# Additive manufacturing processes and materials used for the production of aeronautical components

**A. C. Murariu[1,a], A. V. Bîrdeanu[1,b]**

1)National R&D Institute for Welding and Material Testing - ISIM Timișoara, Romania

[a] *amurariu@isim.ro,* [b] *research@isim.ro*

## Keywords

Additive manufacturing, aeronautic industry, aluminium, titanium, stainless steel

## Abstract

As a result of the growing demands on the movement of goods and people over long distances in a short time, we could say that the aeronautical industry it's about to take off to the next level. On the other hand, the requirements for environmental protection and reduced fuel consumption are increasing, so that in order to be efficient, it is necessary to introduce innovative technologies in industrial production processes. By their nature, aircraft components must be light but also extremely resistant to be able to operate at high speeds and altitudes and in conditions of extreme, variable temperatures. On the other hand, many of these components have complex configurations. The use of special alloys in combination with the innovative additive manufacturing process seems to be the perfect solution for the aircraft manufacturing industry. Thus, we are currently witnessing a revolution in the manufacture of metal products by implementing innovative Additive Manufacturing (AM) / 3D printing technologies, technologies that offer new possibilities for the realization of complex structures with a minimum material consumption. The paper summarizes the materials current used in the aeronautical industry, and presents the main additive manufacturing processes for the production of components.

## 1. Additive manufacturing processes

Unlike classical manufacturing technologies, in which material is removed from a bulk or semi-finished block to make a finished component, when the component is manufactured by additive manufacturing (AM), it is obtained by melting an additive material and depositing it in a layered way [1]. This reduces the waste of cast or forged base material and thus production costs and the production duration are reduced. Additive manufacturing or the more common name "3D printing" is one of the most disruptive technologies with impact on a high number of industrial sectors as well to the consumer industry. The additive manufacturing paradigm get its disruptive effects in direct connection with the "Industry 4.0" concept, focused on the digitization of the manufacturing sector resulting in a faster transfer of the ideas and creations through digital instructions to the physical world. The process is of interest to many industrial sectors, including aerospace, as complex structures and components in an almost finished state can be obtained. Components with internal cavities or other complex geometries can be made, internal structures that cannot be made by the conventional processing technologies.

In additive manufacturing, the component is three-dimensionally designed, each layer containing two-dimensional information related to a transversal section of the component for a certain height. The component is made starting from a base plate on which the molten material is deposited layer by layer. The deposition of the material in each layer is done selectively, depending on the shape of the component. The disruptive effect of the AM technologies was proven by applying some of its peculiar capabilities for self-improvement of the already 3D-printed product, i.e. by using the Multi-Material Deposition (MMD) and Print in Place (PiP) in order to manufacture elastic hinges without any assembly operation [17]. At the same time, the processing of the base material used for 3D printing can lead to different results in terms of engineering characteristics of the standard components; hence, some studies are focused on evaluating and comparing the usual production process and the 3D printing process in respect to the behaviour in respect to further processing or in use performance [20, 21]. Due to the significant benefits of using additive manufacturing to achieve topologically optimized aircraft structures [2], it can substantially contribute to the reduction of aircraft fuel consumption as well of greenhouse gas emissions. In a wider manner, this challenge is addressed through a number of topologies optimisation techniques that are applied especially for additive manufacturing technologies in order to improve the design for the various parts [18, 19].

There are several additive manufacturing techniques that can be used in case of metals, among which one could mention welding additive manufacturing WAM [3] which are using wire or powder and robots or CNC to achieve high level of repeatability and control during component production.

Powder Bed Fusion (PBF) [4] techniques are based on laser usage in two technological variants: Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) to produce metal parts. The main difference between DMLS and SLM techniques is that full melt of the powder is achieves in case of SLM, while on DMLS technique only heats the powder under the melting temperatures until a bond is obtained. DMLS only works with alloys (e.g. Ti and Ni alloys etc.) while SLM can be used for single component metals, e.g. aluminium. To compensate the high residual stresses generated during the process, both techniques require support structures. The application of SLM technique allows engineers to design, develop and implement components with optimized configuration with material properties similar to the casting products [5].

