Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2026, 20(10), 215–223
https://doi.org/10.12913/22998624/224901
ISSN 2299-8624, License CC-BY 4.0

Received: 2026.06.10
Accepted: 2026.07.22
Published: 2026.09.01

Design and evaluation of additive manufacturing technologies for innovative aviation structures

Paweł Guła[1*], Jacek Dudziak[1], Dawid Ulma[1], Jerzy Żółtak[1], Antonio Chiariello[2], Tomasz Łusiak[3]

[1] Lukasiewicz Research Network – Institute of Aviation, Aviation Technologies Center, al. Krakowska
[2] Italian Aerospace Research Center, Via Maiorise, 1, 81043 Capua CE, Italy
[3] Department of Thermodynamics, Fluid Mechanics and Aviation Propulsion Systems, Lublin University of Technology, ul. Nadbystrzycka 36, 20-618 Lublin, Poland
* Corresponding author's e-mail: pawel.gula@ilot.lukasiewicz.gov.pl

ABSTRACT

The aim of the more affordable small aircraft manufacturing (SAT AM) project was to develop the technologies enabling the manufacture of lighter and more cost-effective aircraft airframe structures, supporting the modernization of airframe production. This paper presented the methodology and results of applying additive manufacturing (AM) technologies to produce components for a cabin demonstrator. The benefits of the applied technology – including materials, tools, testing procedures, and design methodology – were discussed, and the results were analyzed to highlight the project's impact on the implementation of AM and its potential significance for future aircraft manufacturing.

Keywords: commuter aircraft, additive manufacturing, material, test, clean sky.

INTRODUCTION

The more affordable small aircraft manufacturing (SAT AM) project was part of the European Clean Sky 2 Programme, aimed at developing technologies supporting an environmentally sustainable European transport system (Small Air Transport - SAT) [1]. Accordingly, the SAT AM project focused on the development and evaluation of cost-effective and energy-efficient manufacturing technologies [2] aimed at reducing production costs as well as environmental impact through improved efficiency and resource utilization.

To validate the proposed manufacturing approaches, two demonstrators based on an existing aircraft platform were selected. The chosen aircraft was M28, designed by consortium partner PZL Mielec (Figure 1). The demonstrators comprised the fuselage cabin structure (Demonstrator A) and the engine nacelle (Demonstrator B), each integrating several innovative manufacturing solutions. This paper focused exclusively on the application of AM technologies in the production of fuselage cabin components.

Additive manufacturing was identified as a key enabling technology within the SAT-AM project, offering potential benefits, such as reduced part count through functional integration, shortened lead times, structural mass reduction, and improved production repeatability [3]

MATERIALS AND METHODS

A newly designed aircraft structure must satisfy stringent operational, certification, and in-service requirements from the earliest stages of the design process. One of the fundamental approaches to addressing this challenge is the application of advanced manufacturing technologies and novel materials in structural design. In particular, the combination of optimization

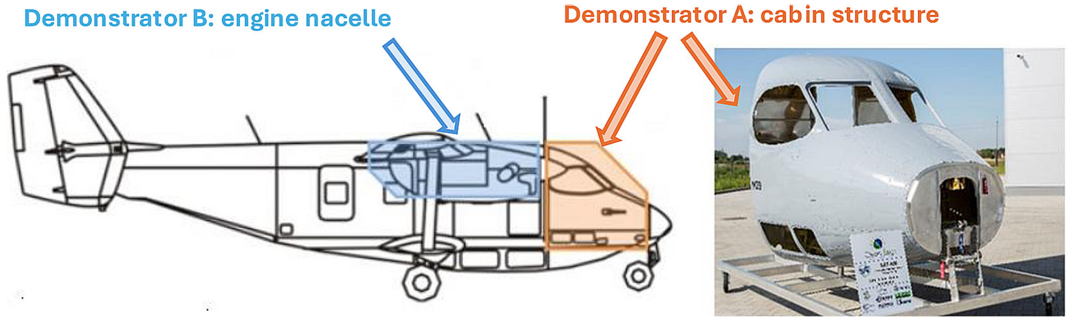

Figure 1. SAT-AM demonstrators: M28 aircraft side view (left), full scale Cabin Demonstrator (right)

methods with three-dimensional (3D) modeling enables the development of lightweight components while maintaining the required levels of strength and stiffness [4]. Depending on the design assumptions and objectives, various optimization strategies may be employed (Figure 2).

