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# The use of additive manufacturing for production of commercial airplane power plants components – a review

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## Abstract

The purpose of this paper is to provide an overview of the available Additive Manufacturing (AM) technologies widely documented in many scientific papers and to attempt to answer the question of whether this technology could be used in the optimization of geometry for aircraft engine parts. The core research method in this article is based on the analysis of the scientific literature related to Additive Manufacturing gathered over the past two decades. The discussion starts with a review of various technological solutions, including Powder Bed Fusion (PBF), Direct Energy Deposition (DED) or Electron Beam Melting (EBM). The technological schemes of the processes or their differences are shown, as well as the advantages, disadvantages, and development opportunities. The article also attempts to divide AM technologies in terms of the materials used. The purpose of this approach is to simplify technology selection from an engineering point of view. At the end of this article, industrial 'in-use' applications in safety orientated aerospace market are overviewed. As a result of the literature analysis, an attempt is made to prove that modern additive technologies could be used to optimize integrated and complex structures like air bleeds in high pressure compressors of airplane powerplants.

**Keywords:** 3D printing, Additive manufacturing, Aerospace, High Pressure Compressor, Safety

## 1. Introduction

Over the past few decades, many academical centres have widely studied Additive Manufacturing (Blakey et al., 2021; Gisario et al., 2019). Such interest is driven by an important number of possible improvements related to this technology, such as machine accuracy, material structure, material properties, etc. This allows scientists to solve unexplained mysteries and physical, chemical or engineering problems. An additional reason is the undeniable advantages coming from this technology. The most important is the production lead time improvement, the possibility of manufacturing very complex structures or reducingwastes in a single process. Because of the mentioned production advantages and the significant improvement in technology, many industries use this technology more and more and in a greater number of applications. This trend is confirmed by an annual worldwide report of AM technologies released by Wohlers (2012), which shows that the market grew from $2.25 billion in 2012 to over $6 billion in 2016 and forecast for this market based on Hubs report for 2023 is at the level of $20 billion (*Hubs Company/article*, 2022).

This trend is also confirmed by the aerospace industry, where AM finds more applications every year, and major players like General Electric, Airbus and NASA, invest in developing this technology. For this market, the most important factor is weight which directly affects fuel consumption and operation costs. Therefore, any technology that could reduce raw material waste and optimize the final part mass compared to the required structural strength would be very attractive and worth investment. Additive Manufacturing, despite many challenges, like accuracy or printed material properties, is potentially the best response to aerospace needs. Therefore, parts made according to this technology are used more often in this industry.

This article aims to provide a general overview of the available AM technologies in relation to the aviation industry. In addition, this article tries to classify different production materials to the appropriate AM technology to help engineers in making selections based on their needs. By using knowledge of existing aerospace solutions that use Additive Manufacturing, researchers also have defined potential design architectures that could be improved by AM technology.

## 2. Additive manufacturing – overview

This section is devoted to additive technologies. The first part concentrates on the history of this manufacturing technology. The evolution, historical milestones and needs behind using and development of additive manufacturing are widely discussed. The second part focuses on the most valuable and advanced AM technologies currently available on the market. In addition to the description of various AM techniques, their advantages and limitations are also discussed. At the end of this section, a table describing which materials can be used in a given AM technology was created using numerous source data.

