Introduction of additive technologies in PJSC «UEC-Saturn»

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Abstract. This article describes the process of assimilation of additive technologies at PJSC UEC-Saturn, introduced and advanced domestic materials for various areas of additive production, the results of manufacturing critical parts of the gas turbine engine by this technology.

1. Introduction
Additive technologies (AT) are a promising and the most dynamically developing direction for improving the production of items in the field of gas turbine engineering. It was made possible due to a number of advantages: the possibility of manufacturing parts of complex shape, significant material savings due to the accurate manufacture of a part of given shape according to a computer model, receiving a higher level of mechanical properties. PJSC «UEC-Saturn» actively implements additive technologies in the process of creating a gas turbine engine.

This article describes the latest achievements in the field of assimilation of additive technologies in PJSC «UEC-Saturn».

2. Results and discussion
The procedure for implementing of AT in PJSC «UEC-Saturn» includes:

1. Analysis of world practices (world experience in use of AT, technological directions of additive production, in demand in the aircraft engine industry, the formation of a technological platform for additive manufacturing);

2. Analysis of the possibility of additive manufacturing of various parts and components of the gas turbine engine (a comprehensive study of the properties of raw materials for additive manufacturing, conducting experimental work on the manufacture of parts by AT, testing synthesized parts in the framework of experimental products);

3. Development of domestic metal powder compositions (MPC), general qualification of synthesized materials (development of documentation for domestic MPC, obtaining domestic materials for additive manufacturing (AM), confirmation of their properties, general qualification and inclusion of materials in the restrictive list of basic AM-materials recommended for application in items of various types of equipment).

4. Development and implementation of screening procedure of parts and components of gas turbine engines for additive manufacturing (selection of parts and components of GTD in their technological and economic feasibility of manufacturing by AT methods, conducting of topology optimization of future parts for reducing of weight and aggregation, improvement of the obtained data for the selected parts and assemblies of GTE).
5. Serial production with the use of AT (conducting of special qualification and certification of GTE with the use of synthesized parts).

Within the framework of the project "Additive Technologies in JSC «UEC», aimed at implementing the strategic task of reducing the development time, the cost of mastering and bringing high-tech, competitive products to the global market, work is actively underway to organize R&D centers of additive technologies at enterprises, including interconnected structures – design-engineering plateaus, research and experimental sites of additive production. The formed centers are equipped with necessary equipment for carrying out work on the design and manufacture of experimental parts of gas turbine engines, conducting tests and introducing them into the design. The enterprises, that are part of JSC «UEC», have covered all the main technological directions of additive manufacturing. Also they have high competencies in the field of introduction into mass production.

The key technological directions of AT implemented at PJSC «UEC-Saturn» are:
- Selective laser melting (SLM) of parts made of heat-resistant cobalt alloys, stainless steel, etc.;
- Electron beam melting (EBM) of loaded GTD parts made of titanium alloys;
- Laser engineered net shaping (LENS), a highly effective technology in the field of repair of parts and components of gas turbine engines;
- Selective laser sintering (SLS) of polymer materials based on polyamide, aimed at solving the problems of casting into shell molds according to burnt models, for the manufacture of tooling and layout.

Any additive manufacturing cycle includes quality and property control. In the process of additive manufacturing, the input control of the metal powder composition, construction and post-processing of item is carried out with constant monitoring of the main parameters of the process. For the period from 2016-2020, the number of parameters for the input control of powder at the enterprise increased by more than 50%, which, in turn, increased the waiting time before the start of work on the synthesis of parts, while increasing the growth of production of parts with the use of AT. In order to preserve the powder throughput, a Lean production project was implemented to improve the efficiency of the operations of input control of metal powder compositions, sampling of MPC and preparation of accounting documentation for additive manufacturing. With the help of the analysis carried out within the framework of improvements and special Lean production tools (spaghetti diagram, fishbone diagram, five whys, etc) the main problem areas, which have an influence on the effectiveness of the MPC input control, were identified:
- Preparation of MPC samples and production culture;
- Loss of time during the transfer of the MPC sample and movements between the means of measuring the parameters of the MPC;
- Loss of time during the preparation of equipment for the input control of the MPC and the preparation of final reports;
- High volume of MPC consumption at the input control.

A reduction by 30% was carried out for two key indicators of the project (the time of sampling and input control of the MPC for one sample from the MPC batch, the material costs of the MPC input control operations for the total number of samples from the MPC batches per year). That effect allowed to maintain the throughput of the MPC input control at the proper level.