Nano particle jetting (NPJ) is another AM technique that uses a liquid, which support nanoparticles or contains metal nanoparticles, loaded into the printer as a cartridge and jetted onto the build tray in very thin layers of droplets. The liquid will be evaporated due to the high temperatures from inside the envelope, leaving behind the solid parts. This technique is used for AM of ceramics or stainless-steel components.

Direct Energy Deposition (DED) is another AM technique that creates components by melting powder material as it is deposited. Electron Beam or Laser is used to melt the wire or metal powder. Laser Engineered Net Shape (LENS) utilizes a deposition head which consists of a laser head, powder dispensing nozzles and tubing for inert gas, used to melt the powder as it is ejected from the powder dispensing nozzles, in order to make layer-by-layer a solid component. The wire or powder is placed / sprayed into the melt pool created by laser in the building area, where it is melted and then solidified. A flat metal plate or an existing component (in case of repairing parts) is typically used as substrate for material added on. The method is used for AM of stainless steel, tool steel, titanium, aluminium or copper.

Electron Beam Additive Manufacture (EBAM) is used to create metal components using wire or metal powder jointed together using an electron beam as a heating source. Producing of components is performed in a similar way to LENS technique, but electron beams are more efficient than lasers. The system operates under vacuum (since the technique originally was designed to be used in space). The method is used for AM of Titanium, stainless steel, 4340 steel, nickel, aluminium or copper.

## 2. Materials used in aeronautic industry

Additive manufacturing (AM) is a technology of the future proIn addition to corrosion, the main degradation mechanism of aircraft structure is fatigue. Thus, aluminium and titanium alloys, as well as some grades of stainless steels are used for production of the modern aircraft. On the other hand, the current structures of aircraft tend to increase the proportion of integral structural components, as their fatigue behaviour is improved due to the reduction of potential place for cracks initiation (fewer welds or rivets) and the rigidity of the assembly is improved.

Behaviour to fatigue crack propagation is a very important factor for the design and performance of modern structural materials. For the evaluation of the service life of integral structures [6, 7] made of aluminium alloys 7010-T76, 2139-T8 and 2050-T8, alloys intended for aircraft construction, the analysis of the propagation behaviour of fatigue cracks is done using WEND asymmetric test specimens with four stiffeners, which have been shown [7] to be more effective than CT specimens currently used for fatigue cracking velocity tests.

Fatigue characteristics are influenced by the microstructure of the material, surface roughness and the internal stresses produced by welding or processing the material, thus in Al-Mg-Si alloys the development of fatigue cracks can be influenced by the dispersion of structural elements and the type of heat treatment of hardening. In the case of these alloys, the dominant mechanisms are those that determine the plasticity and roughness.

In the case of cast aluminium alloys for uses to aircrafts (e.g. A535), the main microstructural characteristic is the grain size, so the difference between the threshold values $\Delta KI$ for fatigue cracks propagation depends on the surface roughness and the structural grain size [8].

Precipitation of intermetallic compounds in artificially aged aluminium alloys, respectively Al2Cu (in alloy 2017A), Al2CuMg (in alloy 2024), MgZn2 (in 7000 series alloys without Cu) or Mg (ZnAlCu2) (in 7000 series alloys containing Cu), lead to improved mechanical properties.

The degree of hardening obtained after the aging heat treatment of the aluminium alloy is dependent on the temperature and the maintaining time. Thus, under-aging treatments maintain enough plastic deformation capacity of the alloy but are less resistant to corrosion than over-aged alloys [9]. It is also mentioned that a retro-regression and aging RRA treatment gives an increase in the damage tolerance capacity of the structural components of the aircraft, made of 7010 aluminium alloy [10].

Titanium alloys are extensively used in the aerospace industry, including in additive manufacturing. The high strength and low density of titanium and its alloys, the high creep and corrosion resistance, play a key role in the use of these materials in applications for aircraft engines and their fuselages.

The use of titanium in aircraft leads to a reduction in their total weight and thus leads to a reduction in fuel consumption, increasing the autonomy of the aircraft and allowing fewer refuelling stops and longer continuous flight times.