### 2.1. A brief history of additive manufacturing

This technology emerged 150 years ago (Thompson et al., 2016; Bourell et al., 2009) when topographical maps were proposed to be built using 2D layers stacked on top of each other. These builds were nothing like modern AM structural prints but provided a concept of building parts layer by layer to create desired shapes. At the turn of the late 1960s and early 1970s, researchers proved the concept of layer-by-layer printing by patenting the photopolymerization process, powder fusion and sheet lamination (Thompson et al., 2016), which were starting points for modern AM technology. In 1981, Hideo Kodama of the Nagoya Municipal Industrial Research Institute published (Schotte, 2019) information on creating solid printed models, thus becoming a precursor of Additive Manufacturing. He used the layer-by-layer manufacturing philosophy working on a rapid prototyping system that could be used in production (*BCN3D,/article, 2020*). After that, the 1980s and 1990s were abundant in patents and publications about various printing technologies. At this time, technologies such as 3D printing process from the Massachusetts Institute of Technology, laser beam melting (LBM) process (Thompson et al., 2016) or stereolithography (SL) (Wohlers, 2014a) were invented. The former was commercialized by several companies and used in electronic manufacturing (Wohlers, 2014a). At the same time, material manufacturers, including DuPont or Loctite, entered the SL market, developing materials for this process. Moreover, in the late 1980s and early 1990s, technologies such as fused deposition modelling (FDM), solid ground curing or laser sintering (Shellabear & Nyrhila, 2004) were invented. These techniques were developed thanks to progress made in computer science and electronic logic controllers, design computer software or CAD/CAM systems (Carlota, 2019). However, industrial applications of these were limited because of the small number of materials selections, high cost and low manufacturing accuracy (Thompson et al., 2016).

Between 1990 and 2000, Additive Manufacturing has undergone tremendous development. New techniques such as Electron Beam Melting (EBM) were created by the Swedish company Arcam. In 1992, DTM developed and introduced selective laser sintering (SLS), which shoots a laser at a powder instead of a liquid (Moore, 2018). Moreover, existing technologies were further developed, and more attention was given to AM software, resulting in, e.g.  CAD Tools for 3D printing being founded in 1993. In addition, such as LEAF (Layer Exchange ASCII Format) or CLI (Common Layer Interface), which are specially dedicated to Additive Manufacturing file formats (Thompson et al., 2016; Pham & Dimov, 2001), were created within technological programs Materialize or CIDES. The dissemination of computer technologies contributed to easy and cheap access to 3D modelling tools, which took AM to the next level. For some people, AM became more like a hobby than futuristic technology. First home AM machines were built in projects such as RepRap (*All3DP/article, 2016*), which many consider the beginning of 'home' AM machines.

The 2000s saw a rapid growth of AM manufacturing equipment and technology developed in the 1980s and 1990s. The expiration of some patents and easier and cheaper access to technology has led to the market opening, creating new demands, new companies, and even creating a worldwide network of amateur AM enthusiasts. Nowadays, Additive Manufacturing supports large businesses such as aerospace, energy or automotive with its technology. It also supports the health industry with the production of implants or prostheses. There has been a wide range of home printers on the market at a reasonable price, which allows manufacturing parts using polymers, metals, or even ceramic materials. More and more, AM is used in high volume production, including fuel nozzles of LEAP engines (General Electric, 2018) or gas turbine components at Siemens (Siemens, 2018).

The history of Additive Manufacturing is quite short in terms of industrial production. However, it is changing very dynamically and provides hope for being quick, precise and high-quality technology used by a wide range of businesses in the near future. Below, in Figure 1, created based on multiple data (Bourell et al., 2009; Moore, 2022; Carlota, 2019; Pham & Dimov, 2001; All3DP, 2022; General Electric, 2018), the most important milestones in AM history can be found.