The simplest strategy is size (sizing) optimization, which involves the gradual removal of material from a component with verification at each step that functional requirements are satisfied. This approach is primarily applicable to relatively simple structures with clearly defined design regions and is well supported by both commercial and research-oriented optimization tools.

Shape optimization, in contrast, focuses on modifying geometric features, such as wall thicknesses or cut-out geometries, while external boundaries are typically kept unchanged. Due to the increased problem complexity and the less explicit definition of design variables, shape optimization relies on dedicated numerical algorithms.

The most general and versatile approach is represented by topology optimization. When the initial conditions, boundary conditions, and load cases are properly defined [5], this method can be applied to components of virtually any geometry. Topology optimization determines the optimal material distribution within a prescribed design space in order to satisfy the constraints related to stiffness, strength, and mass [6].

Respecting its inherent capabilities, topology optimization is expected to play an increasingly important role in future aircraft structural design, particularly in the cases involving multiple and potentially conflicting requirements. [7]

DESIGN AND MANUFACTURING

The implementation of topology optimization applied within the project combined CAD-based modeling with finite element method (FEM) analyses and dedicated (in-house) additive manufacturing software. FEM-based mechanical analyses enabled the identification of regions where material could be retained or removed in order to satisfy predefined strength criteria under specified load cases and boundary conditions. Based on these results, dedicated CATIA optimization modules were used to generate an efficient material distribution while accounting for the constraints of the selected Additive Layer Manufacturing-oriented design philosophy. These constraints included, in particular, the minimum

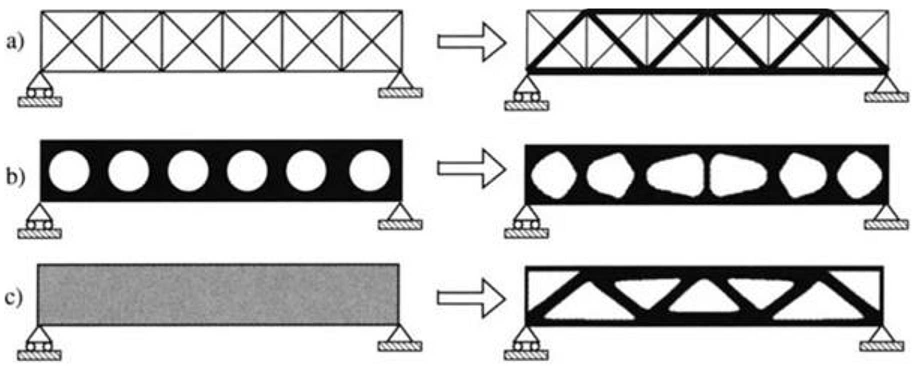

Figure 2. Different approaches to design optimization (a) size optimization, (b) shape optimization, (c) topology optimization [6]

feature size, limitations related to overhangs, and anisotropic material behavior resulting from the layer-wise nature of the manufacturing process. The resulting component topology thus ensured both manufacturability and compliance with the defined design requirements.

The assessment of the applicability of additive manufacturing technologies for the production of aerospace components constituted one of the research objectives of the SAT AM project. Within the project, two additive manufacturing technologies for metallic components were investigated.

The first approach was based on the laser metal deposition (LMD) method [8], developed and implemented by EUROTECH. This process enables multilayer, additive fabrication of components with complex geometries and relatively large dimensions. In the LMD process, a focused laser beam locally melts the substrate, forming a molten pool into which metallic powder is injected. The powder fully melts and forms a metallurgical bond with the base material. By appropriately controlling process parameters and deposition strategies, individual layer thicknesses in the range of approximately 0.2 mm to 1.0 mm can be achieved, while maintaining low heat input and favorable metallurgical and mechanical properties [9].

The analyses conducted during the implementation of the LMD technology indicated that two process modifications were required to improve process stability and quality. The first modification involved the use of a tilting rotary table as the basis for layer deposition. Adjusting the table orientation during deposition ensured a near-vertical alignment of the deposition head when forming successive layers. The second modification was related to the preparation of each subsequent layer. Initial trials demonstrated that technological interruptions during the build process could negatively affect the geometry of the resulting structures and lead to the formation of structural defects. Variations in layer continuity and thermal history resulted in non-uniform material build-up and localized structural discontinuities.

