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Design and optimization of the micro-engine turbine rotor manufacturing using the rapid prototyping technology

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Abstract. This work describes the experience in manufacturing the turbine rotor for the micro-engine. It demonstrates the design principles for the complex investment casting process combining the use of the ProCast software and the rapid prototyping techniques. At the virtual modelling stage, in addition to optimized process parameters, the casting structure was improved to obtain the defect-free section. The real production stage allowed demonstrating the performance and fitness of rapid prototyping techniques for the manufacture of geometrically-complex engine-building parts.

1. Introduction

In the modern aviation background results in a new class of aviation equipment – unmanned aerial vehicles (UAV), which combine the experience of introducing the scientific research results and achievements in the production process. The analysis of the manufactured UAV showed that their outstanding feature is the high speed at comparatively small engine dimensions. Consequently, there is a need in manufacturing of the brand-new micro gas turbine engines (GTE). As we know from the GTE theory, the turbine is the most critical component of the engine. This is connected with the high continuously growing level of temperatures and stresses occurring in the turbine blades as well as with the necessity to considerably extend their service life. As a rule, turbine blades are manufactured of heat-proof nickel alloys (HA) by the directional crystallization casting due to the fact that the HA-category high-melting point alloys are almost non-machinable materials [1-5].

The micro GTE turbine rotor (Figure 1) shall also comply with the raised heat-resistance and high-temperature stability as well as corrosion resistance requirements. For this reason, when manufacturing the hot component of GTE, HA-category high-temperature nickel alloys with the melting temperatures of 1550-1600 °C are used.

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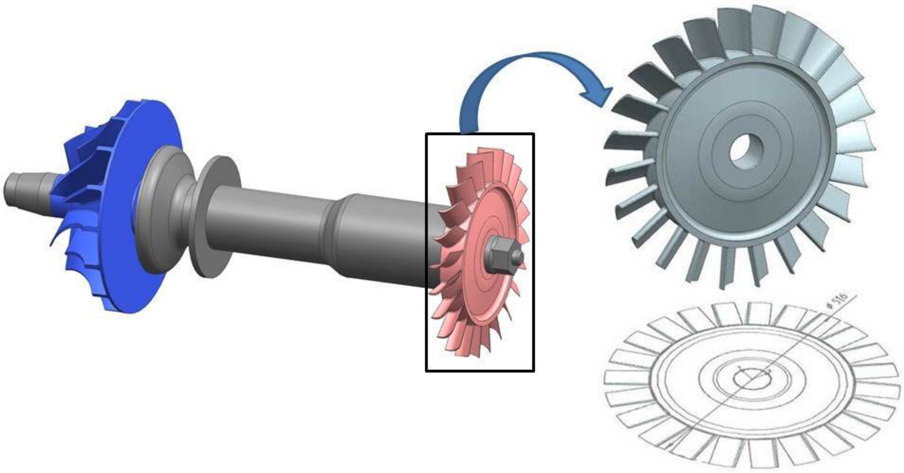


Figure 1. The 3D model of the turbine wheel.

2. The experimental research of the casting process

The traditional manufacturing process of the micro GTE turbine rotor involves casting with directed crystallization in batch pusher furnaces. The whole manufacturing process consists of several stages including: producing metal moulds, creating wax models, manufacturing ceramic shell moulds and making the metal casts. In work [6], a similar manufacturing process for the turbine rotor for Drone's micro engines is considered, however the specific feature of this work is the introduction of a temporary outer ring in the design; the ring thickness is h=1 mm. From the technical point of view, its expediency is explained by the additional metal feed of the blade airfoil end zone due to the considerable airfoil thickness; by the additional structural rigidity – due to the absence of transversal movement of these zones during coating and by the absence of longitudinal movement due to the hampered volume shrinkage, also the ring serves as the process support when coating the model (Figure 2).

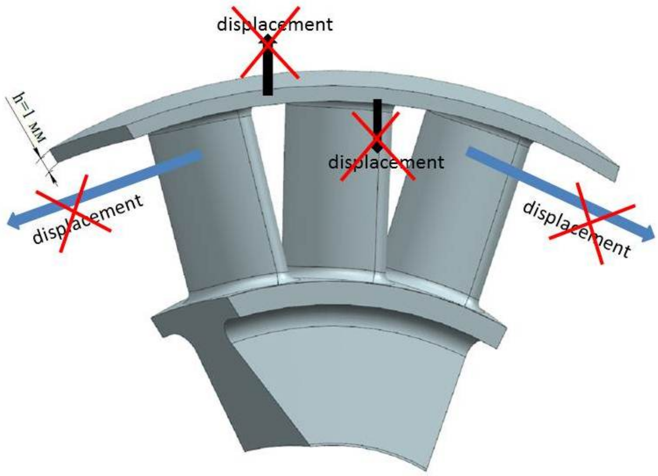


Figure 2. The 3D model of the turbine rotor with the outer rim.