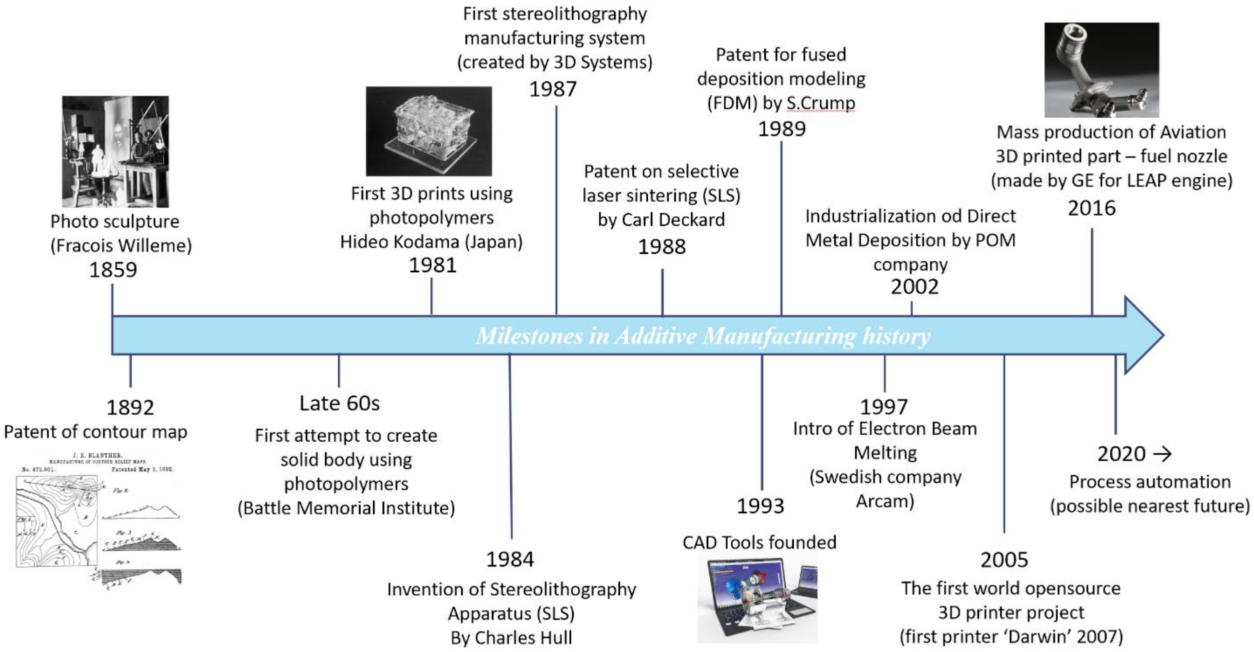

**Figure 1.** Milestones in Additive Manufacturing history

Own study, photos adopted from DL. Bourell et al., 2009; C. Moore, 2022; V. Carlota, 2019; Pham & Dimov, 2001; All3DP, 2022; General Electric, 2018

## 2.2. Types of additive manufacturing

Additive manufacturing, especially AM metallic methods, is currently undergoing constant improvement, providing better and better results in terms of materials properties, porosity, repeatability etc. (Blakey-Milner et al., 2021; Gisario et al., 2019; Wohlers, 2014a; DebRoy et al., 2018). For aerospace industry, methods that provide high quality repeatable products that require minimum mechanical processing after AM process completion are most attractive. Depending on the technology type, some AM processes can produce complex parts with material properties close to or even the same as in conventional manufacturing techniques. Moreover, AM provides the possibility of producing entire assemblies in a single process. This makes it possible to avoid the complexity of the

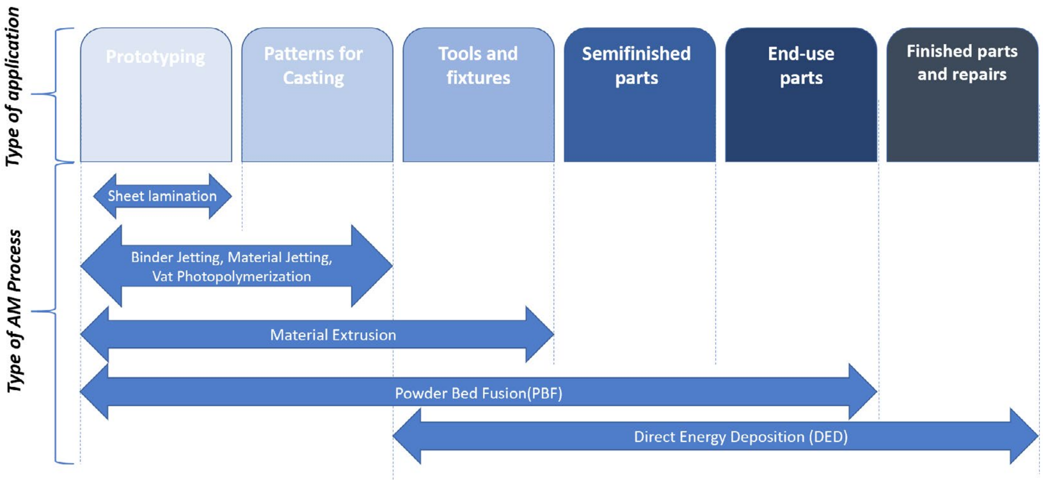

**Figure 2.** Types of process and application for Additive Manufacturing

Own work based on Debroy et al. 2019

joints, reduce mass, and save important qualification efforts since, in the aviation industry, each component must be certified as airworthy (Gisario et al., 2019). Different AM technologies provide different results/products that could be qualified based on the final appearances and usage. The graphical representation below presents this classification (Gisario et al., 2019).

