mechanical properties, to ASTM F3318 standard, which was taken as reference[1], and to the printer manufacturer's datasheet (Ref. 3). Those data demonstrated to be coherent with the ones collected during previous activities and studies (Ref. 4, 5), as well as to Leonardo know-how.

For each build job that followed, an additional set of coupons was 3D printed together with the part, then tested and the results compared with initial ones above mentioned, in order to check the repeatability of the process and prove the consistency of the mechanical properties along different productions.

A specific attention was also given to the powder used. The AlSi10Mg powder was constantly monitored along the production of parts and coupons, according to a procedure that defined the traceability of the powder's Method of Manufacturing and batches, the allowed maximum number of recycles (i.e. how many time the non-melted powder can be reused after sieving without any issue), the consistency of the powder characteristics (chemical, flowability, size and distribution, etc...).Moreover, during each print job, a small capsule was manufactured in which non melted-powder was trapped, to allow, if needed, additional analysis on the powder used for a specific job or part.

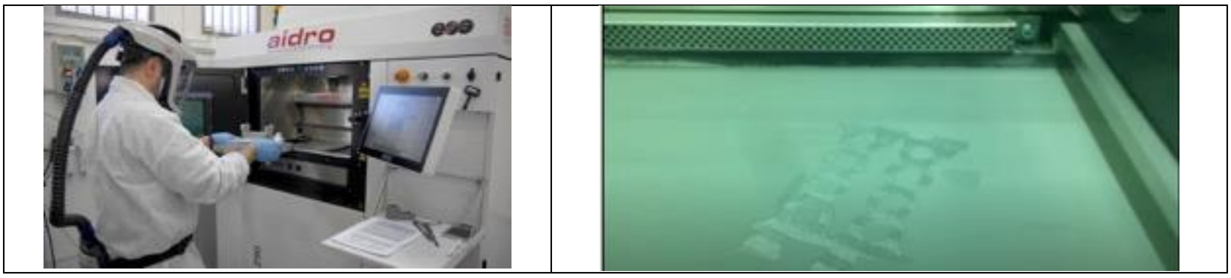

Figure 4 SLM Printing on EOS M290

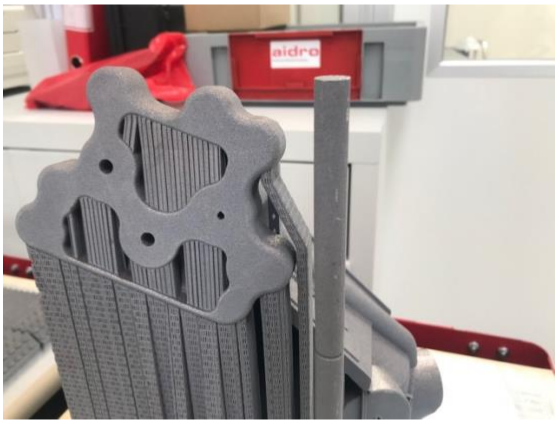

Figure 5. Support structures and test coupon 3D printed with the component

A first manufacturing challenge focused on the component orientation in the available building volume and on the support structures. Those are needed to guarantee heat dissipation and stability, during the buildup of the part, being at the same easy to be removed after the printing without compromising the quality of the parts.

The depowdering phase, i.e. the removal of residual powder from inner volumes or cantilevered parts, required particular attention. In fact, the even minimal presence of residual powder in inner channels or volumes, or its solidification during post printing heat treatment, could affect the functionality of the part so leading it to scrap. The

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[1] Excepted for the minimum value of UTS for which ASTM F3318 in Table 2 shows a questionable value for T6 condition, higher than the as-printed condition. For UTS the minimum threshold is 283 MPa for T6 condition.

adopted depowdering strategy in “dry conditions”, meaning that no contact with fluids was allowed at this stage (fluid contact risks to pack the aluminum powder and make it impossible to remove), demonstrated to be effective, as no indication emerged during CT Scan nor Radiographic Testing, where a lower material density linked to the presence of residual powder can be highlighted.