Therefore, it is difficult to imagine how current performance levels (engine power, weight / power ratio, aircraft speed and travel distance) could be achieved without the use of titanium and its alloys.

Titanium and its alloys are used in aeronautical applications, being used in engines (e.g. rotors, compressor blades), hydraulic system components and nacelles).

Table 1 presents the main titanium alloys used in the aeronautical industry specific applications.

Table 2 presents the titanium alloys with increasing use in the aeronautical industry specific applications [11].

Table 1: Titanium alloys widely used in aeronautical applications [11]

| Grade | Application |
|---|---|
| Ti6Al4V | High strength general purpose alloy |
| Ti6Al2Sn4Zr2Mo (6-2-4-2) | Creep and oxidation resistant engine alloy |
| Ti6Al2Sn4Zr2Mo (6-2-4-2) | Creep and oxidation resistant engine alloy |
| Ti3Al8V6Cr4Zr4Mo (Beta C) | Beta alloy with established spring applications |
| Ti10V2Fe3Al (10-2-3) | Beta forging alloy used for 777 landing gear |
| Ti15V3Cr3Sn3Al (15-3-3-3) | High strength heat treatable beta sheet alloy |
| Ti3Al2.5V | Medium strength alloy used for hydraulic tubing |
| Ti4Al4Mo2Sn (550) | Higher strength heat treatable airframe and engine alloy |
| Ti5.5Al3.5Sn3Zr1Nb (829) | High strength general purpose alloy |

| | |
|---|---|
| Ti5.8Al4Sn3.5Zr0.7Nb (834) | Advanced engine alloy, creep and oxidation resistant |
| Ti5Al2Sn4Mo2Zr4Cr (Ti17) | Advanced engine alloy, creep and oxidation resistant |
| Ti15Mo3Nb3Al0.2Si (21S) | Oxidation and corrosion resistant beta sheet alloy |

Table 2: Titanium alloys with increasing use in aeronautical applications

| Grade | Grade |
|---|---|
| Ti5Al2Sn4Mo2Zr4Cr (Ti17) | Advanced engine alloy, creep and oxidation resistant |
| Ti5.8Al4Sn3.5Zr0.7Nb (834) | Advanced engine alloy, creep and oxidation resistant |

Ti6Al4V titanium alloy accounts for almost 50% of all alloys used in aircraft applications.

The low cycle fatigue (LCF) and high cycle fatigue (HCF) behaviour of the Ti6Al4V alloy deposited by laser additive fabrication using the Powder Bed Fusion (PBF) technique was analysed in [12]. It has been shown that defects occurring in the manufacturing process (e.g. pores and high surface roughness) have an important influence on the fatigue behaviour. Thus, in the tests performed, regardless of the applied load ratio, the initiation of cracks was made in the areas with defects of the production process.

The concept of degradation tolerance (DT) was developed to address the structural integrity issues of fixed wing aircraft and aircraft engines. The general-purpose titanium alloy Ti6Al4V has a high toughness-density ratio, KIC / γ and a threshold-density ratio, ΔKI,TH / γ, compared to other materials generally used for rotor aircraft components (helicopters), such as 15-5PH and 4340 steels or 7075T-73Al alloy.

Due to the following presented advantages of using a titanium alloy [13], the usage of Ti alloys is a valid solution for reducing the weight and size of components:

- High values of alloy threshold ΔKI,TH and toughness KIC lead to large critical cracks and a long duration until the critical cracks grows, which allows to increase the interval of NDT inspections;
- Partially penetrated cracks that grow close to the threshold in the Ti6Al4V alloy show higher ΔKI,TH than for steels and aluminium alloys;
- The growth of cracks partially penetrated in Ti6Al4V is achieved asymmetrically and it have ragged appearance, which indicates a higher crack growth resistance in titanium than in steel or aluminium;
- The crack growth resistance in components made of Ti6Al4V can be further improved by appropriate surface treatments;
- Ti6Al4V alloy is corrosion resistant in most environments specific to rotor aircraft applications.

