Improving the quality of the manufacturing process of turbine blades of the gas turbine engine

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Abstract. This paper describes the results of research and development work, which lead to an increase in the quality of the technological process of manufacturing the working turbine blades of a gas turbine engine. The mathematical description of the four-zone process of directional crystallization made it possible to select the most optimal thermophysical parameters of the casting process that affect the macrostructure of casting the blades. Digital modeling of casting technology, taking into account the proposed mathematical models, as well as the boundary, contact and initial conditions of the process, made it possible to most reliably describe the temperature front distribution in the crystallization zone at discrete points for any moment in any section. The temperature-time optimization of the technological process for casting turbine blades made it possible to select the optimal temperature conditions for the respective areas of the foundry plant, which ultimately allowed a 20% reduction in rejects associated with the mismatch of the macrostructure of castings the blades to the standard.

1. Introduction
The improvement of the technological process for the production of castings of critical parts, as well as the reduction of production costs for the development of technology and the production of the first set of castings for experimental products of new technology is an important scientific and technical task. The requirements are constantly increasing for both products of new technology in general and for its most important components - turbine blades, for the manufacture of which it is necessary to improve the quality of cast sections [1].

Currently, a single digital space is being formed at an increasing pace, covering both design engineering (CAD) and technological production (CAE systems) of experimental products. The increasing computing power of modern computer systems allows the numerical solution of the interdisciplinary problems of heat and mass transfer during crystallization of casting in a formulation that is as close as possible to real production conditions [2].

Effective application of digital modeling methods for process tasks in pilot foundry is impossible without a scientifically based methodology for designing casting processes [3, 4]. In practical terms, the use of digital modeling can significantly reduce the time required to master the production of pilot castings, as well as effectively apply modern technologies for technological preparation of production. In environmental terms, energy and material resources are saved, and harmful effects on the environment and humans are reduced.

2. Mathematics task assignment on casting blades
Due to the complex spatial shape and the lack of developed surfaces for accurate basing of the working blades, the most effective, and in some cases the only way to produce blade sections, is the method of making blade castings by single-crystal casting and subsequent mechanical processing of locking section and shroud flange by non-allowance machining of a profile of a feather [5 - 7].

The practice of manufacturing blades has shown that various casting defects are found: metal shrinkage, warpage in the crystallization process, shrinkage porosity, and others. They arise due to the inability to control the casting process at the micro level, which is associated with an insufficient level of knowledge about the process of crystallization of a single crystal.

Figure 1. Schematic image of the process of manufacturing blanks for working blades of a turbine engine with single-crystal casting: $V_1$ - the area of the body of casting; $V_2$ - a ceramic core; $V_3$ - seed; $V_4$ - a ceramic form; $V_5$ - the area of molten metal; $V_6$ - the area of graphite filler; $V_7$ - the area of graphite flask; $V_8$ - the area of furnace space; $V_9$ - side heaters; $V_{10}$ - foundry body; $V_{11}$ - bottom part of the (sub) foundry; $R_1$ - free surface of the ceramic core; $R_2$ - boundary of contact of the ceramic core and the ceramic mold; $R_3$ - boundary of contact of the ceramic core and the molten metal; $R_4$ - the free surface of the molten metal; $R_5$ - the free surface of the ceramic form; $R_6$ - the boundary of contact of the ceramic form and the graphite filler; $R_7$ - the boundary of contact of the ceramic form and the molten metal; $R_8$ - the free surface of the graphite filler; $R_9$ - the boundary of contact of the graphite flask and graphite filler; $R_{10}$ - the boundary of contact of the seed with the molten metal; $R_{11}$ - the boundary of contact of the seed with the ceramic form; $R_{12}$ - the free surface of the graphite flask; $R_{13}$ - free surface of side heater; $R_{14}$ - the boundary of contact of the graphite flask with the hearth bottom of the foundry; $R_{15}$ - free surface of the foundry installation; $R_{16}$ - the free surface of the casing of the foundry installation; $R_{17}$ - plane of symmetry.

In serial production, working turbine blades are manufactured in specialized plants, the principle of which is based on the fact that the ceramic mold with molten metal is moved along the water-cooled base perpendicular to the direction of crystal growth through the angular thermal front of the plant. The mathematical description of this process is based on the equations of heat and mass transfer, which are written in all zones and boundary conditions on the interface surfaces of the zones (figure 1).

In the process of solidification, it is customary to consider three zones: liquid, crystallization zone and solid. However, increasing requirements for crystal perfection and theoretical developments in the
field of the theory of casting formation allow to take into account the fourth zone — the cluster zone (Figure 1).

As a result of a thorough analysis of the temperature field in the foundry, a mathematical description of the directed crystallization technological process in which a cluster zone is present is proposed (table 1). In this case, the difference in physical constants in the liquid, cluster, two-phase, and solidified zones is taken into account, since thermal conductivity, specific heat, and density are a function of temperature [8].