The experimental pouring of the improved turbine rotor structure was carried out within the research work. However, the obtained casts indicated in Figure 3 had defects represented by misruns and unshaped zones within end sections. The casting process analysis showed that the most apparent and objective reason of defects was the inefficient outer rim structure, namely inability to access the most remote zones of the central feeder due to its small flow area ($S=9$ mm^2). Therefore, the exploratory optimization studies shall be carried out to select the most optimal structure of the outer rim.

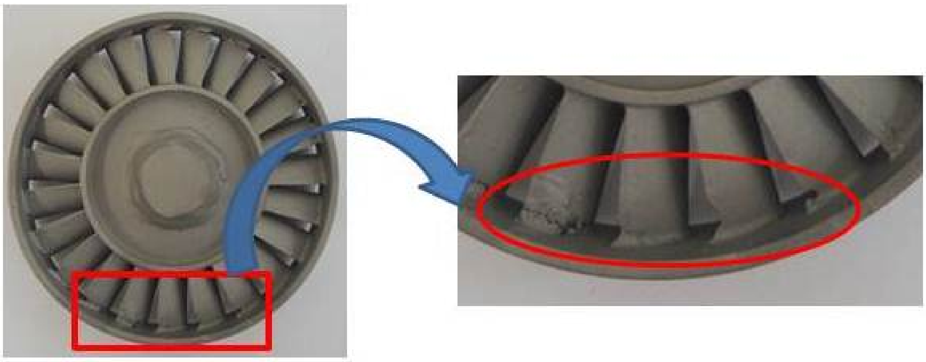


Figure 3. Casting defects of the turbine rotor.

Considering the fact that the directed-crystallization casting technology is a costly process, it is expedient to use the computation modelling systems with performing the experimental studies on developing the casting process parameters on a PC screen. Using the computer modelling system will considerably reduce the cycle time, production costs, and, undoubtedly, improve the quality of the finished part [7-11].

3. Results and discussion

3.1 The results of numerical simulation

Computer modelling was performed using the ProCast software, using the finite element method (FEM). The adequacy of software employed and the convergence of results obtained have been tested many times by the authors and described in works [12-14].

Figure 4 shows the computer modelling results for the turbine rotor casting process of the micro GTE featuring a 1 mm thick outer ring in its design.

By iteration modelling, the optimal process parameters were selected:

Pouring temperature – 1530 °C;

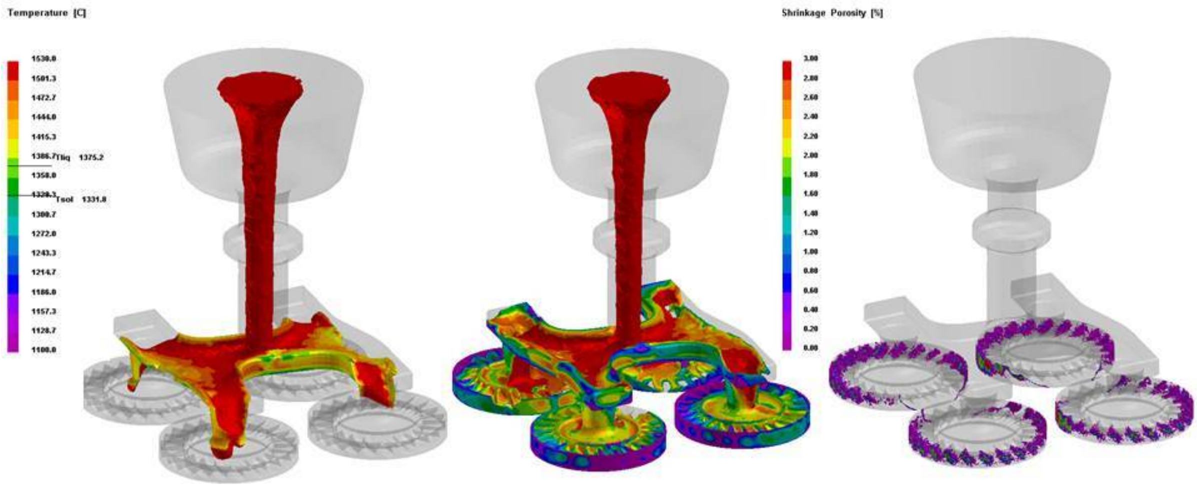
Temperature heating of a ceramic mould – 1300 °C;

Pouring time – 4 s;

Heat transfer rate – 2000 W/m$^{(2\text{-}K)}$;

Pouring rate 130 mm/s.