To mitigate these effects, the process was modified by introducing laser annealing of the working surface prior to the deposition of each subsequent layer. This operation involved positioning the process head close to the working surface and guiding it along the component contour with the laser activated at an appropriately selected power level, while the powder feeder remained switched off [10]. Elevating the temperature of the underlying layer limited its volumetric expansion during the deposition of the subsequent layer, thereby improving structural continuity and geometric accuracy [11]. The production of test components using the LMD technology primarily employed SS 316L and SS 410 stainless steel powders (Table 1), which served as economical substitutes for the materials typically used in aerospace applications. In the final phase of the study, components were also manufactured using titanium alloy Ti-6Al-4V (Grade 5), applying spherical powder with a particle size distribution ranging from 45 to 106 µm.

The second approach employed within the SAT-AM project for the production of test components was based on electron beam melting (EBM) technology, implemented by CIRA [12]. In the EBM process, the energy source is a focused electron beam generated by an electron gun and accelerated to high energies. Through precise electromagnetic focusing and deflection, the beam is used to selectively melt metallic powder according to the cross-sectional geometry of the manufactured component. The process is carried out layer by layer under high-vacuum conditions, which constitutes one of its key distinguishing features compared to the LMD technology. For the manufacturing of the front landing gear bracket using the EBM process, titanium Ti-6Al-4V was used.

Table 1. Chemical composition of the SS Grade Powder

Chemical composition	SS Grade 316L (5520) powder	SS Grade 410 powder (UNS41000):
Carbon	0.012%	0.15%
Chromium	16.7%	12%
Nickel	12.6%	<1%
Magnesium	1.6%	<1%
Silicon	0.7%	<1%
Molybdenum	2.5%	-
Phosphorus	-	<0.04%
Sulfur	-	<0.03%
Iron	Remaining percentage	
Powder granulation	45–125 microns	53–150 microns
Density	8 kg/dm^3	7.8 kg/dm^3

RESULTS AND DISCUSSION

The cabin section (Figure 1 on the right) represents the most complex structural part of a typical all-metal aircraft fuselage. The application of advanced metal manufacturing technologies in this demonstrator illustrates a more cost-effective approach to full-fuselage production for aircraft of this class. The cabin demonstrator was designed and manufactured based on a modified version of the existing M28 fuselage, incorporating changes in material selection, manufacturing processes, and structural design to accommodate the newly applied technologies.

New bracket for full-size cabin demonstrator

The redesign of the bracket was aimed primarily at mass reduction. The mass of the original conventionally designed and manufactured component was 688 g. The optimization process was carried out iteratively. Already the second design iteration, manufactured using stainless-steel powder, resulted in a mass reduction of 53%, yielding a final mass of 362 g (Figure 3a). Subsequent modifications, including a material change to titanium alloys, led to a total mass reduction of 71% relative to the original component (Table 2).

All test brackets manufactured within the project were subjected to comprehensive inspections. From the perspective of geometric accuracy, the produced samples exhibited very high quality (Figure 3b). However, computed tomography inspections of the components manufactured from titanium alloys revealed the cracks caused by residual stresses occurring within the spatial structure (Figure 3c). These stresses resulted from significant thermal gradients generated during the laser metal deposition (LMD) process.

In addition, studies were conducted to assess the influence of layer deposition orientation