On the other hand, the use of Ti6Al4V in rotor aircraft has the following disadvantages: high sensitivity to contact fatigue and it prone to cracking due to it, sensitivity to processing methods, premature failure due to sub-surface defects, and large dispersion of crack growth data in complex stress fields.

In order to avoid the disadvantages of the general purpose Ti6Al4V alloy, other Ti alloys for special applications have been developed, presented in tables 1 and 2. Due to the corrosion resistance at high temperatures and the special creep properties, nickel alloys are used in the aerospace field. These alloys become part of aircraft engine turbines due to the extreme heat to which this part of the engine is exposed. These nickel alloys are also used in exhaust valves, thermostat rods, tanks and pipes for storing liquefied gas.

Even if it is heavier, steel is much stronger than aluminium or titanium. Due to the strength and hardness characteristics, steels represent 11-13% of the total materials that are part of an aircraft. It is used in the landing gear as well as in the manufacture of components to which resistance is essential: hinges, cables and fasteners.

Stainless steels or Cr-Ni alloys are outstanding corrosion resistant materials. Their corrosion resistance is influenced by their surface condition and by the temperature, chemical composition and concentration of the corrosive material. The corrosion resistant alloy Inconel 718 is extensively used in manufacturing aircrafts [14]. In the following paragraph some examples of martensitic steels for aeronautic applications are presented [15]:

- PH13-8Mo (1.4534) is a martensitic precipitation hardening stainless steel that confer high strength and through by applying of various heat treatments and combines excellent strength, hardness, toughness proprieties and proper corrosion resistance. Applications in the aerospace include landing gear parts, lock washers, shafts, pins, various fasteners and fittings.
- 17-4PH (1.4548) is a martensitic precipitation hardening steel containing 17% Chrome and 4%Nickel. It could attain a wide range of strength and toughness properties correlated with the aging temperature used in the hardening process. Applications in the aerospace include landing gear locking and retraction systems, lock washers, pins, shafts, fasteners and fittings.
- 15-5PH (1.4545) is a martensitic precipitation hardening steel containing 15% Chrome and 5% Nickel. It could attain a wide range of strength and toughness properties depending on the precipitation or aging temperature used in the hardening process. Obtained strength is comparable to 17-4PH but the toughness and corrosion resistance are increased. It is extensively used in the aerospace for landing gear locking and retraction systems, braces and lock pins, fitting and actuators.

Due to the high corrosion resistance, austenitic stainless steels are also used in the aeronautical industry, but they must also be resistant to fatigue stress. The fatigue behaviour of X10CrNiNb1810 austenitic steel, AISI 347 (1.4550) was analysed in [16], in all fatigue stress regimes, at ambient temperature and at 300°C.

It has been shown that the metastability of Cr Ni austenitic steels AISI 347 varies greatly with relatively small changes in chemical composition and the different metastability of austenitic stainless-steel influences the service life at fatigue stresses. This is due to the fact that transformation processes take place (i.e. γ→ε; γ→ε→α ‘; γ→α’), with the formation of network defects.

A positive influence on fatigue life was found in fatigue tests, in the HCF regime, when the formation of α’-martensite hardened the steel, significantly reducing the amplitude of plastic stress, which led to increased fatigue strength. At the 300° C fatigue tests, the required specimens showed a very small volume of α'-martensite and reached the fatigue limit. When the stress - number of cycles (S-N) curves was compared, in the high cycle fatigue regime it was observed the decrease of the fatigue resistance with the increase of the temperature. A similar behaviour was evinced in the case of very high cycle fatigue regime at ambient temperature and elevated temperature of 300°C.

## 3. Conclusions

Additive manufacturing (AM) is a technology of the future providing huge competitive advantages over the conventional manufacturing, being one of the key tools for creating of high value-added products, thus being seen as one of the major industrial revolutions of the next years.

The novel concepts for the design of aircraft components, require using of various types of materials for additive manufacturing processes which have to be used as demand increases for lighter structures characterised by highly complex geometries with non-conventional aerodynamics. However, to be implemented in the aerospace industry, innovative materials and technologies must be validated through rigorous safety tests performed according to regulations in the field.