Additive manufacturing technology is classified and standardized according to the international standard ISO/ASTM 52900, which describes seven different process categories, including direct energy deposition (DED) and powder bed fusion (PBF) (ISO, 2015; DebRoy et al., 2018). Both technologies are currently key to the aerospace industry, allowing the fabrication of metal components with high quality results (low porosity and good materials properties). Below, the AM technologies most important to the aerospace industry are described.

### 2.2.1. Powder Bed Fusion (PBF)

This technology is divided into three main types: Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM) – the last two are described below since they are technologies used in the aerospace industry. PBF can be used with both metals and polymeric materials; however, for the aerospace industry, the most significant is the possibility of manufacturing components from Ni-based allows, stainless steels, cobalt alloys, titanium or even tungsten. The useability of such materials is possible because this technology uses a high energy melting source (laser or electron beam). Raw materials, in the form of powder, are spread on the working platform (first layer) or the previous layer using a roller and then fused together using a high energy source. The most important advantage of this process is that manufacturing time does not depend on the part complexity but on the material volume being melted (Blakey-Milner et al., 2021; Gisario et al., 2019). Regardless of the type of PBF, all of them share the same layer-by-layer sintering concept:

1. Spreading the first layer on the build platform
2. Laser fuses powder of the first layer in accordance with the CAD model
3. The next layer of powder is rolled across the previously sintered layer
4. Further layer(s) being molten and sintered to existing layers
5. The process is repeated until the entire component is created. Loose power is removed after completing the process entirely.

The scheme of the PBF process is presented Figure 3 found below:

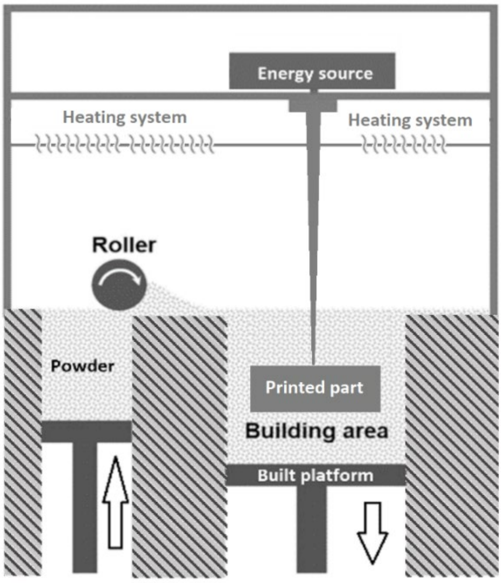

**Figure 3.** Scheme of the PBF process
Own work based on by Blakey-Milner et al., 2021; Debroy et al., 2019; Uhlmann et al., 2015

### 2.2.1.1. *Selective Laser Melting (SLM)*

This technique allows using various metallic materials. In order to obtain the desired results regarding material properties, the quality of the structure or chemical composition and the powder size have to be precisely controlled. Typically for a good surface finish, powder size should be below 100µm (lower size powders are in use and more desirable) (Blakey-Milner et al., 2021; Uhlmann et al., 2015). The manufacturing chamber is pressurized with inert gas to avoid oxidation during the melting/sintering process. Typically, SLS machines provide a range of the deposed layer between 10-100µm, but to obtain components with a proper finish, it is preferable to use layers within a range of 30µm (Gisario et al., 2019). The power of the laser, scanning strategy, gas flow or powder layer thickness might be controlled with other parameters by the operator. The final result of the structure, material properties and surface quality highly depend on these parameters, and a change in any of them may strongly influence repeatability. Even though SLS provides fully dense structures with high quality and accuracy, manufacturing is expensive and provides benefits only in high volume productions where desired component properties exceed costs, such as in the aerospace industry (Blakey-Milner et al., 2021; Gisario et al., 2019). Standard machines can print parts with sizes up to 400mm and precision of single features at levels of 0.2 -0.4mm (Yadroitsev, 2021 & 2021a). Machines with larger printing areas are also available; however, these are typically created for specific productions, customers or even parts.