It should be noted that during modelling, the cast material, namely heat-resistant nickel alloy JS-30 VI, as well as the ceramic shell material – electrocorundum (Al_2O_3) – remained the same.



a *b*

Figure 4. Computer modelling results: *a* – mould filling with metal before the crystallization commencement; *b* – formation of shrinkage porosity 2-3%.

However, according to the virtual process calculations, the porosity of about 3-5%, local misruns and unshaped blade airfoil areas were observed within the end section of blades (which is essential) as well as within the outer ring area. In this connection, it was decided to double the thickness of the outer ring in order to ensure the additional metal supply. Thus, the outer rim acted as a top which subsequently had to be removed during machining.

The results of the virtual experiment with the increased outer ring thickness are given in Figure 5. The analysis of modelling results shows that the defects of blades represented by misruns and unshaped airfoil zones were managed to be compensated by increasing the outer rim thickness. The resulting porosity is less than 0.3% and is concentrated in the outer ring (top), which is cut off in the course of machining. Therefore, by optimizing the structure and casting process parameter, the stage of full-scale experiment on turbine rotor casting manufacture may be proceeded to.

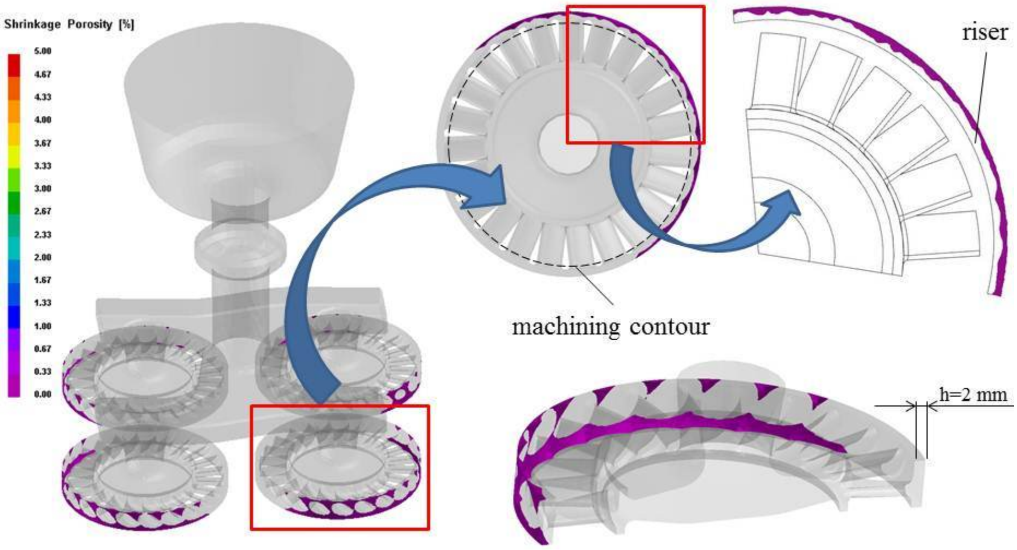


Figure 5. The results for porosity occurring in the outer ring.

3.2 Design manufacturing technology of the turbine rotor

Manufacturing the turbine wheel prototype

The first step in the micro GTE turbine rotor manufacturing process was building the part prototype (a master model) using its volume model with additive technologies [15, 16]. In particular, a success was achieved in manufacturing of the turbine prototype using the PolyJet technology (figure 6 a) with the reproduction precision of 0.02 mm along the X and Y axes and 0.016 mm along the Z axis.

Manufacturing silicone accessory

An elastic silicone mould (Figure 6 b) was manufactured using the built turbine wheel prototype serving for the subsequent pouring of wax and receiving the wax turbine models. An advantage of using the elastic form is its flexibility which, due to the complex structure of the turbine wheel, makes the process of creating the production accessories easier and faster. In addition, silicone is ideal to reproduce the geometry and texture of a part.

Manufacturing the turbine rotor wax models

The turbine rotor wax models were manufactured by the Paramelt investment compound pouring into the prepared silicone mould (Figure 6 c). Pouring with melted wax of the mould cavity was carried out at the temperature of 90 °C. The components of pouring gate and gating system were also manufactured of the wax investment compound. Using heating elements and a soldering station, wax models were assembled in model blocks as shown in Figures 4 and 5.

