Conjugated Heat Exchange in Heat Treatment of Aluminum Ingots Simulation

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Abstract. Casting aluminum to obtain semi-finished products - round ingots, due to uneven cooling in the mold, leads to various defects that affect further machining. To eliminate such defects, heat treatment is carried out - homogenization annealing. One of the homogenization important stages is the cooling of the ingots after heating at a rate that does not lead to the ingot quenching. The cooling medium is air. Knowing the conditions of heat exchange between the cooling air and the high-temperature aluminum billet makes it possible to obtain the ingot’s necessary physical and mechanical properties. The article describes the developed mathematical model of conjugate heat transfer during homogenization annealing of aluminum ingot. It allows analytically calculating the temperature of the ingots depending on the cooling time. To verify the data obtained by the mathematical model, the conjugate heat transfer in the ANSYS program was simulated.

1. Introduction

Modern industry requires a large number of high quality aluminum products. One of the methods for their production is hot pressing from semi-finished products - round aluminum ingots obtained by continuous casting into a cooled crystallizer. As is known [16], when casting round aluminum ingots into a cooled mold, accelerated cooling of the ingots during casting leads to the appearance of a nonequilibrium structure, i.e. dendritic liquation, the appearance of micropores, cracks and non-castings, liquation influx. Such defects in ingots impair their quality, which is certainly revealed at the stage of pressing.

To eliminate them, heat treatment of the ingots is carried out. Heat treatment is one of the most energy consuming methods in heat technologies. Therefore, to reduce energy costs, it is necessary to optimize design factors. One of the types of heat treatment of aluminum ingots is homogenization annealing.

The cooling rate after homogenization is of great importance for the structure of the alloy. Slow cooling of the ingot after homogenization has time to decompose the solid solution of aluminum with alloying components. The alloy acquires increased plasticity and can deform at lower specific pressures and at high speeds. Upon rapid cooling of the ingot after homogenization above the transition temperature of the main alloying elements into a solid solution, the alloy is quenched. The ingot turns out to be more homogeneous and strong, which, on the one hand, contributes to obtaining higher mechanical properties of semi-finished products due to a homogeneous structure and an increase in the recrystallization temperature, and on the other hand, requires higher deformation forces. Thus, the cooling rate of the ingot after homogenization should not exceed the critical cooling
rate [17]. The cooling rate can be controlled in several ways, one of them is holding the ingots after homogenization in the cooling chamber.

For the specified physical and mechanical properties of the material of aluminum billets formation, it is important to know the conditions of heat exchange between the cooling medium and the high-temperature billet under unsteady cooling modes, depending on the thermophysical properties of substances, interaction conditions, geometry, process time and many other factors. The paper considers modeling of conjugate heat transfer between round aluminum ingots and cooling air in a cooling chamber.

2. Literature review
The solving conjugate problems of heat transfer during cooling of aluminum billets complexity is associated with the need to take into account the mutual heat exchange of bodies, taking into account the thermophysical properties of bodies, geometric dimensions, etc.

In the studies carried out, describing the numerical simulation of the flow of Newtonian liquids and gases in channels, the traditional formulation of the problem was adopted: a gas moves at a constant speed along a channel of constant cross-section. The gas temperature over the channel cross section is constant, the wall temperature is constant. The thermophysical parameters of the bodies do not change. Heat transfer is considered only in the transverse direction; boundary conditions of the third kind are set on the boundary of the bodies.

The temperature of the wall and gas was determined as a result of the joint solution of the equations for the gas and the solid wall; therefore, heat transfer was considered conjugate. The solution of the problem in this formulation was carried out to the solution at a constant temperature of the body of the equations of mass, momentum and energy, describing the state of the gas, without taking into account the thermal conductivity in the solid. Then, using the heat transfer coefficient calculated or obtained from the experiment, the heat conduction equation for the body was solved. An example of solving such problems is given in [1] [2].