The T6 heat treatment phase was required in order to homogenize the material properties, reduce stresses and increase elongation, though lowering the mechanical properties (YS and UTS) with respect to the as-printed status. T6 heat treatment can be considered as a standard post process for conventional aluminum parts in aeronautics, however its application to AM, a different manufacturing technique with respect to wrough or cast leading to different microstructures, might be explorative and requiring some fine tuning. Indeed, this phase was critical, not only because it is by itself a special process, but mainly because the components showed low wall thickness (1mm) and other geometrical features that could have been subjected to deformation during the solubilization cycle. In fact, two components previously realized for demonstrative purposes showed not acceptable deformation after the heat treatment trial run (Figure 6). To solve this issue, a specific jig has been designed and manufactured in steel to remain in contact to the parts during the heat treatment phases in order to maintain confined the part and avoid possible deformation out of the acceptable shape tolerances. Measurements have been done by mean of a 3D scanner before and after the heat treatment on each part, and results have been compared. Thanks to the custom-made jig, no deformation out of the tolerances was recorded for the production series components.

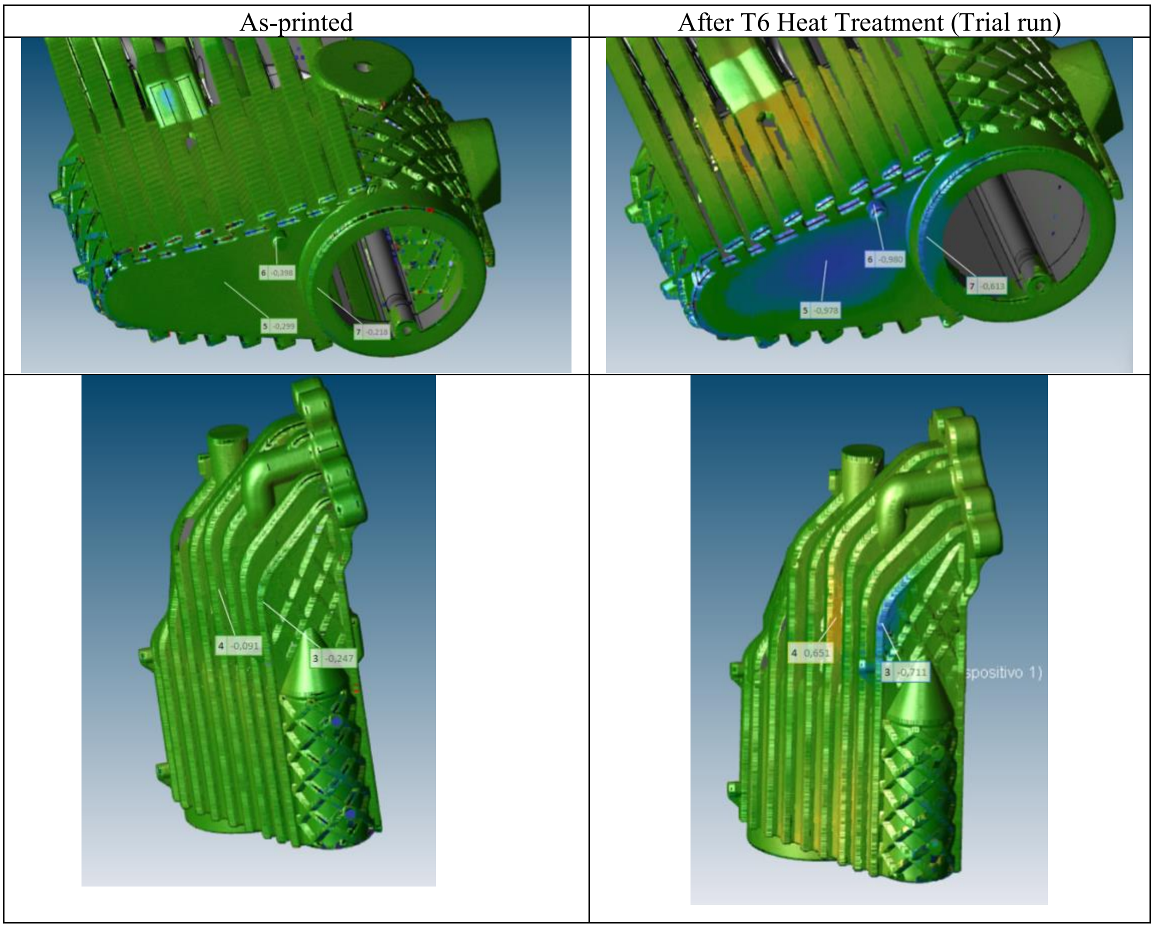


Figure 6. 3D Scan of the Auxiliary tank before and after the trial T6 Heat Treatment run, where some shape deformation beyond acceptable tolerances were recorded. As corrective action, custom jigs where manufactured in order to contain the part during the heat treatment

