Designing of the digital casting process for the gas turbine engine blades with a single-crystal structure

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Abstract. The work represents the approaches for designing the digital casting process of turbine blades. The development of the mathematical model for determining the non-stationary temperature distribution in the “furnace-moulding-flask-filler-metal-stopper” process system has appeared to be the core of the digital blade manufacturing process considering particular structural, geometry and thermal-physical features of this system. The approbation of the developed mathematical model as well as the computer designing methods under the pilot production conditions through manufacturing of the GTE turbine blades has demonstrated the decreased amount of defects in the macrostructure of blanks of turbine blades with the longitudinally-oriented and single-crystal structure by 30\% in total.

1. Introduction
Presently, one of the most important features of engine building is the enhanced reliability of gas turbine engines. Since the reliability of gas turbine engines is, among other things, ensured by process methods, the principal efforts shall be directed to improving the production processes for manufacturing the main motor parts. First of all, this refers to the manufacturing technologies of working path parts, such as turbine blades, since they are the most critical parts of the engine experiencing the maximum loads and conditioning the engine service life.

Due to a complex spatial shape and the absence of extended surfaces for the accurate location of the blades, the most effective and, in some cases, the only method to manufacture the blade blanks is the airfoil non-tolerated method for manufacturing the blade castings by the single-crystal casting method and a subsequent machining of the root area and shroud platform.

The overview of the existing domestic processes for the manufacture of gas turbine engine (GTE) blades [1-6] allowed establishing that the manufacture of non-tolerance turbine blade blanks is extremely unstable and is characterized by a high percentage of defects (approximately 50\%). In the first turn, it is related to the instability of process conditions. A considerable part of the total amount of defects is formed by the inconsistency in microstructure and geometric parameters of the airfoil, whose reasons are the non-stationarity of temperature conditions as well as the imperfection of the local airfoil polishing process.

The existing process solutions aimed at reducing the defects during the manufacture of the GTE turbine blades is currently at a sufficiently high level of elaboration. However, their common deficiency is a weak utilization of the production computing aids. This deficiency is caused by a
number of reasons: 1) low grade of convergence of the computer simulation results and the results of full-scale experiments at different options of control of process parameters; 2) the absence of the methods for determining the optimal process parameters at different turbine blade manufacturing stages; 3) the absence of a complex simulation twin-model for multi-option numerical studies of the manufacturing process of turbine blades.

The work is aimed at improving the quality, performance and reducing the level of defects in manufacturing the blanks of GTE turbine blades obtained by the method of directional crystallization of single-crystal castings due to the elaboration of the finite-element model of the process. The objectives of this work are:
- development of the mathematical model for determining the non-stationary temperature distribution in the “furnace-moulding-flask-filler-metal-stopper” process system considering particular structural, geometry and thermal-physical features of this system;
- development of the finite-element simulation method for the manufacturing process of GTE turbine blade blanks;
- checking the fitness of the developed mathematical model and method for designing the manufacturing process by comparing the results (casting structure parameters, presence and location of casting defects) with full-scale experiments during pilot production of the turbine blades of the 1st stage GTE.

2. Description of the model
2.1 Geometric model
At present, turbine blades are manufactured at the industrial plants by casting with directional crystallization of heat-resistant alloys at PMP-2 units, UVNK high-speed directional crystallization units and VIP-NK vacuum smelting units. The work considers the manufacturing process for blades at the PMP-2 unit. The geometric model of the process diagram designed in the NX CAD software package, is given in figure 1 a. The process diagram comprises a graphite moulding flask, a graphite filler for positioning the ceramic mould, the stopper for tapping the molten metal at a definite moment of time, a plug to add rigidity to the process system, blade blanks and seed.

Finite element model [7] of the process system was designed in the MSC Apex Modeler software and in the Visual-Mesh module of the ProCast software product, allowing to obtain the mesh reliably coupled with the blade casting lattice [8].

Figure 1. Geometric model of process system: a – 3D-model of turbine blade casting and casting block; b – finite element model of the gating and feeding system (LPS) and turbine blade casting;
c – finite-element model of casting block.

A characteristic dimension of the element in the blade blank is 1 mm; in perforation (cooling channels) - 0.5 mm; at the blade root (edge) - 0.3 mm; in the gating system - 2 mm; in the pouring cap and central feeder - 3 mm. The computational region consisted of 3,471,693 nodes and 17,771,077 elements.

