Development and verification of a mathematical model of heating after the metal sample transition to a liquid-solid state in the turbine blades casting process

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Abstract. The paper presents the results of the development of a mathematical model of the melting zone of a discrete-continuous casting installation, and also shows the verification of the results of computer modelling obtained using the developed mathematical model. An important feature of the developed mathematical model is the ability to calculate heat fluxes and temperature fields for all elements of the technological system furnace-flask-filler-mold-metal.

1. Introduction
Blanks of turbine rotor blades of gas turbine engines (GTE) and gas turbine plants (GTP) made of heat-resistant alloys, due to their developed geometric shape, high requirements for the accuracy of geometric dimensions, roughness and quality of the surface layer, can be obtained exclusively by casting with directional crystallization (DC). This method makes it possible to manufacture high-precision blades with a complex spatial shape and developed internal channels of the cooling system; with a minimum allowance or no allowance along the feather of the blade blank due to possible volumetric shrinkage and subsequent machining operations [1].

At the same time, the technological process of casting turbine rotor blades is one of the most complex, time-consuming and expensive methods. The technology of casting blades with a monocrystalline structure significantly increases the cost of the product and complicates the process of manufacturing the blades. Casting with directional crystallization either forms a columnar directional structure of grains, which excludes the appearance of transverse grain boundaries - stress concentrators, or forms a single monolithic crystal, increasing the mechanical characteristics of the blade.

Currently, the use of the DC method in the manufacture of GTE turbine rotor blades is one of the most effective methods. The use of this method makes it possible to improve the main performance characteristics on traditional high-temperature casting alloys of the ZhS class by eliminating the transverse grain boundaries and improving the metallurgical quality of the castings of the turbine blades [2, 3].

Thus, the method of directional solidification, due to the elimination of grain boundaries oriented perpendicularly to the main acting stresses in the blades, provides an increase in the main operational characteristics of heat-resistant alloys, first of all, long-term strength, ductility, and heat resistance.
In most cases, in the production of castings of GTE turbine rotor blades, vacuum melting units are used, heating in which is performed in electric resistance or induction furnaces. Equiaxial, more precisely, equiaxially textured, cast structure of blades is obtained using vacuum induction furnaces semi-continuous melting of molds (class UPPF-3), and blanks of blades with a longitudinally oriented columnar structure are obtained by casting with directional crystallization in continuous continuous-flow method vacuum furnaces (class PMP-2 and PMP-4), in installations of vacuum directional solidification (class UVNK-8P) or in the VIP-NK vacuum melting unit [4 - 7].

For the serial production of turbine blades, productive designs of continuous casting installations with a horizontal crystallization chamber are used, which have a capacity of about 350 blades per day. Such installations include continuous-acting PMP-1 and PMP-2 furnaces. Such high productivity is achieved by changing the technological system of heating and directional cooling of the mold.

In the central part of the PMP-2 installation, there is a working chamber consisting of three conventional zones: heating, melting and crystallization. On both sides of the working chamber, there are lock chambers that serve for automatic loading and unloading of graphite flasks without breaking the vacuum in it. According to the operating conditions of the foundry, the graphite flask is heated to a temperature of 1500–1520 °C throughout the entire volume until the metal crystallizes, being constantly heated to the same temperature. Therefore, the use of stubs made from a working alloy is excluded, since its melting point is lower than the heating temperature of the ceramic mold (1350 °C). For the operating conditions of the PMP-2 installation, stub crystals with a melting point above the melting point of the alloy are used.

2. Description of research models

The stage of the system heating process after the transition of the upper half of the metal sample to the liquid-solid state begins when the upper half of the metal sample reaches the temperature of its transition to the liquid-solid state and ends when the lower half of the metal sample reaches the same temperature. At the initial moment of this stage, the liquid-solid metal flows into the gap between the lower half of the sample and the bowl. Due to the small size of this gap, it is assumed that the temperature of the metal in the lower half of the bowl is equalized and becomes equal to \( T_{17.0}^{0} \) [8 - 10].

In connection with the filling of the gap between the bowl and the initial sample with metal, the heating scheme takes the form shown in the figure 1. At this stage of the process, the calculation formulas for the following heat fluxes and temperatures are changed.

In the calculations, the following assumptions were made.

It is assumed that the temperature of the furnace changes in time according to a linear law, which is determined by the temperature in the corresponding furnace hones and the speed of the train of the flasks. In principle, the intermittent movement of the flask train leads to an abrupt change in the furnace temperature at each moment of time when the flask is pushed. However, taking into account the relatively small value of each movement of the flask, the unevenness of the furnace temperature along the flask and the flow of heat over the flasks, this assumption gives a relatively small error. It is assumed that all thermophysical characteristics of the system are equal to their average value in the calculated temperature range and are constant values.

It is assumed that the initial temperature of the flask-form-metal-stopper system is 20 °C.
Figure 1. Scheme for calculating the heating of the flask-mold-metal-stopper system in the non-stationary temperature field of the furnace.

Based on preliminary calculations, a calculated time interval of $6 \times 10^{-1}$ seconds was adopted, which provides a sufficiently small value of the calculation error.