Before sandblasting, the components have been tested with Penetrant Testing, CT Scan and Radiographic testing. No defects have been recorded, like cracks, nor residues of powder in inner volumes or channels. Some powder residuals have been found on outer surface of the components with ribs (as shown in Figure 7), but this did not affect the functionality of the components and has been easily removed during sandblasting.

Final post-processing operations included CNC machining, low pressure test (air bubble test in water, static oil pressure test at 10 bar, In-line contamination monitoring with oil, to double check the absence of powder residuals inside the parts) surface treatment (chemical conversion), painting and standard installation.

Figure 7. CT Scan showed no defects, nor powder trapped in inner volumes. Some powder residuals on external ribs, not affecting the part functionality, were removed by sandblasting

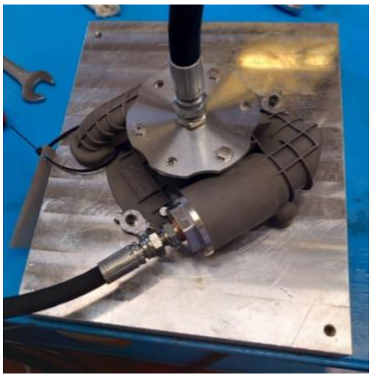
		
Static Oil Pressure test at 10 bar	In-line oil contamination monitoring, to double check the absence of residual powder in inner volumes of the part.	Air Bubble test in water