The accepted assumptions do not describe the real physical picture of conjugate heat transfer, which can be obtained by jointly solving the equations of heat distribution in a gas flow and a solid together with the equations of gas motion. Such a solution would make it possible to obtain the regularities of the change in the temperature of a solid, both in time and in coordinates. The solution of such a problem is possible when the boundary conditions of the fourth kind are set at the interface between the rigid body and the air flowing around, i.e. when the temperature of the contacting surfaces is the same. The statement of problems of conjugate heat transfer for internal heat transfer is given in the works of G.A. Ostroumov, V.R. Shelyag [3] [4], for external flow around bodies in the works of A.V. Lykov, T.L. Perelman. [5] [6]

To solve the conjugate problems of heat transfer between solids and the flowing gas-liquid flow, it is necessary to solve a system of partial differential equations for both the solid and the flow. The solution of such problems is possible both by analytical [7,8,9] and by numerical methods [10,11,12,17,18,19]

3. Research problem statement
Let us consider the problem of formulating a mathematical model of unsteady heat transfer of an aluminum ingot in a cooling medium with specified external boundary conditions. The statement of the conjugate heat transfer problem includes a system of differential equations for aluminum ingots and washing air (2, 3), boundary conditions (4, 5), initial conditions (6, 7):

- heat transfer in solids is described by the differential equation of thermal conductivity Biot - Fourier. In general form, the equation has the form

\[ c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\lambda}{r} \frac{\partial T}{\partial r} + \frac{\partial}{\partial t} \left( \lambda \frac{\partial T}{\partial t} \right) \]  \hspace{1cm} (1)
Taking that \( c, \rho, \lambda = \text{const} \) from equation (1) under the condition that \( \alpha = \frac{1}{c\rho} \) we find

\[
\frac{\partial T}{\partial \tau} = \alpha \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)
\]

(2)

- differential energy equation for air

\[
\frac{\partial t_B}{\partial \tau} + \frac{W}{\rho} \frac{\partial t_B}{\partial x} = \alpha \frac{\partial^2 t_B}{\partial x^2}
\]

(3)

Border conditions:
- boundary conditions on the outer surface of the ingot, washed by air, implying that convective heat exchange occurs

\[
\left. \frac{\partial T}{\partial r} \right|_{r=r_i} = -\frac{\alpha}{\lambda} (T - t_B)
\]

(4)

- in the center of the ingot

\[
\left. \frac{\partial T}{\partial r} \right|_{r=0} = 0
\]

(5)

Initial conditions:
- temperature of aluminum ingots at the initial moment of cooling

\[
T \bigg|_{r=0} = T_0
\]

(6)

- temperature of the cooling air at the initial moment of cooling

\[
t_B \bigg|_{r=0} = t_B
\]

(7)

The heat transfer calculation scheme for the formulation of the problem described is shown in Fig.1.

![Figure 1. Heat transfer calculation scheme to the formulation of the problem in the system. Cooling air - aluminum ingots.](image)

The limitation of this formulation of conjugate heat transfer is the limitation on the cooling rate of the ingots - 70 °C / h in the temperature range 500 - 600 °C.

To simplify the task of conjugate heat transfer and obtain a solution available for use in practice in real production conditions, the assumptions described in [13] were adopted. Analysis of the accepted
assumptions and verification of one of them - the constancy of the air temperature within one ingot - in the ANSYS software package, made it possible to assert their correctness [14].

4. Theoretical part of the research

The described formulation of the problem of conjugate heat transfer between cooling air and aluminum ingots made it possible to obtain mathematical models of cooling both a separate ingot in a row and the entire row. The final mathematical model of convective heat transfer in the cooling chamber of the system aluminum ingots - cooling air is described by the following system of equations

\[
\begin{align*}
T_{B} &= T_{B(N-1)} + \frac{c_{pa} \cdot m_{pa}}{\varepsilon_{pa} \cdot e_{B}} \left( T_{(N-1)} - T_{B(N-1)} \right) - (T_{0} - t_{B1}) \exp(-4 \cdot B1 \cdot F_{0}) \\
T_{N} &= T_{B(N-1)} + (T_{0} - t_{B1}) \exp(-4 \cdot B1 \cdot F_{0}) \\
\frac{T}{\tau} &\leq T_{nom} \text{ in the temperature range } 500^\circ C - 300^\circ C
\end{align*}
\]

where the first equation describes the change in the cooling air temperature; the second is the change in the ingot temperature; the third is the limitation on the maximum ingot cooling rate, where \( T_{nom} \) is the maximum ingot cooling rate. Depending on the grade of the alloy, \( T_{nom} \) lies in the limit of 70-60°C.