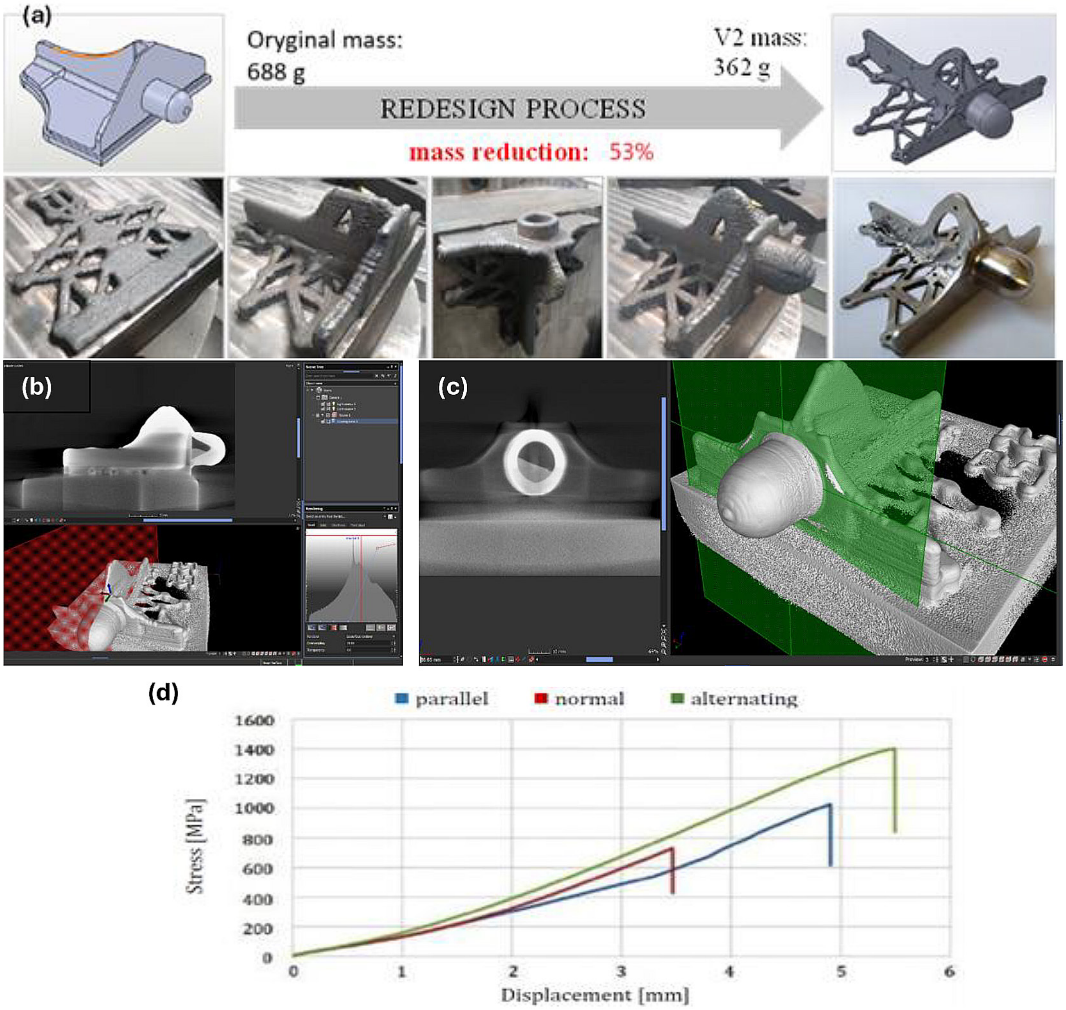

Figure 3. Bracket redesign using topology optimization combined with the LMD additive manufacturing technology: (a) the redesign process (b) geometrical inspection of new bracket (c) tomographic examinations of the part made of stainless steel (d) influence of different layer orientations on stress

Table 2. Influence of material selection on bracket mass reduction

Parameter	Volume [cm^3]	Mass [g] theoretical	Mass [g] actual
Stainless steel – original design	87	678	688
Stainless steel – redesign	39	312	362
Titanium (Ti-6Al-4V) original design	87	385	Not manufactured
Titanium – redesign	39	173	198

during the additive manufacturing process on the mechanical properties of the fabricated brackets. Three sets of tensile specimens were prepared, with deposition layers oriented perpendicular, parallel, and alternating relative to the loading direction. The test results demonstrated that, in the LMD process, the mutual orientation of layers significantly affects mechanical performance. From a mechanical standpoint, the most favorable results were obtained for the alternating layer orientation strategy. For example, tensile strength values of 750 MPa, 1000 MPa and 1400 MPa were obtained for perpendicular, parallel, and alternating deposition orientations, respectively, for the brackets manufactured from stainless steel and titanium alloys (Figure 3d). The presented results were developed based on the statistical scatter of the tested samples. Figure 4 shows three plots containing data from the samples, and Figure 5 shows the data scatter based on 2σ for the case of parallel material arrangement.