The AM process is of interest for many industrial sectors and it can be relatively easily adapted to the demands of each of them. Due to advantages offered, AM technologies start to be implemented in industrial applications (including the aerospace industry), as conventional manufacturing is limited mainly by the complexity of the component, costs and production time, as well as by the large amount of waste of cast or forged materials. Moreover, some conventional processes do not respect the sustainable manufacturing practice related to environmental protection and recycling.

The use of additive manufacturing systems will be developed in the near future, the systems with concentrated energies (laser or electron beam) being more and more present in the production of metal components for industrial / aeronautic application.

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## References

[1]. M. Hinderdael, M. Strantza, D. De Baere, W. Devesse, I. De Graeve, H. Terryn and P. Guillaume: Fatigue Performance of Ti-6Al-4V Additively Manufactured Specimens with Integrated Capillaries of an Embedded Structural Health Monitoring System, Materials 2017, 10, 993; doi:10.3390/ma10090993;

[2]. Meneghin I. et al.: Fatigue in Additive Manufactured Aircraft: The Long Way to Make It Fly, (2020) In: Niepokolczycki A., Komorowski J. (eds) ICAF 2019 – Structural Integrity in the Age of Additive Manufacturing. ICAF 2019. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-21503-3_2;

[3]. M. Kumar, A. Sharma, U. K. Mohanty, S. S. Kumar: Advances in Welding Technologies for Process Development, In: Advances in Welding Technologies for Process Development, Chapter 5, Publisher:CRC press, Taylor and Francis, 2019, DOI: 10.1201/9781351234825-5;

[4]. B. Redwood Additive manufacturing technologies: An overview, https://www.3dhubs.com/knowledge-base/additive-manufacturing-technologies-overview;

[5]. E. Uhlmann, R. Kersting, T. B. Klein, M. F. Cruz, A. V. Borille: Additive manufacturing of titanium alloy for aircraft components, Procedia CIRP 35 (2015), 55-60;

[6]. K. Stonaker et al.: Assessment of Fatigue Behavior of Advanced Aluminum Alloys Under Complex Variable-Amplitude Loading, (2020) In: Niepokolczycki A., Komorowski J. (eds) ICAF 2019 – Structural Integrity in the Age of Additive Manufacturing. ICAF 2019. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-21503-3_7;

[7]. E. Nizery, JC. Ehrström, G. Delgrange, B. Wusyk: A Specimen to Evaluate Susceptibility of Aluminium Alloys to L-S Crack Deviation, (2020) In: Niepokolczycki A., Komorowski J. (eds) ICAF 2019 – Structural Integrity in the Age of Additive Manufacturing. ICAF 2019. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-21503-3_27;

[8]. A. G. Gavras; B. F. Chenelle; D. A. Lados: Effects of microstructure on the fatigue crack growth behavior of light metals and design considerations, Revista Matéria, v. 15, no. 2, pp. 319-329, 2010;

[9]. C. Vargel: Corrosion of Aluminium, Elsevier, 2004;

[10]. M.S. Nandana, B.K. Udaya, C.M. Manjunatha: Influence of Heat Treatment on Near-Threshold Fatigue Crack Growth Behavior of High Strength Aluminum Alloy 7010, (2020). In: Niepokolczycki A., Komorowski J. (eds) ICAF 2019 – Structural Integrity in the Age of Additive Manufacturing. ICAF 2019. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-21503-3_35;

[11]. * * * Titanium Alloys for Aeroengine and Airframe Applications, https://www.azom.com/article.aspx?ArticleID=1569;

[12]. Chastand, V.; Tezenas, A.; Cadoret, Y.; Quaegebeur, P.; Maia,W.; Charkaluk, E. Fatigue characterization of Titanium Ti-6Al-4V samples produced by Additive Manufacturing. Procedia Struct. Integr. 2016, 2, 3168–3176;

[13]. Li X., Krasnowski B.R., Green W.P. (2011) Damage Tolerance of Titanium Alloy Rotorcraft Components: Advantages and Challenges. In: Komorowski J. (eds) ICAF 2011 Structural Integrity: Influence of Efficiency and Green Imperatives. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-1664-3_67;