It is assumed that with contact heat transfer between different temperature zones of the system, the thermal resistance between these zones is determined by the distance between the centres of these zones, and the temperature between the centres of these zones changes according to a linear or logarithmic law (depending on the geometric shape of the calculated zones). However, if any of the zones is heated due to radiation coming from its surface, then the thermal resistance of this zone is determined by its entire thickness. When heat transfer between zones by radiation, it is assumed that the temperature in the entire volume of these zones is the same. Additional calculations have shown that with the available geometric and thermophysical characteristics of the system and a very small (only $6 \times 10^{-1}$ seconds) value of the calculated time interval, this assumption also provides a sufficiently small value of the calculation error.

Based on preliminary calculations, it was found that the heat fluxes along the side walls of the flask and the ceramic mold are much less than the heat fluxes going across these walls; therefore, the heat fluxes along the side walls were not taken into account in the calculations.

It is assumed that the vertical heaters of the furnace form a continuous plane, and that the heating of the flask lid due to radiation from the upper thermal insulation is much less than direct heating from the heater.

It is assumed that the transition of a metal from a solid-liquid to a liquid-solid state occurs in the middle of the crystallization temperature range (at 1330 °C). It is assumed that in the temperature range between the solidus and liquidus of the alloy, the heat spent on its melting is taken into account in the calculations as an additional heat capacity of the alloy.

Calculation of heat fluxes is carried out according to dependencies (1) - (15).
\[ Q_{4,i} = ε_{ii} \cdot C_0 \cdot \left[ \left( \frac{T_{2,i}^0}{100} \right)^4 - \left( \frac{T_{5,i}^0}{100} \right)^4 \right] \cdot H'_4 \cdot (τ_{i+1} - τ_i) \] (1)

\[ Q_{5,i} = ε_{ii} \cdot C_0 \cdot \left[ \left( \frac{T_{3,i}^0}{100} \right)^4 - \left( \frac{T_{8,i}^0}{100} \right)^4 \right] \cdot H'_5 \cdot (τ_{i+1} - τ_i) \] (2)

\[ Q_{6,i} = ε_{ii} \cdot C_0 \cdot \left[ \left( \frac{T_{4,i}^0}{100} \right)^4 - \left( \frac{T_{9,i}^0}{100} \right)^4 \right] \cdot H'_6 \cdot (τ_{i+1} - τ_i) \] (3)

\[ Q_{9,i} = \frac{T_{3,i}^0 - T_{17,i}^0}{D_{\lambda_{ME}}^2} \cdot \lambda_{ME} \cdot F_q \cdot (τ_{i+1} - τ_i) \] (4)

\[ Q_{10,i} = T_{6,i}^0 - T_{17,i}^0 \cdot 2 \cdot π \cdot \lambda_{KEP} \cdot h_{ME} \cdot \left( 1 - \frac{D_{\lambda_{ME}}^2}{D_q^2} \right) \cdot (τ_{i+1} - τ_i) \] (5)

\[ Q_{11,i} = \ln \frac{d_2}{d_1} \cdot \frac{1}{λ_{KEP}} \cdot 2 \cdot π \cdot h_q \cdot (τ_{i+1} - τ_i) \] (6)

\[ Q_{13,i} = ε_{ii} \cdot C_0 \cdot \left[ \left( \frac{T_{7,i}^0}{100} \right)^4 - \left( \frac{T_{10,i}^0}{100} \right)^4 \right] \cdot H'_3 \cdot (τ_{i+1} - τ_i) \] (7)

\[ Q_{14,i} = \ln \frac{d_2}{d_1} \cdot \frac{1}{λ_{KEP}} + \ln \frac{d_2}{d_9} \cdot \frac{1}{λ_{ME}} \cdot \frac{2 \cdot π \cdot h_{ME}}{2} \cdot (τ_{i+1} - τ_i) \] (8)

\[ Q_{16,i} = ε_{ii} \cdot C_0 \cdot \left[ \left( \frac{T_{13,i}^0}{100} \right)^4 - \left( \frac{T_{17,i}^0}{100} \right)^4 \right] \cdot H'_6 \cdot (τ_{i+1} - τ_i) \] (9)

\[ Q_{17,i} = \frac{T_{14,i}^0 - T_{17,i}^0}{\lambda_{CT} \cdot F_{CT} + 0.25 \cdot h_{ME} \cdot \lambda_{ME} \cdot F_{ME}} \cdot (τ_{i+1} - τ_i) \] (10)

\[ Q_{20,i} = \frac{T_0^0 - T_{17,i}^0}{\lambda_{KEP} \cdot F'_{\lambda_{KEP}} + 0.25 \cdot h_{ME} \cdot \lambda_{ME} \cdot F'_{\lambda_{ME}}} \cdot (τ_{i+1} - τ_i) \] (11)
\[ Q_{21,i} = e_i \cdot C_0 \cdot \left[ \left( \frac{T_{14,i}^0}{100} \right) - \left( \frac{T_{2,i}^0}{100} \right) \right] \cdot H_{21} \cdot (\tau_{i+1} - \tau_i) \] (12)