Figure 8. Oil and Air pressure test showed no leakage

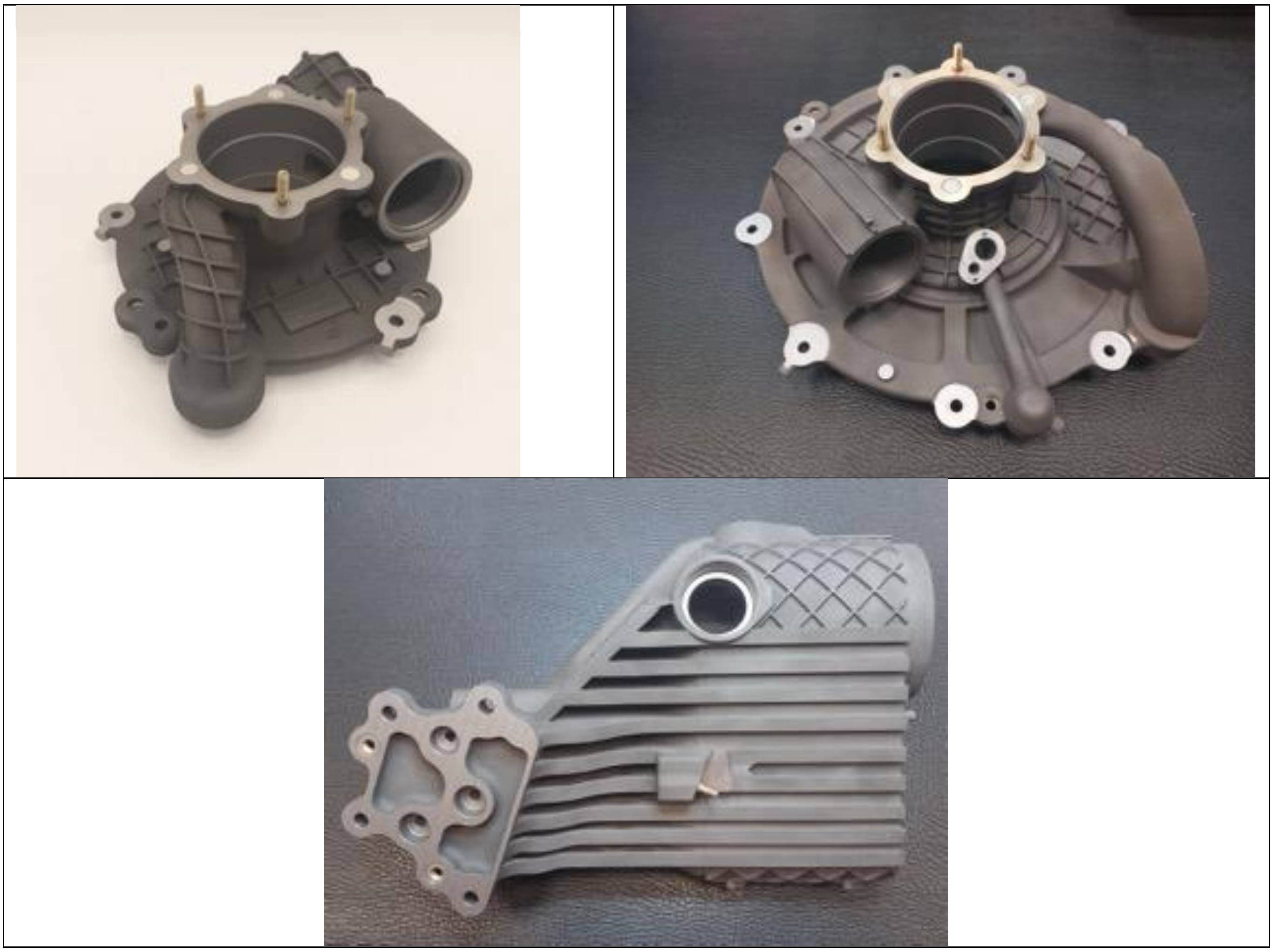


Figure 9. Final components: Oil pump cases (LH and RH), and Auxiliary tank (LH),

Material Characterization of AlSi10Mg T6 coupons

Several components have been produced both for bench testing and for the installation on the Next-Gen Civil Tilt Rotor Technology Demonstrator. This allowed to gather statistical values of static mechanical properties from the coupons printed together with the parts. Fatigue behavior of coupons printed on the specific 3D printer was not here investigated, but was object of a previous study (Ref. 5).

Tensile testing has been done on machined coupons (ASTM E8) derived from 3D printed cylinders with diameter 10mm and length 100mm, build in 4 directions: XY, Z, +/-45° (i.e. build with the main axis respectively parallel to build plate, perpendicular to build plate, with inclination of 45° to build plate). Moreover, Archimedes' density (ASTM B311), hardness test and microstructure analysis has been done on 20mm side 3D printed cubes.

Some coupons have also been extracted from sacrificial 3D printed components.

Average results are shown on Table 1. No significant difference in results were recorded between XY, +/-45° and Z direction coupons, the latter being lower in YS and UTS of few percent with respect to XY, as known in literature. No difference in results was neither remarked between cylindrical coupons and coupons extracted from components (machined, in both cases).

Average Density [g/cm]	Average Hardness [HRB]	Average YS [MPa]	Average UTS [MPa]	Average Elongation [%]
2.62	44	244	311	15.5

Table 1. Average mechanical properties of AlSi10Mg T6 coupons printed together with the components

Some cylindrical coupons have been analyzed with CT Scan (on the volume highlighted in red), prior to tensile testing. A porosity analysis showed that the ratio between volume of defects and the coupon volume (highlighted red in Figure 10), is fully acceptable, being lower than 0.1%, as well as defects distribution.