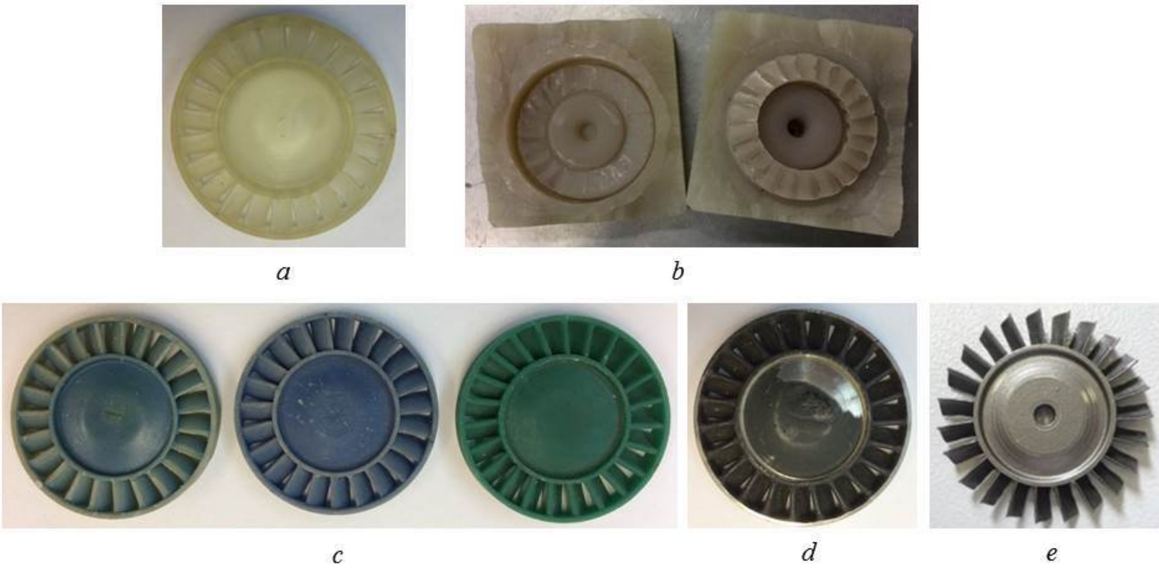


Figure 6. The technology of manufacturing the turbine rotor: a – master model; b – silicone form; c – wax models; d – casts; e –turbine rotor after machining

Manufacturing ceramic moulds and producing casts

The technology for manufacturing ceramic shell moulds consists in coating of moistened casting models with quartz sand and the subsequent drying of each layer [17]. The suspension containing the hydrolized ethyl silicate solution as a binding component was utilized for the first two layers of the mould; the suspension containing liquid glass was employed for the subsequent layers. Silicon dioxide with the grain size of 100 μm was used as a refractory filler of the suspension and a refractory coating material. After the application of the initial two layers using ethyl silicate as a binding hydrolized solution, the alumo-boron phosphate concentrate with the density of 1.25-1.30 g/cm^3 was applied as a separation layer. The nickel-based JS-30 VI heat-resistant alloy was melted and poured into a ceramic mould using a pusher continuous furnace implementing the directed-crystallization pouring method. The results of the experimental pouring of the micro GTE turbine rotor are given in figure 6*d*.

4. Conclusion

The GTE turbine rotor represents the most critical and highly loaded part stipulating the service life and operational reliability of the engine. The performance of the turbine rotor in general, and of its blades in particular, is conditioned not only by the strength characteristics of materials employed and the geometric shape, but, in many respects, by the developing manufacturing methods. Development of the turbine rotor manufacturing technology is connected with the application of experience accumulated in machine building to ensure machining of a relatively high amount of parts with the developed crooked spacial surfaces, including with the use of rapid prototyping methods.

The existing manufacturing process applied for similar category of parts with the developed crooked spacial surfaces is based on the trail-and-error method. Frequently, in practice, several manufacturing cycles are performed in order to achieve the required quality level. This multioptional pattern always results in considerable time and material losses.

Therefore, implementing a complex process combining the computer experiment on optimizing the casting process parameters and its bringing to a perfect state as well as the rapid propotyping method allow reducing costs for the manufacture of parts considerably. The use of the computer modelling system for casting processes allows solving the issue related to the casting defect forecasting in a most complex manner. Using this system allows learning all the processes and phenomena characterizing the cast during crystallization in a rather profound way, understanding the reasons of defects, evaluating the efficiency of the process employed. When the rapid prototyping techniques are employed as the most flexible blank production technology, the initial casts of parts may be manufactured within the shortest term (2-3 weeks). As to the traditional technologies, the manufacture of metal die moulds takes from 3 to 6 months.

Owing to this combined process employed for producing the micro GTE turbine rotor, timeframes required for designing its manufacturing technologies were reduced along with a considerable decrease of the production costs.

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