[14]. * * * https://super-metals.com/news/use-of-nickel-alloys-in-aircraft-components;

[15]. * * * https://www.sd-metals.com/en/s-d-stock-program/stainless-steel-for-aerospace;

[16]. Marek Smaga, Annika Boemke, Tobias Daniel, Robert Skorupski, Andreas Sorich and Tilmann Beck: Fatigue Behavior of Metastable Austenitic Stainless Steels in LCF, HCF and VHCF Regimes at Ambient and Elevated Temperatures, Metals 2019, 9, 704; doi:10.3390/met9060704;

[17]. F. Rosa, M. Bordegoni, A. Dentelli, A. Sanzone, A. Sotgiu, Print-in-place of Interconnected Deformable and Rigid Parts of Articulated Systems, Procedia Manufacturing, Volume 11, 2017, Pages 555-562, ISSN 2351-9789;
[18]. Jihong ZHU, Han ZHOU, Chuang WANG, Lu ZHOU, Shangqin YUAN, Weihong ZHANG, A review of topology optimization for additive manufacturing: Status and challenges, Chinese Journal of Aeronautics, 2020, ISSN 1000-9361;
[19]. Saverio Giulio Barbieri, Matteo Giacopini, Valerio Mangeruga, Sara Mantovani, A Design Strategy Based on Topology Optimization Techniques for an Additive Manufactured High Performance Engine Piston, Procedia Manufacturing, Volume 11, 2017, Pages 641-649, ISSN 2351-9789;
[20]. Ionel Danut Savu, Sorin Vasile Savu, Nicusor-Alin Sirbu, Mirela Ciornei, Robert Cristian Marin, Daniela Ioana Tudose, Laser Marking of PLA FDM Printed Products, Materiale Plastice, 57, 228-238, (2019);
[21]. Christian Wesemann, Benedikt Christopher Spies, Guido Sterzenbach, Florian Beuer, Ralf Kohal, Gregor Wemken, Marei Krügel, Stefano Pieralli, Polymers for conventional, subtractive, and additive manufacturing of occlusal devices differ in hardness and flexural properties but not in wear resistance, Dental Materials, 2020.

## Calendar of International and National Events

| 2021 | | | |
|---|---|---|---|
| 07 - 21 Jul. | THE 74rd IIW Annual Assembly and International Conference | on-line | https://iiw2021.com |
| 25 - 26 Nov. | Innovative Technologies for Joining Advanced Materials - TIMA21 | on-line | http://www.isim.ro/tima/ |


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**Project - PN 19 36 02 01**

**Research on the development of the principle of additive manufacturing, 3d printing, by developing innovative modelling equipment by ultrasonic thermoplastic extrusion**

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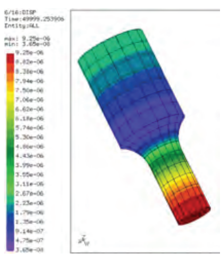
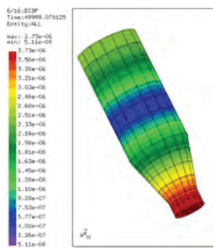
Development period: **2019 - 2022**
Project funded by : **Ministry of Research and Innovation / Ministry of Education and Research**



**Purpose**

③ **The project aims to develop an innovative concept of additive manufacturing - Ultrasonic Fused Deposition Modeling (U-FDM)**
- U-FDM - The classical additive manufacturing by 3D printing (FDM - Fused Deposition Modeling) is combined with the ultrasonic activation technique;
- The new manufacturing method can be used to process polymeric materials (HDPE, ABS, PLA, PVA, PC, PP, PPSU, PPSF, Pa etc.) and / or composites;
- Fields of application: automotive industry, dentistry, metallurgical industry etc.



**Objectives**

③ Development of the level of knowledge in the field of additive manufacturing through the development of the innovative concept U-FDM;
③ Development of specific technologies for given applications, especially in the automotive field;
③ Real-time investigation of process parameters using various techniques, including infrared
③ measurement;
③ Laboratory testing and validation of the innovative U-FDM concept.

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