Application of additive technologies for manufacturing turbine stator parts in aircraft engines

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Abstract. Continuous development of additive technologies and fast prototyping methods makes it possible to use them in manufacturing of complex shape models to a high precision. The traditional technological manufacture process of critical hot gas path parts by investment casting is expensive and time consuming in view of its technological complexity. It is related to the wax casting process which provides complex profiles with high geometrical accuracy. The acceleration of the investment casting process should increase the productivity of the manufacturing process of such hot gas path parts as the turbine stator, however, it is not allowed to decrease the geometric accuracy of the finished product. The aim of this work is to compare technological processes for manufacturing turbine stator parts at various temperatures using the fast prototyping method (wax casting in silicone molds). The dimensional analysis of the stator castings showed that casting in silicone molds provides the required geometric accuracy. Thus, silicone molds can be viewed as a good cost-effective solution for small-scale or pilot production of high-precision complex parts in gas turbine engines. This article describes the procedure for the integrated application of additive technologies and thermographic analysis to accelerate the investment casting process by determining the optimal temperature conditions and cooling period. Ultimately, it reduces the duration of the production cycle and the cost of the finished product while retaining the quality characteristics.

1. Introduction
The turbine stator blade is one of the main components of a gas turbine engine (GTE). The turbine stator characterized by the stringent requirements for manufacturing accuracy is made of heat-resistant nickel-based alloys by investment casting. The precision of the produced wax stator models subsequently determines the precision of metal castings. The technological conditions of the wax model manufacturing process such as pouring time, exposure time, pouring temperature and working pressure play a key role. Thus, monitoring the given parameters makes it possible to prevent defects associated with surface heterogeneity, porosity and deviations from predetermined dimensions which lead to time consuming operations and readjustment of the gating and feeding system (GFS) for metal pouring. One of the main problems of investment casting is the high cost of the process as a whole. It is related to the special purpose equipment, production tooling, binding materials resistant to high temperatures, the complexity of the shell molding process and unavoidable small defects that require subsequent removal. In addition, it takes considerable time to design and manufacture the molds for wax casting.

Taking into consideration the complexity of the production process, the traditional technological process for manufacturing wax models of the turbine stator is time consuming and expensive. In the conditions of multi-nomenclature production with frequent and multi-iterative changes in products, the
speed of preproduction engineering, in particular the manufacture of production tooling, is particularly important. Additive technologies and fast prototyping methods [1-3] show good results as they are easily adapted to the manufacture of complex configuration parts [4, 5] especially cast parts which makes it possible to reduce the production time and cost in general.

The main difference between fast prototyping methods and traditional technologies is as follows:
- significant reduction of preproduction engineering time and cost (about 5 times less);
- significant reduction in the number of technological operations.

Fast Prototyping Technologies is a cost-effective solution for the production of small batches of semi-finished products using investment casting. Following the obtained master model and using additive technologies (3D printing with photopolymer) an elastic silicone mold is made for wax casting. When using this technology, the first wax model is obtained in 3-5 working days while the traditional technology requires from 3 to 6 months for this stage.

This article describes the development and application of additive technologies for a new manufacturing area. The method described in the work can be used for the manufacture of flexible silicone molds for lost wax casting in the production of a turbine stator which is used instead of the traditional production of a metal mold on a CNC machine.

2. Materials and research methods
The object of the study is the hot gas path parts in a gas turbine engine in the form of the solid cast nozzle block. The turbine stator casting is made of a heat-resistant nickel-chromium alloy. The part geometry is characterized by a complex spatial configuration, high requirements for the accuracy of geometric parameters and the quality of the surface layer. Due to the complex spatial configuration and the lack of the developed surfaces for precise locating as well as insufficient inter-blade space, the most effective way to obtain nozzle block blanks is the method of investment casting which does not require machine allowance for the turbine airfoil. To conform to the roughness parameters specified in the engineering documentation, it is necessary to perform an equidistant test run for the turbine airfoil profile on the synthesized master model. This allowance is removed in the operation of the grown master model polishing, thereby ensuring the required surface roughness and quality which are replicated in the wax models of the nozzle block by the silicone elastic form.

The computer master model of the turbine stator was built according to the drawings using Siemens NX CAD / CAM / CAE 3D modeling tool. According to the technological requirements of the drawing, 2D profiles of the cross sections of the blade back and pressure surface were designed. Then, based on the designed profiles, spatial modeling of the turbine airfoil profile was carried out. In addition, the shrinkage coefficient was taken into consideration including:

- wax model shrinkage after pouring into silicone and epoxy molds depending on the coefficient of thermal expansion of the wax used;
- ceramic mold shrinkage;
- heat-resistant alloy shrinkage following its crystallization in a ceramic mold.

In the case of using the heat-resistant nickel-chromium alloy the coefficient of the metal volumetric shrinkage is 1.2%, of model wax is 1% and of ceramic mold is about 0.3%. Thus, the total shrinkage coefficient is 2.5%.

The most responsible and expensive stage is the manufacture of a physical prototype using its 3D model. For that purpose Objet Eden 350 layer-by-layer printing system using PolyJet technology was used [6, 7]. As the main (model) photopolymer material Transparent - FullCure720 material was used with the constant parameters (speed - 12 mm / hour and layer thickness - 16 microns). The material temperature during the samples growth was 75 °C. After growing the support material was removed using WaterJet system. The storage temperature of the samples was 17 ... 19 °C [8].
Prior to the manufacturing process of the silicone mold in order to avoid geometric defects the obtained master model was checked on DEA GLOBAL Performance coordinate measuring machine (CMM) using specialized PC-DMIS CAD ++ Ver. 4.3 MR1 software.

