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FORECASTING THE STRUCTURE OF LARGE-SIZED FLAT PLATES FROM ALUMINUM ALLOYS

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ABSTRACT

This article presents an engineering technique for predicting the size of a grain in a large-sized flat ingot made of aluminum alloy cast in a semi-continuous way, taking the real physical and chemical properties of the alloy and the modifier into account. The comparison of calculation results according to the proposed method with studies of the macrostructure of an ingot manufactured in the industrial conditions of UC RUSAL confirmed the possibility of its application with a sufficient degree of accuracy to determine the ingot structure and assess the modifying capacity of the applied modifier taking into account the real properties of the alloy.

Keywords: ingots from aluminum alloys, semi-continuous casting, method of grain size determination.

INTRODUCTION

An essential part of the overall foundry production of aluminum alloys is the preliminary casting of large-sized flat ingots for flat steel manufacturing. For this reason, excluding the given chemical composition, ingots should have a high density in the solid state and an increased plasticity which is ensured by the uniform fine-grained crystal structure. Otherwise, a large grain in ingots results in the anisotropic properties of deformable semi-finished products and an increase in rejects due to cracks [1- 3]. One of the most effective, simple and reliable methods of grain refinement in world practice is the application of seeding modifiers containing heat-resistant dispersed particles (usually Al-Ti-B systems), which are potential centers of aluminum alloy crystallization. The introduction of modifiers changes the crystallization process which enables the achievement of a fine-grained homogeneous structure, a decrease in gas porosity, and the improvement of the mechanical and technological properties of the alloy [4]. Generally, the structure of aluminum alloy castings and ingots in production is determined by many factors, the most important of which are the rate of cooling and crystallization, the actual chemical composition of the alloy and the modifier, the quantity of the modifier [5, 6]. For this reason, the production of large-sized ingots from aluminum alloys with ensured refinement of an as-cast grain continues to be a crucial production task at the present stage of preliminary casting, especially during the manufacturing of deformable semi-finished products for aerospace engineering.

DEVELOPMENT OF AN ENGINEERING TECHNIQUE FOR GRAIN SIZE DETERMINATION IN A LARGE-SIZED FLAT INGOT MADE OF ALUMINUM ALLOY

The research of the aluminum alloy modification process will be most reliable if it is carried out directly on samples cut out of the commercial ingot. However, the high cost, labor intensity and responsiveness of the given method for large-sized flat ingots allow for its usage only in exceptional circumstances. For this reason, ALCAN-TEST (TP-1) [7] is applied in order to assess the modification process, which allows only for the qualitative assessment of the modifying capacity of the applied modifier, but does not take the real rates of ingot cooling and crystallization into account and does not allow the prediction of the resulting structure. The device developed by the authors of the present article is free from the above mentioned deficiencies [8]. The known methods of computer modeling allow the evaluation of almost any process. However, a problem arises related to the necessity of additional accurate information about the real physical and chemical conditions for the process of ingot casting which may differ from melt to melt to a certain extent. All of these factors lower the accuracy and efficiency of performed computer calculations. In this regard, an engineering technique for predicting the structure of ingots is proposed, which is performed by means of semi-continuous casting, taking the design and process parameters and casting properties of the cast alloy into consideration. The given technique is the symbiosis of analytical and experimental approaches.

The characteristic feature of the semi-continuous ingot casting process is the melt movement in relation to the fixed casting mold. At the same time, the melt sump remains stationary at the established stage of the process. The sizes of a sump are practically independent of variations of alloy and modifier chemical composition, and are dictated by design and process casting conditions. If the sump volume is divided into reference zones (Figure-1), it is possible to determine the cooling rate v_o for each zone with the following formula:

$$v_o = \frac{\Delta T\left(z_i\right)}{\Delta z_i} \cdot v_л \quad , \tag{1}$$

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where $\Delta T_z = T_л - T_s$ is the temperature gradient in the vertical direction for zone i;

Δz_i is the sump height in zone i; $v_л$ is the ingot casting rate.