The obtained mathematical model (8) makes it possible to analytically investigate the regularities of changes in the temperature of ingots and air during convective heat exchange in the cooling chamber, depending on operating and design factors. The operating factors influencing the rate of decrease in the temperature of the ingots and the time of their cooling are only the speed of movement (washing) of the cooling air. Ingot diameter and channel height are design factors. Using the obtained mathematical model (8), we investigate the nature of heat transfer during cooling of one ingot at constant design and operating factors. To verify the mathematical model, we will compare the numerical calculations for the proposed model for one ingot with the results of the solution in the ANSYS program. Let us check how the preservation of constant operating factors - the speed of the cooling air - affects the maximum cooling rate of the ingots. The following data were used for calculations: ingot diameter \( d = 0.24 \) m, cooling air velocity \( W = 1.1 \) m/s, channel height between ingots \( \delta = 0.24 \) m, aluminum thermal conductivity coefficient \( \lambda = 230\) W / m·°C, heat capacity \( c = 0.9\) kJ / kg·°C, the initial aluminum ingot temperature is 600°C, the initial cooling air temperature is 20°C. The heat transfer coefficient was determined by the criterion equation when washing the wave surface [15].

The cooling air flow rate was determined depending on the cooling air velocity \( W \) and the channel height \( \delta \).

We obtain the formula for the numerical calculation of the cooling rate using the equation describing the change in the temperature of the ingot in time. Differentiating in time, we obtain an expression describing the rate of cooling of the ingot in time

\[
\frac{dT}{d\tau} = -4 \cdot \frac{a \cdot d}{\lambda_{AL}} \cdot \frac{a}{d^2} \cdot (T_0 - t_B) \exp \left( -4 \cdot \frac{a \cdot d}{\lambda_{AL}} \cdot \frac{a \cdot \tau}{d^2} \right)
\]

To verify the cooling rates obtained by Eq. (9) in the ANSYS software package, a model of a coupled model was built using the ANSYS Fluent and Transient Thermal modules. The geometry of the computational model was built in the built-in ANSYS module - Design Modeler, which consists of two bodies: an aluminum ingot (bodi) and cooling air (fluid domain). To perform a numerical experiment, the computational mesh was generated in the ANSYS Meshing module. The problem was solved in a non-stationary setting, the boundary conditions were set: the initial ingot cooling temperature \( T_0 = 600\)°C, the cooling air temperature \( t_a = 20\) °C, the heat transfer coefficient \( a = 30\) W / m²·°C, the cooling air speed \( w = 1.1\) m / s.

Fig. 2 shows a three-dimensional temperature field calculated in the ANSYS program.
The obtained mathematical model (8) of cooling an aluminum ingot made it possible to obtain the values of the temperature of the ingot from the cooling time and to determine the cooling rate of one ingot according to equation (9). Similar data were obtained from the calculation of heat transfer in the ANSYS program. The results of changing the cooling rate for one ingot while maintaining a constant cooling air speed \( w = 1.1 \text{ m/s} \) are shown in Fig. 3.

**Figure 3.** The rate of ingot cooling change in time. 1 - cooling rate calculated according to ANSYS data, 2 - cooling rate calculated according to mathematical model data.

### 5. Conclusions

Fig. 3 shows the cooling rates of an aluminum ingot in time, calculated from the temperatures obtained from the ANSYS program (curve 1), and the temperatures calculated using the mathematical model (8) (curve 2). It can be concluded from Fig. 3 that even while maintaining a constant cooling air speed \( w = 1.1 \text{ m/s} \), the cooling rate at the initial moment of time exceeds the critical 70 °C / h, which will lead to the ingots quenching. This suggests that the cooling rate at the initial moment of time should be lower. Fig. 3 also shows that the discrepancy between the data obtained from the ANSYS program and calculated by the mathematical model is 50%. This discrepancy can be explained by the problem in a two-dimensional formulation considering and the accepted assumption that an aluminum ingot is a thermally thin body with the Biot criterion \( \text{Bi} < 0.06 \).

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