### 2.2.1.2. *Electron Beam Melting (EBM)*

The general concept of the EBM process is very similar to the SLM with a difference in the energy source, which uses an electron gun instead of laser (Gisario et al., 2019; Thompson et al., 2016; Murr et al., 2012). This process requires a vacuum chamber for electrons to travel to melt metallic powders. This gives an important advantage in limiting the oxidation of metals. When the powder is deposed on the working table, the system heats the entire working area (not always required) with a rapidly scanning electron beam. The concentrated beam then selectively melts locations following the CAD model. When sintering is finished, the working table is lowered, and another powder layer is deposed for the next heating and sintering process. These four main steps are repeated until the part is fully manufactured. Increased working temperatures controlled in the EBM process are an important advantage of this technology because it minimizes residual stresses for the final component (Thompson et al., 2016; Murr et al., 2012). The high precision of this technology and controlled elimination of residual stresses allow for obtaining mechanical properties of components similar to the cast materials (Parthasarathy et al., 2010). This technology uses larger than SLM/SLS powders; therefore,, the surface roughness of the finished part is higher, but production time is relatively short thanks to the rapid electron scanning. Standard systems allow manufacturing components up to 300-400mm in diameter.

### 2.2.2. Direct energy deposition (DED) technology

The general concept of the DED process (Ramakrishnan & Dinda, 2019; Gadagi & Lekurwale, 2020) is similar to the SLM and EBM; however, feeding material is constantly delivered during the melting process. As a source of energy, this technology typically uses a computer-controlled laser beam (Gadagi & Lekurwale, 2020). There are available technologies where the laser is replaced with an electron beam – Electron Beam Free Form Fabrication (EBFFF) (Duda & Raghavan, 2016). In both cases, the entire system and printing area are closed in a chamber. For the laser control process, the chamber is filled with a noble gas, and a vacuum is required for the electron beam set-up. In both cases, a low oxygen level makes the metal oxidation very low.

DED processes are layer-by-layer process that provides a dense metal structure with good mechanical properties. It can be used in manufacturing new makes and in repair procedures where certain features must be re-build. The biggest advantage of this technology is its high printing rate. When PBF processes reach efficiency at a level of 0.1Kg/h, DED achieves a rate of 4Kg/h (Gisario et al., 2019; Martina et al., 2015). Moreover, this technology does not depend on the powder bed; therefore, the process is not limited in build size (Blakey-Milner et al., 2021). This provides an opportunity to manufacture large components. However, the high manufacturing speed leads to certain disadvantages. The surface of the finished component is very rough and, in the majority of cases, requires additional mechanical operations. Dimensional accuracy is worse than in PBF processes and is around 1mm (Blakey-Milner et al., 2021; Gadagi & Lekurwale, 2020). Although the process provides a dense structure, controlling the microstructure and repeatability are also challenging. An important disadvantage of this process is the residual stresses that remain in the structure after the printing process.

Despite all the challenges of Direct Energy Deposition, technology is widely recognized and developed in the aerospace industry. It provides an opportunity to manufacture large-scale components with fairly good material properties. An excellent example of this technology is the engine nozzles manufactured and tested by NASA.

### 2.3. Possible materials for different Additive Manufacturing processes

This article does not focus on a detailed overview of the materials used in AM technologies. Characteristics such as material properties, microstructure or surface finish are also not discussed since they can be widely found in many scientific papers. The aim of this section is to present a simple breakdown of AM technologies in terms of the materials they use. The table below (Table 1) was created to simplify AM technology selection to manufacture components made from desired material (DebRoy et al., 2018; Jandyal et al., 2021; Lewandowski & Seifi, 2016; Sames et al., 2016; Gadagi & Lekurwale, 2020).