New fitting lug

Another component selected for investigation was the Nose Landing Gear. Two different manufacturing approaches were applied for the production of this component.

In the first approach, the upper part of the Nose Landing Gear designed by ILOT was manufactured by Eurotech using laser metal deposition (LMD) technology. Figure 6a presents the initial design (mass 1.5 kg), the topology optimization stage, and the final manufactured component (mass 0.9 kg). The final component was subjected to non-destructive testing using X-ray computed tomography (CT).

Subsequently, strength tests were conducted to determine the load-carrying capability of the manufactured components. The tests were performed on a specially designed and manufactured test stand (Figure 6b). Load application

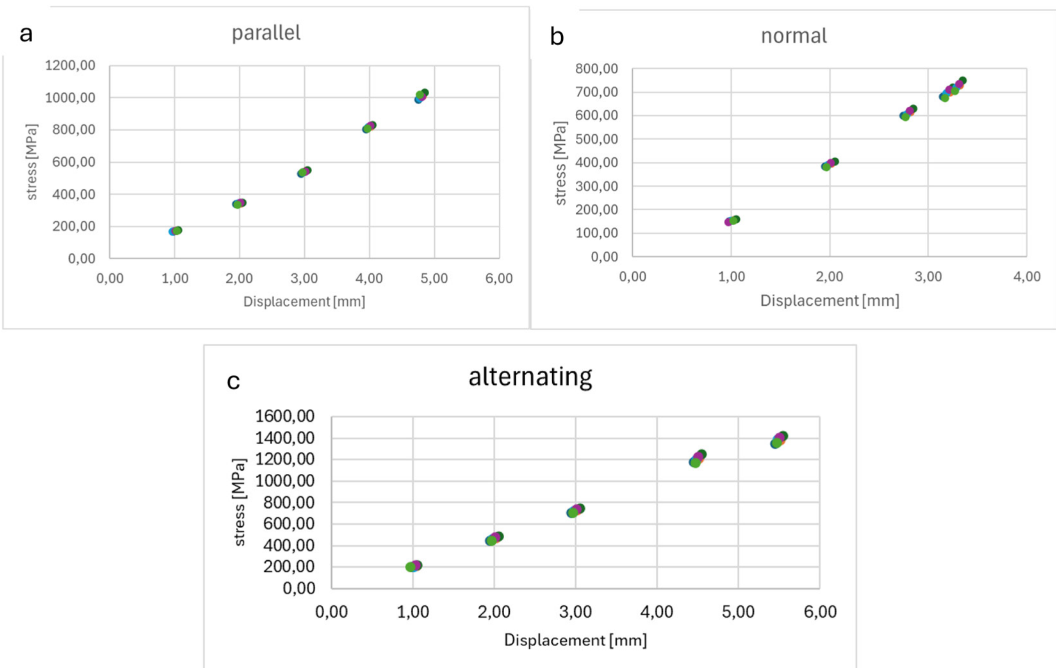

Figure 4. Results of tensile strength tests; a – parallel deposition orientations, b – perpendicular deposition orientations, c – alternating deposition orientations

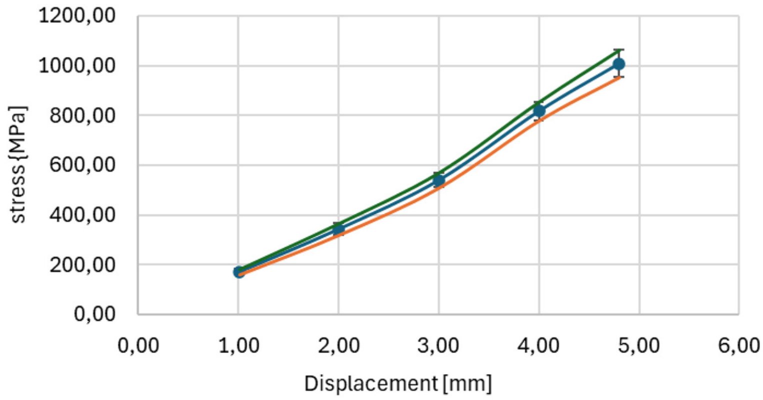

Figure 5. Data scatter based on 2σ for the case of parallel material arrangement

and measurement were conducted continuously throughout the tests.

