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# Constructive factors optimization of the heat exchange model in the cooling chamber

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**Abstract.** The most common method for the production of aluminum products is hot pressing of semi-finished products - aluminum ingots obtained by continuous casting into the mold. This method leads to the formation of a heterogeneous structure. To eliminate this problem, heat treatment is applied, one of which is homogenizing annealing followed by cooling in the chamber. For the study of heat transfer between aluminum ingots and cooling coolant in the chamber, a mathematical model was developed. It showed that the cooling time of ingots in the chamber depends on structural and operational factors. This paper is devoted to the optimization of the design factors of the mathematical model of heat transfer in the cooling chamber of aluminum ingots. The issues of optimization criteria are considered, the objective function is defined with restrictions on the set of feasible solutions of the function.

## 1. Introduction

Currently, products from aluminum alloys are increasingly used. One of the methods of manufacturing such products is hot pressing. Semi-finished products for them are aluminum ingots, obtained by a method of continuous casting into a cooled mold. As is known [1], with this method of casting, accelerated cooling of ingots leads to the appearance of a non-equilibrium structure, i.e. dendrit segregation, the appearance of micropores, cracks and nestlin, segregation flows. Such defects in ingots impair their quality, which will certainly become clear at the pressing stage. To eliminate such defects, heat treatment of ingots carried out, one of the stages of which is cooling in special chambers.

## 2. Relevance

Heat treatment of ingots is carried out in gas convective furnaces. One of the important stages of heat treatment is the cooling of ingots after homogenizing annealing. The effect of cooling rate on the structure and properties of ingots is described in detail in [2]. The use of existing cooling modes does not provide an equal ingot cooling rate, which leads to rejection. Also, the existing cooling modes do not take into account the geometry of the cages and cooling chambers [3].

Therefore, the improvement of the process of cooling aluminum ingots, which ensures an equal cooling rate, is an urgent task that ensures the quality of the products.

## 3. Setting the research task

In order to conduct a heat transfer study, a mathematical model of convective heat exchange between aluminum ingots and cooling air taking into account the influence of structural (height between rows of ingots, diameter of ingots) and regime (cooling air speed) factors was developed. The description of the



mathematical model, the assumptions made in this case are described in detail in [4]. The mathematical model developed allowed the study of heat transfer in the cooling chamber with constant and variable structural and operational factors [5,6].

Studies of the influence of structural factors described in [7] showed that the main factor influencing the heat exchange process in the cooling chamber is the width of the channel between the rows of aluminum ingots  $\delta$ . To determine the optimal channel width, it is necessary to optimize the design parameters.

#### 4. Theoretical part

Complex optimization has the goal to obtain the most advantageous regime and design factors and determine the optimal cooling time for ingots. To optimize design factors, it is necessary to compose a target function, a set of feasible solutions to the problem of the target function, and optimization criteria.

To compose the objective function, we use the multiplicative convolution method [8]. It consists in replacing frequent criteria  $K_i$  with one common criterion  $K$ .

$$K(x) = \prod_{i=1}^n K_i^{a_i}(x), \quad (1)$$

where  $K(x)$  – the general criterion,  $K_i^a(x)$  – the set of particular criteria,  $n$  – the number of partial criteria,  $a_i$  – the relative weight (importance) of the particular criterion  $K_i(x)$ . For weights, the normalization condition  $\sum_{i=1}^n a_i = 1$  must be met. The best solution meets the maximum of the general criterion.

The choice of multiplicative convolution is explained by the multicriteriality of our objective function, and also by the fact that the optimization criteria are mutually independent in importance [9].

The criteria to be optimized for the case will be considered. Based on the analysis of the study of the mathematical model, it can be concluded that the main factor influencing the cooling process is the channel width. The width of the channel determines the overall size of the tank according to the height of the cooling chamber. Increasing the channel width favorably affects the ingots cooling process, leads to a lower final temperature of the ingots, but at the same time reduces the total weight of the charge, which reduces productivity.

Reducing the width of the channel leads to an increase in the final temperature of the ingots, but increases the weight of the charge. This allows you to process a larger number of ingots, improve productivity. Reducing the width of the channel will lead to the fact that the height of the charge will decrease, and not occupy the entire height of the cooling chamber. This will result in empty space at the top of the camera.