**Table 1.** Possible use of materials in a given AM technology

| Material<br>AM Method name | Polymers | Composites | Ceramics | Stainless steel | Titanium | Inconel | Cobal-Chrome | Aluminum | Nickel based alloys |
|---|---|---|---|---|---|---|---|---|---|
| **EBM (Electron beam melting)** | N/A | N/A | N/A | N/A | X | N/A | X | N/A | N/A |
| **DMD (Direct metal deposition)** | N/A | N/A | N/A | X | X | X | X | X | X |
| **SLS/SLM (Selective laser sintering/melting)** | X | N/A | X | X | X | X | X | X | X |
| **Binder Jetting** | N/A | N/A | X | X | N/A | X | N/A | N/A | N/A |
| **DED (Direct energy deposition)** | N/A | N/A | X | X | X | X | N/A | X | N/A |
| **Laminated Object Manufacturing** | X | X | X | N/A | N/A | N/A | N/A | N/A | N/A |
| **FDM (Fused Deposition Modeling)** | X | X | X | X | X | X | N/A | N/A | X |

X – Method can be used for presented material
N/A – Method Not Applicable for presented material

## 3. The use of AM technology in the aerospace industry

The purpose of this section is to present the commercial aviation products that currently use AM technology. The first section is devoted to the three most recognized aviation parts, which are made with AM technology and are in everyday use in aircraft engines. The second part attempts to determine whether AM technology could be used in aircraft engine high pressure compressors to integrate air bleed ports with other static HPC structures.

### 3.1. Existing solutions on a commercial level

General Electric fuel nozzle:
In 2015, the GE Aviation Auburn facility began to produce fuel nozzle tips using additive manufacturing. L-PBF technology with Cobalt-Chrome alloy as a printing material was utilized (Brakey-Milner, 2021). By 2018, over 30,000 fuel nozzles had been manufactured and put into service in the LEAP engines.

**Figure 4**. Fuel nozzle for LEAP aircraft engine
Adopted from: ‘General Electric additive website’, Copyright 2018 by Publisher

The use of additive technology for fuel nozzles allowed for eliminating a single part, welding 20 separate pieces. All of the pieces were replaced by a single 3D printed part, resulting in omitting the costly and time-consuming welding operation. In addition, that operation caused a nozzle tip weight reduction of approximately 25% (GE Additive, 2018).

Significant benefit coming from fuel nozzles production started using additive manufacturing in mass production of airplane power plants. The GE9X engine has additive manufactured parts such as fuel nozzles, turbine blades, combustor mixers, cyclonic inducers or heat exchangers (Blakey-Milner et al., 2021). All these components are made of Cobalt-Chrome alloy using L-PBF technology (Blakey-Milner et al., 2021). Turboprop engine Catalyst is the first mass production powerplant where large 3D sections are printed (GE Additive, 2018a). This allowed the replacement of 800 parts made with conventional methods, with 12 parts made with the AM (GE Additive, 2018a). Such a step caused a mass reduction of 5% and improved fuel consumption by 1% (GE Additive, 2018a).

P&W compressor stator vane parts:

In the engine PurePower PW1500, the compressor stator vanes are made using additive manufacturing technology – as illustrated in Fig. 5. Due to shape complexity and requirements regarding thermal resistance that force the utilization of high-temperature steels, the laser powder bed fusion technique is used. Vanes are sintered from Inconel powder which is precisely sieved before AM process to obtain and use only desired particle sizes. Although the printed parts, completed using the AM process, require thermal and surface treatments and even CNC machining, AM technology saved 15 months of lead-time compared to the standard manufacturing process. Moreover, based on the available open-source information (Peach, 2015), the weight of these structures were reduced by about 50%.