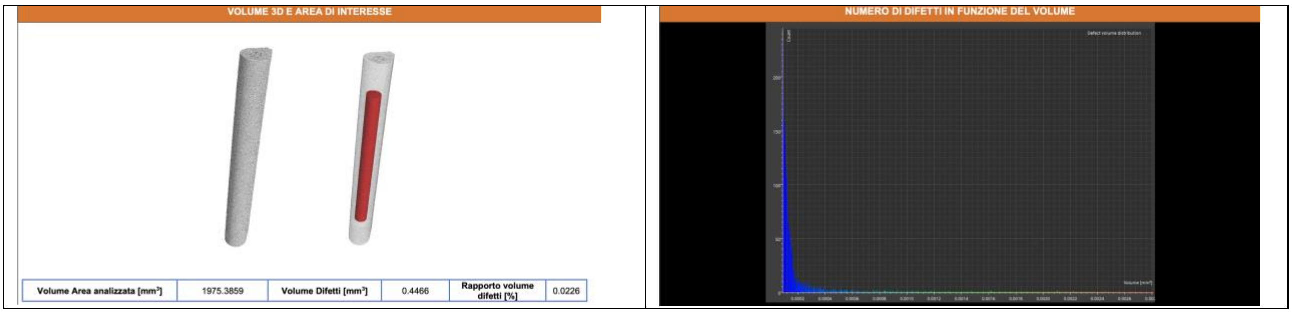


Figure 10. Porosity Analysis on coupons by CT Scan

The micrographic examination was performed on a metallographic specimen obtained by sectioning the starting sample in the longitudinal direction corresponding to the growth direction.

Following metallographic etching (Keller's), the resulting microstructure is homogeneous both on the surface (Micrograph No. 1) and at the core (Micrographs Nos. 2.1 and 2.2) and consists of globular Si compounds uniformly distributed in a matrix of elongated α-Al grains. No melt pools are observed.

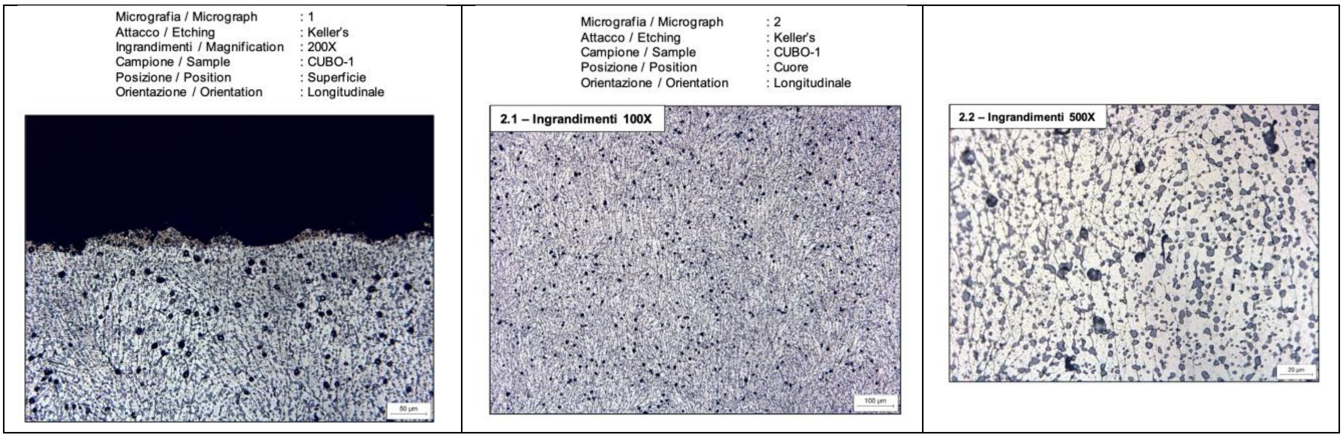


Figure 11. Micrographic examination (ASTM E3, ASTM E407)

Conclusions

The manufacturing approach, from 3D printing to post processing and testing, proved to robust. No defects were found after 3D printing or during NDT; no problems nor criticalities were found during heat treatment, CNC machining, surface treatment including anodizing and painting and standard installation. Static oil pressure test and air bubble test showed no leakages of the parts; In-line oil contamination monitoring confirmed that no residual powder was left inside the parts, in accordance with NDT testing. Experimental data gathered from coupon mechanical testing were consistent along the production.