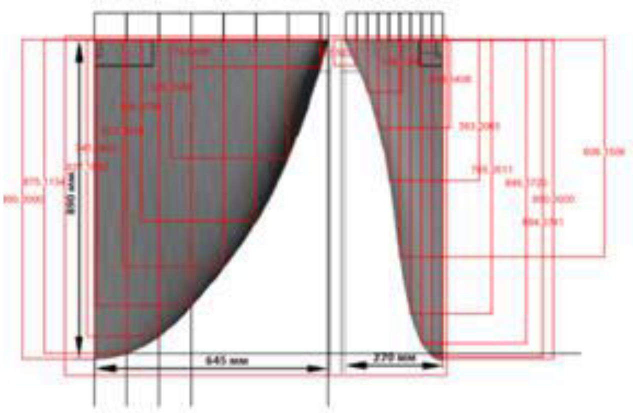

Figure-1. Sump profile in two mutually perpendicular planes for a flat ingot (S.V., the red color in the diagram should probably be changed, otherwise it will blend into the gray color in the journal when published, and nothing will be discernible).

The following values of semi-continuous flat ingot casting process parameters were accepted for the calculation of sump sizes and prediction of alloy grain structure:

- the alloy chemical composition was consistent with grade 5083 according to EN 485-2 2007 (the foreign analogue of the *AMg 4.5* alloy according to GOST 4784-97 [9]);
- the casting rate is 60 mm/min;
- the temperature of the melt in the mixer is 720±5°C;
- the temperature of the melt in the tray upstream to the foundry table is 700±5°C;
- the size of the Wagstaff casting mold is 560x1630 mm [10];
- the applied modifier is *AlTi5B1* (manufactured by KBM Affilips) with a flow rate of 2.5 kg/t with the following quantitative composition of intermetallic compounds in an alloy bar with a diameter of 9.5 mm:
- Al_3Ti (particle sizes from 3÷132 µm) - with a volume ratio of 8.03 %;
- TiB_2 (particle sizes from 3÷5 µm) - with a volume ratio of 16.92 %.

Changes in cooling rates were determined for each zone (refer to Table-1). Then, the thermal conditions of crystallization for laboratory samples of the studied alloy were determined within the set range of cooling rates of selected ingot zones. Samples had the same chemical composition and were obtained with the use of a treatment for the melt with a similar modifier for modeling the thermal conditions of crystallization during large-sized ingot casting. The casting form for sample casting was manufactured from copper of grade and is presented in Figure-2.

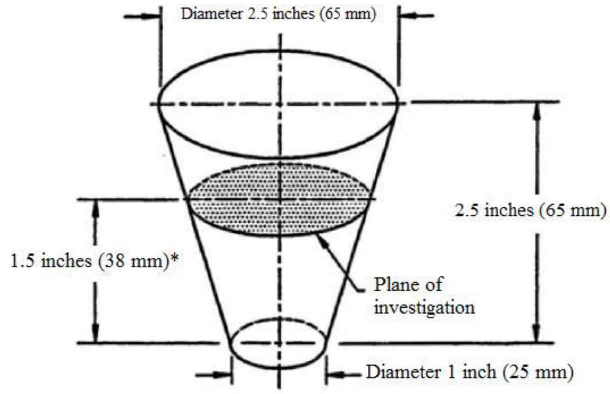

Figure-2. Casting form for sample casting.

To modeling the real thermal conditions during the crystallization of each zone of a large-sized ingot and laboratory samples, casting forms were heated to various temperatures with the help of the device [8], and the temperature of sample casting corresponded to the temperature of large-sized ingot casting. In order to ensure the accuracy of laboratory studies, the modeling of thermal conditions of crystallization was performed for each mode of laboratory sample casting with the help of ProCAST software system.

MODELING RESULTS

Results of modeling in accordance with the proposed engineering technique are given in Figure-3.

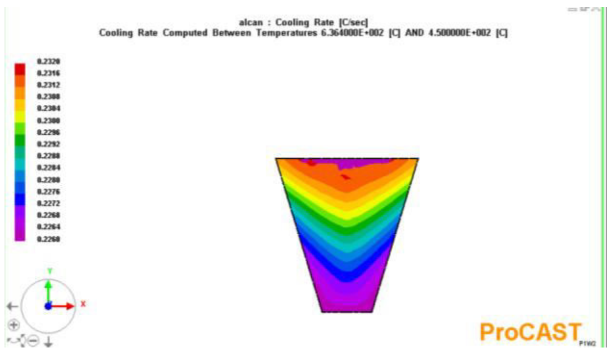

Figure-3. Temperature change on the vertical section of the laboratory sample during its crystallization.