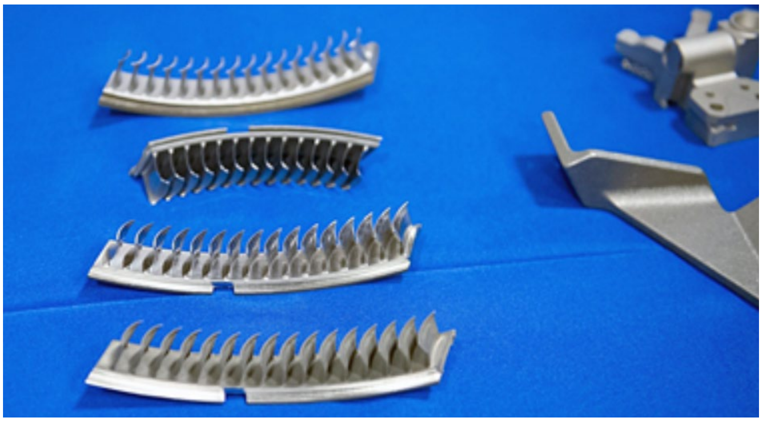

**Figure 5.** Compressor vane sectors from PW1500 engine, produced using AM technology
Adopted from 'Pratt&Whitney website', Copyright 2022 by Publisher

Technology results were so promising that the manufacturer set up an Additive Manufacturing Innovation Center in cooperation with Connecticut University to develop AM capabilities.

Oerlikon turbine blades

An excellent example of an industrialized use of AM technology is a Switzerland-based enterprise, OC Oerlikon, which uses different AM technologies to support the aerospace, automotive, medical, and power industries. Its comprehensive manufacturing includes prototyping, series production, design & application and post-processing. By using AM techniques such as L-PBF (Laser Powder Bed Fusion) or E-PBF (Electron Powder Beam Fusion) (Oerlikon Additive Manufacturing, 2021 & 2021a), various structures made of materials including Aluminum, Nickel alloys, Cobalt alloys, or Titanium are proposed. With the exception of metallic materials, components made of polymers or ceramics can be found in production. They use materials like polyamide or ABS with SLS technology for producing polymeric structures. For ceramics, the Material Jetting process is used for sintering zirconia powders.

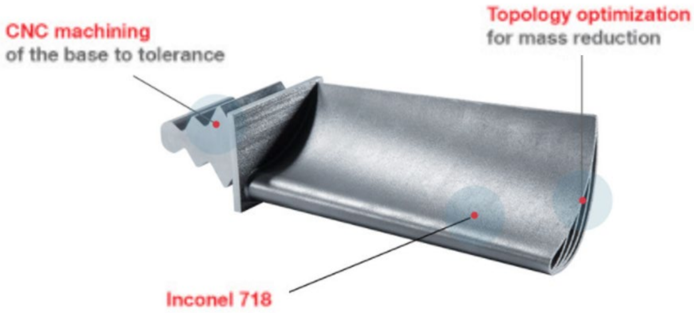

**Figure 6.** Hollow turbine blade offered by Oerlikon company
Adopted from: 'Oerlikon website', Copyright 2022 by Publisher

A very interesting design solution for turbine vanes/blades structures is presented in Fig. 6. To improve the performance of the component and the engine turbine module, complex and partially hollow internal geometries of the vanes are proposed (*Oerlikon Additive Manufacturing, 2021).* Such a design significantly reduces the component's mass but complicates the manufacturing process. Hollow internal structures with smooth and continuous external surfaces are impossible to produce using conventional manufacturing technologies. However, Additional Manufacturing has proven to be a solution in this case. Such a design is proposed not only for the power industry but also for aerospace.

### 3.2. Potential AM useability in aerospace industry

As described in previous subsections of this paper, additive manufacturing grows and develops very rapidly, enabling the production of 'ready to use' parts in various industries. In our opinion, one of the main advantages of AM for the aerospace industry is the possibility of manufacturing complex structures in a single process. This advantage of AM is the most important because it directly decreases manufacturing lead time compared to conventional technologies. Also, it reduces components/structures' mass and simplifies assembly (Blakey-Milner et al., 2021; Gisario et al., 2019; Thompson et al., 2016; Uhlmann et al., 2015). All these aspects significantly contribute to the improvement of performance, which in the aerospace industry is a crucial parameter.