In accordance with airworthiness requirements, the tested component must be capable of sustaining the limit load without permanent damage or deformation after unloading. In the present test program, the structure was loaded with the force component F_{xz} up to 100% of the nominal design load specified in the test requirements. After reaching this level, the loading was continued until structural failure occurred.

The following sequence of damage was recorded:

- at F_{xz} = 6927 daN (95.6% of the program load) – fracture of the left arm;
- at F_{xz} = 8788 daN (121.3% of the program load) – fracture of the right arm;
- at F_{xz} = 9038 daN (124.8% of the program load) – fracture of the middle arm.

The final condition of the tested component is shown in Figures 6c and 6d. Inspection of the

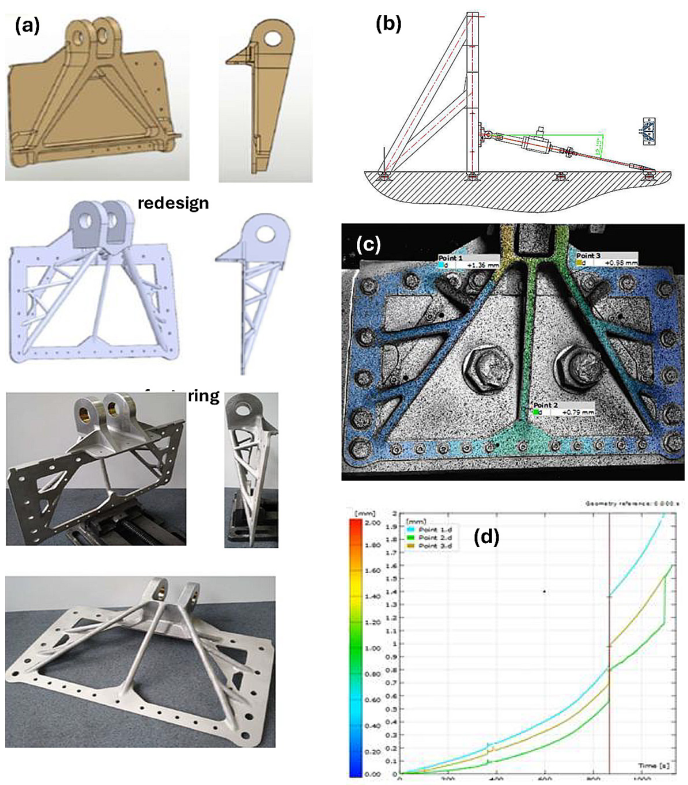

Figure 6. The upper Nose Landing Gear redesign using topology optimization combined with the LMD additive manufacturing technology: (a) the redesign process (b) static test stand configuration (c-d) Digital Image Correlation (DIC) – measure deformation during the static tests