2.2 Mathematical model

This section is devoted to the development of the mathematical model for determining the non-stationary temperature distribution in the process system of “furnace-moulding-flask-filler-metal-stopper” considering particular structural, geometric and thermal-physical features of this system. It was established that the main control effect may be produced on the process through changing: the power of heaters, temperature conditions of each of the zone of PMP-2 unit, the moving speed of the flask train in the unit (pushing cycle). For manufacturing of turbine blade blanks considered in the process, the heat exchange process is the most relevant for defining the blade single-crystal structure quality.

In the volume of the material of solid bodies furnace-moulding flask-filler-metal-stopper, the heat transfer processes along the entire range of temperatures are described by a classic heat-transfer equation (1):

\[ c(T)\rho(T)\frac{\partial T}{\partial t} = \text{div}(\lambda(T)\text{grad}T) \]  

where \( T(t,\vec{r}) \) – temperature at the moment of time \( t \) in the point with coordinate \( \vec{r} \) inside of each body of the system; \( c(T), \rho(T) \) and \( \lambda(T) \) – specific heat capacity, density and thermal conductivity factor of the materials, different for each system.

For the metal weight, considering that during heating the material should be transferred to the liquid phase, the heat conductivity equation shall be represented in the following form (2) considering the possibility of its smelting in the solidus and liquidus temperature range:

\[ c_{\text{ef}}(T)\rho(T)\frac{\partial T}{\partial t} = \text{div}(\lambda(T)\text{grad}T) \]  

where the parameter \( c_{\text{ef}} \) is determined from the equation (3):

\[ c_{\text{ef}} = c(T) - \frac{L}{T_L - T_S} \varphi \left( \frac{T - T_S}{T_L - T_S} \right) \left[ \eta \left( \frac{T - T_S}{T_L - T_S} \right) - \eta \left( \frac{T - T_L}{T_L - T_S} \right) \right] \]  

where \( T_L \) and \( T_S \) – solidus and liquidus temperature of the alloy; \( \varphi((T - T_S)/(T_L - T_S)) \) – the alloy melting rate expressed in the effective heat capacity using the Heaviside function \( \eta(v) \), equal to zero at \( v < 0 \) and set to unity at \( v \geq 0 \) (here \( v = (T - T_S)/T_S \) or \( v = (T - T_L)/T_L \), the body volume region \( T_L \leq T(t,\vec{r}) \leq T_S \) is explicit, in which the heat is adsorbed during the metal smelting).

To solve these heat conductivity equations, the initial temperature for all the bodies shall be set, which is uniform and equal to the temperature in the shop along with setting the limiting conditions at all the surfaces of the model depending on the time for each zone of material furnace.

The boundary conditions for surfaces heated in the PMP-2 vacuum furnace from thermal heaters or surfaces of other bodies shall be determined by heat radiation and have the form (4):

\[ \lambda \frac{\partial T}{\partial n} = \varepsilon \sigma [T^4 - T_c^4], \text{ at } r = r_{\text{INT}} \]  

where \( n \) – external normal to the considered surface; \( \varepsilon \) – heat adsorption factor of the surface; \( \sigma \) – Stefan-Boltzmann constant; \( T_c \) – temperature of the surface which radiation exchange is effected with;
The system of equations for each body forms a closed system of equations relative to the temperature of each body.

The primary factors determining the quality of turbine blade manufacturing process are the operating temperature conditions in each of the zones of the casting unit and the speed of movement of the moulding flask train (by changing the induction motor power).

3. Boundary and initial conditions

3.1. Initial conditions

The manufacturing process for single-crystal turbine blades of heat-resistant nickel alloys takes place in the modernized PMP-2 through-type continuous furnace. From the thermal point of view, this installation represents a conduit with the flasks moving in it. On both sides of the flask train, flat heaters are located. A thermal node of the furnace consists of 8 conditional zones, forming 3 regions: heating region (zone I, II); melting region (zone III, IV) and the crystallization region (zones VI-IX).

Each zone is characterized by a certain temperature, which is set by the individual power system. At the interface region of zones IV and VI (in a strictly defined point), the mechanical stopper device is activated allowing to open the runner with metal tapping to the form in front of the crystallizer.