One of the aircraft engine structures that could be considered for using AM technology could be the air bleed system in high pressure compressor module. The standard of air bleeds is separation gaps (all around) between the successive steps of the module (between the rotor and variable vanes). This solution is simple in terms of manufacturing; however, it drives to the complicated assembly system with many joints. Simplifying the assembly and removing some of the joints could be achieved by integrating bleed ports with compressor parts – scheme drawing on Fig.7

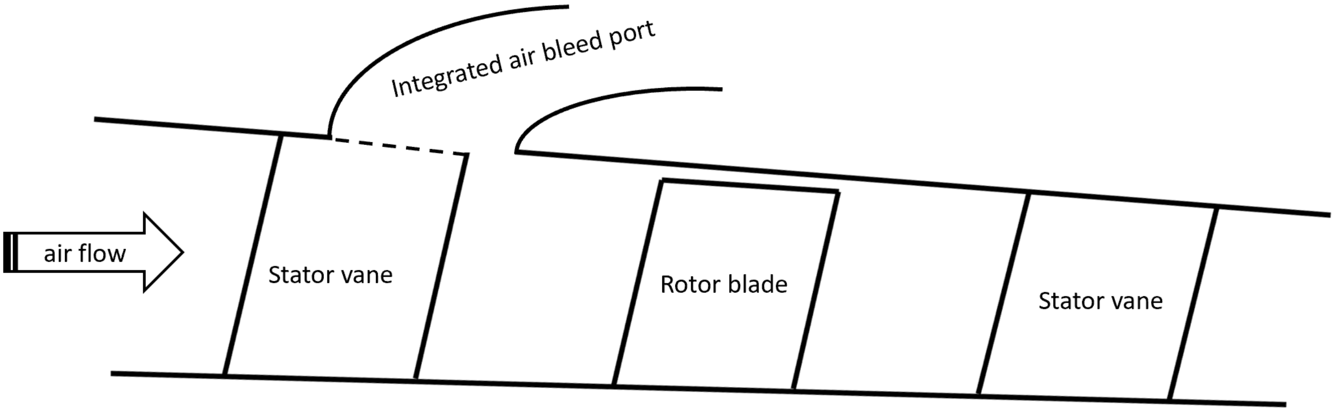

**Figure 7.** Concept of integrated air-bleed horn on high pressure compressor module in aircraft engines
Own work.

Such a solution could not only improve the assembly process but also could decrease mass due to the elimination of joints or even entire parts. Several studies (Cui et al., 2013; Siggeirsson et al., 2021; Spanelis & Walker, 2022;) have also shown that this kind of integration could positively change air flow parameters. Considering all these aspects, the integration of the air bleeds may contribute to the HPC module performance increase and the entire aircraft engine.

Typically, for aerodynamics and flow stability, air bleeds in commercial power plants are located on higher compressor stages. The temperature between Stages 6 and 10 for large engines may vary between 300°C and 600°C, which causes limitations in the choice of materials. Usually, structural parts at these stages (between 6 to 10), where pressure and temperatures drive structural integrity, are made of stainless steel or Inconel alloys. Based on the research results presented in previous parts of this article regarding the possibility of using materials in a given AM technology, the most promising technique for manufacturing integrated bleeds using stainless steel or Inconel material would be Powder Bed Fusion. This technique not only allows the possibility of sintering desired materials but also allows the production of complex shapes with decent precision and structural strength. In addition, PBF allows obtaining relatively low surface roughness, which is very important in terms of air flow.

As discussed in this section, compressor case geometry and potential AM technology that could be used for this hardware manufacturing is conceptual work based on the research and knowledge widely described in this article. The final selection of the AM technology should be selected and precisely planned with AM technologists to obtain the desired results in terms of geometry, strength and surface finish.

## 4. Conclusions

Even though AM technology is relatively young, it shows a wide range of opportunities for different types of industries. The rapid development of AM machines, material powders, and process accuracy contribute to the fact that this technology has more and more applications in aerospace. The confirmation of this may be significant investments in this technology by companies such as General Electric, Airbus or Oerlikon.

Despite high unit costs, the industry has proven that massive production is beneficial thanks to mass reduction, joint elimination or more straightforward assembly. Various available technologies (e.g., SLM, LBM, DED) with constantly improving powder market allow for the use of AM in more critical airplane engine locations, including vanes, bleeds or nozzles. The extremely rapid development of AM technology and the possibility of producing complex structures in a single production cycle indicate that more and more aerospace components will be manufactured using AM.

## Declaration of interest

The author/authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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