Table 1. Mathematical models describing the processes in each installation zone.

| Zone | Temperature range | Balance equation for temperature |
|------|-------------------|---------------------------------|
| I – superheated melt zone | \([T_{\text{out}};T_L]\) | \[
\frac{\partial T}{\partial t} = A_1 \frac{\partial^2 T}{\partial x^2}
\]
| Boundary conditions (I – II zones) | | \[-\lambda_1 \frac{\partial T_1(x_i,t)}{\partial x} = -\lambda_2 \frac{\partial T_1(x_i,t)}{\partial x}; \quad T_1(x_i,t) = T_1(x_i,t) = T_L\]
| II – cluster zone | \([T_L;T_{cc}]\) | \[
\frac{\partial T_2}{\partial t} = A_2 \frac{\partial^2 T_2}{\partial x^2} + \frac{4\pi q}{c_2} \int_{a_0}^a da^3 V(a) f
\]
| Boundary conditions (II – III zones) | | \[-\lambda_2 \frac{\partial T_2(x_i,t)}{\partial x} = -\lambda_2 \frac{\partial T_1(x_i,t)}{\partial x} + L \rho_2 [1 - \psi(x_i,t)] \frac{\partial T_1}{\partial t}; \quad T_2(x_i,t) = T_1(x_i,t) = T_L\]
| III – two-phase zone | \([T_{cc};T_s]\) | \[
\frac{\partial T_3}{\partial t} = A_3 \frac{\partial^2 T_3}{\partial x^2} + \frac{q \rho_3 \partial \psi}{c_3 \rho_3} \frac{\partial T_3}{\partial t}
\]
| Boundary conditions (III – IV zone) | | \[-\lambda_3 \frac{\partial T_1(x_i,t)}{\partial x} = -\lambda_4 \frac{\partial T_4(x_i,t)}{\partial x}; \quad T_1(x_i,t) = T_4(x_i,t) = T_s\]
| IV – solidified melt zone | \([T_s;T_{cool}]\) | \[
\frac{\partial T_4}{\partial t} = A_4 \frac{\partial^2 T_4}{\partial x^2}
\]

The following notation is used in the mathematical model: \(i = 1\) – superheated melt zone, \(i = 2\) – cluster zone, \(i = 3\) – two-phase zone (overcooled melt zone), \(i = 4\) – solidified alloy zone; \(T\) – temperature, \(K\); \(t\) – time, \(s\); \(x\) – coordinate, \(m\); \(A\) – thermal diffusivity, \(m^2/s\); \(\lambda\) – thermal conductivity, \(W/(m\cdot K)\); \(\rho\) – density, \(kg/m^3\); \(c\) – specific heat, \(J/(kg\cdot K)\); \(q\) – specific heat of crystallization, \(J/kg\); \(a\) – cluster size, \(m\); \(f\) – distribution function; \(\psi\) – relative volume of solid phase.

The presented mathematical models allow us to determine the temperature gradient, as well as the actual crystallization rate. The results of computer calculations make it possible to determine the width of the two-phase zone, that is, the width of the liquid melt poured in portions at which a casting with the best characteristics will be formed [9, 10].

Based on the proposed mathematical model, a digital model is constructed that determines the temperature field distribution over the casting height at discrete points for any moment in any section.

3. Digital simulation results

A numerical solution of mathematical models in a three-dimensional formulation is presented in figure 2. It shows the boundary of the liquid phase during crystallization of the melt in ceramic form. The red color denotes the melt, and the gray color indicates the solid phase crystallized by 90%. These results allow us to conclude that the distribution of temperature fields in the casting of the blade is relatively uniform. The influence of the thermal unit in the feeder is observed, which leads to an increase in temperature in the body of the casting. Despite the uniform cooling of the block of castings of the blades, the temperature at the outlet edge changes directionally along the axis of the blade, which leads to the
formation of a temperature gradient and timely directed crystallization of the outlet edge compared to the rest of the casting body.

Figure 2. The pattern of distribution of the solid phase in the casting of the blade during crystallization at various points in time.

4. Discussions

The numerical experiments carried out in accordance with the developed mathematical models in the transition zones of the crystallization process made it possible to select the most optimal temperature conditions.

For the heating zone of the technological system, the casting unit - flask - filler - ceramic mold - metal - stopper, the temperature front should gradually increase from 1350°C to 1450°C for 6400 seconds.

For the melting zone of the pouring material, the temperature front should vary from 1510°C to 1540°C for 6400 seconds.

In the crystallization zone of the molten metal, the temperature front should be stable and equal to 1540°C for 3200 seconds and then gradually decrease to 1490°C during 3000 seconds. In the area of a water-cooled mold, the technological system is located for 6300 seconds with a smooth change in the temperature front from 1420°C to 1360°C.

Owing to the proposed temperature-time optimization of the crystallization process, it was possible to improve the quality indicators for the macrostructure of castings of working turbine blades (figure 3), give it a more uniform character and eliminate the presence of spurious grains [11, 12]. Figure 3a shows the macrostructure of the casting of the blade before using temperature-time optimization, and figure 3b after adjusting the temperature conditions.

Figure 3. Macrostructure of castings of working turbine blades of the 1st stage.
5. Conclusions
The developed temperature-time dependence in the form of mathematical models for each of the zones of the crystallization process made it possible to discretely describe the processes of the phase transition of the molten metal and select the optimal temperature conditions both in the working areas of the foundry plant and in the transition zones. The use of the calculated temperature conditions in production conditions resulted in reducing the defect by 20% due to the mismatch between the macrostructure of the castings of the blades and the standard. To assess the accuracy of manufactured products, the geometry of complex-profile surfaces was controlled. The control process took into account factors that affect the accuracy of measurements [13]. To assess the deviation of the shape and location of aerodynamic surfaces, common and specialized methods were used [14].

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