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Development of methods for designing and manufacturing aircraft components with additive technologies

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This article is the description of the additive technology used for the production of aviation parts made of stain-less steel and titanium, and shows the direction of further research and development of this technology for the needs of the aviation industry. The application of the robot-controlled LBDMD system (robotized laser based direct metal deposition for aircraft parts), which uses a 6-axis robot arm with a rotary table, has been shown in this paper. The LBDMD system simplifies the development of the multidirectional deposition process for complex parts, significantly reducing their production time. The benefits obtained from the use of additive manufacturing (AM) technology in the production of aviation parts were presented.

KEYWORDS: additive manufacturing, laser based direct metal deposition, 8-axis robot

Introduction

Additive Manufacturing (AM) also known as 3D printing, rapid prototyping or the production of any shapes and forms, is the process of joining materials to create objects from 3D model data, usually layer by layer, as opposed to waste production methods, such as machining.

The use of additive manufacturing with metal powders is a relatively young and emerging industry sector (fig. 1). Additive technology has become an appropriate process not only for the prototypes as before, but also for the production of complex metal parts in the form of openwork elements and bionic shapes.

Additive manufacturing currently allows both a design revolution and an industrial revolution in various industry sectors, such as the aerospace, energy, automotive, medical, tool and consumer industries. It is one of the elements of Industry 4.0.

Unlike machining technologies, such as cutting, additive manufacturing involves the application and bonding of successive layers of material. This is a new additional production technique that is increasingly used (fig. 2).

Fig. 1. The rapid development of additive technology in the world [6]

Fig. 2. Percentage share of AM technology revenues in individual types of industry [6]

Additive technology in aviation still requires a lot of research and testing. Especially if it is to be used where people's safety is at stake.

The requirements for the production of parts for civil aircraft are based on US federal FAR aviation regulations, without which aircraft type certification cannot be obtained. The regulations are extensive and detailed, but for the additive technology, the most relevant records can be found in part 14 of chapter 25, subchapter D, subsection 25.605: the use and strength of used materials of parts, which damage may adversely affect safety, must be: determined from experiments or tests, ensure compliance with approved standards (both industrial or military) that ensure their strength and other properties in the assumptions of the design data, and take into account the impact of environmental conditions, such as temperature and humidity, anticipated during operation of these aviation parts. This means that the introduction of additive technology in aviation requires evidence-based research [2, 3].

The possibilities of additive technology

In order to fully utilize the possibilities of designing additive technology (AM), it is important above all to redesign parts which has been made so far, using conventional technologies [1].

Design optimization can be done in several directions:

- reducing the total number of parts (we turn the assembly into one part).
- designing for the functionality of parts so that they are multifunctional.
- part weight reduction.
- topological optimization of parts.
- designing the parts ensuring the ease of production.

Additive technology allows the production of one part. To produce such a part in traditional technologies it was required to make several details and then they had to be assembled into one unit.

Additive technology therefore also avoids the labor consumption associated with the assembly process. The benefits of additive technology are becoming more widely known.

As expected, this technology has quickly revolutionized production processes in many industries (fig. 2) [2, 3].

Additive technology (AM) in the aviation industry

At present, the aviation industry is one of the largest innovators in the area of development and implementation of additive technologies (fig. 2), largely due to the high outlay budgets available to aviation research units. In the aviation industry, an important standard is the weight of the aircraft, e.g. reducing the weight of the aircraft by one kilogram is enough for the machine to emit 25 tons of carbon dioxide less throughout its lifetime. Manufacturers are therefore looking for lighter and more durable materials. Additive technologies, which are already used by major aviation manufacturers such as Airbus and Boeing, come to the rescue.

Boeing has been using additive technology (AM) since 2003 and currently performs with its help approximately 50,000 parts. Some brackets as 3D parts printed at the University of Oxford were used in the air revitalization system, interior closeouts and support structures on three STARLINERS, i.e. Boeing's space taxi, which began test flights in 2018. Airbus has introduced new parts to its aircraft. For example, a new titanium bracket was made and installed during the serial production of the A350 XWB aircraft. This bracket is a critical part of the pylon connecting wings with engines. The new Airbus A350 XWB aircraft already contains more than 1,000 manufactured parts in additive technology (AM).

Elements printed in 3D are about 50% lighter than those made with traditional techniques. In addition, they reduce material consumption by up to 95% [5]. This is why additive technology has been attracting the attention of large global aviation industry companies for years. Large corporations and small companies in this industry are producing more and more parts for aircraft and helicopters in AM technology, as well as lighter and more efficient propulsion units such as engines or turbines.

Additive technology saves time and reduces costs. It is important that it can also be used for already utilized aircraft. One of the advantages is also that e.g. spare parts can be designed virtually, made in additive technology and then tested in a very short time.

It is also worth mentioning about technologies based on direct energy supply, including LENS (Laser Engineering Net Shape) and EBAM (Electron Beam Additive Manufacturing). In these methods, the material stream is supplied through the nozzle and cured by means of a laser or electron stream directly on the surface on which it falls [11]. The undoubted advantages of these technologies are: the possibility of applying the material on surfaces of any shape and a wide selection of materials.