\[ Q_{25,i} = e_i \cdot C_0 \cdot \left[ \left( \frac{T_{4,i}^0}{100} \right) - \left( \frac{T_{8,i}^0}{100} \right) \right] \cdot H_{25} \cdot (\tau_{i+1} - \tau_i) \] (13)

\[ Q_{26,i} = \frac{T_{18,i}^0 - T_{19,i}^0}{\ln \frac{d_{2}}{d_{1}}} \cdot 2 \cdot \pi \cdot \lambda_{KEP} \cdot h_{ME} \left( \frac{D_{ME}^2}{D_{q}^2} - \frac{1}{2} \right) (\tau_{i+1} - \tau_i) \] (14)

\[ Q_{27,i} = \frac{T_{18,i}^0 - T_{25,i}^0}{\ln \frac{d_{2}}{d_{1}} + \ln \frac{d_{1}}{d_{0}}} \cdot 2 \cdot \pi \cdot h_{ME} \left( \frac{D_{ME}^2}{D_{q}^2} - \frac{1}{2} \right) (\tau_{i+1} - \tau_i) \] (15)

The calculation of temperature fields is carried out according to dependencies (16) – (21).

\[ T_{5,i+1}^{0} = \frac{Q_{4,i} + Q_{5,i} + Q_{13,i} + Q_{27,i} - Q_{9,i}}{C_{ME} \cdot \rho_{ME} \cdot F_{q} \cdot h_{q}^{\prime}} + T_{5,i}^{0} \] (16)

\[ T_{6,i+1}^{0} = \frac{Q_{9,i} - Q_{10,i}}{C_{KEP} \cdot \rho_{KEP} \cdot F_{p}^{\prime} \cdot h_{p}^{\prime}} + T_{6,i}^{0} \] (17)

\[ T_{7,i+1}^{0} = \frac{Q_{10,i} - Q_{15,i}}{C_{KEP} \cdot \rho_{KEP} \cdot F_{p}^{\prime} \cdot h_{p}^{\prime}} + T_{7,i}^{0} \] (18)

\[ T_{17,i+1}^{0} = \frac{Q_{9,i} + Q_{14,i} + Q_{20,i} + Q_{21,i} + Q_{37,i} + Q_{46,i}}{C_{ME} \cdot \rho_{ME} \cdot F_{q} \cdot h_{q}^{\prime}} + T_{17,i}^{0} \] (19)

\[ T_{18,i+1}^{0} = \frac{Q_{25,i} - Q_{26,i}}{C_{KEP} \cdot \rho_{KEP} \cdot F_{p}^{\prime} \cdot h_{p}^{\prime}} + T_{18,i}^{0} \] (20)

\[ T_{19,i+1}^{0} = \frac{Q_{26,i} - Q_{27,i}}{C_{KEP} \cdot \rho_{KEP} \cdot F_{p}^{\prime} \cdot h_{p}^{\prime}} + T_{19,i}^{0} \] (21)

3. Results

As a result of the calculation of the heating of the technological system, the following results were obtained: the first melting point of nickel (1453 °C) was reached by the fusible diaphragm. This happened 3597 seconds after the start of heating the flask and furnace. In this case, the distance from the mold box to the refrigerator is 1.07 m (a distance that is not a multiple of 0.2 m (the length of the mold box) is obtained because the movement of the mold box is considered continuous in the calculation). The furnace temperature in this place is 1472 °C. At this moment, the temperature of the retaining ring is 1441 °C, the average temperature of the metal is 1445 °C, the temperature difference between the upper and lower surfaces of the metal \( \Delta T_{0}^0 = 16 \) K. The heat flux between the diaphragm and the metal is directed from the diaphragm to the metal. The total amount of heat...
received by the metal sample through the upper and lower ends and the side surface is distributed as follows: 33.5 % flows through the upper end, 61.3 % through the side surface, and 5.2 % through the lower end. It should be borne in mind that the surface area of the end face of a metal sample with a diameter of \( 2 \times 10^{-2} \) m and a height of \( 1 \times 10^{-1} \) m is \( 28.2 \times 10^{-4} \) m\(^2\), and the area of the lateral surface of this sample is \( 188.5 \times 10^{-4} \) m\(^2\). Since the area of the lateral surface of the sample is 6.68 times greater than the area of its end, the amount of heat entering the sample through the unit area for the upper end is 3.68 times greater than for the lateral surface.

4. Conclusions

Thus, based on the calculations performed, the following conclusions can be drawn. In order for the temperature of the metal during draining to exceed the melting temperature of the diaphragm, it is necessary that the heating rate of the diaphragm and the retaining ring be less than the heating rate of the metal. The solution to this problem is possible in four main ways: the first is to reduce heat transfer to the diaphragm and retaining ring. The second way is to increase the heat capacity of the diaphragm and retaining ring. The third method is to increase the intensity of metal heating. The fourth method consists in the selection of the corresponding geometric and physical parameters of the form-metal-stopper system [11 - 12].

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