Designing a duplicate model of the GTE turbine blade casting process

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Abstract. The work describes the results of developing a duplicate model of the gas turbine engine blade casting process. The work was based on the development of the digital “furnace-flask-filler-mould-metal-stopper” process system considering the geometrical, structural and thermophysical specifications of the turbine blade casting process. The industrial approbation of the developed process under the experimental production conditions exemplified by the manufacture of the GTE turbine moving blades demonstrated a 3- to 4-fold decrease in time of the blade blank manufacturing cycle due to the virtual multi-iteration optimization of the process.

1. Introduction
One of the most important tasks of digital simulation of technological processes is the complex research into the interconnected physical phenomena to minimize the production faults. The process of manufacturing the turbine blade castings is extremely unstable and is characterized by a great percentage of faults. In the first turn, it is related to the instability of process conditions. The application of computer simulation in this situation will allow reducing financial loses, since the optimization of temperature and velocity parameters is carried out without the use of real costly melts but by means of the multioptional numerical studies.

Presently, in designing of digital models applied while studying the casting processes a comprehensive approach is used which combines a number of disciplines: thermodynamics, hydrodynamics, theory of phase transformations, theory of heat and mass transfer. The works are devoted to building digital duplicate models describing the casting processes [1-7]. Despite of considerable achievements in computer simulation of casting processes, there is a need to develop an comprehensive holistic approach to studying particular casting processes for the efficient use of simulation in the industrial environment. A considerable lag in the development of computer simulation consists in its insufficient experimental and industrial verification. In theoretical studies, hypothesis and simplifications are frequently assumed which prevent from considering the multifactorial nature of the process and disregard the parameters which play a key role in the manufacture of castings. Therefore the purpose of designing, studying and adapting the multifactorial digital duplicate model for the turbine blade casting process, its verification and approbation in the experimental manufacture is a topical issue.
2. Description of the model

2.1 Physical model

The geometric and mathematical problem statement was considered in detail in the works [8]. This section will consider the problem statement from the physical point of view by representing the study object - turbine moving blade - as a temperature-time description.

Turbine blades are manufactured 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.

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. The furnace heating unit consists of 8 conditional zones forming 3 areas: a heating area (zone 1, 2); a melting area (zones 3, 4) and a crystallization area (zones 6 – 9). Each zone is characterized by a particular temperature. At the interface region of zones 4 and 6 (in a strictly defined point), the mechanical stopper device is activated allowing to open the runner with metal tapping to the mould in front of the crystallizer (figure 1 a and b).

![Diagram](image)

**Figure 1.** Time interpretation of PMP-2 furnace zones: a – heating of process system; b – metal tapping and crystallization.

G1 – free surface of ceramic mould; G2 – free surface of the seed; G3 – contact boundary of the seed and ceramic mould; G4 – ceramic mould surface in the heat field; G5 – free surface of metal; G6 – contact boundary between metal and ceramic mould; V1 – casting body area V2 – ceramic mould; V3
3. Boundary conditions

Simulation of the process of manufacturing of the GTE turbine moving blades with monocrystalline structure in the PMP-2 unit was performed in two stages. At the first stage, the process of furnace stabilization was simulated with the subsequent heating of a ceramic mould, resulting in the temperature distributions in the process system of “furnace-flask-filler-mould-metal-stopper”. At the second stage of simulation these data were used as the initial conditions for the selection of a temperature field in the crystallization zone.

In simulating the process of flask train movement in the furnace body, the most complex task is a reliable representation of the conditions of the radiation heat exchange in the metal heating and melting area and convective heat exchange in the crystallizer area. Due to the fact that the thermal condition of particular parts of the graphite flask during the thermal conduction is different, then in the general case the temperature $T$ will be the function of coordinates $x, y, z$ and time $t$, i.e. $T = f(x, y, z, t)$. Therefore, to avoid a large amount of experimental smelts in order to find the optimal parameters of the process, there occurred the need to develop the user functions to determine the ratio between the thermal condition of the unit zones and the moving velocity of the flask train in the furnace.

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 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 though the constant movement velocity of flasks were replaced by time values (figure 1 a and b).

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 occurred in a vacuum, therefore, the appropriate values of the emissivity factor and temperature were 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 heat-resistant casting alloy.

![Figure 2](image_url)

**Figure 2.** Diagram of boundary conditions: a – liquid metal - ceramic mould contact zone; b – hard metal - ceramic mould contact zone.

V2 – ceramic mould; V4 – hard metal; V5 – molten metal; G6 – contact boundary between metal and ceramic mould; G14 – the gap between hardened metal and ceramic mould.

The developed user functions allowing to define the temperature fields in the furnace-moulding flask-filler-metal-stopper process system during the directional crystallization are based on the
following assumptions: heat exchange processes in the mould are considered non-stationary, thermophysical properties of materials depend on the temperature; the crystallization process of heat resistant casting alloy is accompanied by the generation of latent heat of crystallization in the temperature interval from the liquidus temperature \((T_L)\) to the solidus temperature \((T_S)\); the outer surface of the mould does heat exchange due to radiation with the furnace body (boundary G4) and due to the convection in the liquid crystallizer (boundary G9); the gap occurred between the ceramic mould and crystallizing surface of the casting due to the alloy shrinkage (boundary G14, figure 2) is considered (boundary G14, figure 2).

4. Results and discussion

The numerical solution of the user functions 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 moulds to a more accurate degree. Figure 3 and 4 represent the simulation results for heating of the process system and selection of the temperature field in the crystallization zone. Crystallization of the central part of the airfoil is rather dynamic (figure 3). Provided this pattern of hardening, fine shrinkage porosity (macroporosity) is possible as a result of the volumetric crystallization phenomena. The airfoil crystallizes in a non-uniform manner resulting in the so-called peaks - elongated liquid metal sections. This adversely affects the crystallization process. Minor weaknesses and shrinkage porosity may be predicted in the upper shroud of the casting (figure 4). The simulation results were compared with the LUM testing data for the turbine moving blade casting. High degree of consistency of the results may be noted, which is a practical validation of the appropriateness of the developed digital duplicate model of the process for manufacturing the GTE turbine moving blade blanks.

![Figure 3. The pattern of crystallization process in the blade casting.](image1)

![Figure 4. The porosity and weakness distribution pattern.](image2)

The occurrence of porosity and weakness in the casting is the result of formation of heating units. The casting defect represented by weakness is conditioned by the concentration of fine (microscopic) shrink cavities, uniformly or non-uniformly located along the casting body. To avoid such defects, increase the heat treatment temperature of the furnace-moulding flask-filler-metal-stopper process system by increasing the temperature modes in the heating and melting zones of the casting unit. 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 area. The availability of parasitic grains may be explained by the use of a complex mathematical model [9] in the CAFÉ calculation module of the ProCast software product and, as a result, a computer simulation error.
5. Conclusions
A cycle of numerical experiments of the process for manufacturing the turbine blade castings showed that at the pouring temperature of 1540 °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 casting unit with regard to the macrostructure at a minimum percentage of defects (figure 5).

Figure 5. Castings of the GTE turbine moving blades obtained in the use of the developed digital duplicate model for the casting process in the industrial environment.

Employing the developed user-defined functions allowed obtaining the dependence of the migration speed of graphite flasks in the furnace on time based on solving of the temperature problem. 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%.

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