Due to the lack of resistance, the cooling air will escape into this space, cooling the cage only along the edge. To eliminate this drawback, it is necessary to increase the hydraulic resistance of this space. This can be done by installing a metal box.

Thus, the width of the channel  $\delta$  directly affects the mass of the charge  $M_{al}$ .

Load mass  $M_{al}$  is the first optimization criterion  $M_{al}=K_1(x)$ . It is necessary to strive to increase it, so that the width of the channel  $\delta$  is greatest and the installation of a metal box is not required.

We define the first optimization criterion  $K_1(x)$ . The mass of the charge is determined by the expression

$$M_{al} = m_1 \cdot n \cdot z, \quad (2)$$

where  $m_1 = \frac{\pi d^2}{4} \cdot l \cdot \rho_{al}$  – the mass of one ingot,  $n=A/d$  – the number of ingots in a row,  $A$  – the width of the charge,  $z = \frac{h+\delta}{d+\delta}$  – the number of rows in height,  $h$  – the height of the charge.

In this way,

$$M_{al} = \frac{\pi d^2}{4} l \cdot \rho_{al} \cdot \frac{A}{d} \left( \frac{h+\delta}{d+\delta} \right) = \frac{\pi}{4} l \cdot \rho_{al} \cdot A \cdot d \left( \frac{h+\delta}{d+\delta} \right). \quad (3)$$

From the analysis of expression (3) it follows that for an ingot of one diameter, the changing parameter that affects the optimization criterion is only the width of the channel  $\delta$ . Consequently,

$$M_{al} = \frac{\pi}{4} l \cdot \rho_{al} \cdot A \cdot d \left( \frac{h+\delta}{d+\delta} \right) = K_1(\delta), \quad (4)$$

Where  $\delta$  – an optimized parameter.

The second optimization criterion is the total cooling time of the ingot  $\tau_c$ , i.e.  $K_2(x) = \frac{1}{\tau_c}$ . The total cooling time of the ingot  $\tau_c$  is not affected by the width of the channel  $\delta$  and determined only by the diameter of the ingot and the required final temperature of the ingot. Lower ingot temperature requires a long cooling time and increases the cost of electricity. In addition, the cooling time in any case should not exceed the heat treatment time in the homogenization furnace. The second optimization criterion  $K_2(x)$  defined. Using the mathematical model of ingot cooling [1] to determine the cooling time presented

$$\frac{(T_\kappa - t_B)}{(T_0 - t_B)} = \exp(-Bi \cdot Fo \cdot 4). \quad (5)$$

The cooling time from it is got. When logarithmizing and transforming (5) we got

$$\tau_c = -0,25 \cdot c_{Pal} \cdot \rho_{al} \cdot d \cdot \frac{1}{\alpha(\delta)} \ln \frac{(T_f - t_a)}{(T_0 - t_a)} = \frac{1}{K_2(\delta)}. \quad (6)$$

After determining the optimization criteria, it is necessary to determine the relative weight (importance)  $a_i$  of each particular criterion. In our case, both particular criteria are equally important, since It is important to have minimal cooling time and greater productivity, i.e. mass. There fore  $a_1=a_2=0.5$

The target function

$$K(\delta) = K_1^{\alpha_1}(\delta) \cdot \frac{1}{K_2^{\alpha_2}(\delta)} = \frac{K_1^{\alpha_1}(\delta)}{K_2^{\alpha_2}(\delta)} \quad (7)$$

Optimization criteria are substituted

$$K(\delta) = -1,76 \frac{\left( \pi \cdot l \cdot A \left( \frac{h+\delta}{d+\delta} \right) \right)^{0,5}}{\left( c_{Pal} \cdot \frac{1}{\alpha(\delta)} \ln \frac{(T_f - t_a)}{(T_0 - t_a)} \right)^{0,5}} \quad (8)$$

Expression (8) is a zero-order objective function that has a set of feasible solutions, in the following constraints:

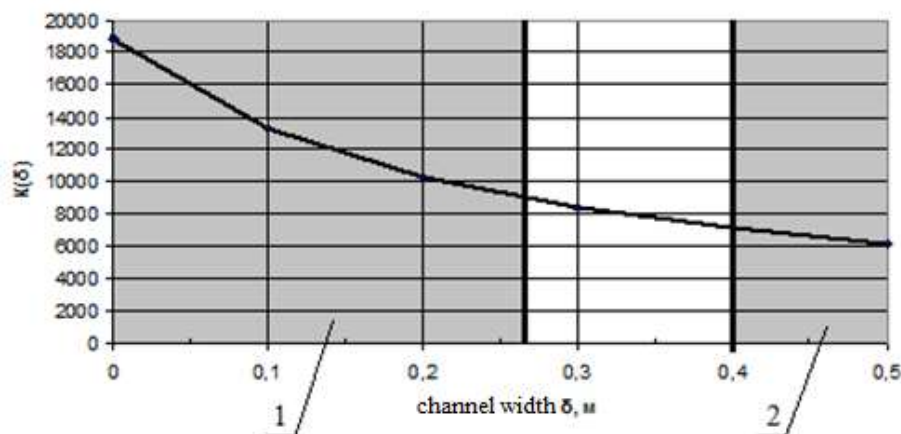
- the speed of the cooling air should not exceed 15 m/s.
- the weight of the charge, which should not exceed 20 tons, in order not to exceed the loading capacity of the loading machine.

Thus, the objective function of optimization of design factors can be written with restrictions in the following form

$$\begin{cases} K(\delta) = -1,76 \frac{\left( \pi \cdot l \cdot A \left( \frac{h+\delta}{d+\delta} \right) \right)^{0,5}}{\left( c_{Pal} \cdot \frac{1}{\alpha(\delta)} \ln \frac{(T_f - t_a)}{(T_0 - t_a)} \right)^{0,5}} \rightarrow \max. \\ 0 < w < 15 \text{ m/s} \\ M_{al} \leq 20 \text{ t} \end{cases} \quad (9)$$

Optimization of the system of equations (9) is a linear single-factor problem, which can be solved by using numerical methods of unconditional optimization. In our case, the method of coordinate descent (Gauss-Seidel) is chosen.

Figure 1 presents the results of optimization of design factors for an aluminum ingot  $d=0.24\text{ m}$ . When optimizing, the following initial data are used: set width  $A=2.5\text{ m}$ , set height  $h=2.0\text{ m}$ , length of ingots  $l=8\text{ m}$ , initial temperature of cooling air  $t_a=20^\circ\text{C}$ , initial temperature of cooling of ingots  $T_0=500^\circ\text{C}$ , final temperature of cooling of ingots  $T_f=60^\circ\text{C}$ . The heat transfer coefficient  $\alpha$  was determined depending on the set value of the channel width  $\delta$  and air velocity  $w$ .



**Figure 1.** Dependence of the objective function of the channel width  $\delta$  for ingot  $d=0.24\text{ m}$ .

## 5. Practical significance

Figure 1 shows the dependence of the objective function on the parameter being optimized — the width of the channel  $\delta$ , for an ingot  $d=0.24\text{ m}$ . As noted above, the objective function has limitations on the width of the channel  $\delta$ : in terms of the speed of the cooling air  $0 < w, \text{ m/s} < 15$  and in the mass of the load  $M_a \leq 20\text{ t}$ . In fig.1 these restrictions are shown by areas "1" and "2". The area "1" shows the values  $\delta$  at which the speed of the cooling air exceeds the values  $15\text{ m/s}$ , which increases the power of the blowing devices and increases the cost of electricity. Increasing the speed of cooling air, as noted in [10], will lead to the hardening of aluminum ingots. Area "2" shows the values  $\delta$  at which the mass of the charge exceeds the maximum possible. The optimum is the largest value of the channel width from the specified area for each ingot. With this value, a large, but not the maximum possible, mass of the charge and a lower cooling air velocity had.

## 6. Summary

The search for the most optimal ratios of the constructive factors of the mathematical model of convective heat exchange made it possible to determine the optimal height of the channel between ingots with a diameter  $d=0.24\text{ m}$ . A similar study can be conducted for ingots of any diameter.

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