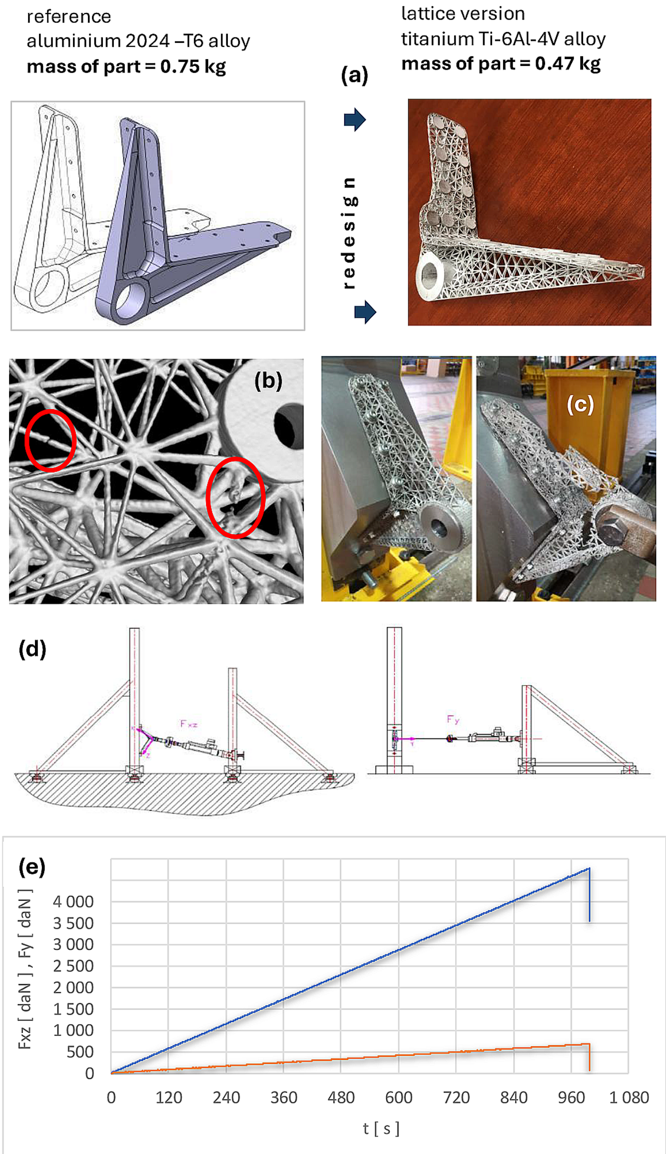

Figure 7. The bottom nose landing gear redesign using topology optimization combined with the EBM additive manufacturing technology: (a) the redesign process (b) tomographic inspection of manufactured part – defects detected, (d) lug after static test (left) and after destructive test (right), (d) test stand – scheme of the forces acting on the tested component, (e) destructive strength test results

failures indicated that the left arm of the component had a previously undetected material/manufacturing defect.

In the second approach, implemented by CIRA, the lower Nose Landing Gear fitting was manufactured using electron beam melting (EBM) technology. The reference geometry, originally produced from aluminum alloy 2024-T6 with a mass of 0.75 kg, and the final lattice-optimized configuration manufactured from titanium alloy Ti-6Al-4V with a mass of 0.47 kg are shown in Figure 7a. The application of additive manufacturing resulted in a mass reduction of approximately 37% [13, 14]

The manufactured component was subjected to non-destructive testing using X-ray Computed Tomography (CT). The tomographic analysis revealed the presence of internal microcracks oriented perpendicular to the layer build plane, as illustrated in Figure 7b. These defects are most likely associated with thermally induced residual stresses generated during the additive manufacturing process. In particular, the rapid cooling of lattice or openwork structural elements can result in excessive material shrinkage, thereby promoting crack initiation.

Subsequently, static strength tests were conducted to evaluate the load-carrying capability of the manufactured component. The tests were performed using a specially adapted test stand, shown in Figure 7d. The loads specified in the test program were applied using two electrohydraulic actuators, while load application and measurement were performed continuously throughout the test sequence.

In accordance with airworthiness requirements, the tested component was required to sustain the limit load without exhibiting any permanent damage or deformation after unloading. For the component manufactured using EBM technology, the allowable horizontal and vertical load values were determined analytically as F_{xz} = 4304 daN and F_y = 612 daN, respectively. During testing, the applied loads were increased at a constant rate, reaching the predicted limit load levels after approximately 15 minutes. Once the maximum load values were achieved, they were maintained for an additional 5 s without any visible damage or permanent deformation [15].

Following the limit load test, an ultimate load test leading to structural failure was performed. Structural failure occurred at load levels of F_{xz} = 4775 daN and F_y = 677 daN, as shown in Figure 7e. The final condition of the tested component is presented in Figure 7f. The observed damage, manifested as localized structural degradation, indicates the regions subjected to the highest stress levels under the applied loading conditions [16].

CONCLUSIONS

The broader integration of small aircraft into transport systems requires continuous technological advancement supported by targeted investment efforts. Although the present study focused on a selected sub assembly and manufacturing technology, it demonstrates substantial potential for redesigning existing aircraft structures in parallel with the implementation of advanced manufacturing methods such as AM. This approach enables gradual and cost effective modernization based on validated load cases, materials, and structural configurations, thereby reducing development risk and certification effort.

Topology optimization is increasingly recognized as a core design methodology in aerospace engineering, enabling lightweight, efficient, and structurally robust components. By optimally distributing material within a defined design space, it allows mass reduction while maintaining required stiffness, strength, and stability. Integration with numerical simulation and CAD tools accelerates early stage design as well as supports the evaluation of multiple variants. While topology optimized geometries are particularly suited for Additive Manufacturing, ongoing advances in material qualification and certification are progressively expanding their applicability to flight-critical structures.