At the moment, PJSC «UEC-Saturn» has completed work on the general qualification and inclusion of the following basic materials for AM, recommended for use in aviation equipment products, in the restrictive list:
- Cobalt alloy (KH28M6), obtained by SLM;
- Stainless steel (H15N5D4B), obtained by EBM;
- Titanium alloy (VT6), obtained by SLM.

The leading Russian enterprises in the field of powder metallurgy have mastered their serial production.

In PJSC «UEC-Saturn», research work was carried out on the corrosion resistance of synthesized materials based on the cobalt heat-resistant alloy KH28M6 and stainless dispersion-hardening steel
H15N5D4B in order to introduce these materials into the restrictive list "Materials, coatings and solders approved for use in marine gas turbine engines". The result was the successful qualification of KH28M6 and H15N5D4B materials within the framework of the project "Repair of foreign-made marine gas turbine engines", which allows the use of additive technologies in the process of repairing marine gas turbine engines.

Currently, the use of corrosion-resistant alloys in the manufacture of gas turbine engine parts in all-climatic conditions is widespread. The use of aluminum alloys in additive technologies is justified in the manufacture of external communication parts and brackets for aviation gas turbine engines. The use of heat-resistant aluminum alloys instead of traditional titanium alloys significantly increases the efficiency of the gas turbine engine due to the high manufacturability and strength/weight ratio of this type of alloys. Alloys, based on γ-TiAl intermetallic, have attractive properties for use at temperatures of 650-850°C with the prospect of replacing nickel alloys of similar application due to almost twice the lower density. The use of an alloy based on γ-TiAl intermetallic compound of the STU33H2B5 brand is one of the key ways to reduce the mass of the gas turbine engine and, accordingly, increase its efficiency.

For the possibility of introducing new materials into the aircraft and engine design in accordance with the AR-33 aviation rules, new synthesized alloys are currently being introduced into the company's products. PJSC «UEC-Saturn» has developed technical specifications for a list of MPC made of materials based on nickel (HN55M3BTU, HN48K19TVYUB, HN63M9B), aluminum (AK10M) and titanium (VT6) bases for selective laser fusion technology, as well as from an alloy of the γ-TiAl system of the brand (STU33H2B5) for electron beam melting technology.

Within the framework of PJSC «UEC-Saturn», work was carried out to create a methodology for selecting parts for additive manufacturing. As additive manufacturing technologies improve, there is also a growing need for rational and effective methods for determining parts suitable for production using additive technologies, as well as for getting an idea of what advantages the use of these technologies opens up for a particular part. The choice of parts for the manufacture of GTE parts is carried out taking into account the possibility of providing pre-production, which provides an interconnected solution of design and technological tasks, aimed at reducing the cost and time of manufacturing parts, the possibility of providing added values when designing them for additive manufacturing (for example, weight reduction or aggregation of several adjacent parts into one).

The introduction of a marker that allows us to assess the feasibility of applying additive technologies to the manufacture of a part, based on its geometry, seems to be the most correct solution. Comparing details by estimating the ratio of the area of a body to its volume will be wrong, because change of area of a body will vary with to the square of the size that determines its volume (for example, the area of a sphere grows in proportion to the square of the radius). In this case, the coefficient describing the complexity of the geometry will change with the change in the scale of the body. For this reason, it will be more objective to evaluate the complexity of bodies, the coefficient of additivity, by comparing their areas (S) to the equivalent area of the sphere (Seq), the volume of which is equal to the volume of the body under study (V = Veq) [1].

Based on the fact that the volume of a sphere is equal to:

\[ V_{eq} = \frac{4\pi r^3}{3}, \]

determine its area, expressing through the volume of the studied body:

\[ S_{eq} = 4\pi r^2, \]

where \( r \) is equal to:

\[ r = \sqrt[3]{\frac{3V}{4\pi}} = 0,6203 \times \sqrt[3]{V}; \quad (1) \]

\[ S_{eq} = 4\pi \times (0,6203 \times \sqrt[3]{V})^2 = 4,836 \times V^{\frac{2}{3}}; \quad (2) \]
Then the additivity coefficient is calculated by the formula:
\[ K_{AT} = \frac{S}{S_{eq}} = \frac{S}{\frac{4.836 \times V^2}{3}} = 0.207 \times S \times V^{-\frac{2}{3}}. \]  \tag{3}

Considered intervals of area distribution (the intervals are derived experimentally, after conducting a certain amount of analysis of parts):
- \( K_{AT} < 2 \) – parts with a simple shape obtained using traditional technology for a minimum number of technological operations. The production of such parts is advisable only from the point of view of reducing the production time. During the selection process, it is proposed not to take into account such details.
- \( 2 < K_{AT} < 4 \) – details that are worth considering, but the probability of obtaining a positive effect from their manufacture using AT is small. The parts need to be finalized or combined assembly units.
- \( K_{AT} > 4 \) – parts with complex geometry and a large number of technological operations in the production cycle. Such details are recommended for mandatory consideration for implementation.