It was established [9] that the surface roughness is significantly affected by the layer-by-layer (stepwise) method of growing parts which is used in all technologies related to additive production. In view of the layer-by-layer model synthesis, the thickness of the grown layer will have a significant effect on the surface roughness. The surface roughness was measured on Hommel - Etamic Tester W55 profilograph in two directions, in horizontal Ra 2.5 μm and vertical Ra 12.5 μm.

To achieve the required surface roughness of the turbine stator master model, the following operations were performed:

- control of the master model roughness on the profilometer after growing;
- polishing of the path surfaces and the turbine airfoil to the required roughness Ra 1.6;
- control of the master model roughness on the profilometer after polishing;
- control of the geometric parameters of the path surfaces and the turbine airfoil.

The geometric parameters control showed that the part master model of the turbine stator meets the design requirements for geometry deviations of the airfoil surface. The profile deviation was within the specified tolerance of -0.15 ... + 0.2 mm. After the final control of the geometric dimensions and the surface quality of the nozzle block master models the next stage was the manufacture of an elastic silicone mold.

An elastic silicone mold manufacture is a fairly simple and proven method. The mold solidifies due to the chemical reaction of the components. First, the master model is positioned in a plexiglass container thereafter all the contents are filled with the silicone compound in order to accelerate the polymerization process of the silicone compound, afterwards the filled form is placed in a temperature cabinet for 2 hours with a temperature of 80 °C. When the mold is finally cooled it is cut and the master model is removed. During the subsequent assembly between the parts of the silicone mold a cavity is obtained that is completely of the same geometry as the master model. After filling this cavity with the wax model composition in a vacuum, a precise copy of the model is obtained.

The technological modes of the wax model composition casting into an elastic silicone mold such as the pouring temperature of the wax composition, pouring pressure, exposure time and mold temperature significantly affect the geometric accuracy of the resulting wax model. The pouring temperature and holding time play the greatest role in obtaining precise dimensions. The exposure time depends primarily on the mold cooling rate, waxing and melting point. Thus, after the manufacture of silicone mold the influence of the exposure time on the final wax model accuracy was verified by conducting a thermographic experiment in order to determine the optimal conditions for pouring the wax model mass into a heated silicone mold. A series of experimental pouring of wax compound was carried out at a temperature of 95 °C using the forced cooling system by blowing the cast mold and without it, the results are shown in figure 1. The graph shows that it takes the silicone mold 2 hours and 30 minutes to be cooled using blowing and the silicone mold requires 4 hours to be cooled without blowing. From an economic point of view, it is better to use the first option with the forced cooling system as in this case we save time and get more wax models.

A set of experiments was also carried out which involved pouring a wax model composition with a change in the pouring temperature of the wax composition (95 °C, 100 °C, 105 °C, 110 °C). After removing the wax model from the silicone mold the geometric dimensions of the aerodynamic profiles were measured using DEA GLOBAL Performance CMM. The smallest deviations in the casting dimensions as well as the mold cooling time were obtained at a pouring temperature of 95 °C. With an increase in the pouring temperature of the wax composition by every 5 °C its cooling time also increases by an average of 10-12 minutes.
Based on the results of the experiments the following conditions were selected for pouring the wax model composition into a silicone mold: cooling - forced blowing, pouring temperature - 95 °C, exposure time of wax models in the mold - 2 hours 30 minutes.

![Mold cooling diagram]

**Figure 1.** Thermographic analysis of silicone mold cooling.

The obtained wax models were assembled into foundry blocks consisting of a central riser, feeders and the wax model of the blank. Gating trees containing 1 wax model were formed. The pouring was carried out according to standard investment casting technology [10, 11]. The finished casting of the turbine stator is shown in figure 2.

![Turbine stator casting]

**Figure 2.** Turbine stator casting.

3. Results and discussions

An analysis of the experimental studies on the use of fast prototyping technology and additive production algorithms showed that these technological methods provide a cost-effective solution for the production of small batches of stator blades in gas turbine engines. The process of layer-by-layer growing of products at Objet Eden 350 printing system using PolyJet technology is applicable for the manufacture of a master model using its 3D digital model.

Silicone tooling has a number of advantages compared to traditional technologies which consists mainly in the reduction of the technological cycle duration and cost reduction. Practical experimental studies have shown that elastic silicone molds are suitable for the manufacture of geometrically complex blank parts which do not require machine allowance for the turbine airfoil of the hot path in gas turbine equipment as they provide the specified parameters of geometric accuracy and surface roughness.
4. Conclusions
The use of elastic silicone molds for the manufacture of wax models of critical engine parts, for example, a turbine stator, requires additional costs associated with control operations. It is necessary to control the geometric dimensions of the master model before and after turbine airfoil polishing and it is also necessary to control each wax model for compliance with the turbine airfoil geometry deviations and the ceramic rod location.

However, in mass production the traditional method of wax models manufacture provides greater accuracy of the final products and a longer service life of tooling, therefore, it remains the most preferred method.

Acknowledgements
This study was conducted as part of the Russian Federation presidential grant project for the government support of postdoctoral research workers (MK–2019 grant).

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