For the laboratory sample investigation (Figure-4), the amount of grains $n_з$ and average grain size $d_з$ were determined in the cross section by means of the intercept method using the following formula:

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$$d_з = \sqrt{\frac{4F_{обр}}{\pi n_з}}, \quad (2)$$

where

$F_{обр}$ is the investigated area of a laboratory sample, mm^2;

$n_з$ is the amount of grains in the investigated area of a laboratory sample.

Figure-4. Experimental structure of the laboratory sample cross section.

Russian and foreign researchers have established [1, 2, 11-13] that the unequivocal dependence of average grain linear dimensions on the cooling rate (modification equation) is obtained within the range of sizes in which ingots and castings are made from aluminum alloys under industrial conditions:

$$d_з = K_м / v_o^{n_м}, \quad (3)$$

where $d_з$ is the grain size; K_M and $n_м = 0,3 \div 0,5$ are empirical coefficients;

v_o is the cooling rate.

Then, the empirical coefficients of the modification equation were determined (3). Let us assume that for one cooling rate v_{o1} of the laboratory sample the average grain size is $d_{з1}$, and for the other cooling rate v_{o2} the grain size is $d_{з2}$ respectively. It is necessary to determine empirical coefficients for the modification equation for the given alloy.

We perform the following system of equations:

$$\begin{cases} d_{з1} = K_м / v_{o1}^{n_м} \\ d_{з2} = K_м / v_{o2}^{n_м} \end{cases} \quad (4)$$

After several transformations, we get the solutions of the given system of equations:

$$n_м = \frac{\ln\left(d_{з2}/d_{з1}\right)}{\ln\left(v_{01}/v_{02}\right)}; \qquad К_м = d_{з1} v_{o1}^{n_м} = d_{з2} v_{o2}^{n_м} \quad (5)$$

With the help of the obtained modification equation for a certain alloy, it is possible to predict the grain size in the volume of a large-sized ingot cast by means of continuous casting, considering the design and process parameters and casting properties of the cast alloy, as well as to assess the modifying capacity of various modifiers under conditions similar to industrial ones. Furthermore, the modification equation allows us to solve the inverse problem, i.e. to calculate the cooling rate or the casting rate for obtaining the grain of the required size:

$$v_o = \sqrt[n_м]{K_м / d_з} \quad (6)$$

The results determining grain sizes according to the established engineering technique of predicting ingot structure were compared with the results of metallographic examination of the commercial ingot samples (Table-1).

Table-1. Grain sizes obtained as a result of the engineering technique of predicting ingot structure and as a result of metallographic examination.

Cooling rate v_o,˚C/s	**0.17**	**0.23**	**0.34**	**0.65**	**2.2**	**5.5**
Temperature for heating casting form for sample casting, ˚C	500	400	300	200	100	20
Average grain size, $d_з$, μm (metallographic investigation)	198	171	152	146	138	130
Average grain size, $d_з$, μm (engineering method of prediction)	182	138	127	116	109	96

According to Table-1, the results of grain size investigation obtained with the engineering technique and with metallographic examination differ by 8…26%, with calculation error increasing from the middle of the ingot to its edge - from 8÷12% to 23÷26%. Computer modeling undoubtedly allows us to perform all calculations more accurately, but additional experimental investigations are required to take the real physical and chemical properties of the melt and the modifier and significant timing for numerical calculation into account [14-19]. The proposed engineering technique is free from these disadvantages. The given technique will allow prompt prediction of the ingot structure with the sufficient degree of accuracy, and the assessment of the modifying capacity of the applied modifier for the commercial alloy. If necessary, the process engineer can adjust the casting process during melting.

CONCLUSIONS

As a result of the investigations performed, an engineering technique has been developed for the determination of grain size in a large-sized flat ingot made of aluminum alloy, cast in a semi-continuous way. The technique takes the real physical and chemical properties of the alloy and the modifier into account, as well as the design and process conditions of casting. The comparison of calculation results according to the proposed technique with studies of the macrostructure of an ingot manufactured under the industrial conditions of UC RUSAL has proved the possibility of applying this technique for determination of ingot structure and assessment of the modifying capacity of an applied modifier, taking the properties of the alloy and casting conditions into account.

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