As a result, the selection procedure for additive manufacturing can be formulated as follows:
1) Sort parts by sizes (dimensions).
2) Sort available parts by used materials.
3) Exclude parts made of sheet material, as well as parts with simple geometric shape from the list;
4) Calculate the additivity coefficient;
5) Make a decision on the technical feasibility of additive manufacturing of the part and the need for redesign;
6) Conduct an economic justification of the full production cycle in traditional and additive manufacturing (taking into account post-processing) [1].

Also, PJSC «UEC-Saturn» has developed and implemented a single cycle of designing parts and manufacturing AT with the use of topological optimization, which allows to reduce the time of development and implementation of new parts and assemblies in the design documentation, increasing the material utilization rate with minimal manufacturing time and subsequent processing.

In the period 2020-2021, the design departments of PJSC «UEC-Saturn» developed documentation for more than 200 synthesized parts, more than 2,700 parts were manufactured from various MPC. The most common types of parts currently manufactured by AT methods are sectors of straightening devices, elements of combustion chambers, parts of bearing supports, brackets, etc. The following are brief descriptions of the use of additive technologies for these types of parts and technological processes:

1) Sectors of outlet straightener (OS)

During the analysis of the parts, the production of which is possible with the use of additive technologies, it was determined that the forming of types of parts «Outlet straightener» (Figure 1) has a significant potential. As a result, it became necessary to develop the technology of their synthesis. The production of segments for the preparation in the assembly with traditional technologies was almost unfeasible.

A number of requirements are imposed on parts of this type:
- the roughness of the flow channel is not more than Ra 2 \( \mu \text{m} \);
- deviations of the geometry of the flow channel:
  - deviations of the blade airfoil profile no more than \( \pm 0.15 \text{ mm} \);
  - deviations of the area of the interscapular channels not more than 1%;
- operating temperatures up to 1100 °C.

In the process of design-engineer study, the configuration of the outlet straightener was determined, which allows to manufacture it by AM.

This technical solution allowed:
- integrate multiple parts into one;
- significantly reduce the amount of machining, welding and soldering, a number of control operations, as well as burning of the holes;
- the design of the developed part is maximally unified with the similar sector of the OS of engine, which allows the use of serial technologies (soldering of bushings and washers for sealing of the air supply pipeline) and allows the use of equipment already available in production.

To obtain a suitable workpiece, a number of measures were carried out, aimed at eliminating of defects, identified by the results of manufacturing the first experimental model:
- the walls, closed the flow channel, are included in the geometry of the workpiece;
- easily removable ribs are introduced in the interscapular space;
- added auxiliary technological elements, that prevent linear deformations;
- auxiliary perforated supporting structures have been developed to facilitate locksmith processing;
- the perforated supporting structures are reinforced by a system of local "anchors" along the periphery of the workpiece;

The cycle of manufacturing of sectors of straightening devices obtained using additive technologies for testing has been reduced by 10 months.

2) Elements of combustion chambers

The most loaded and responsible elements of the front device of the flame tube are the central and peripheral swirlers (Figure 2), which provide the supply of primary air to the combustion zone and the formation of a swirling flow, which contributes to air turbulence and better mixing it with fuel. To obtain an experimental swirler, the manufacturing process was simulated by the method of layer-by-layer synthesis without additional technological elements in the software «Simufact Additive». Based on the obtained results, technological elements have been developed that reduce deformations and warping of the workpiece.

The results of the introduction of swirlers made by the method of additive technologies:
- Improving the reliability of the structure during operation
- Reducing the number of parts in the structure by integrating several parts into one
- Reducing the cost of manufacturing by reducing the number of operations and reducing the equipment involved
- Simplification of operations for replacing large nodes with a bitter part
- Application of this technology in GTE with a capacity of 130 and 160 MW
Figure 2. Swirlers of the front device of the flame tube of GTE (peripheral and central)

It was produced more than 2500 swirlers for ground-based GTE by SLM. The savings compared to traditional production amounted to more than 27 million rubles, the production cycle was reduced by 30%.

