Cooling simulation of an aluminium ingot during heat treatment

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Abstract. This paper is devoted to the cooling process of aluminum ingots after heat treatment. The defects of semi-finished aluminum and methods for their elimination are considered. A mathematical model of cooling one aluminum ingot is presented.

1. Introduction
Currently, products from aluminum alloys are increasingly used. One way to manufacture such products is by hot pressing. Semi-finished products are aluminum ingots, obtained by continuous casting in a cooled mold. As is known [1], 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 segregation, the appearance of micropores, cracks, liquidation influx. Such defects in ingots worsen their quality, which will certainly be revealed at the pressing stage.

To eliminate such defects, the ingots are heat treated. Heat treatment is one of the most energy-intensive in thermal technology. The costs in the heat treatment process are influenced by many design factors. Therefore, to increase the energy efficiency of the process, optimization of design factors is necessary. One type of heat treatment is homogenization annealing.

The cooling rate after homogenization plays an important role in the alloy structure. Upon slow cooling of the ingot after homogenization, the solid solution of aluminum with alloying components decays. The alloy acquires increased ductility and can be deformed at lower specific pressures and at high speeds. Upon rapid ingot cooling after homogenization above the transition temperature of the main alloying elements into a solid solution, the alloy quenches. The ingot turns out to be more homogeneous and strong, which on the one hand contributes to obtaining higher mechanical properties of the semi-finished products due to the homogeneous structure and increase in the temperature of recrystallization, 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 [2].

The cooling rate regulation can be done in several ways, one of which is the aging of ingots after homogenization in the cooling chamber. The author proposed the design of a chamber with a convective method of cooling aluminum ingots with air.

One of the issues that arose during the design of the chamber was the determination of the total cooling time. For a theoretical calculation of the cooling time, it is necessary to develop a mathematical model of heat transfer between the ingot and the cooling medium.

Problem statement
This article discusses the mathematical model of a single ingot cooling. The ingots are cooled by air at a speed $W$, m/s. Cooled ingots are cylinders with a diameter 0.24-0.127 m. During cooling, the
temperature of the ingot decreases from initial $T_0$ to final $T_1$. The air during the heat exchange is heated from the initial temperature $t_w$ to the final $t_{w1}$.

The following assumptions are accepted:
1. when washing the ingot, the air temperature within this ingot, $t_w \approx \text{const}$,
2. the ingot is a thermally thin body ($Bi<0.5$), therefore, the temperature over the cross section of the ingot $t_v \approx \text{const}$.

As a result of such assumptions, the heat transfer picture will change (Figure 1). The ingot will cool from temperature $T_0$ to $T_1$, and the air temperature within the ingot will be constant $t_w \approx \text{const}$.

![Figure 1. Ingot cooling scheme](image)

The amount of heat $dQ_w$ that air will receive from the heated ingot during convection at $dt$

$$dQ_w = \alpha(t - t_w) \cdot F \cdot dt$$

(1)

where $\alpha$ - heat transfer coefficient from heated ingot to air, $t$ - current ingot temperature.

The ingot cools down during the same time $dt$ due to thermal conductivity for the same amount of heat

$$dQ_{\text{C,L}} = c_{\text{P,Al}} \cdot m_{\text{Al}} \cdot dt$$

(2)

where $dt$ - ingot temperature drop over time $dt$.

We compose the heat balance equation in time $dt$

$$-dQ_{\text{C,L}} = dQ_B$$

$$-c_{\text{P,Al}} \cdot m_{\text{Al}} \cdot dt = \alpha(t - t_w) \cdot F \cdot dt$$

(3)

Equation (3) is an ordinary differential equation with separable variables. We divide the variables and after a series of transformations we finally get

$$\frac{(T_1 - t_w)}{(T_0 - t_w)} = \exp(-Bi \cdot F_0 \cdot t)$$

Equation (4) is a mathematical model of cooling one aluminum ingot. Here $T$ is the final cooling temperature of the ingot, $T_0$ - is the initial cooling temperature of the ingot, i.e., the temperature at which the ingot begins to cool, $t_w$ - is the temperature of the cooling air, $F_0$ -is the Fourier criterion.

Figure 2 shows a graph of the temperature change of the aluminum ingot over time for the following initial data: initial temperature of ingot cooling $T_0=500^\circ\text{C}$, initial temperature of air heating $t_w=20^\circ\text{C}$, cooling time $t=11$ h, speed of cooling air $W=1,1 \text{ m/s}$.
Figure 2. The change in temperature of the ingot during cooling over time

Results verification

To verify the accepted assumption that the temperature of the cooling air is constant when washing the ingot, a study was made of heat transfer in the Ansys Fluent software package using finite element analysis methods. The geometry of the calculation model was built in the ANSYS module - Design Modeler, which consists of two bodies: an aluminum ingot (bodi) and cooling air (fluid domain). To perform a numerical experiment, a computational grid was generated in the ANSYS Meshing module. In the process of constructing the computational grid, the boundary layer was not taken into account - the grid construction function was not used in the inflation boundary layer. The problem was solved in the stationary formulation of Steady, a type of solver based on Pressure-Based pressure. Gravity was not taken into account when solving. A laminar model of the flow of cooling air was used, heat transfer between the ingot and air was taken into account by the energy equation. To solve the problem, the initial conditions were adopted: the initial temperature of the cooling air $t_0=20^\circ$C, the initial temperature of cooling of the ingot $T_0=600^\circ$C. The ingot temperature is taken constant to reduce the time it takes to solve the calculation model, as well as simplify the solution. For a more accurate solution, it is necessary to take into account the change in temperature of the ingot during cooling due to thermal conductivity using the Ansys Transient Thermal module. The boundary conditions for solving the problem were set: at the input (inlet) - type of the boundary condition velocity inlet 0.5 m/s, at the output (outlet) - type of the boundary condition pressure outlet.

The calculation results are presented in Figure 3 as a temperature loop.
Findings

Equation (4) allows one to study the heat transfer between cooling air and an aluminum ingot. In fact, the cooling chamber is designed to cool a large number of ingots, which are located in height in several rows. The width of the channel between the rows of ingots is one of the design factors, the optimization of which can reduce energy costs, in particular for electricity [3]. Equation (4) made it possible to obtain a heat transfer model for ingots rows. This model made it possible to optimize the channel width for conducting the cooling process of aluminum ingots with a minimum time [4].

References

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