The following elements were included in the design region of the turbine blade casting process: 1st stage blade casting model at a minimum wall thickness of 1 mm; a ceramic rod; a seed; a plug; a ceramic mould with the thickness of 10 mm; graphite filler; a stopper; a graphite flask [9, 10, 11].

The following initial process parameters were used:
- Smelting-pouring of ZhS30-VI alloy in the PMP-2 batch furnace;
- Stucco material (of a ceramic mould) is aluminium oxide Al₂O₃;
- Pouring time – 4-6 sec;
- Pouring temperature – 1510 °C;
- Temperature conditions by PMP-2 furnace zones:
  Zone I  1290 +10 °C;  zone VI  1510 +10 °C;
  Zone II 1370 +10 °C;  zone VII  1450 +10 °C;
  Zone III 1400 ±10 °C;  zone VIII 1390 +10 °C;
  Zone IV 1510 +10 °C;  zone IX  1370 +10 °C.

The temperature fields obtained from the solution of the problem of initial heating of the graphite flask were used as the initial thermal conditions for all elements of the computational region.

3.2 Boundary condition and loading.

Using the User Function module of the ProCast software product enables effecting flexible control of boundary conditions in time and space, i.e. changing the radiation exchange conditions in the heating region initially set at the surface of the graphite flask by the convective heat exchange conditions in the crystallization region and thus simulating the movement of the flask train in the body of the PMP-2 furnace.

The furnace body consisting of 8 zones, was divided into two identical parts, for each of which the user-defined functions were written in the C++ programming language. The geometric dimensions of the furnace zones were replaced by time values through a constant flask moving speed (0.25 mm/s). To simplify the displaying of the boundaries of the elements of the process system, the adjacent zones of the graphite flask, graphite filler and ceramic form will be considered as a single whole.

In designing of user functions, much attention was paid to heat exchange of the furnace-moulding-flask-filler-metal-stopper process system with the external environment. In this case, heat exchange occurs in a vacuum, therefore, the appropriate values of the emissivity factor and temperature shall be set on the corresponding surfaces of the bodies of the process system (figure 2). In addition, the heat transfer factor was set at the boundary “ceramic mould - seed” along with all the necessary thermophysical properties of the ZhS30-VI alloy.
Figure 2. Boundary and initial conditions of the furnace-moulding flask-filler-metal-stopper process system: a – during heating of ceramic mould and graphite flask; b – during pouring and block cooling

ε_h – emissivity factors of heaters; ε_f – emissivity factor of PMP–2 furnace; ε_gf – emissivity factor of graphite flask; ε_cm – emissivity factor of ceramic mould; ε_s – emissivity factor of seed; ε_cast – emissivity factor of the casting; ε_lc – emissivity factor of liquid crystallizer; T_H.I–IV – temperature of heaters in zones I–IV, °C; T_H.VI–IX – temperature of heaters in zones VI–IX, °C; T_B – PMP-2 furnace body temperature, °C; T_gf – initial temperature of graphite flask, °C; T_fil – temperature of graphite filler, °C; T_seed – initial temperature of ceramic mould, °C; T_cm – temperature of ceramic form, °C; T_s – stopper temperature, °C; T_seed – seed temperature, °C; T_p – pouring temperature, °C; T_c – liquid crystallizer temperature, °C; v_p – average speed of pouring of molten metal in ceramic mould, mm/s; v_t – flask train movement speed, mm/s; h_cm-fil – heat transfer coefficient at the boundary between the ceramic mould and graphite filler, W/(m^2·K); h_cm-seed – heat transfer coefficient at the boundary between the ceramic mould and the seeds, W/(m^2·K); h_cm-cast – heat transfer factor at the boundary between the ceramic mould and casting, W/(m^2·K); h_gf-cast – heat transfer factor at the boundary between the graphite filler and the graphite flask, W/(m^2·K); h_cast-seed – heat transfer factor at the boundary between the casting and the seeds, W/(m^2·K); h_cm-stopper – heat transfer factor at the boundary between the stopper and the ceramic mould, W/(m^2·K); h_gf-stopper – the heat transfer factor at the boundary between the graphite flask and the liquid crystallizer, W/(m^2·K).

4. Results and discussion

4.1 Process system heating

The numerical solution of the mathematical model in the three-dimensional setting was carried out with the help of the finite-element method of the ProCast software product, since this method is capable of describing the complex geometry of castings and generators of ceramic forms to a more accurate degree. Figure 3 represents the simulation results for the process system heating.