3) Large-sized parts

In the framework of the investment passport for the development of additive technologies of JSC «UEC», in 2020, selective laser melting equipment with a working field of 400x400x400 mm, which has no analogues in the perimeter of JSC «UEC», was introduced in PJSC «UEC-Saturn». Currently, work is underway to study the intersection zones of lasers on synthesized materials based on nickel, cobalt and stainless steel.

One of the priority uses of equipment for large-sized products is the manufacture of the main swirler of project of clean combustion chamber. This swirler was designed to produce a homogeneous fuel-air mixture and supply it to the combustion zone when operating at modes above 0.5 nominal and ensuring environmental requirements for ground-based gas turbine engines. The main problem of this swirler is its mass, which makes it difficult to install the swirler on the product. With the aim to reduce the mass of the swirler, reduce the number of parts included in the design of the swirler, it was redesigned for additive manufacturing (Figure 3).

Figure 3. CAD-model of main swirler of project of clean combustion chamber of GTE.
Size part Ø360x260mm
As a result:
- all internal channels are obtained during the manufacturing of the swirler and do not require additional mechanical processing, 6 component parts are integrated into one, welds with a total length of \(\approx 8\) meters are excluded, mechanical processing is reduced by \(\approx 56\%\) (by the number of surfaces intended for processing).
- the mass of the swirler is reduced by 18%.
Also, at the moment, research is underway on the manufacturing of a structurally similar element of the bearing support of low pressure turbine by SLM, made of MPC of the PS-HN55M3B5TU brand on equipment such as EOS M series and 3DSystems ProX series.
4) Hybrid technologies
Additive technologies have also found application in hybrid technologies, taking advantage of different methods of manufacturing and connecting of parts. The serial technology of manufacturing of shaped workpieces of blades for isothermal stamping that existed at the enterprise was associated with the following problem:
- a long cycle of manufacturing shaped workpieces, due to a large number of transitions and equipment settings;
- a fairly large percentage of rejection and costs for technological needs;
- high labor intensity of in-process cleaning operations, which are performed manually (locksmith processing, cleaning, etc.).
- the features of the process and the available equipment do not allow to obtain shaped workpieces with a stable geometry and the required volume of metal.

In connection with the above-mentioned problems of the process, the technical specialists of PJSC «UEC-Saturn» have developed a technology of "hybrid stamping" with the production of a shaped workpiece with additive technologies made of VT6 alloy.

To obtain a shaped workpiece, it was proposed to use the process of selective electron beam melting (EBM), which proceeds in a vacuum at high temperatures (heating of the applied layer, stable temperature in the working area), reaching about 850°C.

![Figure 4. Comparison of number of technological operations using hybrid technology of additive stamping](image-url)
Replacement of traditional heading and rolling operations for the production of shaped workpieces of blades (semi-finished products) for isothermal stamping by EBM-method, it allows:
- to obtain a high-precision and stable (repetitive) geometry of the shaped workpiece, as close as possible to the ideal, calculated (modeled) in software QForm 3D, which will allow to perform the final stamping operation without defects and eliminating of cleaning operations;
- to increase the material utilization rate by reducing the material consumption rate, due to the absence of metal waste during cleaning operations;
- to obtain a microstructure of the blade material with a uniform globular (α+β) structure and the absence of alpha case;
- reduce the total number of operations, equipment and departments involved in the process of obtaining the workpiece;
- reduce the time and cost of technological preparation of production.

3. Conclusions
The organized structure of the R&D centers of additive production of JSC «UEC» is ready to meet the demand for complex development and serial production of parts for enterprises of the perimeter of Rostec State Corporation.

To ensure technological and technical independence, favorable conditions for the large-scale assimilation of additive manufacturing in key manufacturing sectors of the Russian Federation, it is necessary to develop two basic areas:
- development of domestic production of serial industrial 3D printing equipment and component base that meets the high requirements of the aircraft engine industry.
- improvement of existing production facilities for materials used in additive manufacturing, creation of new optimized regulations for certification and approval of materials and technologies for use in various products.

Reference
[1] D. V. Fedoseev, P. Y. Kozlyakov, A.V. Poparetsky, P. A. Starikov Selection of GTE parts for manufacturing using additive technologies / Additive technologies, 4/2020 20-23.