Acknowledgments

These studies were carried out as part of the SAT-AM: More Affordable Small Aircraft Manufacturing project (project no. 699757) co-financed by the Clean Sky2 program (807083—AIRFRAME ITD) and the Ministry of Science and Higher Education of the Republic of Poland (contract: No.W90/CLEANSKY/2018).

REFERENCES

1. Iwaniuk A, Piwek K. Preliminary design and optimization for fleet to be used in the Small Air Transport system. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2018; 232(14): 2615–2626, https://doi.org/10.1177/0954410018800138
2. Dudziak J, Guła P, Gawlik A, Kondracki J. Design and manufacture of nacelles for small turboprop aircraft. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2017; 231(12): 2239–2247, https://doi.org/10.1177/0954410017725544
3. Eyers D, Potter A. Industrial additive manufacturing: A manufacturing systems perspective. Computers in Industry. 2017; 92: 208–218, https://doi.org/10.1016/j.compind.2017.08.002
4. Kłonica M, Kuczmaszewski J, Samborski S. Effect of a notch on impact resistance of the epidian 57/Z1 epoxy material after thermal shock. Solid State Phenomena. 2016; 240: 161–167, https://doi.org/10.4028/www.scientific.net/SSP.240.161
5. Bendsøe MP, Sigmund O. Topology Optimization: Theory, Methods and Applications. 2003, https://doi.org/10.1007/978-3-662-05086-6
6. Dudziak J, Gawlik Arkadiusz, Guła P, Tabor M, Ulma D, Żurawski R. Topology optimization in rotorcraft applications. In European Rotorcraft Forum; 2019; Warszawa.
7. Seifi M, Salem A, Satko D, Shaffer J, Lewandowski J. Defect distribution and microstructure heterogeneity effects on fracture resistance and fatigue behaviour of EBM Ti–6Al–4V. Int. J. Fatigue. 2017; (94): 263–287, https://doi.org/10.1016/j.ijfatigue.2016.06.001

8. Puja G, Manik CM, Anangamohan C. Study on direct laser metal deposition. Materials Today: Proceedings. 2018; 5(5): 12509–12518, https://doi.org/10.1016/j.matpr.2018.02.232
9. Adamski W and Michalcewicz J. Development of methods for designing and manufacturing aircraft components with additive technologies. 2020; 93(3), 8–14, https://doi.org/10.17814/mechanik.2020.3.7
10. Frazier. Metal additive manufacturing: A review. Journal of Materials Engineering and Performance. 2014; 23: 1917–1928, https://doi.org/10.1007/s11665-014-0958-z
11. Ding Y, Dwivedi R, Kovacevic R. Process planning for 8-axis robotized laser-based direct metal deposition system. Robotics and Computer-Integrated Manufacturing. 2017; 44: 67–76, https://doi.org/10.1016/j.rcim.2016.08.008
12. Koerner C. Additive manufacturing of metallic components by selective electron beam melting – A review. International Materials Reviews. 2016; 61: 361–377, https://doi.org/10.1080/09506608.2016.1176289
13. Li MX, Qu WQ. Electron beam additive manufacturing and its applications in aerospace field. Materials Science Forum. 2014; 789: 377–383, https://doi.org/10.4028/www.scientific.net/MSF.789.377
14. Di Palma L, Sorrentino A, Vitiello P, Izz C. Composite structural health monitoring for MALE UAV application. SAE Technical Paper. 2013; 2013-01-2159, https://doi.org/10.4271/2013-01-2159
15. Pirozzi C, Franchitti S, Borrelli R, Chiariello A, Di Palma L. The effect of post-processing on the mechanical behavior of Ti6Al4V manufactured by electron beam powder bed fusion. Aerospace. 2020; 7: 75, https://doi.org/10.3390/aerospace7060075
16. Zhao X, Li S, Zhang M, Liu Y, Sercombe TB, Wang S, et al. Comparison of the microstructures and mechanical properties of Ti–6Al–4V fabricated by selective laser melting and electron beam melting. Mater. Des. 2016; (95): 21–31, https://doi.org/10.1016/j.matdes.2015.12.135