Laser Based Direct Metal Deposition (LBDMD)

In Laser Metal Depositing of materials (LMD), the laser beam melts the surface element containing the metallic material locally. The filling material is introduced into the weld pool of the molten material and there it is completely melted. Depending on the process control and process variant, the layers can be applied in one layer with shaped of joints, low heat input and layer thicknesses from 0.01 mm to 1.5 mm. In the LMD process, you can apply multiple layers (can be manufactured additively), create parts with high complexity and dimensions, and complex geometry. Then the laser beam heats the workpiece locally and causes a liquid metal pool. From the nozzle of the optical system, fine metal powder is dosed directly into the pool. There it melts and combines with the base material to form a $0.2 \div 1$ mm thick layer. If necessary, multiple layers on top of each other can be built. Argon is very often used as protective gas. To reflect lines, surfaces and forms, the optical system is automatically controlled in regard to the workpiece. Intelligent sensory system ensures a constant layer thickness [7–9].

Laser Based Direct Metal Deposition (LBDMD) is a prospective additive manufacturing technology that is perfectly suited for the production of complex metal structures, small-lot production, and repair or modification of parts [7–9]

It is widely used in the automotive, biomedical and aviation industries.

Subject of ongoing research at Eurotech, SAT-AM project (CLEAN SKY 2)

This article is a development of additive technologies used to manufacture aircraft parts and shows the direction of further research and development at Eurotech. The robot-controlled LBDMD system was used. It uses a 6-axis robot arm with a turntable. The system simplifies the development of the multidirectional deposition process for complex parts, significantly reducing their production time (fig. 3). For the production of metal parts, the Laser Metal Deposition (LMD) [10] method was used without using an additional working chamber.

Prior to research and testing, the following similar issues related to AM additive technology were analyzed:

- additive manufacturing,
- laser sintering of the new nickel alloy IN625 Direct,
- 3D printed non-metallic elements,
- examples of aviation parts made in additive technology (AM).

Fig. 3. Robotic station with laser deposition: FANUC M20-iA/20M – robot 6-axis arm with 1813 mm reach, lifting capacity up to 20 kg

Eurotech Company conducts research to develop additive technology (AM) for manufacturing and production of parts for aircraft made of stainless steel or titanium using a custom robotized station. The robotized station with laser deposition consists of the following equipment:

- coating head,
- FANUC M20-iA 20M robot (manipulator of the coating head),
- rotatably pivoting turntable,
- fibre-optic laser of high power 1kW,
- powder feeder with two tanks,
- CAM software,
- 5-axis CNC milling machine,
- CT scanner.

The subject of research was the additive technology of selected aircraft parts of the Polish M-28 Commuter class aircraft.

The first step was the implementation of the aircraft bracket No. 66999.09.09.00.00 v1 in additive technology made of stainless steel (SS410) designed to be made in subtractive manufacturing technology on CNC machines. The process proceeded as shown in figs. 4 and 5.

The same 3D model was used that had been used to make this bracket in subtractive manufacturing technology on CNC machines. In the next stages, the entire bracket was made in the additive technology (AM) and then finishing was performed on the CNC machine tool. The effect that was obtained was reduction of waste by ~ 90% when producing a bracket made of full material (70 × 120 × 150 mm) [1, 4].

Fig. 4. A robotized station with laser deposition during the manufacture of the bracket

3D Model

Stages of performance in additive technology

Ready part

Fig. 5. Old bracket 3D model for additive manufacturing (from left): existing 3D model, one during AM production and after production on a CNC machine

In the second step, the new bracket No. 66999.09.09.00.00 v2 was designed in such a way to reduce its weight while maintaining strength parameters, to take advantage of the full potential of additive technology. The topological optimization of the bracket was made (figs. 6 and 7). The second version achieved a 47% weight reduction: from 688 g to 362 g (table).

The change in the construction form [1] of the bracket and its material in the final result gave a 71% reduction in the weight of the part (fig. 8).

Fig. 6. Redesigned bracket for additive manufacturing with topology optimization (from left): after topology optimization, one during production and after production

Fig. 7. Bracket made in AM technology of stainless steel material (SS410)

Fig. 8. Bracket made in AM technology of titanium alloy material (Ti-6Al-4V)

TABLE. Physical properties of the tested bracket No. 66999.09.09.00.00

Part No. 66999.09.09.00.00	Volume [cm ³]	Theoretical mass [g]	Total mass [g]	Weight reduction [%]
stainless steel (SS410) – original design (density 7.8 g/cm ³)	87	678	688	
stainless steel – new design	39	312	362	53
titanium alloy (Ti-6Al-4V) – original design (density 4.43 g/cm ³)	87	385	no data	
titanium alloy (Ti-6Al-4V) – new design	39	173	198	55 (theoretically)

The material samples of the finished parts looked very good from the point of view of geometry. There were no cracks or porosity as demonstrated by later tomographic images. The process of making these samples in different directions was also not a problem. The samples passed the endurance as well as metallographic tests.