The process system is heated by flat heaters located in the installation on both sides relative to the flask train. The heating process is uniform, the temperature front is formed on the outer surfaces of the graphite flask with spreading to the centre of the process system, namely to its bottom part, which allows concluding on the directed nature of heating. Along with the heating of the furnace-moulding flask-filler-metal-stopper process system, melting of the charge of the heat-resistant metal occurs.
These two interrelated processes end at the end of the melting region, before the crystallization area approximately in 7 hours after the start of the process cycle. At this point, a mechanical stopper device is triggered; the runner is opened with tapping the molten metal into the ceramic mould.

4.2 Filling a ceramic mould with the molten metal
The results of numerical simulation for heating of the process system were used as initial conditions for simulating the problem of filling a ceramic mould with molten metal (figure 4). The analysis of the results of simulation of the melt flow showed the inefficiency of the runner-feeding system, connected with separation of the metal flow into two parts, as well as the non-simultaneous filling and, as a consequence, crystallization of the castings, which eventually would adversely affect the macrostructure of the blade.

4.3 The casting macrostructure simulation results
The computer research of the process of macrostructure formation in the blade casting was performed using the CAFÉ module of the ProCast software product, in which the results of the solved heat problem by finite element method were interpolated for performing the calculations by the cellular automata method. Finally, the result of computer simulation for macrostructure in the blade casting were compared with the structure of a real turbine blade subjected to chemical etching (figure 5). It should be noted that a series of numerical experiments on determining the macrostructure of blade
casting were carried out with the selected optimal grain size growth parameters: $\Delta T_n = 55 ^\circ C$, $\Delta T_o = 10 ^\circ C$ and $n_{\text{max}} = 4.7 \times 10^7 m^3$.

While analysing the results, it should be noted that the macrostructure obtained by the computer simulation method qualitatively coincides with the macrostructure of the real blank of the turbine blade obtained in the course of chemical etching. Characteristic columnar grains are distinguished in the blade airfoil region. The availability of parasitic grains (figure 5, a) as opposed to the macrostructure of real castings (figure 5, b), may be explained by the use of a complex mathematical model [12] in the CAFÉ calculation module of the ProCast software product and, as a result, a computer simulation error.

![Figure 5](image.png)

**Figure 5.** Comparison of the macrostructure of a turbine blade obtained in the course of numerical simulation with real casting: a – macrostructure obtained after computer simulation; b – macrostructure obtained after chemical etching.

5. Conclusion
A cycle of numerical experiments of the process for manufacturing the turbine blade castings (table 1) showed that at the pouring temperature of $1540 ^\circ C$, graphite flask pushing cycle of 12 min and the metal running cycle of 4, high quality of blade castings with regard to the macrostructure may be achieved in the PMP-2 discrete continuous unit with regard to the macrostructure at a minimum percentage of defects.

| Zone I, $^\circ C$ | Zone II, $^\circ C$ | Zone III, $^\circ C$ | Zone IV, $^\circ C$ | Zone VI, $^\circ C$ | Zone VII, $^\circ C$ | Zone VIII, $^\circ C$ | Zone IX, $^\circ C$ | Defect reduction, % |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-----------------|
| 1150              | 1330              | 1460              | 1450              | 1440              | 1380              | 1310              | 2                 |
| 1200              | 1270              | 1480              | 1500              | 1425              | 1420              | 1360              | 3                 |
| 1320              | 1400              | 1470              | 1500              | 1480              | 1410              | 1380              | 4                 |
| 1200              | 1265              | 1470              | 1510              | 1420              | 1400              | 1340              | 7                 |
| 1210              | 1290              | 1485              | 1540              | 1430              | 1420              | 1370              | 15                |
| 1350              | 1450              | 1510              | 1540              | 1490              | 1420              | 1360              | 30                |

Employing the developed user-defined functions allowed obtaining the dependence of the migration speed of graphite flasks in the PMP-2 furnace on time based on solving the temperature problem (figure 6). Using the obtained dependence in the real production conditions at the enterprise allowed to reduce the defects in manufacturing the 1st stage GTE turbine blade blanks by 30%.
Figure 6. Calculated time-temperature relationships in the PMP-2 unit zones.

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