CASE STUDY NR. 2 – TILT ROTOR SCALED MODEL

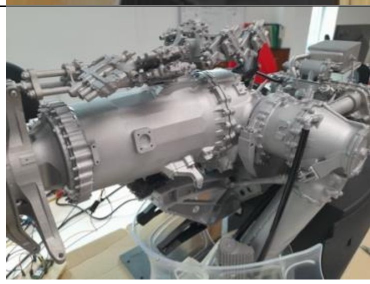
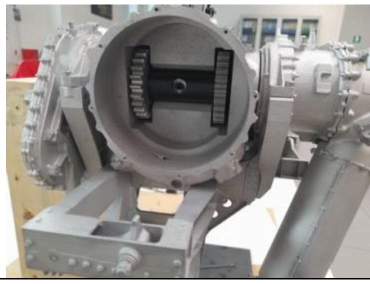
Figure 12. 3D printed Auxiliary tank in LPBF (left) and its 1:5 scaled model in BJ (right)

For dissemination purposes in the frame of Clean Sky 2, a 1:5 scaled model of the full tilt rotor gearbox has been commissioned to Aidro. Starting from a multitude of CAD geometries, including the ones of the real functional components, Aidro designers firstly made some simplification, then chose the optimal Additive Manufacturing technique to produce and assemble the various elements. Aidro realized then an electro-actuated scaled model capable to represent the most interesting features of the tilt rotor, which is the tilting of only a portion of the gearbox. AlSi10Mg and SLM were not the only choice in regards of material and manufacturing technology. As a matter of fact, the technology of metal Binder Jetting (BJ) proved to be the most adequate to guarantee high part resolution with little or no need of post processing, generally a time-consuming operation, given the very short time constraint for the delivery (2 months). 3D printed polymers were as well chosen for some part of the model.

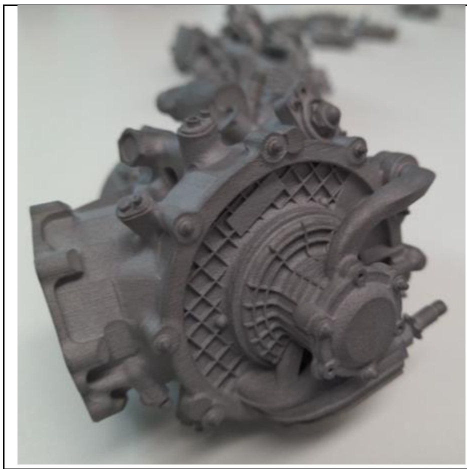
In total were produced and assembled the following 3D printed parts: 40 in SLM both in aluminum AlSi10Mg and steel 316L, 30 in BJ in steel 17-4PH, 2 in transparent resin, 2 in polymer. Carbon fiber and steel plates were also used.

Beyond the dissemination purposed related to the NGCTR-TD project, the creation of this scaled 3D model using different additive manufacturing technologies showcases the versatility and potential applications of each technology providing a practical demonstration of their respective unique advantages, specific characteristics and innovation potential.



1:5 scaled tilt rotor model which adopts various Additive Manufacturing techniques



Details of 3D printed metal parts in metal Binder Jetting

Details of 3D printed metal parts in metal Binder Jetting

The 1:5 scaled tilt rotor model assembly phases

Figure 13. 1:5 scaled model of the tilt rotor.

CONCLUSIONS

Additive Manufacturing techniques proved to be adequate to produce on industrial level, even still for small series, lightweight and complex shaped parts for aeronautical applications. The response from the supply chain, which involved special processes (Additive Manufacturing, heat treatment, NDT, surface treatment) demonstrated the ability to withstand the challenges posed by new design approaches. Moreover, an extent of AM techniques, including SLM and BJ, confirmed to be winning for fast realization of demo parts and assemblies.

More in general, to develop an industrial perspective of AM application to the design and manufacturing of this category of parts, considering the typical production rate of helicopters industry, it's crucial to understand that this technology truly shines where traditional production methods fall short. Integrating cost evaluation, both recurring and non-recurring, right from the initial stages is essential for a project's success and sustainability. It's not just about innovation; it's a pragmatic approach that considers all economic and technical variables. Moreover, design for additive manufacturing must be intrinsically linked to industrial feasibility. This includes not only the design phase but also all aspects related to certification and the qualification of process, materials and parts.

The ability to produce what would otherwise be impossible or uneconomical with other technologies is the true added value of AM.

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