The same was done during tests of the parts made. Although the shape and geometry were correct, there were cracks visible during the CT scan. Tomographic examinations of the part made of titanium alloy (fig. 11) showed cracks resulting from residual stress in spatial structures which was caused by the change in temperature during the LMD (Laser Material Deposition) process that arose during the creation of structures of this part with complex shapes.

Endurance tests were performed using standard samples (fig. 10). Three different types of samples were prepared for tensile tests with layers applied in parallel, perpendicularly and alternating.

Endurance tests were carried out on the basis of normative samples (figs. 9 and 10), as a result of which the parameter of the tested material was obtained: tensile strength. The research shows that LDM technology of alternating layering proved to be the best strength parameters among the technologies examined.

Therefore, the direction of the manufacturing process has a clear impact on the strength of the samples, which can be seen in fig. 9.

Fig. 9. Impact of the manufacturing process on the strength of test samples

Fig. 10. Example of a test sample with layers applied perpendicularly

The mechanical properties of parts produced by the additive technology are usually better than the properties obtained in the casting process and slightly worse or close to the conventional part made by plastic forming (forging).

According to AMS 4928, the tensile strength of the Ti-6Al-4V titanium alloy is 950 MPa. As a result of tests at Eurotech for variously made samples of titanium alloy Ti-6Al-4V achieved: layers were applied alternately – 1400 MPa; transversely – 750 MPa; in parallel – 1000 MPa (fig. 9).

In order to find the optimal solution and eliminate the existing metallurgical defects of the manufactured parts, many experimental changes in the process parameters were made in order to finally select the most appropriate ones. When the energy density was exceeded 40 J/mm³, the interior of the structure as well as the surface layer of the part were practically free from defects [12]. Depending on the change in energy density, not only the number of pores changes, but the morphology of the defects is also different. These defects were analyzed and the surface layer morphology, shape and size of inclusions were determined.

At low energy density, when the scanning speed is high, the samples have large ($> 100 \mu\text{m}$) and irregular defects due to partial melting of the particles, which causes imperfect powder deposition.

At high energy densities and at low scanning speeds, the pores are spherical and small ($< 100 \mu\text{m}$) as a result of gases trapped in the molten material.

Defect analysis and material density were completed with roughness measurements. The lowest roughness values ($Ra = 10 \div 12 \mu\text{m}$) ensuring better surface quality are obtained at low energy density ($< 30 \text{ J/mm}^3$). However, in these conditions the subsurface porosity of the part is too high. By slightly increasing the energy density to 30 J/mm^3 , the porosity is still low, and the pores in the surface are significantly reduced.

At higher energy densities, although the number of pores is minimal in the surface layer, the porosity, however, deteriorates.

In this example, it can be concluded that energy densities exceeding 40 J/mm^3 are necessary to obtain a part with a relative density of $99.7 \div 99.9\%$, while an energy density of 30 J/mm^3 is sufficient to achieve both better surface layer quality, as well as minimized surface defects. [12]

The optimization of parameters should be carried out both for the interior structure of the part and its surface layer, where a good balance of minimized defects and low roughness is sought.

In order to achieve high mechanical strength and adequate fatigue behavior, it is important to produce parts with high density and optimal quality of the surface layer and minimal defects by optimizing process parameters. In this way, an operating field with a specific set of laser parameters is obtained, in which parts with high density and low porosity are guaranteed [12].

The value of energy density is a key factor in laser processes:

$$E = \frac{P}{v \cdot h \cdot t}$$

where: E – energy density, P – laser power [W], v – scanning speed [mm/s], h – hatch [mm], t – layer thickness [mm].

To melt the powder particles of the processed layer and the previous layer, such an energy density is needed to ensure the correct connection between successive layers and to avoid lack of fusion and porosity. Excessive energy can cause the material to evaporate, causing defects and reducing the density of the material. The key element is the selection of appropriate process parameters for the manufacture of the part.

Fig. 11. Test results of titanium alloy bracket (Ti-6Al-4V) made in AM technology

Summary

The following results were obtained from the use of additive technology (AM) in the production of aviation parts.

It is possible to make part geometry that is impossible to produce with other technology known to date. It is suitable for making very complex shapes that are extremely difficult or even impossible to produce in a conventional production process.

The short production time of prototype parts in AM technology enables the rapid implementation of a new project concept for testing and production.

It is possible to produce parts without the use of specialized equipment and with significantly less material consumption.

Significant material savings were achieved, final part weight reduction of 71% was achieved.

Costs were reduced by shortening the cycle time for making the parts, cost savings of up to 40% were achieved compared to a bracket with similar applications made according to conventional methods

All joining and assembly processing operations were eliminated.

Production of all components and details in one step was achieved (fast production).

High accuracy of the parts was achieved.

High mechanical resistance of the manufactured part was achieved.

High production flexibility was developed.

Additive technology (AM) is faster and has high performance, accuracy, and the parts have good and high strength.

Additive technology (AM) is suitable for the production of parts from materials difficult in subtractive manufacturing technology, such as, for example, nickel-based stainless steel.

By analyzing the above results, it can be unequivocally stated that obtaining successive layers of parts by laser deposition method, using a robotized deposition station is a promising and good way for mass production of aviation parts.

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